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STO TECHNICAL MEMORANDUM **TM-AVT-ET-194**

Mobility Assessment Methods and Tools for Autonomous Military Ground Systems

(Méthodes d'évaluation de la mobilité et outils destinés aux systèmes terrestres militaires autonomes)

This report documents the findings of AVT's Exploratory Team 194.

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Editors: Michael Letherwood and Paramsothy Jayakumar

The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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2-D	Two-Dimensional
3-D	Three-Dimensional
AASHTO	American Association of State Highway and Transportation Officials
ABM	Automatic Brake Modulator
ABS	Anti-Lock Braking System
AC	Air Conditioner
ALFUS	Autonomy Levels for Unmanned Systems
AMC	Army Materiel Command
AMSAA	Army Materiel Systems Analysis Activity (United States)
ANCF	Absolute Nodal Coordinate Formulation
AOPM	AMSAA Optimal Path Model
API	Application Program Interface
ARL	Army Research Laboratory
ASA	Advanced Science and Automation
ASME	American Society of Mechanical Engineers
ATV	All Terrain Vehicle
AVT	Applied Vehicle Technology (Panel)
AWD	All Wheel Drive
BRDF	Bidirectional Reflectance Distribution
BW	Bekker-Wong
C2	Command and Control
CAD	Computer-Aided Design
CAE	Computer Aided Engineering
CFD	Computational Fluid Dynamics
CG	Center of Gravity
CGS	Coarse Grained Soil
CH	Clay, High Plasticity
CI	Cone Index
CL	Clay, Low Plasticity
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
CRREL	Cold Regions Research and Engineering Laboratory
CSO	NATO Collaboration Support Office
CTIS	Central Tire Inflation System
CTS	Combinatorial Trade Study
CVT	Continuously Variable Transmission
DEM	Digital Elevation Model
DEM	Discrete Element Method
DFARS	Defense Federal Acquisition Regulation Supplement (United States)
DIL	Driver In the Loop
DIS	Dynamic Interactions Simulator
DOD	Department of Defense (United States)
DOE	Design of Experiment
DOS	Disc Operating System

DP	Drawbar Pull Force
DRI	Discrete Roughness Index
DTED	Digital Terrain Elevation Data
DTM	Digital Terrain Model
DVI	Digital Visual Interface
ERDC	Engineer Research and Development Center
ESC	Electronic Stability Control
ET	Exploratory Team
FANG	Fast Adaptable Next-generation Ground Vehicle
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Model
FFT	Fast Fourier Transform
FGS	Fine Grained Soil
FMI	Functional Mock-up Interface
GCW	Gross Curb Weight
GIS	Geographical Information System
GOTS	Government Off-The-Shelf
GP	Gaussian Process
GPGPU	General Purpose Graphics Processing Unit
GPU	Graphics Processing Unit
GUI	Graphical User Interface
GVW	Gross Vehicle Weight
HGTM	High-Resolution Ground Vehicle and Terrain Mechanics
HIL/HITL	Hardware In The Loop
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HPC	High-Performance Computing
IMU	Inertial Measurement Unit
INRMM	Initial NATO Reference Mobility Model
ISO	International Organization for Standardization
ISTVS	International Society for Terrain-Vehicle Systems
IT	Information Technology
IVRESS	Integrated Virtual Reality Environment for Synthesis and Simulation
IVT	Infinitely Variable Transmission
Lbf	Pounds-force
LETE	Land Engineering Test Establishment
LIDAR	Laser Imaging Detection and Ranging
LVSR-TD	Logistics Vehicle System Replacement – Technology Demonstrator
M&S	Modeling and Simulation
MAN	Maschinenfabrik Augsburg Nürnberg
MBD	Multibody Dynamics
MEDEVAC	Medical Evacuation
MGRS	Military Grid Reference System
MIT	Massachusetts Institute of Technology
MMP	Mean Maximum Pressure
MOE	Measures of Effectiveness
MOP	Measures of Performance

MOUT	Military Operations on Urbanized Terrain
MPCTD	Marine Personnel Carrier Technology Demonstrator
MSIE	Modeling and Simulation Integrating Environment
NAAG	NATO Army Armament Group
NAFEMS	National Agency for Finite Element Methods and Standards
NASA	National Aeronautics and Space Administration (United States)
NATC	Nevada Automotive Testing Center
NATO	North American Treaty Organization
NG-NRMM	Next Generation NATO Reference Mobility Model
NORMMS	NATO Operational Reference Mobility Modeling Standards
NRCS	Natural Resource Conservation Service
NRMM	NATO Reference Mobility Model
NRMM (H)	NG-NRMM for Manned Vehicles
NRMM (I)	NG-NRMM for Intelligent Vehicles
NTU	Number Terrain Unit
NTVPM	Napean Tracked Vehicle Performance Model
NVH	Noise, Vibration and Harshness
OBSDP	Obstacle Crossing Module, Double Precision
ObsMod	Obstacle Crossing Module
OEM	Original Equipment Manufacturer
OGC	Open Geospatial Consortium
ONR	Office of Naval Research
OSRF	Open Source Robotics Foundation
OWL	Web Ontology Language
PID	Proportional–Integral–Derivative
PSD	Power Spectral Density
Q&A	Question and Answer
R&D	Research and Development
RCI	Rating Cone Index
RFI	Request for Information
RMS	Root Mean Square
ROS	Robot Operating System
RSM	Research Specialists' Meeting (STO)
RTG	RTO Task Group
RTO	NATO Research and Technology Organization
RWS	Research Workshop (STO)
SAE	Society of Automotive Engineers
SIL	Software in the Loop
SLA	Short Long Arms (Suspension)
SLAMD	System Level Analysis Mobility Dashboard
SMG	Speed Made Good
SPH	Smoothed Particle Hydrodynamics
SRS/PVSS	Shock Response Spectra/Pseudo Velocity Shock Spectra
STO	NATO Science and Technology Organization
TAP	Technical Activity Proposal
TARDEC	Tank Automotive Research, Development and Engineering Center
TBD	To Be Determined

TCS	Traction Control System
TMC	Technical Management Committee
TTCP	Technical Cooperation Program
U.S. /USA	United States of America
UDF	Universal Disk Format
UGV	Unmanned Ground Vehicle
UMM	Urban Maneuverability Model
UQ	Uncertainty Quantification
USCS	Unified Soil Classification System
USDA	United States Department of Agriculture
USGS	United States Geological Survey
V&V	Verification and Validation
VCI	Vehicle Cone Index
VEHDYN	Vehicle Dynamics Part of NRMM Code
VI	Vehicle Intelligence
VSDC	Vehicle System Dynamics and Controls
VTI	Vehicle Terrain Interface; Vehicle Terrain Interaction
WES	Waterways Experimental Station
WG	Working Group
WNS	Wave Number Spectra
XML	Extensible Markup Language Extension

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Mobility Assessment Methods and Tools for Autonomous Military Ground Systems

(STO-TM-AVT-ET-194)

Executive Summary

Recognizing the need for autonomous ground systems to operate in the unknowns of a mission, the North Atlantic Treaty Organization, or NATO, is making investments in ground vehicle autonomous mobility modeling and simulation to improve and prepare for future off-road operations. NATO engineers and scientists from around the world are working diligently and purposefully to shape future operational capabilities and, as a ground force, remain ready and resilient. As NATO looks to the future, there is an opportunity for the ground vehicle community to help shape the unique role of land forces in achieving national and international security objectives. As intelligence, surveillance, target acquisition, and reconnaissance capabilities are rapidly developing, assured autonomous mobility and operation becomes even more important. NATO's future force must be able and ready to be called upon for a variety of missions in extreme conditions so it must be ready to apply land power/ground forces toward achieving strategic outcomes across the full range of military operations.

Autonomous ground systems are a key part of the future military strategy for many NATO nations, and commercial companies are racing to develop autonomous systems to be first to market. In this race to field these systems, there is still a lack of understanding of the capabilities and reliability of these systems. One key performance measure of autonomous ground systems is their mobility on- and off-road. Development and deployment of autonomous weapons systems generally point to several military advantages such as acting as a force multiplier, and, more importantly, may require fewer warfighters for a given mission. Unlike commercial autonomous systems, the military must operate in unknown and unstructured environments where roads may not exist, but the supplies must reach the front lines. On the battlefield, mobility is the key to survivability, and it is crucial for commanders to know which vehicle to deploy on what terrain. Commanders need to have the ability to assess their own and opposing forces vehicle mobility in the area of operations, which will increase confidence in mission planning and reduce the risk of mission failures due to compromised vehicles.

An Exploratory Team (ET) was assembled and comprised of subject matter experts from eleven (11) NATO nations which were brought together to explore methods and approaches to assess the performance and reliability of autonomous ground systems and, more importantly, cultivate a strategy to develop an overarching framework to develop, integrate, and sustain advanced manned and autonomy-enabled ground system capabilities for the current and future force. This activity leveraged results from AVT-ET-148, AVT-248 and AVT-CDT-308 on the Next-Generation NATO Reference Mobility Model (NG-NRMM) and, together, they demonstrated that autonomous vehicles have specialized modeling and simulation requirements with regard to mobility. Subsequently, task areas were developed and teams assembled to work on:

- Challenges and special requirements for M&S of autonomous military systems;
- Definitions related to autonomous military systems;
- Current software available for assessing the mobility of autonomous systems;
- Approaches to assessing the interdependence of mobility with communications with data; and
- Building on NG-NRMM AVT-248 results to determine approaches for assessing off-road mobility of autonomous systems.

This effort has delivered a document providing a concise summary of existing capabilities, planned future activities on the subject, and strategic direction for the follow-on Research Task Group (RTG). This summary report will detail those accomplishments and provide recommendations for the development and implementation of an autonomous navigation framework. The ET follow-on activity will be an RTG which will work on this cooperative research project through the 2020 – 2023 timeframe.

Méthodes d'évaluation de la mobilité et outils destinés aux systèmes terrestres militaires autonomes

(STO-TM-AVT-ET-194)

Synthèse

L'Organisation du Traité de l'Atlantique Nord reconnaît la nécessité de systèmes terrestres autonomes pour intervenir lorsqu'une mission implique des conditions inconnues. L'OTAN investit donc dans la modélisation et simulation de la mobilité autonome des véhicules terrestres afin d'améliorer et préparer les futures opérations tout terrain. Les ingénieurs et scientifiques de l'OTAN du monde entier travaillent avec rigueur et détermination dans le but de créer de futures capacités opérationnelles et de maintenir la préparation et la résilience de la force terrestre. À l'avenir, l'OTAN décèle une opportunité pour la communauté des véhicules terrestres d'aider à façonner le rôle unique des forces terrestres dans la réalisation des objectifs de sûreté nationale et internationale. Les capacités de renseignement, surveillance, acquisition d'objectifs et reconnaissance évoluant rapidement, il est d'autant plus important de disposer d'une mobilité et d'un fonctionnement autonomes garantis. La future force de l'OTAN doit être capable d'intervenir et prête à intervenir dans diverses missions terrestres en conditions extrêmes, afin d'obtenir des résultats stratégiques dans tout l'éventail des opérations militaires.

Les systèmes terrestres autonomes sont une pièce essentielle de la future stratégie militaire de nombreux pays de l'OTAN et les entreprises commerciales se dépêchent de mettre au point des systèmes autonomes pour être les premières sur le marché. Dans cette course à la commercialisation, la compréhension des capacités et de la fiabilité de ces systèmes fait encore défaut. Une mesure de performance clé des systèmes terrestres autonomes est leur mobilité sur route et tout terrain. La mise au point et le déploiement de systèmes d'arme autonomes visent généralement à offrir plusieurs avantages militaires, tels que servir de multiplicateur de force et, plus encore, réduire le nombre de combattants nécessaires à une mission donnée. À la différence des systèmes autonomes commerciaux, les systèmes militaires doivent fonctionner dans des environnements inconnus et non structurés, lorsqu'il n'y a pas forcément de route, mais que le ravitaillement doit atteindre les lignes de front. Sur le champ de bataille, la mobilité est essentielle à la capacité de survie et il est crucial que les commandants sachent quel véhicule déployer sur quel terrain. Les commandants doivent avoir la capacité d'évaluer la mobilité de leurs propres véhicules et de ceux des forces opposées dans la zone d'opérations, ce qui augmentera la certitude pendant la planification des missions et réduira le risque d'échec des missions à cause de véhicules compromis.

Une équipe exploratoire (ET) composée de spécialistes de onze (11) pays de l'OTAN a été constituée. Elle avait pour but d'étudier les méthodes et démarches d'évaluation des performances et de la fiabilité de systèmes terrestres autonomes et, plus important encore, de définir une stratégie pour mettre au point un cadre général permettant de développer, intégrer et soutenir des capacités de système terrestre perfectionné avec et sans pilote, pour la force actuelle et future. Cette activité a utilisé les résultats de l'AVT-ET-148, l'AVT-248 et l'AVT-CDT-308 sur le modèle de mobilité de référence de nouvelle génération de l'OTAN (NG-NRMM) et a démontré que les véhicules autonomes avaient des besoins spéciaux de modélisation et simulation de la mobilité. Par la suite, des domaines de travail ont été définis et des équipes ont été assemblées pour étudier :

- les défis et besoins spéciaux de M&S des systèmes militaires autonomes ;
- les définitions liées aux systèmes militaires autonomes ;

- les logiciels actuellement disponibles pour évaluer la mobilité des systèmes autonomes ; et
- les démarches d'évaluation de l'interdépendance de la mobilité avec les communications et les données et pour s'appuyer sur les résultats de l'AVT-248 sur le NG-NRMM afin de déterminer des démarches d'évaluation de la mobilité des systèmes autonomes tout terrain.

Ces recherches ont abouti à la rédaction d'un document fournissant un résumé concis des capacités existantes, des futures activités planifiées sur le sujet et de l'orientation stratégique du groupe de recherche (RTG) de suivi. Le présent rapport abrégé détaille ces réalisations et propose des recommandations pour l'élaboration et la mise en œuvre d'un cadre de navigation autonome. L'activité de suivi de l'ET sera un RTG qui travaillera à ce projet de recherche collaborative entre 2020 et 2030.

Chapter 1 – INTRODUCTION / OBJECTIVES / BACKGROUND

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1.1 INTRODUCTION

For ground autonomous mobility, it has been shown that autonomous ground vehicles have the potential for superior mobility over tele-operated vehicles and NATO is implementing a roadmap towards assessing autonomous mobility through M&S. It is developing an understanding of how to leverage autonomy and autonomous systems – understanding not only the technological value of these new capabilities, but also how the off-road mobility has a huge impact on successful autonomous operation and mission completion. Modernization efforts of NATO Nations' militaries involve the integration of communications and control technologies, which is called autonomous technologies, to provide greater operational capability. Autonomous operations, in general, have the potential to significantly reduce costs and improve understanding of current and future autonomous system performance. One example is that autonomous systems and autonomy-enabled manned ground platforms are enabling capabilities that provide force multiplication (Figure 1-1) to warfighting functions.

Figure 1-1: Utilizing Autonomous Systems as Force Multipliers (Unmanned Smaller Vehicles).

Mobility is regarded as a vital component of autonomy. These capabilities are major objectives of NATO's research and development programs as it continues to collaborate with its' partner nations to integrate technologies and develop advanced capabilities that improve warfighter effectiveness and efficiency. The emergence of intelligent ground vehicles and their dependence upon quantitative analysis of mobility has infused terrain vehicle systems M&S with a new relevance and broader scope than ever before. Mobility metrics and analysis for robotics and Vehicle Intelligence (VI) is a very active and prolific research area and is an essential element of M&S from two application perspectives:

1) Inclusion of robotics and VI in mobility metrics and assessments for operational planning, acquisition, and design; and
2) Embedding M&S models and metrics into robots and VI algorithms because they are standards for mobility assessment and decision making.

Also, propagation of variabilities of input parameters to mobility, such as Speed-Made-Good (SMG), are critical for generation of stochastic mobility maps. The intent is to generate models and data products for predicting autonomous vehicle performance that can be used to plan and execute desired mission scenarios over specified regions. How fast can the system move and how reliably can it reach its destination under a wide range of conditions? How well can these autonomous systems maneuver with soldiers under a variety of operations? How are these measures defined? These are important topics that need to be addressed in order to fully field and operationalize these new technologies. Beyond operational use, these capabilities can be used for autonomous vehicle development as well as the acquisition process.

Specifically, this report will address the challenges and special requirements for modeling and simulation of autonomous military systems, definitions related to autonomous military systems, current software available for assessing the mobility of autonomous systems, approaches to assessing the interdependence of mobility with communications with data, and demonstrate the use of NG-NRMM AVT-248 results to determine an approach for assessing off-road mobility of autonomous systems.

1.2 OBJECTIVES

The overall objectives of this activity were to explore the methods and approaches to assess the mobility performance and reliability of autonomous ground systems. Specifically:

- Identify the challenges and special requirements associated with modeling and simulation of autonomous military systems.
- Determine the current state-of-the-art software for assessing the performance (mobility) of autonomous military systems.
- Leverage the results from other existing and related NATO STO and TTCP activities with collaboration from multiple nations and tri-services interested in this topic area.

A secondary objective was to include assessment approaches of current ground platforms in NATO, both from an acquisition and operational perspective.

1.3 BACKGROUND

The current mobility assessment methodology is called the NATO Reference Mobility Model (NRMM) and is a simulation tool aimed at predicting the capability of a vehicle to move over specified terrains and has no ability to assess autonomous vehicle capabilities. It is empirically based and developed using decades-old data and technology, but it is also broadly understood to be theoretically limited and difficult to adapt to contemporary vehicle design technologies and to implement within modern vehicle dynamic simulations. To address the problem, a NATO RTG AVT-248 committee was established in 2016, which consisted of 70 members from 15 nations, to develop a Next Generation NATO Reference Mobility Model (NG-NRMM) which is defined to be any M&S capability that predicts land and amphibious vehicle mobility through coordinated interoperation of Geographic Information Systems (GIS) software and multibody, physics-based vehicle dynamics M&S software. NG-NRMM is a new capability that lacks extensive experience and maturity, and its' development involves rapidly evolving technologies and scope. The physics of vehicle-terrain interaction is better understood today due to the advancement of M&S capabilities. As depicted in Figure 1-2, the goal is to place the physics-based mobility software at the center of the geospatial terrain data and soil maps so that mobility performance metrics such as a Go/No-Go map (which will be explained later) can be derived. This mobility metric can be used in the acquisition process and in operational planning as is done today using NRMM.

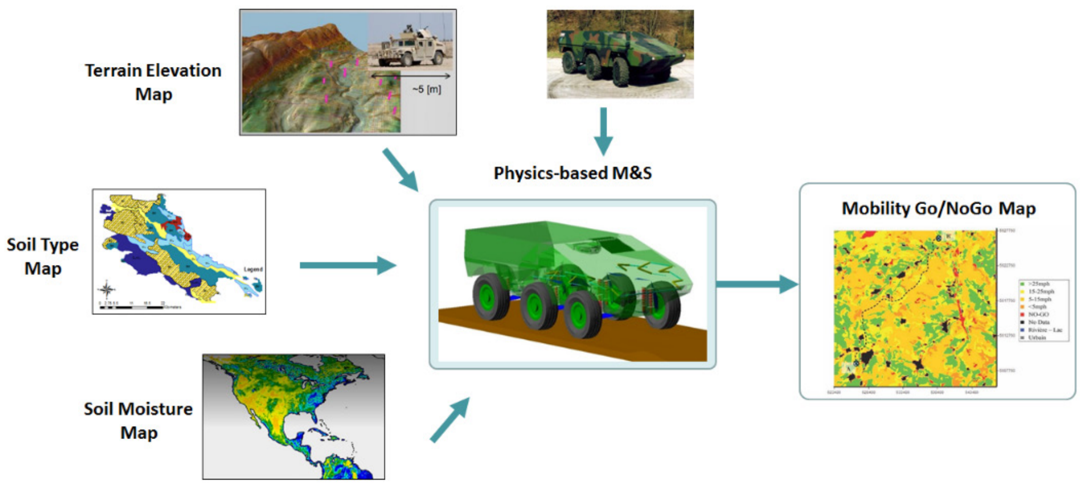


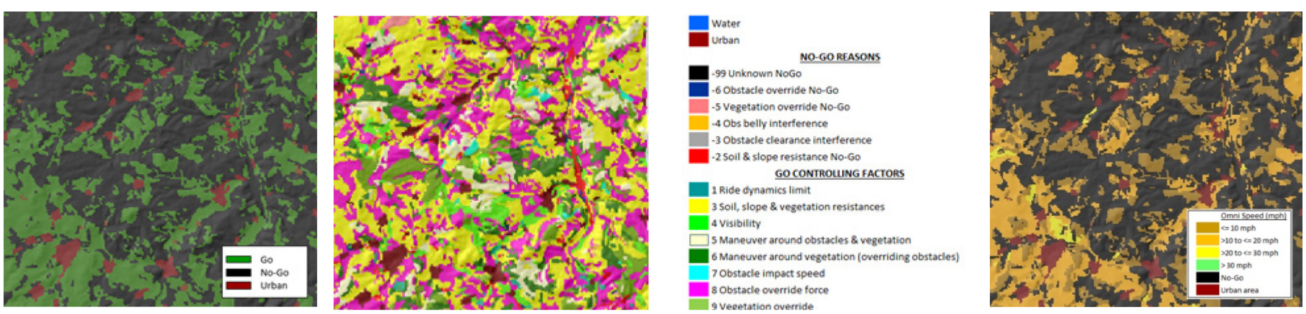
Figure 1-2: NG-NRMM Terramechanics Modeling.

The M&S software must be capable of utilizing terramechanics to properly assess vehicle-terrain soft soil interactions, incorporate capabilities to portray autonomous control systems, as well as include Uncertainty Quantification (UQ) to enable probabilistic M&S. Terramechanics modeling is focused on vehicle-terrain interaction that accounts for soft soil (i.e., deformable soil) effects on mobility. NG-NRMM has the potential to significantly reduce procurement risks enabling alternative solutions to be considered and will also provide operational decision makers with a tool for assessing their own and opposing vehicle mobility in the area of operations, which will increase confidence in mission planning and reduce the risk of mission failures due to compromised vehicles. The vision is to reach a point where nearly all virtual prototyping and operational effectiveness can be determined up front leading to rapid fielding of technology with a clear understanding of the operational capability of the technology. The goal of NATO's M&S investments is to minimize the need to build physical prototypes, and to fill the gaps in mobility M&S capabilities especially for autonomous operations.

NG-NRMM will not be a specific computer code but a set of NATO standards and benchmarks spelled out in a STANdardization RECommendation (STANREC) which is a NATO non-binding standardization document defining processes, procedures, terms, and conditions for common military technical procedures or equipment between the member countries of the alliance. The objective of the AVT-327 NATO effort is to implement the development of a prototype NG-NRMM involving several areas of effort including:

- Integration of GIS-based terrain data and implementation of mobility mapping metrics into mobility simulation software.
- Identification of vehicle-terrain interaction models.
- Development of in-situ and real-time measurement tools to identify required terrain parameters.
- Integration of terramechanics models into modern vehicle dynamic simulation software, and development of efficient, automated tools that will enable the use of high performance computational techniques.
- Identification of the type and form of desired responses, to yield rich mobility predictions and useful auxiliary outputs.
- Development of stochastic mobility outputs by embedding stochastic terrain and vehicle data.

NG-NRMM software tools must be capable of predicting a real vehicle's mobility results on any given terrain map to support operational analysis and mission planning purposes, to include selecting the optimum vehicle path on a terrain map based on the mission requirements. It must also be capable of replicating the existing NRMM output products which includes Go/No-Go trafficability and Speed-Made-Good (SMG) maps as well as speed limiting reason codes and single-pass/multi-pass results. The output results are in two categories – Go areas and No-Go areas. Go/No-Go maps identify areas where the modeled vehicle can and cannot go. The Go areas are usually portrayed as "green" areas on the map, while No-Go areas are normally portrayed as either "red" or "black" (as seen in Figure 1-3(a)). In this example, the "Urban Areas" are also identified since the cross-country prediction modules for NRMM ignore them.



(a) Go/No-Go Map. **(b) Go/No-Go Reason Code Map.** **(c) SMG Map Example.**

Figure 1-3: Go/No-Go Trafficability and Speed-Made-Good Maps.

NG-NRMM must also generate a list of "reason codes" that provide further insight into the causes behind a vehicle's immobilization as shown in Figure 1-3(b). These additional insights can shape route planning, choice of a vehicle for a selected mission, and inform vehicle acquisition / modernization decisions. Example reason codes include: inability to negotiate/overcome obstacles; inability to negotiate vegetation; and inability to overcome soft soil/slope resistances. Lastly, as depicted in Figure 1-3(c), NG-NRMM must be capable of predicting maximum safe speed for each terrain unit. SMG maps enable users to quickly and easily determine the best areas to conduct operations. Other newly desired output metric capabilities also included generating results for vehicle stability/handling, urban maneuverability, path modeling, fuel consumption/range estimation, and rut depths created.

NG-NRMM is intended to expand the basis of the legacy NRMM to define innovative M&S mobility capability that develops and facilitates interoperation with current and evolving M&S capabilities including: GIS, physics-based vehicle dynamics and terramechanics, vehicle intelligence, autonomous navigation, and UQ supporting probabilistic M&S. Figure 1-4 depicts the flow of data through the NG-NRMM analysis process.

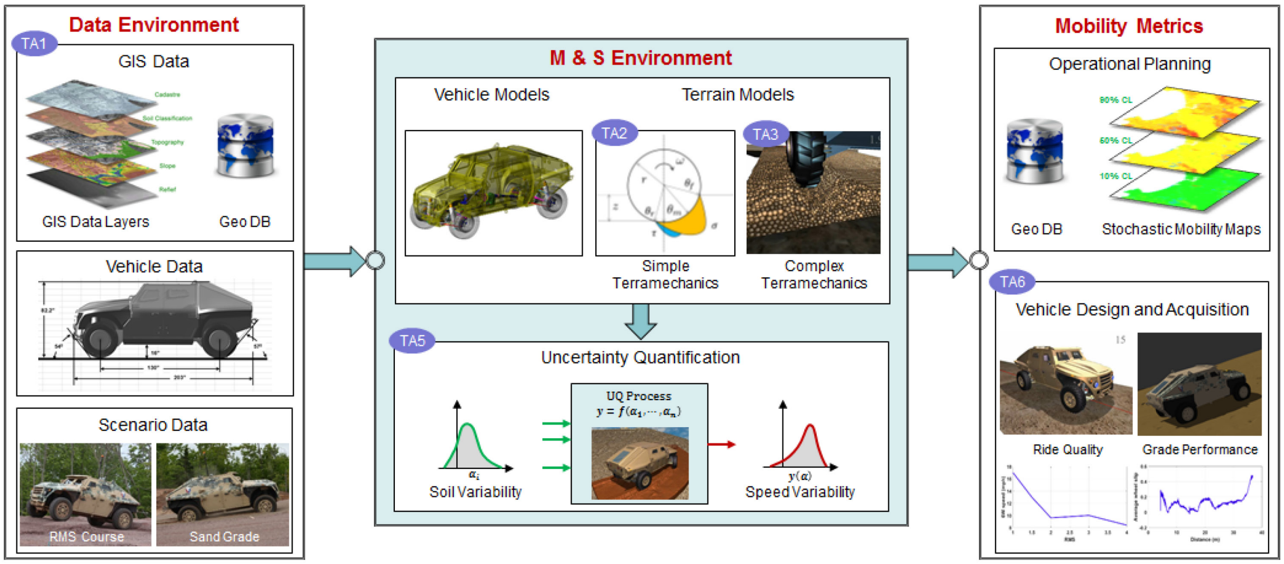


Figure 1-4: NG-NRMM Software Architecture.

First, GIS data is collected and aggregated into a file geodatabase using standard GIS tools and processes. Properly characterizing terrain is critical to generate accurate, operationally-relevant ground vehicle performance results using NG-NRMM. In order to achieve this, the NG-NRMM imports and aggregates remotely-sensed GIS data and generates terrains that can be analyzed in the NG-NRMM vehicle/terramechanical analysis software. The data in the file geodatabase are processed to generate the terrain properties needed by the multibody, physics-based vehicle dynamic M&S software. High fidelity physics-based vehicle dynamics are critical to evaluating more accurately the system and sub-system level performance criteria and Vehicle-Terrain Interaction (VTI). At the same time, capturing the accurate soil mechanical properties such as internal friction and cohesion are critical for evaluating soft soils and for VTI and this is possible with physics-based terramechanics modeling. The Multibody Dynamic (MBD) vehicle M&S software executes vehicle runs using the terrain files and generates results for each terrain unit. NG-NRMM compliant software preserves the spatial orientation of the data by linking the results to the original terrain file. Using GIS software, the data can now be visualized to produce spatially-oriented, map products. GIS data is critical to building the required terrains needed to support coalition mission planning and operational effectiveness analyses.

Once the prototype software was developed, the NG-NRMM team conducted a virtual demonstration which was an “end to end software demo” that demonstrated how NG-NRMM adopted new technologies, modeling techniques, and computational tools to enable physics-based simulation of any vehicle design, in complex environments and scenarios. The event showcased prototype demonstrations of both simple and complex terramechanics which are both physics-based, but the complex model provides a vision of the future possibilities to produce real-time mobility simulations necessary for autonomous navigation made possible with high performance computing. The demo also demonstrated how an open and modular architecture was used to weave together CDT technologies to include GIS data inputs, terrain and soils data, the latest modeling and simulation technology, terramechanics, mobility event studies, uncertainty quantification, and mobility maps into an integrated set of tools and methodologies for mobility prediction that allows for incorporation of new methods as they become available, i.e., autonomy. Finally, the team conducted a set of Verification and Validation (V&V) field exercises, using both a tracked and wheeled vehicle, to evaluate the state of the terramechanical models. Overall NG-NRMM capable software was demonstrated to be in better agreement with tests compared to NRMM and can offer significantly better mobility and trafficability predictions but will still require investments in research and development to bring it to a fully mature state.

Chapter 2 – ORGANIZATION

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2.1 ET-194 ORGANIZATION

The Assessment Methods and Tools for Mobility of Autonomous Military Ground Systems committee, ET-194, was approved by NATO in December 2018 at the meeting in Athens, Greece. Dr. Paramsothy Jayakumar of the United States and Dr. Lounis Chermak of the United Kingdom were named as the Co-chairpersons and the United States was named as the lead nation. In 2019, Dr. Ekaterina Fedina of Sweden was named as a third co-chairperson.

Starting in January 2019, the Group held monthly teleconferences through the end of year with a membership of forty-two (42) appointed members and seventeen (17) contributing members from twelve (12) nations (Canada, Czech Republic, Denmark, Estonia, Germany, Poland, Romania, South Africa, Sweden, Turkey, United Kingdom, and the United States).

In addition to the monthly teleconferences, the Group physically met twice, in:

- Liptovský Mikuláš, Slovakia – from May 20 – 24, 2019.
- Trondheim, Norway – from October 07 – 11, 2019.

The two meetings were attended by thirty-five (35) members from eleven (11) Nations, and thirty (30) members from eleven (11) Nations, respectively.

The overall project was divided into six task areas, each with one or more thrust leads. All of the members of ET-194 selected one or more theme teams to join, depending on their interest and area of expertise. The six (6) task areas and their task leads were:

- **Task 1:** Scope Definitions, Scenarios, Perception, Planning, Control — Tulga Ersal, Lounis Chermak
- **Task 2:** Virtual Environments, Sensors, UQ — Daniel Carruth, Nick Gaul
- **Task 3:** Vehicle System Models — Vladimir Vantsevich
- **Task 4:** Software, Hardware, Data, Communication — William Smith
- **Task 5:** Mobility V&V — Scott Bradley, Sally Shoop
- **Task 6:** Benchmarks — Daniel Carruth

Chapter 3 – INDIVIDUAL TASK OVERVIEW AND REQUIREMENTS

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As stated earlier, ET-194 was organized around six (6) task areas. The requirements of each task group are defined below.

3.1 TASK 1: SCOPE, DEFINITIONS, SCENARIOS, PERCEPTION, PLANNING, AND CONTROL

As the core component of autonomous mobility systems, the goal of Scope, Definitions, Scenarios, Perception, Planning, and Control research task group was to explore methods for evaluating algorithms and determine the M&S requirements for supporting those evaluations as follows:

- Define autonomous mobility, reliability, levels of autonomy.
- Define the operational environments and scenarios.
- Determine the scope (on-road vs. off-road, teleoperation to full autonomy, single vs. multi-vehicle systems).
- Determine the minimum set of scenarios that needs to be supported (maneuver requirements, mission requirements, etc.).
- Determine the requirements for supporting external perception, planning, and control algorithms, e.g., interface requirements for all levels of autonomy specified in the "Scope, definitions, and scenarios" task), modularity, synchronization, sensor models.

3.2 TASK 2: VIRTUAL ENVIRONMENTS, SENSORS, AND UNCERTAINTY QUANTIFICATION

The Virtual Environments, Sensors, and Uncertainty Quantification task group was tasked to evaluate the requirements for representing the operational environment within a modeling and simulation framework for evaluating autonomous mobility of military ground vehicles and, for modeling and simulation of the sensors used by autonomous systems to perceive the environment as follows:

- Determine the requirements for representing the virtual environment: e.g., on-road and off-road terrains, structured and unstructured environments, adversarial environments, static and moving obstacles, obstacle types (vegetation, buildings, people, other vehicles, etc.), atmospheric conditions (lighting, visibility, precipitation, etc.).
- Determine the state of the art for open source (e.g., *OpenScenario)* and existing data sets.
- Determine the sources of uncertainty that need to be considered.
- Determine the state of the art for measuring and modeling these uncertainties:
  - Identify the gaps.
- Determine how robustness of an autonomous vehicle will be quantified.

3.3 TASK 3: VEHICLE SYSTEM MODELS

The Vehicle System Models research task group was task with identifying distinctive features of the modeling and simulation of autonomous mobility and to formulate requirements for autonomous vehicle models, which could be common or different as compared to the requirements for conventional (with a driver) vehicle models, as follows:

- Understand the reason and the purpose of transition from conventional to Autonomous Vehicles (AVs) and, thus, formulate requirements for functional features and operational properties that AVs and AV systems should demonstrate in combat and tactical conditions.
- Define the modeling requirements for the vehicle system: e.g., vehicle dynamics, vehicle powertrain, vehicle-terrain interaction, sensors (including the effects of the environmental factors), actuators, onboard and remote operators.
- Analyze mobility assessment methods for their compliance with the functional features and operational properties of autonomous vehicles, and, thus, for being suitable to assess autonomous mobility in the process of vehicle movements.

3.4 TASK 4: SOFTWARE, HARDWARE, DATA, AND COMMUNICATION

The Software, Hardware, Data, and Communications team was responsible for describing the requirements for software and hardware tools used in the simulation of autonomous ground vehicles as well as data and communication characteristics as follows:

- Determine the needs for communication and connectivity that the simulation needs to support, e.g., human-vehicle communication, inter-vehicle communication, vehicle-infrastructure communication, trust, quality of communication (e.g., latency, noise, drop outs, bandwidth).
- Determine the requirements for the input and output data: data types and formats for defining the models, scenarios, inputs, outputs, information exchange between modules, visualization, machine learning, open source (e.g., OpenCRG, OpenDRIVE), etc.
- Determine the software level requirements: e.g., modularity, open source, real-time needs, support for X-in-the-loop simulation, standard APIs, scalability, etc.
- Determine the hardware requirements: e.g., support for hardware-in-the-loop, human-in-the-loop, software-in-the-loop, emulation of hardware limitations such as computational power or memory.

3.5 TASK 5: MOBILITY ASSESSMENT, VERIFICATION, AND VALIDATION

The Mobility Assessment, Verification, and Validation team was responsible for developing the requirements for assessing mobility as well as verifying and validating simulation results as follows:

- Determine the methods and metrics for assessing mobility: the dimensions to be evaluated, scoring schemes, gross metrics (e.g., autonomy and mobility maps, mission performance potential MPP), stochastic vs. deterministic evaluations, statistical tests to be utilized.
- Determine how the simulation results will be verified and validated: procedures for component level V&V, system level V&V, resources needed, potential demonstrations, standards development (e.g., ISO 26262, STANAG 4609).

- Compile use cases (hereafter called scenarios vs user needs) and determine requirements.
- Determine how use cases (scenarios) will be validated.
- Identify vehicle dynamics modeling needed for autonomy and validation.
- Identify mobility requirements needed for the use cases (scenarios).
- Determine how the sensor models will be validated.
- Address how to quantify environmental conditions – how much rain, sun, etc. affects the sensors.
- Focus on outward looking sensors required for situational awareness.

3.6 TASK 6: BENCHMARKS

The benchmarks team was task with reviewing a large set of modeling and simulation tools to determine whether the tools meet the defined requirements as follows:

- Review a large set of modeling and simulation tools to determine whether the tools meet requirements.
- Understand the capabilities of current modeling and simulation frameworks for mobility assessment.
- Determine what kind of benchmarks are needed.
- Determine how they will be defined and obtained.
- Establish a procedure for evaluating available tools.
- Determine the state of the art in current capabilities and identify the gaps.

Chapter 4 – SCOPE, DEFINITIONS, SCENARIOS, PERCEPTION, PLANNING, AND CONTROL

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4.1 INTRODUCTION

In the military context, mobility is a key factor for success, which leverages warfare considerations in terms of strategical approaches. Autonomy for ground vehicles has been heavily investigated over the past years and made significant technological leaps in terms of mobility with advanced developments toward self-driving cars. Similarly to civilian applications, there are huge interests and opportunities not only to keep up with cutting edge technology but also to help improve the reaction and responsibilities of military ground vehicles though intelligent and autonomous mobility. Achieving autonomy is not only about vehicles, it also benefits human operators by preventing them from being exposed on the battlefield. If fully autonomous systems are intended to ultimately function without human intervention, they – at this day – do not exist yet. Nevertheless, it is important to facilitate this, by defining adequate methods and tools to assess future possible autonomous military ground systems.

4.2 LITERATURE

4.2.1 Mobility

Vehicle mobility has been studied by the Department Of Defense (DOD) for many years, and the private sector [1], [2]. Studies were focused on developing the empirical relationships between vehicles and the surrounding terrain including soft soils, frozen ground, and snow covered surfaces. Once developed, these relationships were implemented in computer software programs to predict vehicle mobility in these environments. One of the main programs used by the DOD to predict vehicle mobility is the NATO Reference Mobility Model (NRMM). This code can be used during the vehicle design process to compare the mobility of different designs/platforms over multiple terrain conditions, or it can be used to predict the mobility of existing platforms on current or forecasted terrain conditions. Limitations of this approach include the inability to conduct physics based mobility predictions using state of the art soil/terrain modeling techniques or high-fidelity multi-body dynamics. The NATO AVT-248 "Next-Generation NATO Reference Mobility Model (NG-NRMM) Development" sub-committee was setup to address some of these shortcomings by allowing the use of any mobility modeling program when accessing a vehicles performance under specified terrain conditions, so long as, simulations were conducted using a physics based approach, rather than an empirical approach, and provided the required output [3]. Goodin et al. provides an example of high-fidelity physics based modeling coupled with state of the art soil modeling [4].

NRMM and NG-NRMM both focus on predicting vehicle mobility under specified terrain conditions with neither having the ability to assess autonomous ground vehicle. This is a very difficult task especially since autonomous mobility is in its infancy and largely focused at on-road applications with little in the way of off-road or demanding terrain and environmental conditions. This leaves a large gap in Unmanned Ground Vehicle (UGV) mobility studies for an ever increasing need in the commercial and military sectors.

By combining the need to predict vehicle mobility and autonomy it now requires the vehicle to "think" as it is maneuvering over the terrain because there is limited or no human interaction with the vehicle depending on the level of autonomy. This intelligent and autonomous mobility, which combines the inherent difficulties of predicting vehicle mobility with the latest in autonomous navigation presents an extremely difficult challenge that is largely unsolved in demanding operating environments. This requires the use of sensors coupled with mobility algorithms to allow the vehicle to understand where it is and what the environmental conditions are before determining where it can traverse.

4.2.2 Autonomy

The need for characterizing levels of autonomy has been recognized by various communities and has attracted the interest of researchers for decades starting with Sheridan's classification given in Figure 4-1 [5]. This classification considers a generic human-computer collaborative framework and describes ten (10) levels of autonomy depending on how the computer assists the human in the decision making and acting process. As such, it presents a linear scale for characterizing levels of autonomy. Note that the decision making, and acting processes mentioned in this classification can be mapped to the planning and control tasks defined above, but autonomy in the perception task does not have a corresponding mention in this classification.

(1) The computer offers no assistance; the human must do it all.

(2) The computer offers a complete set of action alternatives, and…

(3) narrows the selection down to a few, or…

(4) suggests one, and…

(5) executes that suggestion if the human approves, or…

(6) allows the human a restricted time to veto before automatic execution, or…

(7) executes automatically, then necessarily informs the human, or…

(8) informs him after execution only if he asks, or…

(9) informs him after execution if it, the computer decides to.

(10) The computer decides everything and acts autonomously, ignoring the human.

Figure 4-1: Sheridan's Original Definition of Levels of Autonomy [5].

Similar linear scales for classifying levels of autonomy have also been developed by other communities, such as the 4-level scale offered by the NATO Industrial Advisory Group, Study Group 75 (Table 4-1) [6], the 4-level scale of NATO STO Task Group AVT-175 (Table 4-2) [7], or the 6-level scale in Table 4-3 that has been attributed to the US Navy Office of Naval Research [8]. Perhaps the most widely known classification of levels of autonomy in the domain of ground vehicles is the definitions established by the Society of Automotive Engineers (SAE) summarized in Table 4-4 [9].

Table 4-1: The 4-Level Scale Offered by the NATO Industrial Advisory Group, Study Group 75 [6].

Level 1	Remotely Controlled System	System reactions and behaviour depend on operator input.
Level 2	Automated System	Reactions and behaviour depend on fixed built-in functionality (pre-programmed).
Level 3	Autonomous non-learning system	Behaviour depends upon fixed built-in functionality or upon a fixed set of rules that dictate system behaviour (goal-directed reaction and behaviour).
Level 4	Autonomous self-learning system	Behaviour depends upon a set of rules that can be modified for continuously improving goal directed reactions and behaviours within an overarching set of inviolate rules/behaviours.

Table 4-2: The 4-Level Scale of NATO STO Task Group AVT-175. This scale is called the Non-Contextual Autonomy Potential (NCAP) [7].

Level 1	Remotely Controlled System	System reactions and behaviour depend on operator input.
Level 2	Automated System	Reactions and behaviour depend on fixed built-in functionality (pre-programmed).
Level 3	Autonomous non-learning system	Behaviour depends upon fixed built-in functionality or upon a fixed set of rules that dictate system behaviour (goal-directed reaction and behaviour).
Level 4	Autonomous self-learning system	Behaviour depends upon a set of rules that can be modified for continuously improving goal directed reactions and behaviours within an overarching set of inviolate rules/behaviours.

Table 4-3: The 6-Level Scheme Attributed to the US Navy Office of Naval Research [8].

Level	Name	Description
1	Human operated	All the activity in the system is a direct result of human-initiated environment, although it may have information-only responses to sensed data.
2	Human assisted	The system can perform activity in parallel with human input, acting to augment the human's ability to perform the desired activity, but has no ability to act without accompanying human input. An example is automobile automatic transmission and anti-skid brakes.
3	Human delegated	The system can perform limited control activity on a delegated basis. The level encompasses automatic flight controls, engine controls, and other low-level automation that must be activated or deactivated by a human input and act in mutual exclusion with human operation.
4	Human supervised	The system can perform a wide variety of activities given top-level permissions or direction by a human. The system provides sufficient insight into its internal operations and behaviours that it can be easily understood by its human supervisor and appropriately redirected. The system does not have the capability to self-initiate behaviours that are not within the scope of its current directed tasks.
5	Mixed initiative	Both the human and the system can initiate behaviours based on sensed data. The system can coordinate its behaviour both explicitly and implicitly. The human can understand the behaviours of the system in the same way that he or she understands his or her own behaviours. A variety of means are provided to regulate the authority of the system with respect to human operators.
6	Fully autonomous	The system requires no human intervention to perform any of its designed activities across all planned ranges of environmental conditions.

Table 4-4: The SAE Levels of Autonomy [9].

Level	Name	Narrative definition	*DDT*		*DDT fallback*	*ODD*
			Sustained lateral and longitudinal vehicle motion control	*OEDR*		
Driver* performs part or all of the *DDT						
0	**No Driving Automation**	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	**Driver Assistance**	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	**Partial Driving Automation**	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
ADS* (“*System*”) performs the entire *DDT* (while engaged*)						
3	**Conditional Driving Automation**	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	**High Driving Automation**	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	**Full Driving Automation**	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

While such linear scales may be useful for tracking technological trends, making high level classifications, and assisting with policy or regulatory decisions, they ignore, sometimes by an explicitly stated choice [7], that level of autonomy is a multi-dimensional and context dependent concept. Understanding and expressing this dependence clearly may be critical in certain cases, as a vehicle that is deemed to a high level of autonomy in one dimension or context may be heavily dependent on a human in another one. For example, an SAE Level 4 vehicle that can operate in a driverless manner in a geofenced area that may need to be completely driven by a human outside that area due to its inability to localize itself in the absence of a high-definition map.

Hence, merely stating that the vehicle has an SAE Level of 4 may not be sufficient to communicate what the vehicle can and cannot do in different circumstances. As such, defining the scope of the level of autonomy clearly becomes an important need. Recognizing this need, researchers have developed multi-dimensional scales based on a simple four-stage model of human information processing. These stages are sensory processing, perception / working memory, decision making, and response implementation [10]. Note the direct correspondence to the perception, planning, and control classification introduced earlier (Table 4-4). An example of such a multi-dimensional scale is shown in Figure 4-2 [10].

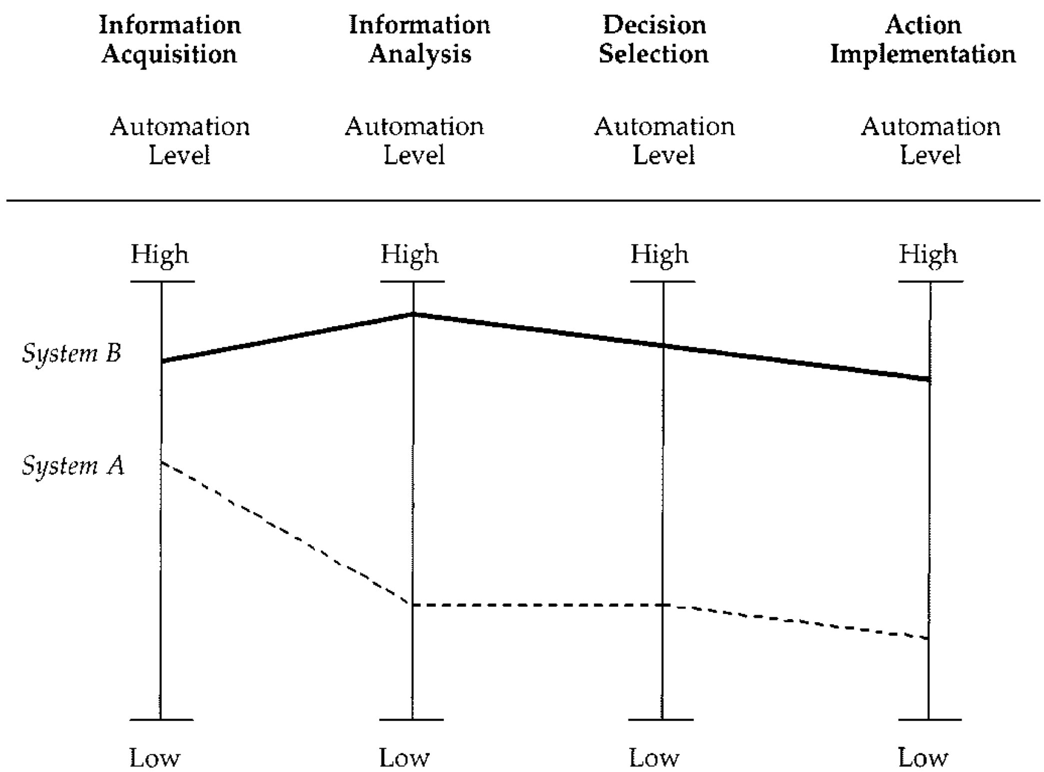


Figure 4-2: The Multi-Dimensional Assessment Framework of Parasuraman et al. [10].

Other researchers from the US Air Force Research Laboratory and NASA also made this multi-dimensional aspect explicit, but still preferred to reduce the level of autonomy back to a single number as illustrated in Table 4-5 and Table 4-6, respectively [11], [12].

Another classification method that emerged out of the need to make the context explicit when defining the level of autonomy is the Autonomy Levels for Unmanned Systems (ALFUS) framework (Figure 4-3) [13]. In this framework, the autonomy level or human independence is characterized against two additional dimensions that grade the environmental and mission complexity, thereby providing some scope to the level of autonomy.

The fact that there are many frameworks to characterize the level of autonomy of a vehicle as briefly outlined above is a statement in and of itself that while the concept of level of autonomy may be easy to understand, it is not as easy to define, quantify, and communicate in a universally accepted and useful manner. This has led different groups to create their own frameworks to best serve their own purposes.

Table 4-5: The 11-Level Scale from the Air Force Research Laboratory [11].

Level	*Level Descriptor*	*Observe* Perception/Situational Awareness	*Orient* Analysis/Coordination	*Decide* Decision Making	*Act* Capability
10	*Fully Autonomous*	Cognizant of all within Battlespace	Coordinates as necessary	Capable of total independence	Requires little guidance to do job
9	*Battlespace Swarm Cognizance*	Battlespace inference - Intent of self and others (allies and foes). Complex/Intense environment - on-board tracking	Strategic group goals assigned Enemy strategy inferred	Distributed tactical group planning Individual determination of tactical goal Individual task planning/execution Choose tactical targets	Group accomplishment of strategic goal with no supervisory assistance
8	*Battlespace Cognizance*	Proximity inference - Intent of self and others (allies and foes) Reduced dependance upon off-board data	Strategic group goals assigned Enemy tactics inferred ATR	Coordinated tactical group planning Individual task planning/execution Choose targets of opportunity	Group accomplishment of strategic goal with minimal supervisory assistance (example: go SCUD hunting)
7	*Battlespace Knowledge*	Short track awareness - History and predictive battlespa data in limited range, timeframe, and numbers Limited inference supplemented by off-board data	Tactical group goals assigned Enemy trajectory estimated	Individual task planning/execution to meet goals	Group accomplishment of tactical goal with minimal supervisory assistance
6	*Real Time Multi-Vehicle Cooperation*	Ranged awareness - on-board sensing for long range, supplemented by off-board data	Tactical group goals assigned Enemy location sensed/estimated	Coordinated trajectory planning and execution to meet goals - group optimization	Group accomplishment of tactical goal with minimal supervisory assistance Possible close air space separation (1-100 yds)
5	*Real Time Multi-Vehicle Coordination*	Sensed awareness - Local sensors to detect others, Fused with off-board data	Tactical group plan assigned RT Health Diagnosis; Ability to compensate for most failures and flight conditions; Ability to predict onset of failures (e.g. Prognostic Health Mgmt) Group diagnosis and resource management	On-board trajectory replanning - optimizes for current and predictive conditions Collision avoidance	Group accomplishment of tactical plan as externally assigned Air collision avoidance Possible close air space separation (1-100 yds) for AAR, formation in non-threat conditions
4	*Fault/Event Adaptive Vehicle*	Deliberate awareness - allies communicate data	Tactical plan assigned Assigned Rules of Engagement RT Health Diagnosis; Ability to compensate for most failures and flight conditions - inner loop changes reflected in outer loop performance	On-board trajectory replanning - event driven Self resource management Deconfliction	Self accomplishment of tactical plan as externally assigned Medium vehicle airspace separation (100's of yds)
3	*Robust Response to Real Time Faults/Events*	Health/status history & models	Tactical plan assigned RT Health Diag (What is the extent of the problems?) Ability to compensate for most control failures and flight conditions (i.e. adaptive inner-loop control)	Evaluate status vs required mission capabilities Abort/RTB if insufficient	Self accomplishment of tactical plan as externally assigned
2	*Changeable Mission*	Health/status sensors	RT Health diagnosis (Do I have problems?) Off-board replan (as required)	Execute preprogrammed or uploaded plans in response to mission and health conditions	Self accomplishment of tactical plan as externally assigned
1	*Execute Preplanned Mission*	Preloaded mission data Flight Control and Navigation Sensing	Pre/Post Flight BIT Report status	Preprogrammed mission and abort plans	Wide airspace separation requirements (miles)
0	*Remotely Piloted Vehicle*	Flight Control (attitude, rates) sensing Nose camera	Telemetered data Remote pilot commands	N/A	Control by remote pilot

Table 4-6: The 8-Level Scale from NASA [12].

Level	Observe	Orient	Decide	Act
1	Human is the only source for gathering and monitoring (defined as filtering, prioritizing and understanding) all data.	Human is responsible for analyzing all data, making predictions, and interpretation of the data.	The computer does not assist in or perform ranking tasks. Human must do it all.	Human alone can execute decision.
2	Human is the prime source for gathering and monitoring all data, with computer shadow for emergencies.	Human is the prime source of analysis and predictions, with computer shadow for contingencies. The human is responsible for interpretation of the data.	The human performs all ranking tasks, but the computer can be used as a tool for assistance.	Human is the prime source of execution, with computer shadow for contingencies.
3	The computer is responsible for gathering and displaying unfiltered, unprioritized information for the human. The human still is the prime monitor for all information.	Computer is the prime source of analysis and predictions, with human shadow for contingencies. The human is responsible for interpretation of the data.	Both human and computer perform ranking tasks, the results from the human are considered prime.	Computer executes decision after human approval. Human shadows for contingencies.
4	The computer is responsible for gathering the information for the human and for displaying all information, but it highlights the nonprioritized, relevant information for the user.	The computer analyzes the data and makes predictions, though the human is responsible for interpretation of the data.	Both human and computer perform ranking tasks, the results from the computer are considered prime.	Computer allows the human a preprogrammed restricted time to veto before execution. Human shadows for contingencies.
5	The computer is responsible for gathering the information for the human, but it only displays nonprioritized, filtered information.	The computer overlays predictions with analysis and interprets the data. The human shadows the interpretation for contingencies.	The computer performs ranking tasks. All results, including "why" decisions were made, are displayed to the human.	Computer allows the human a context-dependent restricted time to veto before execution. Human shadows for contingencies.
6	The computer gathers, filters, and prioritizes information displayed to the human.	The computer overlays predictions with analysis and interprets the data. The human is shown all results.	The computer performs ranking tasks and displays a reduced set of ranked options while displaying "why" decisions were made to the human.	Computer executes automatically, informs the human, and allows for override ability after execution. Human is shadow for contingencies.
7	The computer gathers, filters, and prioritizes data without displaying any information to the human. Though, a program functioning" flag is displayed.	The computer analyzes, predicts, interprets, and integrates data into a result which is only displayed to the human if result fits programmed context (context-dependent summaries).	The computer performs ranking tasks. The computer performs final ranking and displays a reduced set of ranked options without displaying "why" decisions were made to the human.	Computer executes automatically and only informs the human if required by context. It allows for override ability after execution. Human is shadow for contingencies.
8	The computer gathers, filters, and prioritizes data without displaying any information to the human.	The computer predicts, interprets, and integrates data into a result which is not displayed to the human.	The computer performs ranking tasks. The computer performs final ranking but does not display results to the human.	Computer executes automatically and does not allow any human interaction.

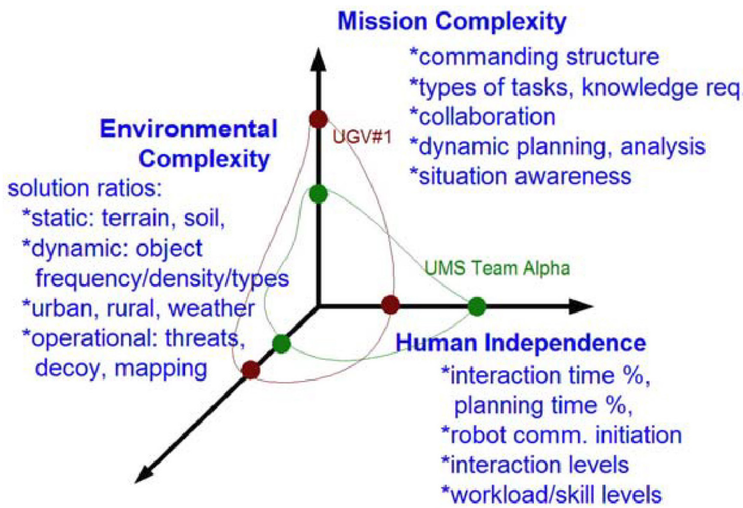


Figure 4-3: The Autonomy Levels for Unmanned Systems (ALFUS) Framework Concept [13].

4.2.3 PEGASUS Model

In recent years, the feasibility of automated driving systems has been investigated and their functional development driven forward in numerous studies and projects. The verification and validation of the systems was usually done with distance-based methods. Since this approach means billions of kilometers to prove sufficient safety, a scenario-based approach to testing, verification and validation seems more feasible, which is also used in the software development for example.

The PEGASUS project aims to establish generally accepted quality criteria, tools and methods as well as scenarios and situations for the release of highly automated driving functions. An overall approach for the verification and validation of highly automated driving functions (SAE Level 3+) was established, which uses a scenario-based approach. 17 scientific and industry partners were involved in the project, which lasted from 2016 to 2019 and was funded by the German Federal Ministry for Economic Affairs and Energy.

The PEGASUS method describes the methods, tools and processes for the verification and validation of highly automated driving functions.

The process flow of the overall method, Figure 4-4, is described with five basic elements: Definition of requirements, Data processing, Information storage and processing in a database, Assessment of highly automated driving function, and Argumentation. The process elements summarize the relevant methods, tools and processes, which are executed sequentially as executable process steps. The generation of scenarios takes place in the process element *data processing.* Therein the source information *Knowledge (1)* is based on road regulations, guidelines and driving maneuver and serves as input data for the *Systematic Identification of Scenarios (4)* [14].

Description of scenarios with the 6-Layer-Model. The PEGASUS approach for the systematic knowledge-based identification of scenarios is the description of scenarios of traffic pattern using ontologies. Ontology is a formal model for the structured integration of information and its relations in a knowledge network for the automatic processing in various computer applications. The PEGASUS process for the knowledge-based scenario generation using an ontology is shown in Figure 4-5.

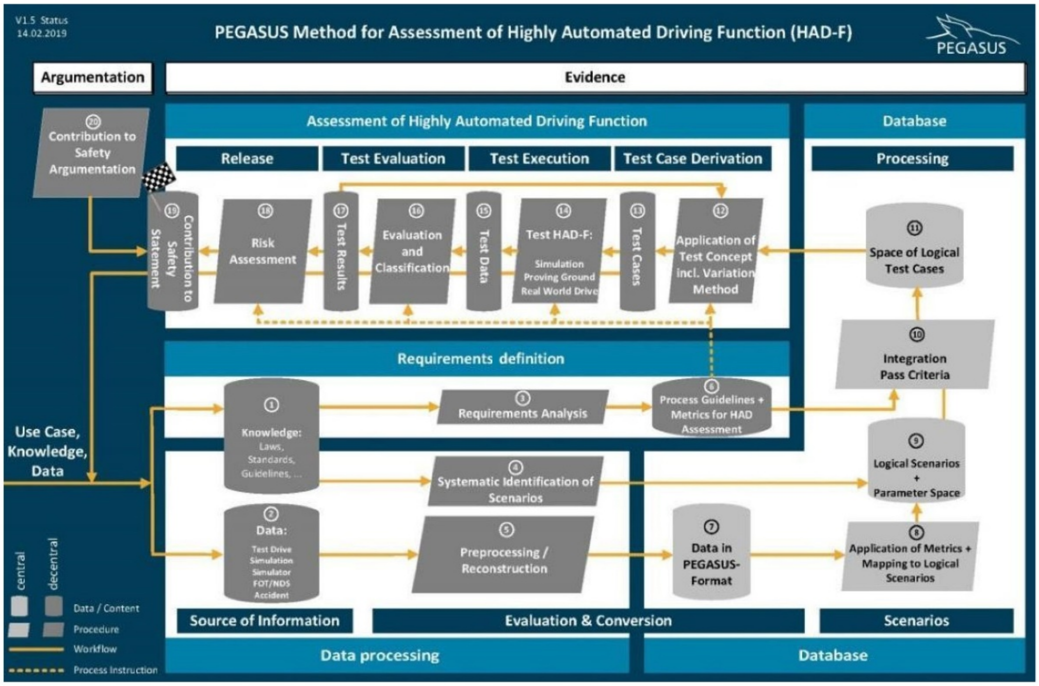


Figure 4-4: The Architecture of the PEGASUS Method for Assessment of Highly Automated Driving Function [14].

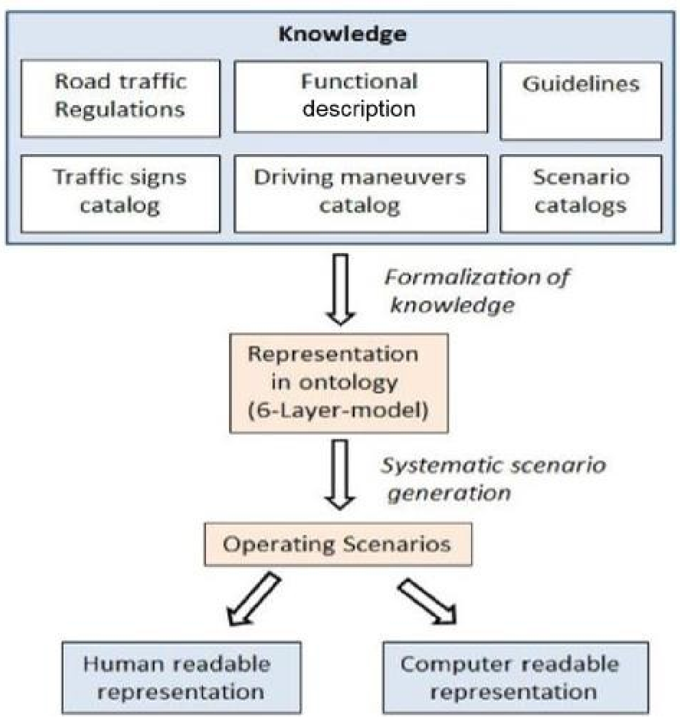


Figure 4-5: Ontology-Based Process for Scenario Creation [14].

In the first step, linguistically described knowledge is identified, conceptualized and formalized. To formalize the knowledge, an ontology in the Ontology Web Language (OWL) is implemented. Therefore, the knowledge is represented through hierarchic classes as well as semantic relations and restrictions between these classes. The knowledge modeled in the knowledge base is structured according to a 6-layer-model, Figure 4-6.

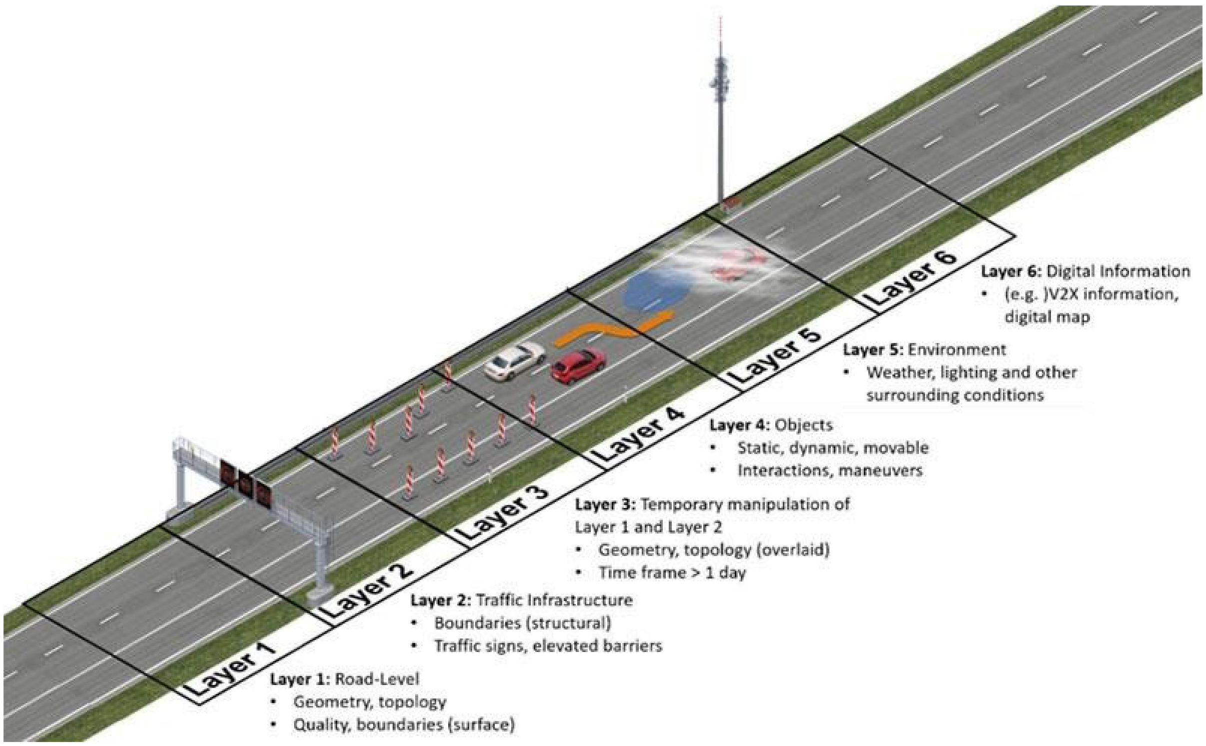


Figure 4-6: Model for a Systematic Description of Scenarios with Six Independent Layers [14].

On the first and second layer, the road network is described according to the guideline on how to construct motorways. The third layer describes temporary manipulations of layers one and two (like road construction sites). On the fourth layer, the interactions of traffic participants are represented through maneuvers. On the fifth layer, weather conditions are modeled. The sixth layer describes digital information, such as V2X and digital data.

In the second step, scenarios are automatically and systematically deduced by varying classes and instances defined in the ontology. For variation, possible combinations and restrictions specified in the knowledge base are considered. Therefore, scenarios are created stepwise [14].

In the 6-layer-model the parameter space describes all possible scenarios. The limitation of this huge parameter space to the Operational Design Domain (ODD) describes the test space for the verification and validation of the driving functions and defines the range of validity. In order to reduce the number of tests, the safety-critical combinations can be identified by means of sensitivity analysis, optimization methods as well as reliability and robustness tests.

Description of Scenarios for the Development Process. In the development of automated driving functions, the V-model based development process based on ISO 26262 is state of the art, Figure 4-7.

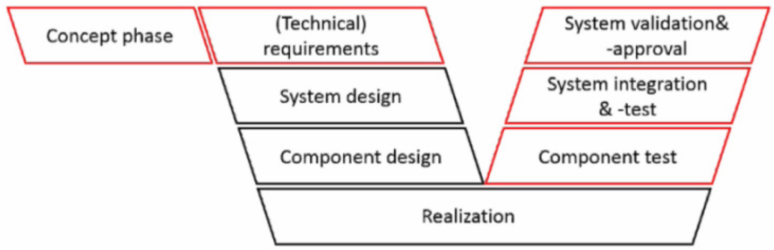


Figure 4-7: V-Model Based Development Process Based on ISO 26262.

Scenarios support the development process in ISO 26262 in various process phases with different requirements on the manner of representation of scenarios. By defining scenarios in three levels of abstraction the requirements of the complete development process can be fulfilled [14] (Table 4-7).

- In the **concept phase** *functional scenarios* define the subject of development and are used for hazard analysis and risk assessment. The representation of functional scenarios is based on a natural language on a high level of abstraction.
- For the **technical development** and **generation of test cases** *logical scenarios* are used. The logical scenarios are described with parameter ranges for physical states in a formal data format.
- For **test case execution** and **assessment** *concrete scenarios* are used. The concrete scenarios depict a concrete representative of a logical scenario and are written in a common data format.

The conversion of a logical scenario into a concrete scenario is done by selection of a concrete value from the parameter range in the logical scenario (Table 4-7).

Table 4-7: Levels of Abstraction Along the Development Process of the ISO 262 Standard [15].

Concept Phase	System Development Phase	Test Phase
Functional Scenarios	**Logical Scenarios**	**Concrete Scenarios**
Base Road Paved track in bend with slope	**Base Road** Split Friction µ [0,4 ...0,6 ...0,8] Roughness RMS [2 …10] cm Curve radius [30 …90] m Slope [2...10%]	**Base Road** Split Friction µ: 0,6 Roughness RMS: 2 cm Curve radius: 30 m Slope 5 %
Moveable Objects Car, convoy; Interaction: car in maneuver approaching convoy	**Moveable Objects** End of convoy [0 …100] m Convoy speed [0…30] km/h Car distance [50 …300] m Car speed [40 …60] km/h	**Moveable Objects** End of convoy 50 m Convoy speed 30 km/h Car distance 150 m Car speed 50 km/h
Environment Summer, rain	**Environment** Temperature [10 … 45] °C Droplet size: Rain amount [0,1 . 5] mm/h	**Environment** Temperature: 22 °C Droplet size: 30 um Rain amount [4 mm/h]
` **Number of Scenarios** **Level of Abstraction**		

4.3 FRAMEWORK

4.3.1 Why A Framework?

In the previous section, we presented the two main areas of interest are mobility and autonomy. If as described the two fields have been investigated independently, it appeared, with emerging technology and advancement of ever growing autonomous systems aiming at handling more complex situations, that autonomy need to encompass the various aspects of mobility. These would be an important step towards development of more complete application or at least a first step to identify related challenges. This is especially true for rough terrain, or even off-road environments.

Vehicle mobility is a mature field with established processes and methodologies. If the field of autonomy is also fairly well grown and mainly focused on perception and decision making, these approaches are using rather simple vehicle models and assuming trivial or no considerations in terms of terrain interaction. Thus, in order to enable these two fields to operate complementarity, the symbiosis cannot be operated by integrating more complex mobility model on autonomy processes with elementary interactions. In fact, there is a need for a structure offering tools and rules allowing the capture common as well as specific elements of mobility and autonomy. In this regard, a framework that would initially provide set of views enabling the visualization of specific elements through a structure. Then relationship between common elements can be created through single, interlink or multiple link elements. These elements may provide the variation in terms of element level detail.

The PEGASUS approach is an interesting example of the implementation of a framework. If it does not fully address the problem, we are investigating there are inspiring features we would be focusing on. The framework enables the generation of scenarios for autonomous mobility evaluation by interlocking layers. The layers are the first remarkable feature associating the different elements of the scenario through a sequential structure. The second key feature is the level of abstraction to define elements from a functional high level to then a logical range of parameters, and finally a concrete single value within range. This transition from language elements to a specific technical instance does not only provide common terminology and an analysis tool between management people and engineers/technicians but also it offers the ability to multiply from a single functional definition the variations of a specific scenario into several use cases.

That being said, the PEGASUS approach is being strictly dedicated to on-road urban and infrastructural networks environment, there are many factors peculiar to our investigation context that are ignored but are fundamental to this exploratory team. These are the military context with related operations, vehicle and configurations specificities, the nature of off-road mobility, as well as environmental considerations. The combination of all these elements provides a more realistic description of an actual warfare scenario but at the same time greatly increases the complexity to capture and relate with coherence and consistency these specific military aspects. That is why, a wise approach to this problem needs to be addressed through a dedicated framework that thoroughly list the essential elements related to warfare considerations and takes them into account while associating mobility and autonomy in a coherent and unifying scheme.

4.3.2 Methodology

The methodology we are proposing is based on framework designed to address the complexity of autonomous mobility of Unmanned Ground Vehicle in a military context. If this framework does not exist yet, its principles are inspired from existing features of the PEGASUS approach. These are aimed to be extended to offer a more compressive and adaptable structure to different scenario and continuous evolving technology. In order to achieve such aspiration, it is necessary to enumerate the key elements from a strategical, environmental and technological point of views composing operational scenario. The scenarios form the big picture, and each element would analogically be a piece of the puzzle. However, in this problem a piece might have multiple dependencies. Thus, breaking down the complexity of the scenario by creating a structure with associated categorization is fundamental and will be the essence of the presented framework.

4.3.2.1 Breaking Down Complexity

As mentioned in Section 4.3.1 the multi-dimensionality of autonomous systems taking into account mobility in a military context requires a dedicated framework in order to tackle the complexity and multi-level interlinks between the different elements of the problem. Thus, as mentioned earlier, it is fundamental to create a framework able to break down this complexity into set of categories, elements and sub-elements in a smart and coherent manner. If this makes complete sense, the pathway toward this goal is challenging and not obvious. Consequently, since the focus of our topic are autonomous systems it is logical to start from its pipeline and main components as baseline in order to analyze and determine the critical elements.

Figure 4-8 shows an illustration of the key components of an autonomous system pipeline. It starts from:

- Sensing the environment though a specific collection of sensors.
- Sensed data are then processed and converted from raw input into meaningful and high level information allowing interpretation through dedicated algorithms.
- From the interpreted data representing the perceived environment, decision making algorithms will select the suitable action or set of actions required for the next move.
- Decided actions are transmitted to actuators to implement the given commands.
- Finally, the implemented actions are assessed quantitatively accordingly to established metrics enabling the update of the autonomous system status.

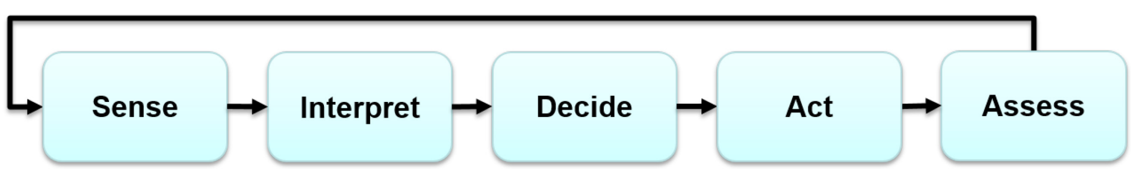


Figure 4-8: Illustration of an Autonomous System Pipeline.

Figure 4-9 illustrates a more comprehensive view of an autonomous system pipeline introducing the key processes. Each of the autonomous pipeline elements are related to one or several processes. Sensing related to sensors, interpretation relates to perception and localization which both provide mapping. Decision relates to guidance and control while actions to actuators. These three processes provide navigation ability.

Subsequently, it is these elements that describe an autonomous pipeline that the framework needs to be articulated to. Indeed, the idea is to figure out which are the external and internal elements that will impact the components and processes. The questions do not restrain which elements can be used but it also implies how it does and in which magnitude. Determining accurately these elements will allow us to design a general and generalizable enough structure aimed at capturing and adaptive autonomous systems technology while providing the tools to include other fields such as mobility to the relevant level of interaction.

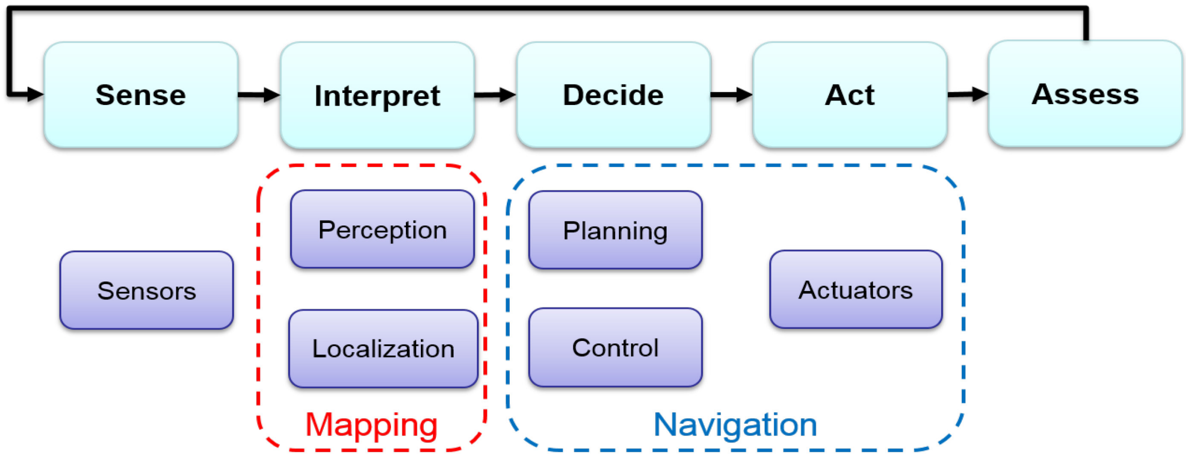


Figure 4-9: Illustration of an Autonomous System Pipeline with Key Processes.

4.3.2.2 Scenario Elements

A scenario is defined by the various external and internal factors influencing how autonomous mobility will handle specific situations. There are five categories defining the scenarios elements. As for the external elements, there were two categories identified as follows:

1) Operation; and
2) Environment.

As for the three remaining categories, belonging to the internal factors, are as follows:

3) Ground Vehicle and Configuration;
4) Sensors; and
5) Autonomy Capabilities.

External factors are aspects over which there is limited to no control and which need to be leveraged by the internal factors. Internal factors are aiming to respond to external considerations but contain other constraints such as technical or technological limitations. Each of the scenarios are related to one or more of the processes of the autonomous system elements as shown Figure 4-10. These will be expanded on Section 4.4.

4.3.2.3 Levels of Abstractions

The level of abstraction are one of the two features inspired from the PEGASUS approach in order to define scenarios. This three level description is extremely useful as it displays in a relevant manner the information and address to the right recipient in the right format. This brings an additional dimension helping to visualize transition from a high level scenario requirement to test or instance parameter that we also call an attribute (see Section 4.3.3.2). This provides an interesting tool for simulation and validation and verification tasks. Indeed, the logical level gives a range of value for a specific attribute, where each individual value can be a specific setting or configuration of a scenario variance. Consequently, the combination of selections within range of several attributes in a single scenario offers a myriad of declination of this scenario by selecting specific concrete values within these ranges.

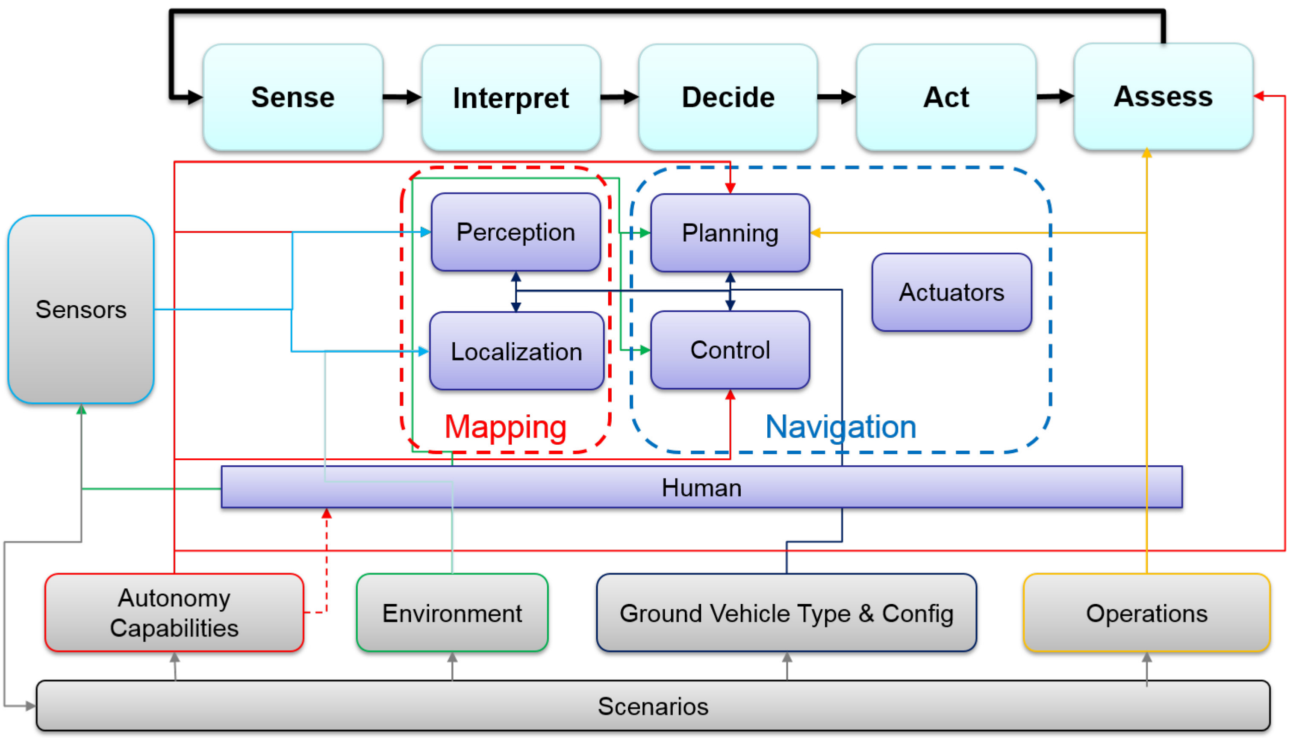


Figure 4-10: Illustration of an Autonomous System Pipeline with Key Processes and Scenario Elements Relationship.

Figure 4-11 illustrates each abstraction level and their relationship, from function, to logical and finally concrete.

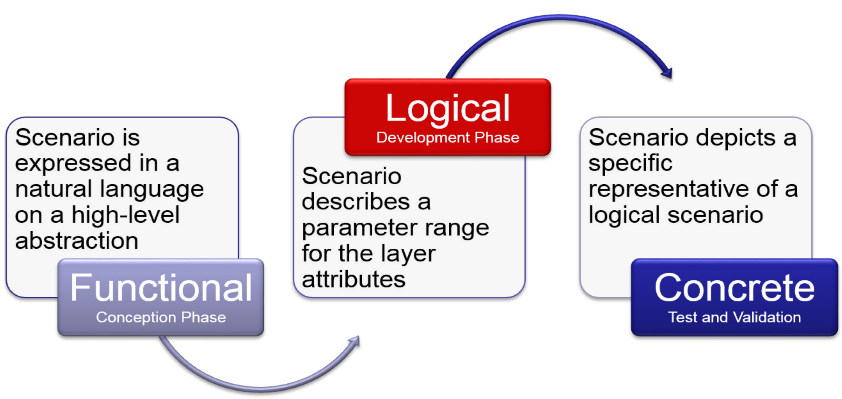


Figure 4-11: Illustration of the Overall Structure of the Proposed Framework with its Related Component to Break Down Scenario Complexity.

4.3.3 Structure

As depicted in Figure 4-12, the structure of the framework is composed of three main and hierarchically related components.

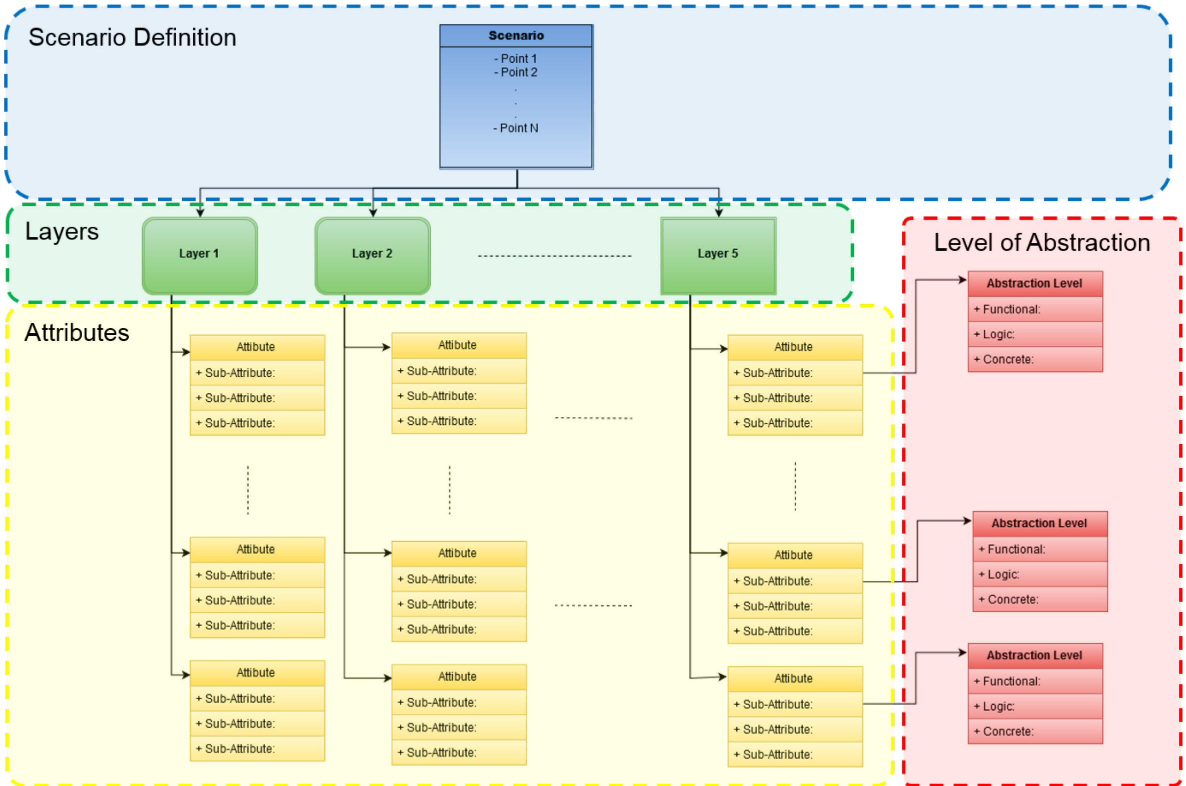


Figure 4-12: Illustration of the Overall Structure of the Proposed Framework with its Related Component to Break Down Scenario Complexity.

These components are the following:

- Scenario definition:
  - This is the highest element which list in a plain text the requirement for a scenario.
- Layers:
  - The layers break down into the categories (see Section 1.3.3.2) the list of requirements from the scenario definition. Certain requirements might fall into several layers under various aspects.
- Attributes and sub-attributes:
  - The attributes are specific instances that describe a specific feature related its related layer. These features are general instances that can be decline into one or more sub-attributes.
- Level of abstraction:
  - This is the last element of the chain. This expands the sub-attribute into functional, logic and concrete abstraction levels.

A scenario requirement can be represented by different layers and sub-attributes which can also belong to different attributes; however, it will be present a different aspect of the sub-attribute which will be distinguished by his abstraction level definition. If the relationship between the components of the structure are hierarchically sequential, interdependencies might also appear between attributes and/or sub-attributes of a same layer or even from different layers. However, these interdependencies are not within the scope of this report.

4.3.3.1 Layers

The layers are designed to break down the scenario elements (Section 4.3.2.2) into different categories where each category corresponds to a layer. In this ET we have identified five layers which will be detailed in the later Section 4.3.4 and succinctly described as follows:

- Operation Layer:
  - Operational goal and related strategical requirements and constraints to be considered to achieve autonomous mobility.
- Environment Layer:
  - Surroundings and environmental conditions in which the operation takes place.
- Ground Vehicle and Configuration Layer:
  - Platform enabler and associated configuration without or with other actors to achieve mobility.
- Sensors Layer:
  - Sensors enabling vehicle self-awareness (e.g., localization) and environmental awareness (i.e., perception) to achieve autonomous mobility.
- Autonomy Capabilities Layer:
  - Level of independence from a human required while executing the operation.

4.3.3.2 Attributes and Sub-Attributes

The attributes are hierarchically linked to Layers which define specific instances that characterize layers. Each attribute can be self-contained or may be composed of several sub-attributes that expand the properties of the attribute. Certain, sub-attributes might belong to different attributes; however, they will exhibit a varying property characterized by its layer-attribute relationship and defined by its functional, logic, and concrete abstraction levels. Additionally, some sub-attributes can also expand into sub-sub-attributes. Below is a non-exhaustive list of attributes by Layers:

- Operation Layer:
  - **Attributes:** Start, End, Threat Level, Signature.
- Environment Layer:
  - **Attributes:** Terrain, Road Network, Objects, Controllers, Conditions.
- Ground Vehicle and Configuration Layer:
  - **Attributes:** SAE, ALFUS.
- Sensors Layer:
  - **Attributes:** Ego, Other, Configuration.
- Autonomy Capabilities Layer:
  - **Attributes:** Vision, Ranging, Mobility, Atmospheric.

Appendix 1 contains an example of a scenario (Section 4.1.3.1) implemented into our proposed framework. Below (Figure 4-13 and Figure 4-14) are some illustrations of attributes and sub-attributes variations defined earlier in this section.

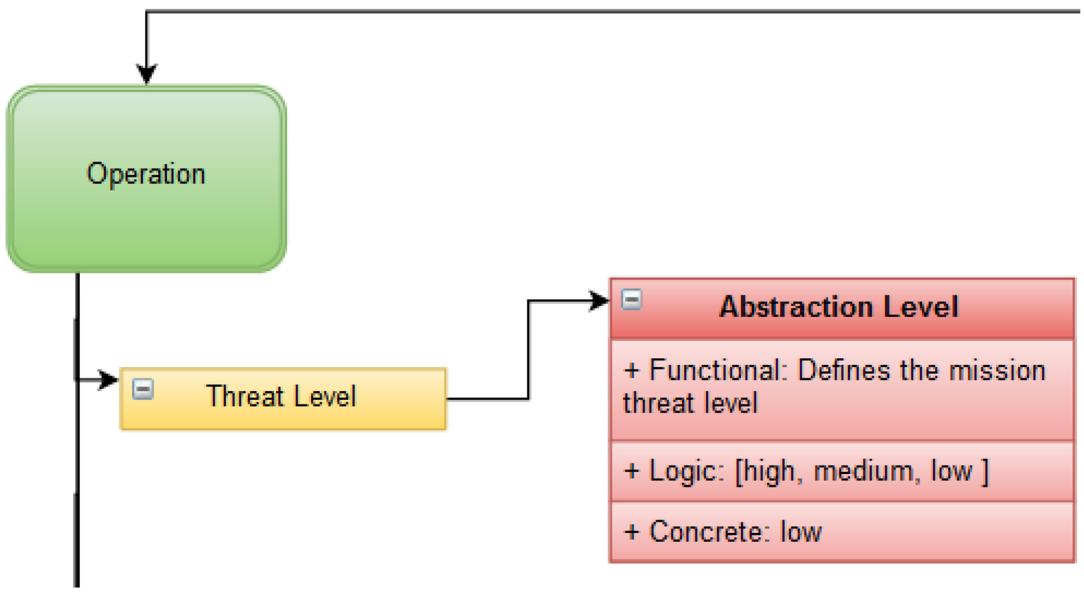


Figure 4-13: Illustration of a Layer with a Self-Contained Attribute and Related Abstraction Level.

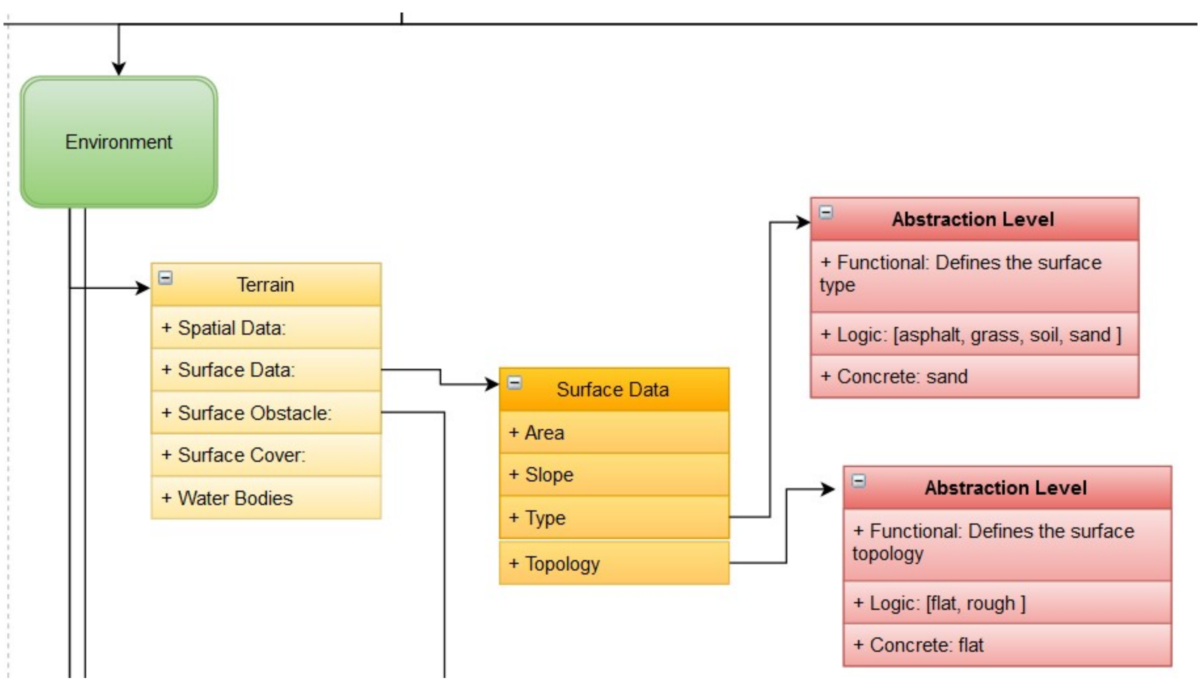


Figure 4-14: Illustration of a Layer with an Attribute Having Several Sub-Attributes and Sub-Sub-Attributes and its Respective Levels of Abstraction.

4.3.4 Layer-Attribute Relationship

In this section we aim to describe the relationship between each layer and some of the corresponding main attributes, and even some sub-attributes. Each of the layers will detail how the scenario is broken down through the use of attributes, sub-attributes and even sub-sub-attributes.

4.3.4.1 Operations

The operations layer defines operational tasks as well as their purposes and goals. An operational task can be related to tactical requirements, and the constraints to autonomous mobility are dictated by the purpose and goal of the task. The suggested attributes of the operations layer are tasks, route, contingency, threat level and signature as illustrated in Figure 4-15. If put together, the attributes constitute a description of an operational task and how it is to be executed. For instance, the mission that an autonomous ground vehicle is given is to conduct reconnaissance of an area with a purpose of being a forward observer for artillery fire mission. Considering the threat level, the task should be completed while minimizing signatures and travelling under as much cover as possible. The route defines the starting point and end point, the contingency action is to, if discovered, return to point A.

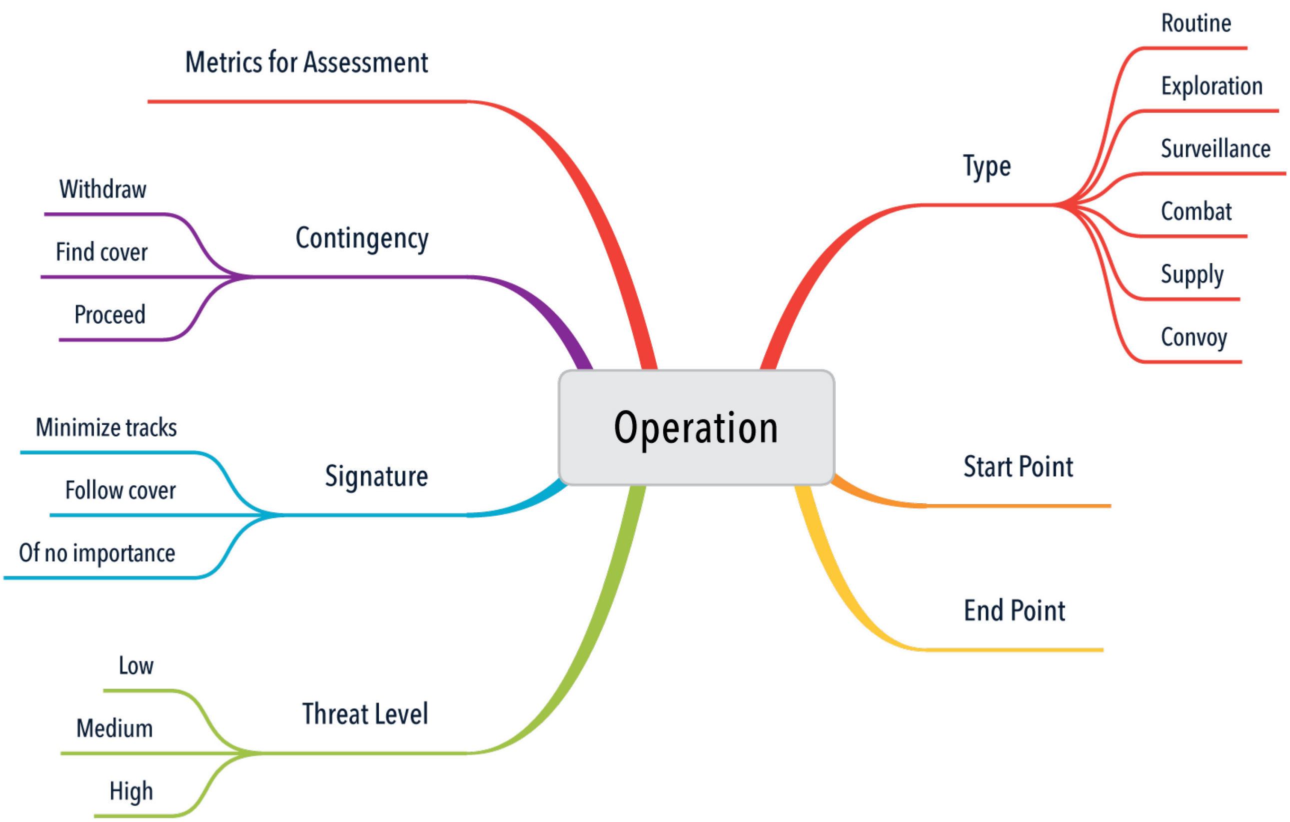


Figure 4-15: Illustration of the Operation Layer and Its Attributes.

Further examples of attributes with their respective sub-attributes are listed below:

- Tasks:
  - Reconnaissance.
  - Surveillance.
  - Combat Task.
- Contingency:
  - Retreat.
  - Return to point X.
- Threat Level:
  - High.
  - Medium.
  - Low.
- Signature:
  - Follow tracks.
  - Remain in cover.
- Route:
  - Start Point.
  - End Point.
  - Range.
  - Route options (follow path, allow path deviation, move from A to B through C).

4.3.4.2 Environment

The environment layer defines the scene in which the autonomous vehicle will perform its mission as depicted in Figure 4-16. The environment definition is roughly based on the environment layers described by the PEGASUS project, with extensions to improve support for modeling off-road environments. Our environment includes sub-surface soil properties, ground surface properties, topography, road network elements, objects (buildings, trees, etc.), agents (humans, vehicles, and animals), time and weather conditions, and digital networks. See Chapter 2: Virtual Environments, Sensors, and Uncertainty Quantification for additional information on requirements related to the environment.

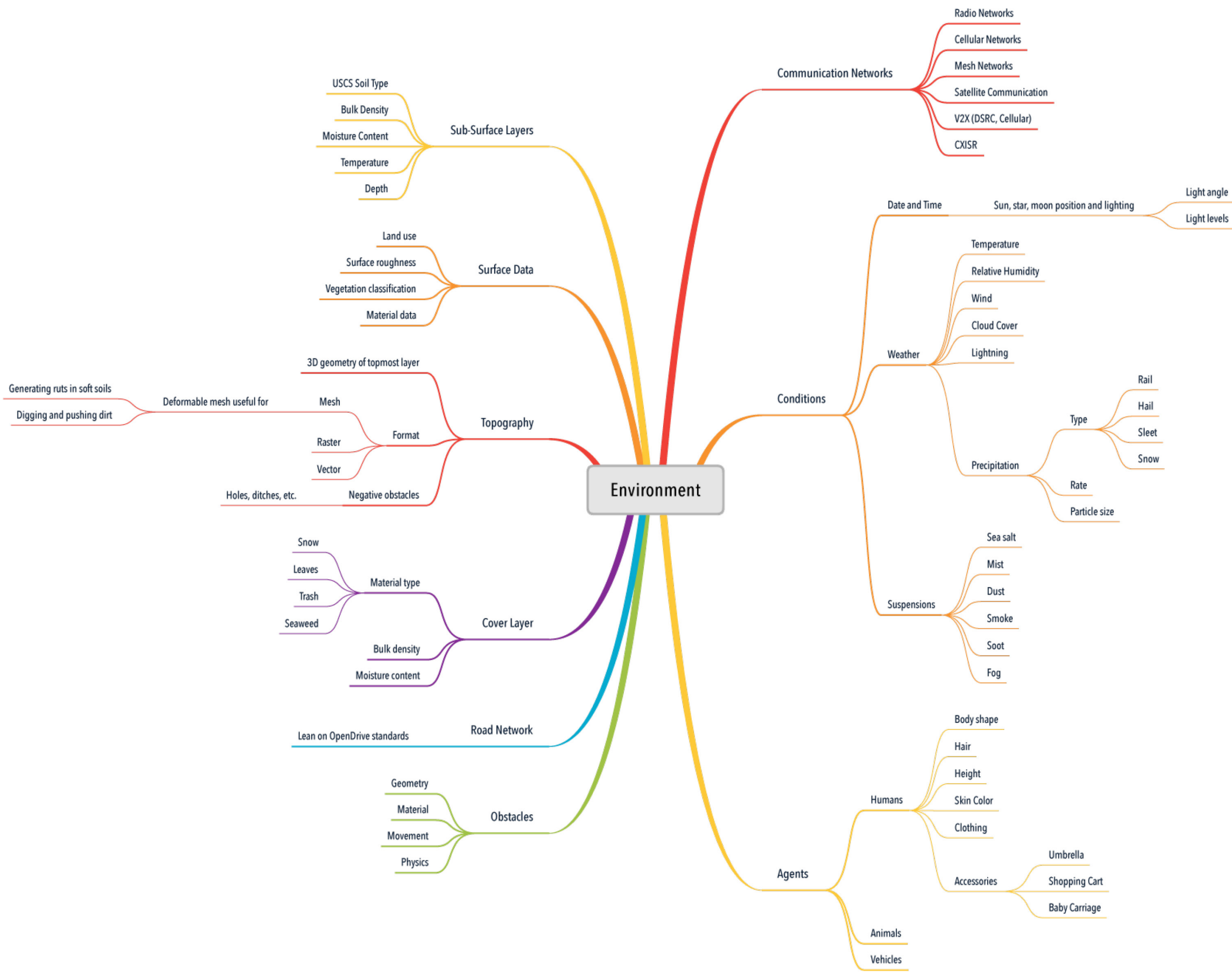


Figure 4-16: Illustration of the Environment Layer and Its Attributes.

4.3.4.3 Ground Vehicle and Configurations

The ground vehicle and configurations layer illustration in Figure 4-17 defines mobility enabling platform and associated configuration without or with other actors to achieve mobility.

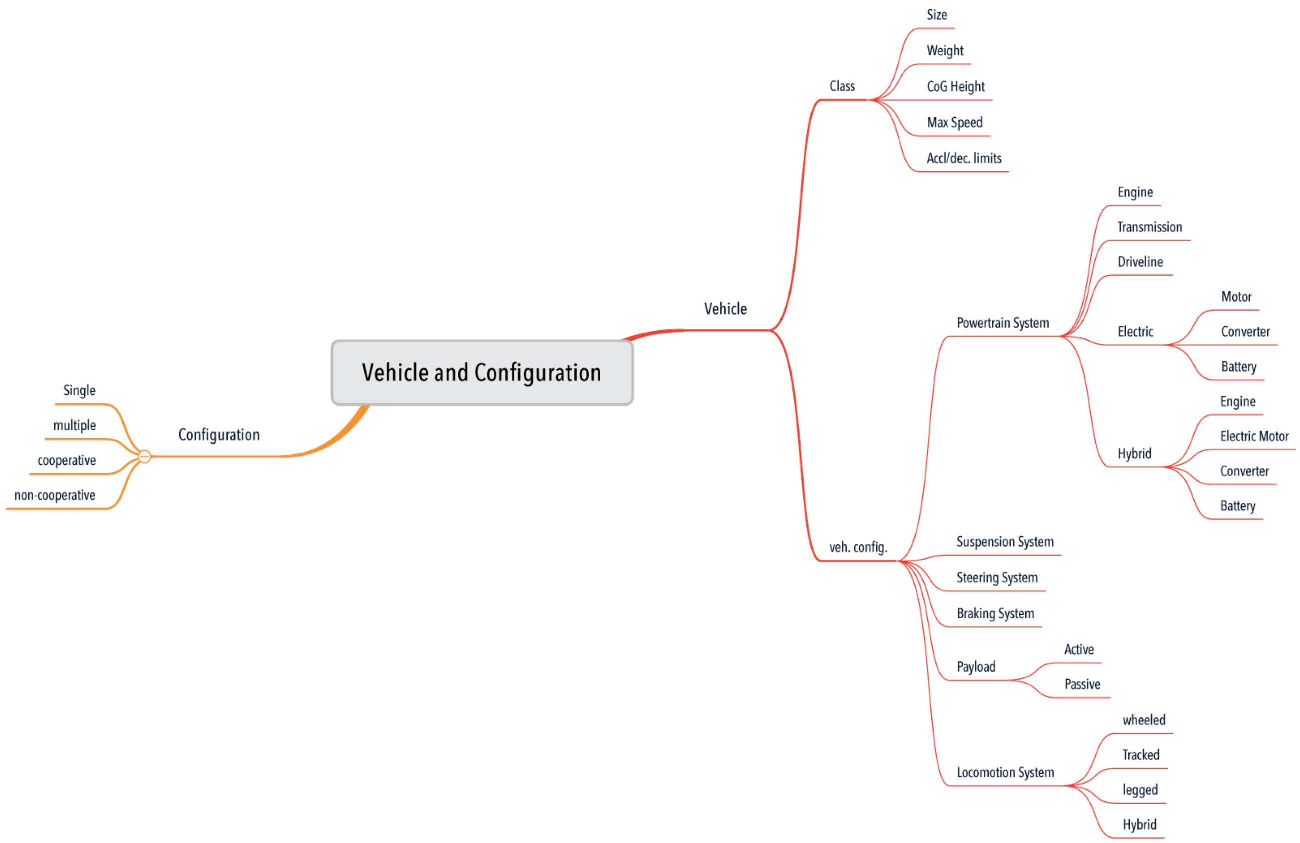


Figure 4-17: Illustration of the Ground Vehicle and Configuration Layer and Its Attributes.

4.3.4.4 Sensors

The sensors layer, as shown in Figure 4-18, defines the set of sensors equipping a vehicle enabling vehicle self-awareness (localization and health monitoring) and environmental awareness (perception) to achieve autonomous mobility. See Chapter 2: Virtual Environments, Sensors, and Uncertainty Quantification for additional information related to vehicle sensors.

4.3.4.5 Autonomy Capabilities

The autonomy capabilities layer explicitly describes which aspects of the driving task the vehicle needs to have independence from the human and to what degree. To this end, different aspects of the driving task are broadly classified under the three key categories of perception, planning, and control. For the purposes of this document, these categorical tasks are defined as follows:

Perception: The procedure through which sensor data are processed to extract knowledge about the environment and the vehicle's states that is relevant for planning purposes.

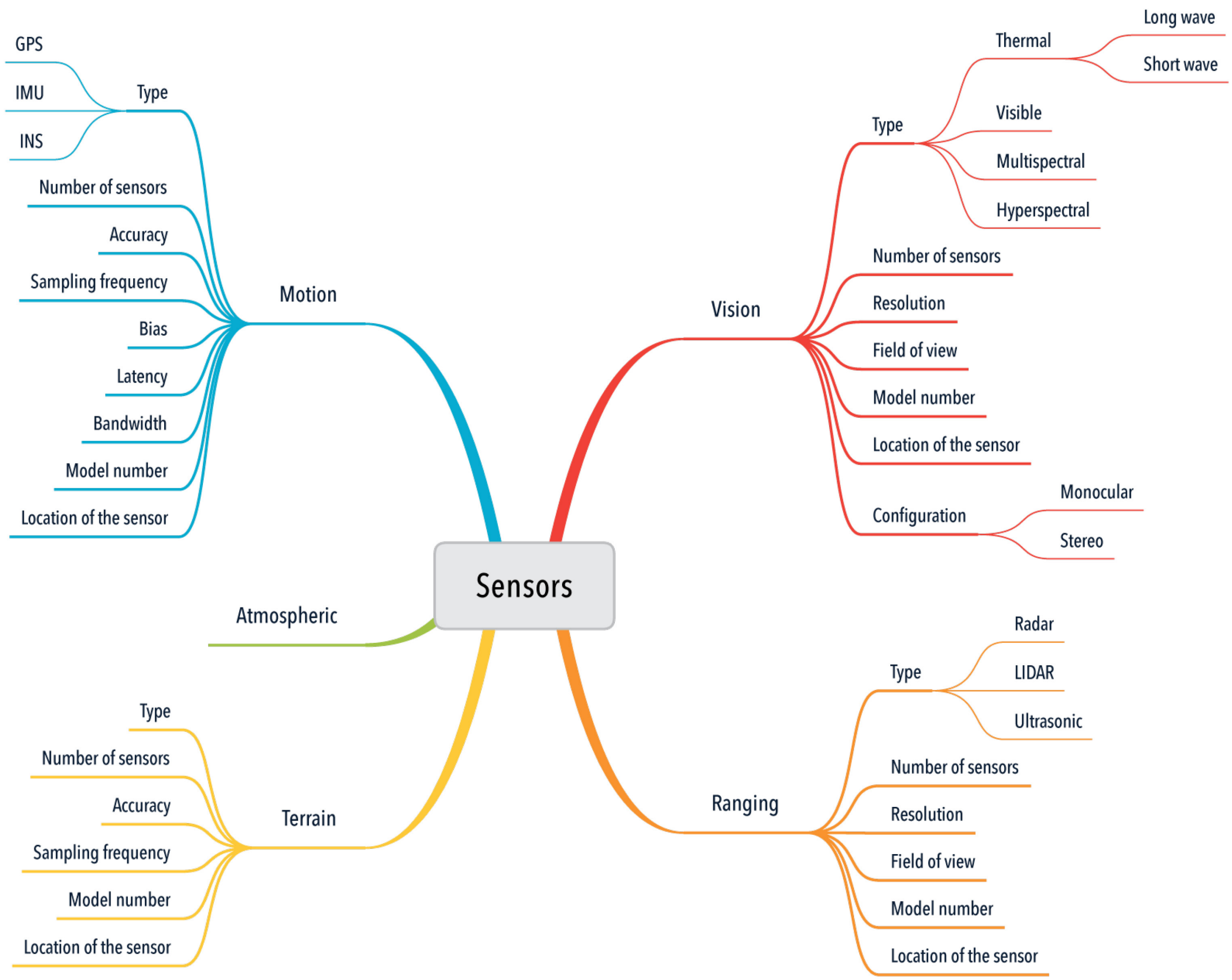


Figure 4-18: Illustration of the Sensors Layer and Its Attributes.

Planning: The process of making decisions about the motion of the vehicle to accomplish the vehicle's task, e.g., how to go from point A to B, or how to cover a given area.

Control: The process of determining the vehicle control commands (i.e., speed and steering) such that the vehicle can successfully execute the plan, e.g., determining the steering commands to follow a given path. Autonomy is enabled by the algorithms that partially or fully address one or more of these tasks, as well as the hardware – i.e., sensors, actuators, and computing hardware – that these algorithms depend on. The closed-loop relationship that is formed by the integration of these algorithms with the vehicle is illustrated in Figure 4-19. The figure reflects the fact that for the autonomous mobility simulation environment envisioned in this document, the physical elements of environment and vehicle along with its sensors and actuators are considered to be within the scope of the simulation environment, whereas the algorithms that enable autonomous perception, planning, and control are treated as external entities, the integration of which with the simulation environment needs to be supported through appropriate interfaces.

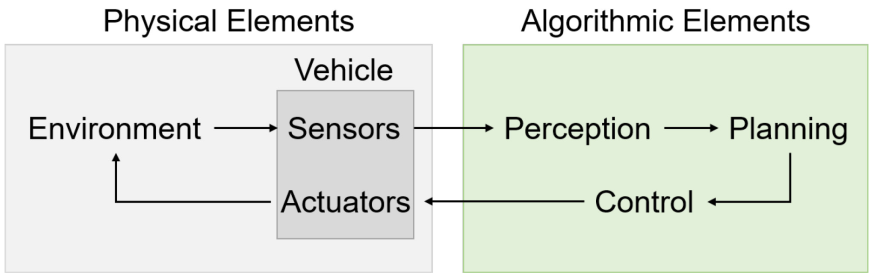


Figure 4-19: The Closed Loop Formed Between the Algorithmic and Physical Elements of an Autonomous Vehicle.

The fact that algorithms may address the perception, planning, and control tasks only partially gives rise to the concept of levels of autonomy, which has been subject to much research and discussion and presents a challenge in terms of defining the simulation scenarios clearly. To better explain this challenge, a brief overview is given in Section 4.2.2 on the different approaches to define levels of autonomy. Each framework reviewed in Section 4.2.2 has its own advantages and disadvantages that could be discussed in depth. For the purposes of this document, however, they share a key shortcoming, which is summarized as follows.

The existing frameworks to characterize levels of autonomy do not help define and communicate what autonomous functions are needed to implement in a scenario in an unambiguous way. This is an important need if one would like to create a specific scenario with specific autonomy capabilities that is to be recreated in many different simulation tools, potentially by different groups of people, to assess their capability to evaluate autonomous mobility. Existing levels of autonomy frameworks are not born out of this need. Instead, many dramatically different autonomy technologies can be mapped into the same level of autonomy in these frameworks. Therefore, they do not serve the purposes of the autonomy capabilities layer well.

In light of this identified gap, it is proposed to define a set of autonomy capability attributes under perception, planning and control explicitly and in detail. A first draft of such a list of attributes is shown in Figure 4-20 as a mind map at a high level and explained next.

The high level attributes that need to be defined under the perception category are as follows:

1) **Ego States:** This attribute defines which states of the ego vehicle need to be perceived as part of the desired autonomy capability. Examples include the vehicle position, vehicle velocity, roll, pitch, and yaw angles and their rates, wheel speeds, and steering angle.
2) **Path:** This attribute defines to what extent the vehicle needs to perceive a path. For example, a vehicle may be given a path or waypoints to follow by a higher level vehicle coordinator, and path perception may not be necessary. Alternatively, there may be a track that the vehicle is expected to identify and follow, such as the lanes on a road or a trail in the woods. A higher level of autonomy capability may be demanded by, for example, expecting the vehicle to navigate itself even if there are no tracks. In this case, the vehicle may need to perceive the drivable space entirely on its own without any pre-identified pathways.
3) **Surface:** This attribute defines to what extent the surface properties need to be perceived. Potential sub-attributes include the type (e.g., asphalt, gravel, sand, or grass), conditions (e.g., dry or wet, hard or soft, etc.), and topology (e.g., flat or uneven) of the surface. A vehicle that is to operate on well-maintained grounds may not need any level of surface perception. On the other extreme, a vehicle that is expected to operate on a variety of terrains is likely to need to be fully aware of all the surface attributes.

4) **Objects:** This attribute defines what level of perception is required to recognize different kinds of objects. Objects may be obstacles that need to be avoided. Obstacles may be positive (i.e., above the ground surface, such as walls or trees) or negative (i.e., below the ground surface, such as holes or ditches), they may be stationary or static, and they may have different threat levels. Objects may also be agents with which the vehicles need to collaborate or coordinate, or simply be aware of because they may pose threats beyond just being an obstacle to be avoided. As such, differentiating their type (e.g., other vehicles, people, and fauna), movement, and intent may be important. Requirements on how to handle each one of these sub-attributes would place different requirements on perception and are thus important to describe explicitly.

5) **Traffic Controllers:** This attribute defines to what extent the various forms of traffic controllers need to be perceived. Examples include traffic lights, traffic signs, and traffic police.

6) **Illumination:** This attribute defines under which illumination conditions all the other perception capabilities are required to be maintained. Examples include light vs. dark conditions (i.e., intensity), whether or not perceiving the colors is important, and high vs. low contrast scenes.

7) **Weather:** This attribute defines the weather conditions under which all the other perception capabilities are required to be maintained. Examples include sunny, cloudy, rainy, snowy, and foggy weather.

The sub-attributes given as examples above are summarized in Figure 4-21 as a separate mind map for the perception category alone.

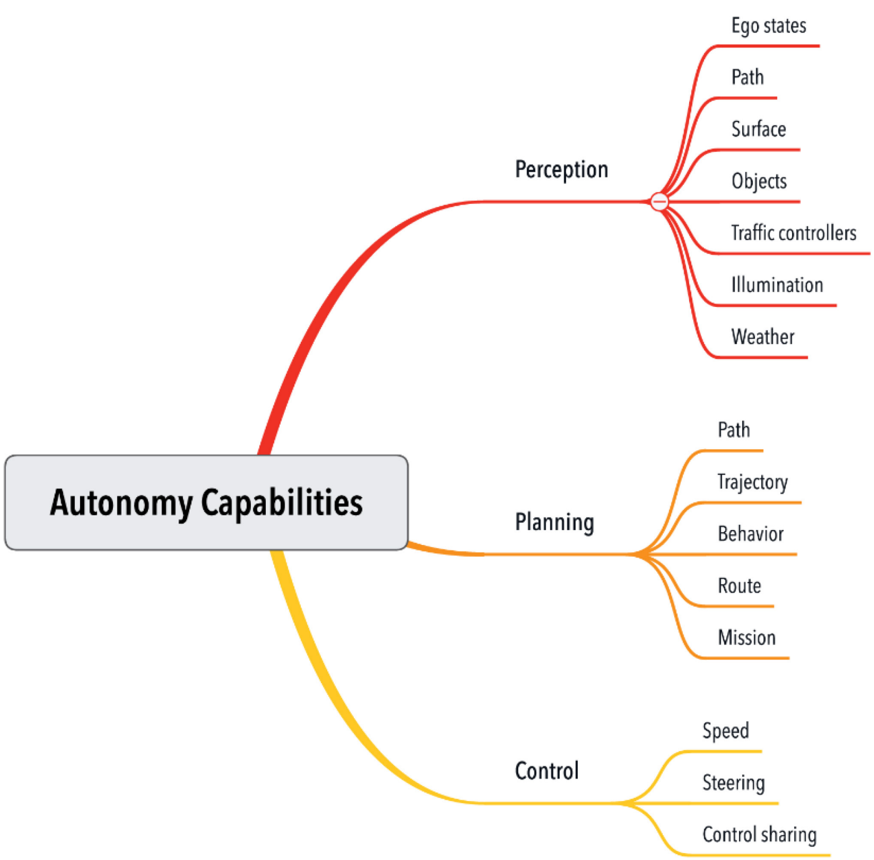


Figure 4-20: The Attributes of the Autonomy Capabilities Layer.

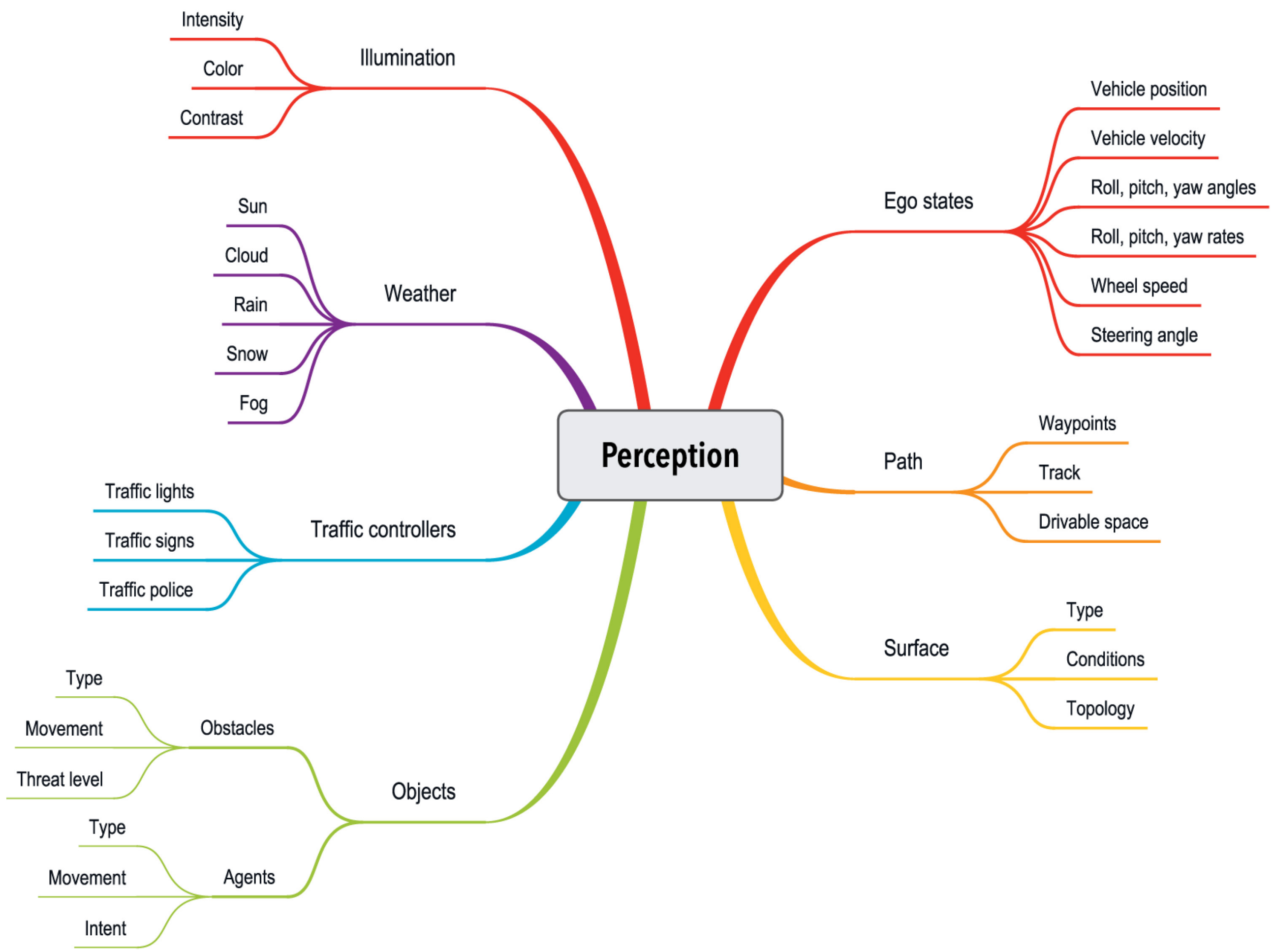


Figure 4-21: Example Attributes and Sub-Attributes for the Perception Category.

The high level attributes that need to be defined under the planning category are as follows:

1) **Path:** This attribute defines the capabilities at the path planning level. A vehicle that only needs to track a given path may not need any path planning capability. However, even a simple obstacle avoidance maneuver requires some path planning ability. Path planning with vehicle kinematic constraints may suffice if the vehicle dynamics are not critical. Taking vehicle dynamics into account at the path planning stage may be a necessity if a vehicle is expected to operate close to its limits of handling. Defining such differences explicitly is expected to help with defining comparative studies to assess the benefits of different path planning technologies.

2) **Trajectory:** This attribute defines the trajectory planning capabilities. The distinction from the path planning attribute is that a trajectory is parameterized by time. Thus, trajectory planning encompasses path planning and further includes the problem of planning the velocity along that path. Similar to the discussion given above for the path planning attribute, trajectory planning may consider only the kinematic constraints of a vehicle, or its dynamic constraints, as well. Such differences are important to specify in the definition of a scenario to be simulated to allow for trade-off studies between different trajectory planning technologies. This attribute enables the expression of such differences.

3) **Behavior:** This attribute defines the extent to which the vehicle needs to plan its behaviors. Example behavioral planning questions include whether to overtake of keep following the preceding vehicle, or whether to speed up and merge in front of or slow down and merge behind a vehicle when merging to a highway. The capabilities in making such decisions autonomously can be spelled out using this attribute when defining a scenario.
4) **Route:** This attribute defines to what extent route planning is handled autonomously. A vehicle may be given a route or required to plan a route by itself depending on various metrics such as minimum distance, minimum time, minimum energy, or minimum risk. Differences in such capabilities can be defined using this attribute.
5) **Mission:** This attribute defines to what extent the vehicle needs to plan its mission autonomously. If the vehicle will always be given a destination point or a path to track without questioning why it needs to do so, autonomy in mission planning may not be needed. If, however, the vehicle is expected to understand that it needs to perform a reconnaissance mission and plan the details of how to best execute that mission on its own, this will require more sophisticated autonomy capabilities, which can be specified through the mission planning attribute.

Finally, the high level attributes that need to be defined under the control category are as follows:

1) **Speed:** This attribute defines the autonomy capabilities a given vehicle has in controlling its speed. If all the safety constraints have been carefully taken into account at the planning stage and the planning loop times are sufficiently short, autonomy in the speed control attribute may be low, as it may reduce to tracking the given speed references. Otherwise, additional autonomy capabilities may be needed at the speed control level to ensure safety. This attribute allows for specifying these aspects of a scenario.
2) **Steering:** This attribute defines the autonomous steering capabilities. Similar to the example given above for speed control, these capabilities may be limited to tracking given steering trajectories or may involve more autonomy in calculating and executing the steering commands to stay on a desired path under disturbances.
3) **Control Sharing:** This attribute captures any capabilities that may be required to allow for sharing the control with an on- or off-board human driver. If autonomy is sharing the control of the vehicle with a human, then it may need to communicate with and adapt to the human, and make decisions about when and how to take over or relinquish control, or how to negotiate control authority. Such capabilities can be described using this attribute.

The framework described above aims to provide sufficient information to portray the autonomy capabilities of a vehicle as part of defining a scenario. This information, either in and of itself or in combination with the other scenario definition layers, could also be used to derive the level of autonomy in the sense of one or more of the existing classification schemes, if desired. For example, the information provided under the control category about how the vehicle controls its speed and steering and how that control authority is coordinated with a human driver can help to determine the vehicle's SAE Level. Alternative level of autonomy definitions could also arise. For example, each attribute could be graded as level 0 if there is no autonomy in that attribute, level 1 if the vehicle is assisting a human driver with that attribute, level 2 if the vehicle is mainly in charge, with assistance from human when needed, or level 3 if the vehicle is completely autonomous with respect to that attribute. The grades could be summed across all attributes to come up with a total grade to represent an overall level of autonomy. Yet another alternative is to let the level of autonomy become an outcome of the simulation. For example, miles per disengagement is a metric used by industry to track how the self-driving technology is evolving within a company or across companies as illustrated in Figure 4-22 [10]. Hence, the framework described here can support the calculation or derivation of a cumulative level of autonomy metric if needed and is not meant to replace the existing schemes.

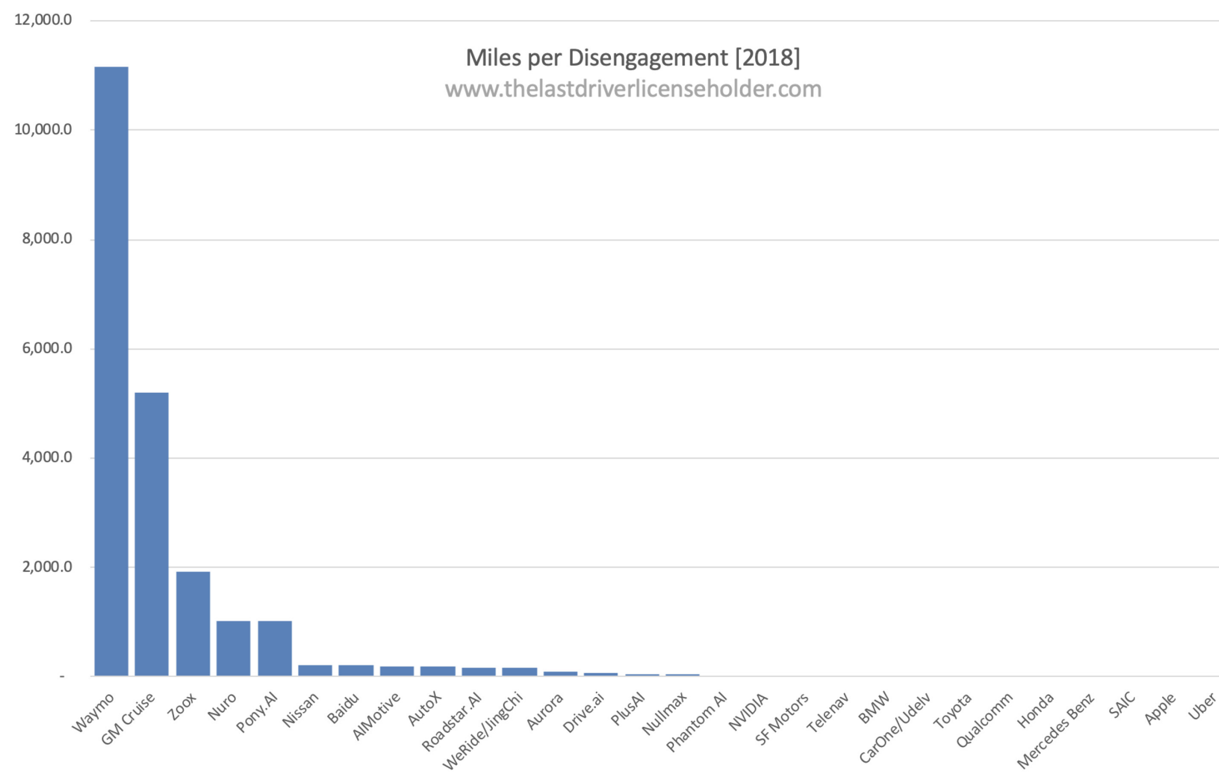


Figure 4-22: The Miles per Disengagement Report of 2018 [10].

4.4 SCENARIOS

Scenarios generated by the framework should be reflect the situations that an autonomous military ground vehicle would be utilized in as well as posing mobility challenges. Scenarios in which mobility assessment occurs are not to be confused with the scenarios that are constructed for V&V purpose, which can be simpler and more constrained. Recent reports and news articles [16], [17], [18], describing recent advances and fielding of a military UGV usually depict the following task that are assigned or envisioned to be assigned to an autonomous ground vehicle:

- Support (e.g., mule, convoy, logistics);
- Surveillance;
- Reconnaissance;
- Mine/IED clearance; and
- Combat.

These different tasks pose different challenges for and requirement of the autonomous mobility. Support tasks, such as mule or convoy, entail following a leader, be it a soldier or another vehicle. The mobility challenge consists mainly of following tracks, keeping distance/speed/angle to the leader. Moreover, the task can entail being able to march from point A to point B while carrying supplies/ammunition, which would require capability of path planning and obstacle avoidance.

Surveillance and reconnaissance as tasks pose demands on signature management and fuel consumption. Thus, making the autonomous mobility to optimize the paths or choosing paths according to specifications. While for mine and IED clearance tasks require advanced abilities in obstacle crossing, e.g., wading and crossing trenches and rough terrain. Combat task will include working alongside manned armored vehicles and soldiers, where the ability to maneuver at different speeds will be crucial. The task will embody the demands of over tasks, from the ability to follow a leader or navigating previously unknown terrain to a vantage position to provide fire support.

Many of these autonomous mobility capabilities are still in the lower TRL level or on the drawing board. Current capabilities of autonomous mobility consist of remote controlled (semi-autonomous), waypoint navigations that are GNSS supported and leader-follower functionality. Being able to autonomously maneuver in GNSS-denied environment or perform obstacle avoidance and off-road path planning is generally deemed to be many years into the future. The assessment of the autonomous mobility may need to be conducted in a simulated environment, for a set of use cases that aim at capturing the mobility challenges that different UGV tasks will pose, thereby assessing current capabilities of autonomy algorithms.

4.4.1 Uses Cases

A modeling and simulation framework for autonomous mobility of military ground vehicles could be applied to multiple uses. In the first case, the framework could be used by those developing autonomous vehicles and the software that will operate them. A modeling and simulation framework has many advantages for development: a developer does not need an expensive physical prototype, M&S can abstract away complex parts that are not directly relevant to a developer's specific goals, many more simulated tests can be run than physical tests, etc. A second use case is assessment of autonomous ground vehicles for acquisition. In this case, the user is provided a ground vehicle design defined by a developer and is evaluating its performance against a defined set of requirements. As with the developer, modeling and simulation should allow rapid testing against many scenarios including those that may be expensive, dangerous or even impossible to perform in physical testing. In this case, the modeling and simulation framework must support all of the tests required and must be validated to provide confidence that the test results reflect real world performance.

Modeling and simulation frameworks can also be used to predict mission performance in field operations. A user may want to determine the likelihood that an autonomous vehicle can perform a mission before choosing between an autonomous system and a crewed vehicle. In this case, the modeling and simulation framework must be easy to use, support input of data collected in the field, and generate results quickly on limited data. With the described scenarios in mind, three use cases have been selected to cover the majority of the tasks that an autonomous military ground vehicle would face, focusing in particular on the mobility capability. The use cases are designed to increasingly raise the challenge that the autonomous systems need to overcome in order to complete the assigned task.

The cases are:

- *A to B.* This case aims to represent missions such as reconnaissance, re-supply and surveillance.
- *Leader – follower*. This case aims to represent tasks such as mule and convoy.
- *Dynamic environment.* This case aims to represent tasks combat and mine-clearance.

A brief description of the respective case and an example of a functional scenario breakdown are presented in the following sections.

4.4.1.1 A to B

This case involves a single vehicle (ego) in operation whose goal is to reach one or several specific locations. The route can be free of or include fixed obstacles that need to be avoided in order successfully reach the (geolocalized) target location. Subtasks include:

- Assessing forward area for possible positions, pick best (reachable) one.
- Maneuvering in terrain to reach the position while minimizing signature.
- Do this in the shortest possible time.

Measures of Merits for scenario evaluation regarding mobility assessment:

- Time;
- Signature; and
- Mobility post task completion.

A functional breakdown of this use case is shown below where the attributes have been specified. Note that different attributes can be assigned (e.g., night instead of day light conditions), thereby generating scenarios and altering the mobility challenge.

- Operation:
  - Task: reconnaissance:
    - Given a start point.
    - Given an area for end point.
    - Task criteria/constraints:
      - Must be able to make observation from point B.
      - Keep own signature low.
      - Reach B in by the quickest route.
      - Once in target area, ego needs to assess the “best” point B based on task criteria.
  - Range: A to B:
    - Ego moves from A to B, does obstacle static avoidance.
    - Ego needs to worry about vehicle safety (stability).
  - Signature (sound, tracks, cover if possible).
    - Ego needs to perceive the surface.
    - Ego needs to perceive surroundings.
  - Route options:
    - Ego needs to be able to estimate the best route between A to B.
    - The route is estimated based on task criteria/constraints.

- Contingency: withdraw:
  - Same as for Route options.
- Threat level: high:
  - Same as for Signature.

- Environment:
  - Sunny.
  - Wooded.
- Autonomy capabilities:
  - Specific algorithms.
  - ALFUS 1 – 3 (4 – 6).
- GV and configuration:
  - Light combat UGV.
- Embedded sensors:
  - Vision.
  - Ranging.
  - Localization.
  - Navigation.

4.4.1.2 Leader-Follower

Involves a single vehicle (ego) that is posed as an autonomous mobility challenge in a collaborative or uncoordinated manner with one or more vehicles. This constitutes the ability to follow tracks and maneuver with a lead vehicle while keeping a set distance and angle.

Subtasks:

- Maintain distance to the vehicle in front (estimate distance/speed?), alternatively maintain velocity over time (constant/variable?).
- Identify and follow tracks of vehicle in front.
- If risks ("getting stuck", obstacle, etc.) too high, make (minimal) deviation from track.
- Measures of Merits for scenario evaluation regarding mobility assessment:
  - Ability to maintain speed/distance when following leader.
  - Signature (track deviations).
  - Fuel economy.

A functional breakdown of this use case is shown below where the attributes have been specified. Note that different attributes can be assigned, e.g., threat level attribute can be altered there by changing the constraints on mobility.

Operation:

- Task: Advance:
  - Given a lead vehicle and initial position with regard to leader.
  - Task criteria/constraints:
    - Follower to perceive the distance to lead, speed of lead, position of lead, etc.
    - Keep own signature low – follow in tracks of leader, minimum deviation.
- Range:
  - Lead vehicle moves A to B, does obstacle static avoidance.
  - Follower is given no data (e.g., no V2V).
- Threat level: Low (no immediate threat):
  - Follower does not need to worry about other objects cutting in between.
  - Follower needs to worry about vehicle safety (stability).
- Signature (sound, track deviation):
  - Follower does need to perceive the surface.
  - Follower needs to be able to follow in the leaders tracks.
- Contingency: Stop and find cover:
  - Follower needs to have a notion of "cover".
  - Follower needs to perceive surroundings.
- Route options:
  - Follower is allowed only minimal deviation from leads track to maintain low signature.

Environment:

- Sunny;
- Dusty;
- Late afternoon; and
- Rocky terrain.

Autonomy capabilities:

- Specific algorithms.
- ALFUS 4 – 6.

GV and configuration:

- Logistics UGV.

Embedded sensors:

- Vision;
- Ranging;
- Localization; and
- Navigation.

4.4.1.3 Dynamic Environment

Involves a single vehicle (ego) following a route in a dynamically changing environment. The autonomous mobility challenge lies in the environmental changes surrounding of ego, requiring higher levels of adaptation to achieve mobility.

Subtasks:

- Identify obstacles and optimal path;
- Maintain maximum velocity;
- Avoid dynamic obstacles (collapsing buildings, falling trees, wreckage, humans); and
- Minimize signature (follow cover).

Measures of Merits for scenario evaluation regarding mobility assessment:

- Time to reach rendezvous point;
- Time in threat area;
- Damage sustained; and
- Signature.

A functional breakdown of this use case is shown below where the attributes have been specified. Note that different attributes can be assigned (e.g., night instead of day light conditions), thereby generating another scenario and thereby altering the mobility challenge.

Operation:

- Task: retreat:
  - Given a start point A;
  - Given a stop point B.
  - Task criteria/constraints:
    - Reach stop point B; and
    - Select quickest route possible at given time.
- Range: A to B, dynamic route:
  - Ego moves from A to B, does dynamic (seeing, arising continuously) obstacle avoidance.
  - Ego maintains as high speed through terrain as possible.

- Threat level: high:
  - Ego needs to worry about vehicle safety;
  - Ego needs to worry about vehicle "health";
  - Ego needs to assess time passed maneuvering;
  - Ego needs to have a notion of "cover";
  - Ego follows cover when possible;
  - Ego does need to perceive the surface; and
  - Ego needs to perceive surroundings.
- Signature:
- Route options:
  - The route is estimated based on task constraints.
  - See also Environment – dynamic and task constraints.

Environment:

- Sunny;
- Rocky;
- Urban;
- Dynamic, a.k.a. "throw the map away and figure what to do by yourself":
  - Ego does need to perceive the surface;
  - Ego needs to perceive surroundings.

Autonomy capabilities:

- Specific algorithms; and
- ALFUS 7 – 10.

GV and configuration:

- Light combat UGV.

Embedded sensors:

- Vision;
- Ranging;
- Localization;
- Navigation; and
- Assessing self-health.

4.4.2 Framework Approaches

The introduction of the use cases is presenting three situations which gives the ability to capture most of actual situations that are plausible in an operational configuration. These are used as baseline to generate scenario requirements. Once scenario requirements are defined, it will be included in the proposed framework. In order to validate the coherency and consistency of our framework we propose two approaches. Generalization or top-bottom approach and validation which is the opposite bottom-top approach.

4.4.2.1 Generalization: Top-Bottom

The top-bottom approach is the natural way to use the framework and is illustrated in Figure 4-23. Its starts from defining the scenario requirements. This list of requirements is then broken down into the five layers (Operation, Environment, Ground Vehicle and Configuration, Sensors and Autonomy Capabilities). Then for each layer, relevant attributes and sub-attributes may be selected accordingly to the given scenario with the specific concrete value of their abstraction level. Once the scenario requirement is mapped into the framework the simulation can be run and a variant of this scenario can be also run simply by modifying a concrete value within the range defined by the logic level of abstraction.

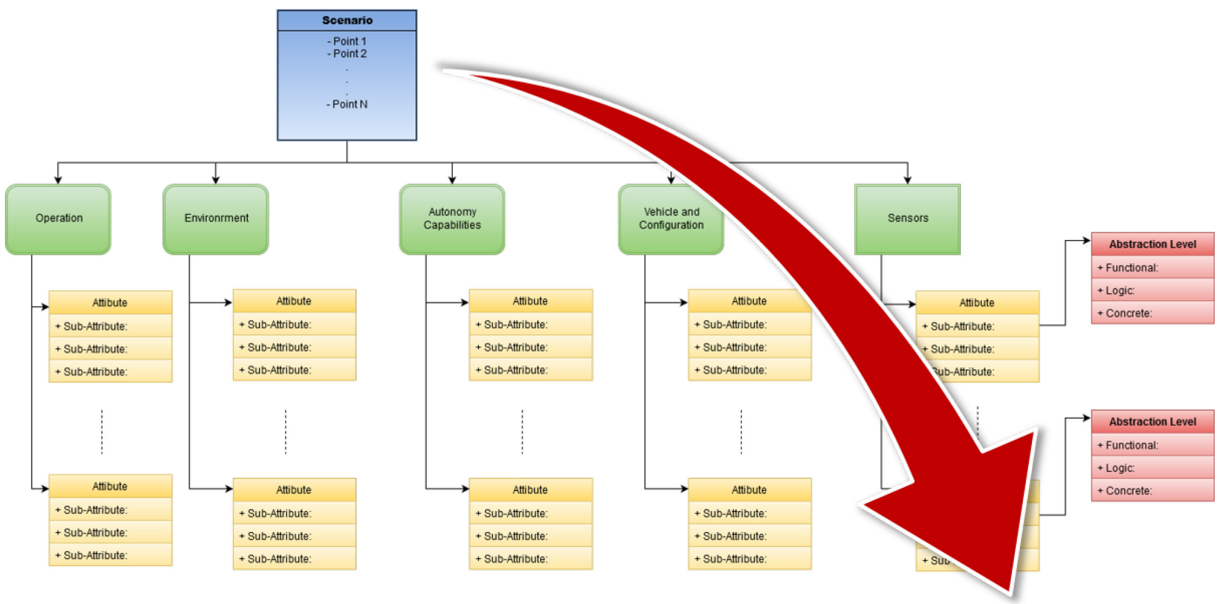


Figure 4-23: Illustration of the Top-Bottom Approach.

4.4.2.2 Validation: Bottom-Top

In the previous section the top-bottom which is the normal process was explained. This obviously applies for a proven process which is not yet the case. Thus, in order to find the possible missing gap or potential incoherencies of our proposed framework, the bottom-top approach is proposed (Figure 4-24). This reverse-engineering approach aims to start from an existing simulation and map it back to the framework. Starting from the lowest elements sub-attributes, then attributes and layers. Finally, the scenario requirements should be matched if the mapping was consistent. If not, then the missing link can be accurately identified and corrected. This missing link can be characterized by a non-referenced attribute, or a missing link between attributes or else.

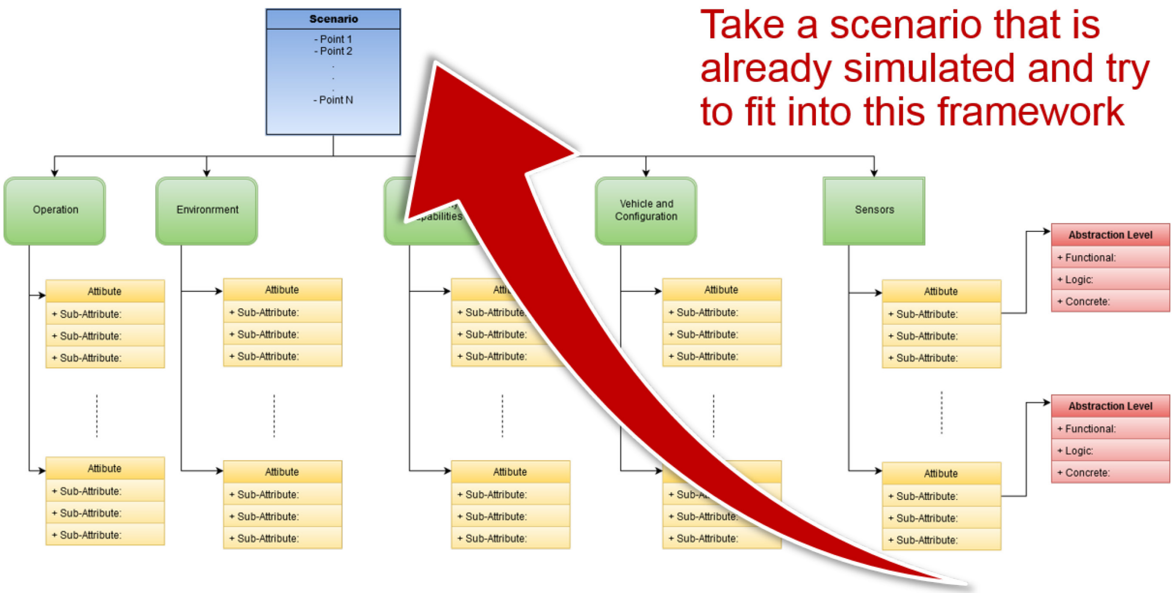


Figure 4-24: Illustration of the Bottom-Top Approach.

4.4.3 Concrete Application of Parameterized Scenarios

4.4.3.1 Case #1

As an example case study, the scenario definition framework described above has been applied to capture the simulation scenarios in Chapter 5 of Ref. [19] that are aimed to test the capabilities of vehicle dynamics aware navigation algorithms [20], [21], [22], [23] using the nonlinear optimal control software framework called NLOptControl [24]. The scenario of interest of Ref. [19] is illustrated in Figure 4-25.

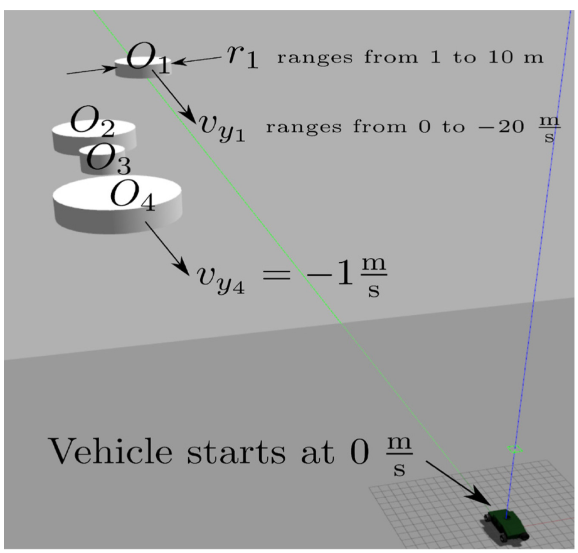


Figure 4-25: Depiction of the Test Scene Used in Case Study 1 [19].

The vehicle platform is a notional High Mobility Multipurpose Vehicle (HMMWV) modeled in Chrono [25]. The vehicle is assumed to be equipped with a 2D LIDAR and employ the Kalman filter based perception algorithm described in Ref. [26]. For simplicity, the vehicle states are assumed to be known and are directly fed from the plant model. Hence, no state sensors are considered such as GPS, IMU, or wheel encoders. The vehicle employs the model predictive control based trajectory planning algorithm developed in Refs. [20], [21]. No behavioral, route, or mission planning capability is considered. The planned trajectories are executed using two feedback controllers. In particular, a PID controller tracks the planned speed trajectory, whereas the steering commands are determined using the pure pursuit path tracking algorithm [27]. The test scene contains four obstacles denoted as O_1-O_4. The obstacle O1 is parameterized by its radius and y velocity to generate a range of scenarios. Obstacles O_2 and O_3 are stationary, whereas obstacle O_4 is moving with constant speed.

The terrain is assumed to be flat, the surface rigid, and no weather conditions or illumination challenges are considered. The details can be found in Ref. [19].

Even though the concrete simulation example of Ref. [19] is not derived from a layered scenario description framework with functional, logical, and concrete definition levels, it is possible to conceive such a flow as exemplified in Table 4-8. Note that this example is simplified to demonstrate proof-of-concept and how this existing simulation example can be mapped to the scenario description framework, rather than providing all the details to fully describe the scenario.

Table 4-8: Example Functional, Logical, and Concrete Descriptions of Case Study 1.

Functional	Logical	Concrete
Operation: Move supplies from point A to point B as quickly as possible.	**Operation:** • Threat level [low, medium, high]. • Contingency [withdraw, find cover, proceed]. • Signature [minimize tracks, follow cover, of no importance]. • Point A coordinates [X1, X2, X3, X4, X5]. • Point B coordinates [Y1, Y2, Y3, Y4, Y5].	**Operation:** • Threat level: low. • Contingency: proceed. • Signature: of no importance. • Point A: X3. • Point B: Y5.
Environment: Relatively flat terrain with obstacles during daytime.	**Environment:** • Terrain [rigid, sand]. • Topology [flat, rough]. • Weather [clear, cloudy, rainy]. • Number of obstacles [1, 2,…, 10].	**Environment:** • Terrain: rigid. • Topology: flat. • Weather: clear. • Number of obstacles: 4.

Functional	Logical	Concrete
	Environment (cont'd): • Size of obstacles [within 1 – 12 m radius]. • Locations of obstacles [within -50 – 50 m in x direction and 50 – 300 m in y direction]. • Speeds of obstacles [within -20 – 20 m/s].	**Environment (cont'd):** • Size of obstacles: 7 m, 10 m, 5 m, 12 m. • Locations of obstacles: (0,275)m, (-25,168)m, (-25,145)m, (-25,110)m. • Speeds of obstacles: -10 m/s, 0, 0, -1 m/s.
Autonomy Capabilities: Vehicles may or may not have humans available to assist with driving.	**Autonomy Capabilities:** • Ego states perception [full]. • Path perception [none, track]. • Surface perception [none, type]. • Object perception [static and moving obstacles, other vehicles]. • Traffic controller perception [none]. • Illumination perception requirements [none, daylight]. • Weather requirements for perception [none, sun, cloud, rain]. • Path planning [kinematic, dynamic]. • Trajectory planning [kinematic, dynamic]. • Behavior planning [none]. • Route planning [none]. • Mission planning [none]. • Speed control [none, PID]. • Steering control [none, pure pursuit]. • Control sharing [none, haptic shared control of steering].	**Autonomy Capabilities:** • Ego states perception: full. • Path perception: none. • Surface perception: none. • Object perception: static and moving obstacles. • Traffic controller perception: none. • Illumination requirements for perception: none. • Weather requirements for perception: none. • Path planning: dynamic. • Trajectory planning: dynamic. • Behavior planning: none. • Route planning: none. • Mission planning: none. • Speed control: PID. • Steering control: pure pursuit. • Control sharing: none.

Functional	Logical	Concrete
Vehicle and Configuration: Vehicles are at least the size of a medium truck with conventional powertrains.	**Vehicle and Configuration:** • Model [HMMWV, FED Alpha]. • Number of vehicles [1, 2, 3]. • Number of humans [0, 1, 2, 3].	**Vehicle and Configuration:** • Model: HMMWV. • Number of vehicles: 1. • Number of humans: 0.
Sensors: Only GPS, IMU, cameras and LIDARs are available for the vehicles.	**Sensors:** • Cameras [FLIR Grasshopper3, MVBlueFox 2]. • LIDAR [Generic 2D, Velodyne VLP-32C, VLP-16]. • GPS/IMU [VectorNav VN100, VN200, VN300].	**Sensors:** • Generic 2D (1x).

4.4.3.2 Case #2

In a second example case study, we apply the framework to an evaluation of an autonomous vehicle platform navigating a road segment blocked by a manmade obstacle under varying environmental conditions. The objective of the study was to evaluate the effect of two environmental conditions on the likelihood of detecting and avoiding the obstacle. The first condition was a suspension of dust co-located with the manmade obstacle. Performance was evaluated at increasingly dense levels of dust. The second condition evaluated performance at increasingly heavy levels of rainfall.

The vehicle platform also focused on a High Mobility Multipurpose Vehicle (HMMWV) modeled in Chrono [25]. In this case, the vehicle could be equipped with either a stereo camera perception system or one of three 3D LIDAR systems (Ouster 64-beam, Velodyne VLP-32C, or Velodyne 16). Two obstacle detection algorithms were assessed: a geometric algorithm and a neural network classifier algorithm. Vehicle odometry was updated based on data provided by simulations of a GPS with RTK correction and an on-board IMU. Steering control was determined using a pure pursuit tracking algorithm. The environment consisted of a single undeveloped 100 m road segment with randomly placed natural obstacles (trees) on either side of the road segment. At the mid-point of the road segment, a single man made obstacle (Jarsey barrier) was placed in the center of the road segment. For this example, the terrain is flat, the segment path is straight, and the surface is rigid.

As with the first case, this example (Table 4-9) is simplified to demonstrate how an existing simulation example can be described using the scenario description framework.

Table 4-9: Example Functional, Logical, and Concrete Descriptions of Case Study 2.

Functional	Logical	Concrete
Operation: Traverse a roadway while avoiding manmade barriers with global and local environmental effects.	**Operation:** • Threat level [low]. • Contingency [proceed]. • Signature [of no importance]. • Starting point [0,0]. • Objective point [Start + 100 m].	**Operation:** • Threat level: low. • Contingency: proceed. • Signature: of no importance. • Starting point [0, 0]. • Objective point [100, 0].
Environment: Relatively flat terrain with off-road natural obstacles and on-road manmade obstacles during daytime with local dust disturbance and global rain levels.	**Environment:** • Terrain [rigid, dirt]. • Topology [flat]. • Weather [clear, raining]. • Rain rate [0, 4, 8, 12 mm/hr]. • Dust cloud density [0, 1, 2, 3, 4, 5, 6, 7]. • Number of natural obstacles [100]. • Position of natural obstacles [0, 100, within +/- 1-5 m of trail]. • Number of manmade obstacles [1].	**Environment:** • Terrain: rigid. • Topology: flat. • Weather: clear. • Rain rate: 8 mm/hr. • Dust cloud density: 0. • Number of natural obstacles: 20. • Position of natural obstacles: [(6, +1), (30, -3), …, (92, +1)]. • Number of manmade obstacles: 1.
Autonomy Capabilities: No human intervention, obstacle detection using geometric algorithm or neural-network classifier.	**Autonomy Capabilities:** • Ego states perception [full]. • Path perception [none, track]. • Surface perception [none, type].	**Autonomy Capabilities:** • Ego states perception: full. • Path perception: none. • Surface perception: none. • Object perception: static and moving obstacles.

Functional	Logical	Concrete
Autonomy Capabilities: (cont'd.)	**Autonomy Capabilities (cont'd):** • Object perception [static natural and manmade obstacles]. • Traffic controller perception [none]. • Illumination perception requirements [none]. • Weather requirements for perception [none, sun, cloud, rain]. • Path planning [kinematic, dynamic]. • Trajectory planning [kinematic, dynamic]. • Behavior planning [none]. • Route planning [none]. • Mission planning [none]. • Speed control [none, PID]. • Steering control [none, pure pursuit]. • Control sharing [none, haptic shared control of steering].	**Autonomy Capabilities (cont'd):** • Traffic controller perception: none. • Illumination requirements for perception: none. • Weather requirements for perception: none. • Path planning: dynamic. • Trajectory planning: dynamic. • Behavior planning: none. • Route planning: none. • Mission planning: none. • Speed control: PID. • Steering control: pure pursuit. • Control sharing: none.
Vehicle and Configuration: Testing specific vehicle configuration: single HMMWV.	**Vehicle and Configuration:** • Model [HMMWV]. • Number of vehicles [1]. • Number of humans [0].	**Vehicle and Configuration:** • Model: HMMWV. • Number of vehicles: 1. • Number of humans: 0.
Sensors: Vehicles equipped with GPS+RTK sensors plus Stereo Camera or LIDAR.	**Sensors:** • Stereo Cameras. • Visual quality. • LIDAR [Ouster 64 beam, Velodyne VLP-32C, VLP-16]. • GPS/IMU.	**Sensors:** • Stereo Camera with Neural-Network Classifier. • GPS/IMU.

4.4.4 Reflections

The proposed framework presents a structure aiming to integrate vehicle mobility principles in more and more autonomous ground platform solutions and thus extending the NG-NRMM. As discussed earlier there are many standards to define levels of autonomy, if none of these are consensually considered as the model to be followed it seems that ALFUS could be the most appropriate to the context of this study. The main reason depends on its situational nature and extension of this model that will be evoked later on. The final point lies on the structure based framework for scenario generation and validation. If the PEGASUS approach was inspirational, especially with its layers and abstraction level definitions, it is still limited to on-road and does not encompasses several important factors linked to autonomous mobility of ground vehicles. This is why we laid the foundation of a framework which aims to handle on-road and off-road situation, but also all the factors that we were able to list so far and that have an impact on autonomous mobility regardless of the context. Thus, the proposed framework goal is the generalization and adaptability to situational and technological changes that will certainly happen in the future.

That being said, this framework is an initial work and a first attempt toward this goal. We are conscious of its limits and need for improvement. Thus, we propose below a list of recommendations which could be considered as a road map to achieve the above described generalization:

- Case #1 and #2 are the start of the validation and improvement process of the framework to be more comprehensive. After translating an existing simulation back to a scenario representation from the perspective of our framework criteria, there is a need to complete the process and carry on several examples in order to capture missing attributes, links, sub-layers or even layers.
- Validation should continue in both ways bottom-top and top bottom.
- ALFUS need to be extended some propositions suggested to assign related metric value to how much each attribute could affect one of the three situational factors of this model.
- Measure of merit giving a metric value when measuring the relative success of a scenario needs to be further investigated, concrete and accordingly defined to complete the framework.
- Sensor/system failures were overlooked during this study and need to be taken into account in the future.
- Investigations and conclusions from the different thrust areas need to be harmonized accordingly to the above cited points as illustrated in the following Figure 4-26 and Figure 4-27.

4.5 RTG CONSIDERATIONS

The proposed RTG is uniquely positioned to address the research challenges at the intersection of perception, planning, and control. Traditionally, perception, planning, and control problems and their subtasks and sub-layers have been studied in isolation. While this divide-and-conquer approach made the scope of the individual problems more tractable and allowed leveraging, the unique domain expertise corresponding to each problem (e.g., perception has been mainly viewed as a computer science problem, whereas control scientists focused on the planning and control tasks), it did not foster dialog across disciplines or nurture a convergent research approach. However, autonomous mobility is a research challenge that is far bigger than the sum of the individual components in perception, planning, and control. As such, addressing this grand challenge requires multi-disciplinary and convergent research. In other words, research with a specific focus on the problems in the gray zones between perception, planning, and control tasks and subtasks, as well as at their interface with the ego vehicle and environment is critically needed to fully understand, evaluate, and improve autonomous mobility.

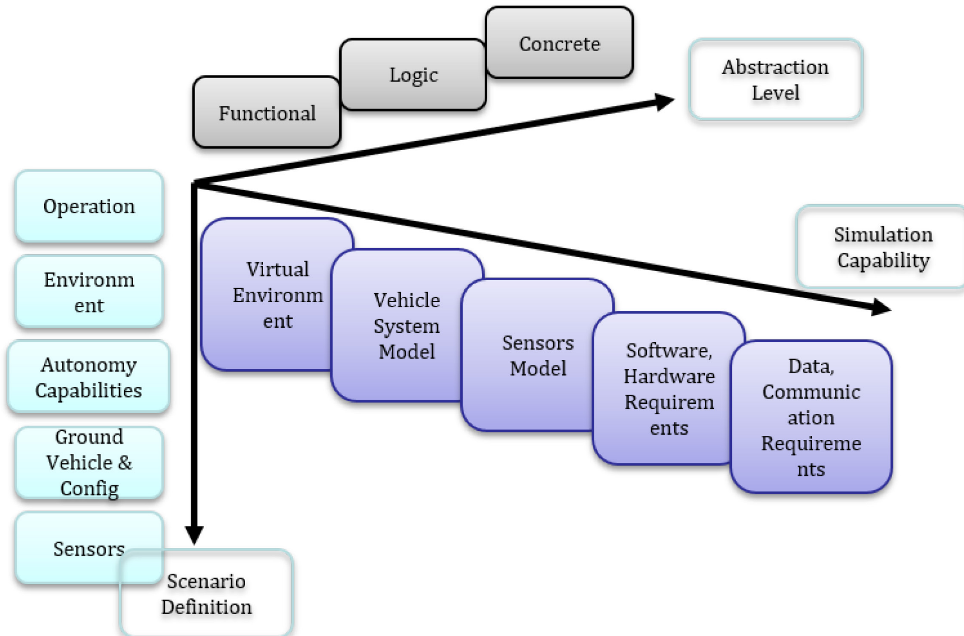


Figure 4-26: Illustration of Simulation Capability Based on Layers-Abstraction Level-Related Thrust Areas.

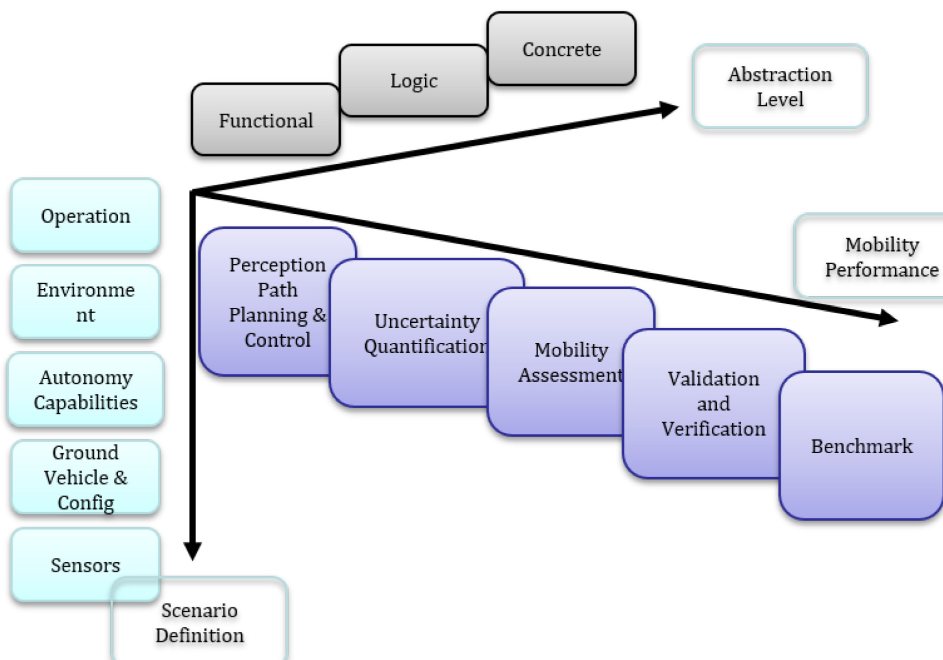


Figure 4-27: Illustration of Mobility Performance Based on Layers-Abstraction Level-Related Thrust Areas.

The proposed RTG is well positioned to address these convergent research challenges for two reasons; first, the simulation tools it will create will be uniquely comprehensive in terms of bringing the perception, planning, and control elements together in a directly army-relevant context, second, the proposed group provides the required diverse multi-disciplinary expertise and supports the culture of dialog among these disciplines. Therefore, with the right focus, right tools, the right people, and the right culture, the proposed RTG can address some of the most challenging research questions facing autonomous mobility. Examples of such research questions include, but are not limited to:

1) Understanding the impact of the performance of the perception algorithms on the performance of the planning algorithms, and the performance of the planning algorithms on the performance of the control algorithms.
2) Understanding the impact of external factors on the performance of perception, planning, and control algorithms, such as the environment and the other agents in the environment.
3) Understanding the impact of different set of algorithms and autonomy capabilities on the performance of other team members, be it other vehicles or humans.
4) Being able to capture these impacts in models and recreate them in simulation.
5) Developing the tools and methodologies that can identify the most suitable set of perception, planning and control algorithms for a given use case.
6) Developing methods to efficiently assess the reliability of an autonomous vehicle in simulation for a given use case and set of algorithms.

NRMM is the primary model to evaluate and compare the ability of military vehicles to travel over various terrains. It was initially developed in the 1960s and 1970s and is a combination of physics and empirical based vehicle-terrain relations. It was adopted by NATO in 1977. The current official release is NRMM2.8.2a. Upgrades have since been made, particularly in relation to winter mobility. Lacking is inclusion of newer vehicle technology such as anti-lock brakes and traction control. Also, computer technology and analytical capabilities have advanced greatly allowing for more numerically intensive investigations that were previously prohibitive. NRMM was originally used to facilitate comparison between vehicle design candidates but has subsequently also been used to support seasonal operational planning support. NATO's multi-national Applied Vehicle Technology (AVT) Panel, AVT-248, Next-Generation NATO Reference Mobility Model (NG-NRMM), was tasked with defining the limitations and gaps in NRMM and developing a framework to address these deficiencies to which future mobility models should adhere [28].

4.5.1 Objectives

STANREC 4813 (2018) abstracts and expands upon the original valid basis for the legacy NRMM to define NG-NRMM to be any mobility M&S capability that produces map-based probabilistic mobility predictions of ground and amphibious vehicles through interoperation of M&S tools that include: Geographic Information Systems (GIS) software, 3D physics based vehicle dynamics, terramechanics models for off-road operations, autonomous control M&S software, as well as Uncertainty Quantification (UQ) software for probabilistic M&S. Through this NG-NRMM standard, an agreed ground vehicle mobility modeling and simulation architectural specification is established. The standard is applicable to the full range of ground vehicle geometric scales and running gear morphologies [28].

An important component of AVT-248 was the development, verification, validation, and bench-marking of both simple (shear, pressure-sinkage relations) and complex (particle-particle interactions) terramechanic mobility models with which the recommendations of AVT-248 could be tested. Commercial, government, and academic organizations participated. The culmination of these efforts was a NATO Cooperative Demonstration of Technology (CDT).

4.5.2 Alignment to CDT

CDT-308 was held at the Keweenaw Research Center (KRC), 24 – 27 September 2018. Extensive vehicle and terrain data were collected as part of the CDT-308 and was used by the various organizations to calibrate and benchmark their models. The best results were obtained for dry fine sand followed by wet fine sand and dry coarse sand. The data collected as part of CDT-308 is the richest data set ever in terms of both quality and quantity as related to vehicle-terrain interactions for a wheeled vehicle. It can be used by autonomous vehicle and virtual environment developers to test their designs. However, more such databases are needed for different soil types, saturation levels, as well as winter effects using both wheeled and tracked vehicles to fully predict seasonal off-road mobility. Other findings of CDT-308 are that uncertainty quantification, development of soil models using complex terramechanic tools, and standardization across industries are important to advancing capabilities.

4.6 CONCLUSION

A framework was proposed in order to provide tools and methods to assess the mobility of autonomous ground vehicle platforms. If mobility is a mature field, the autonomy part on the other hand, in the sense of an autonomous system is a wide field where there is no strict consensus, and which is constantly evolving. With this in mind a framework was designed that aims to integrate both fields while providing a scenario generation and validation process. This process is inspired from the PEGASUS approach to which layers and level abstraction features where extended from the on-road only context to handle off-road as well as a wider range of situations. The presented framework also proposes to extend the NGRMM model by integrating autonomy into it. Similarly, an ALFUS level of autonomy situational approach, although limited, was found to be a strong foundation to propose an extended version. All of these together will enable generalization and adaptability to continuous change in situational and technological aspects. In this regard, the competition as well as the two planned CDTs will test and mature this novel framework through simulation and field tests in order to validate and benchmark solutions for autonomous ground vehicle mobility in a military context.

4.7 REFERENCES

[1] Wong, J., 1984. On the Study of Wheel-Soil Interaction, Journal of Terramechanics, 21(2), 117-131.

[2] Richmond, P.W., Shoop, S.A., and Blaisdell, G., 1995. Cold Regions Mobility Models, CRREL Report 951.

[3] Balling, O., Bradbury, M., Bruce, J., Cammarere, M., Choi, K.K., Dasch, J., Foster, C., Funk, M., Gaul, N., Hodges, H., Jain, A., Jayakumar, P., McCullough, M., Niemann, J., Ramyar, E., Scalia, J., Wasfy, T., and Wojtysiak, B., 2019. AVT-248 Next-Generation NATO Reference Mobility Model (NG-NRMM) Development, NATO Science and Technology Organization (STO), Report STO-TR-AVT-248.

[4] Goodin, C., Mange, J., Pace, S., Skorupa, T., Kedziorek, D., Priddy, J., and Lynch, L., 2017. Simulating the Mobility of Wheeled Ground Vehicles with Mercury, SAE International Journal of Commercial Vehicles, 10(2), 498-502.

[5] Sheridan, T.B., 1992. Telerobotics, Automation, and Human Supervisory Control, The MIT Press.

[6] NATO Industrial Advisory Group – Study Group 75, 2004. Pre-Feasibility Study on UAV Autonomous Operations.

[7] NATO STO Task Group AVT-175, 2016. Unmanned Systems (UMS) Platform Technologies and Performances for Autonomous Operations, STO Technical Report TR-AVT-175.

[8] Williams, A.P., and Scharre, P.D., 2015. Autonomous Systems: Issues for Defence Policymakers, The Hague, Netherlands: NATO Communication and Information Agency.

[9] Society of Automotive Engineers, 2018. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, Standard J3016_201806.

[10] Parasuraman, R., Sheridan, T.B., and Wickens, C.D., 2000. A Model for Types and Levels of Human Interaction with Automation, IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans, 30(3), 286-297.

[11] Clough, B.T., 2002. Metrics, Schmetrics! How The Heck Do You Determine A UAV's Autonomy Anyway? Performance Metrics for Intelligent Systems Workshop, Gaithersburg, MD.

[12] Proud, R.W., Hart, J.J., and Mrozinski, R.B., 2003. Methods for Determining the Level of Autonomy to Design into a Human Spaceflight Vehicle: A Function Specific Approach, Performance Metrics for Intelligent Systems.

[13] National Institute of Standards and Technology (NIST), 2007. Autonomy Levels For Unmanned Systems (ALFUS) Framework - Volume II: Framework Models, Version 1.0, NIST Special Publication 1011-II-0.

[14] PEGASUS, 2019. Available at: https://www.pegasusprojekt.de/en/pegasus-method. Accessed 20 November 2019.

[15] PEGASUS, 2019. Available at: https://www.pegasusprojekt.de/files/tmpl/PDF-ZE/04_Szenarienbeschreibung.pdf.

[16] Wolf, A., 2019. Standardised Unmanned Ground Vehicle with Open Architecture (SUGV), European Defence Agency, EDA Project Ref: 17.CAT.OP.047.

[17] Winston, G., 2019. New 'Drone' Tank Unveiled for US Army, 06 11 2019. Available at: https://www.warhistoryonline.com/news/tank-3.html. Accessed 12 December 2019.

[18] Milrem Robotics, 2019. FN Herstal and Milrem Robotics deploy weaponized UGV at Estonian military exercise, 04 05 2019. Available at: https://milremrobotics.com/fn-herstal-and-milrem-robotics-deploy-weaponized-ugv-at-estonian-military-exercise/. Accessed 12.12.2019.

[19] Febbo, H., 2019. Real-time Trajectory Planning to Enable Safe and Performant Automated Vehicles Operating in Unknown Dynamic Environments, PhD Dissertation, University of Michigan.

[20] Febbo, H., Liu, J., Jayakumar, P., Stein, J.L., and Ersal, T., 2017. Moving Obstacle Avoidance for Large, High-Speed Autonomous Ground Vehicles, American Control Conference.

[21] Liu, J., Jayakumar, P., Stein, J.L., and Ersal, T., 2017. Combined Speed and Steering Control in High Speed Autonomous Ground Vehicles for Obstacle Avoidance Using Model Predictive Control, IEEE Transactions on Vehicular Technology, 66(10), 8746-8763.

[22] Liu, J., Jayakumar, P., Stein, J.L., and Ersal, T., 2018. A Nonlinear Model Predictive Control Formulation for Obstacle Avoidance in High-Speed Autonomous Ground Vehicles in Unstructured Environments, Vehicle System Dynamics, 56(6), 853-882.

[23] Liu, J., Jayakumar, P., Stein, J.L., and Ersal, T., 2019. Improving the Robustness of an MPC-Based Obstacle Avoidance Algorithm to Parametric Uncertainty Using Worst-Case Scenarios, Vehicle System Dynamics, 57(6), 874-913.

[24] Febbo, H. NLOptControl, 2017. Available at: https://github.com/JuliaMPC/NLOptControl.jl.

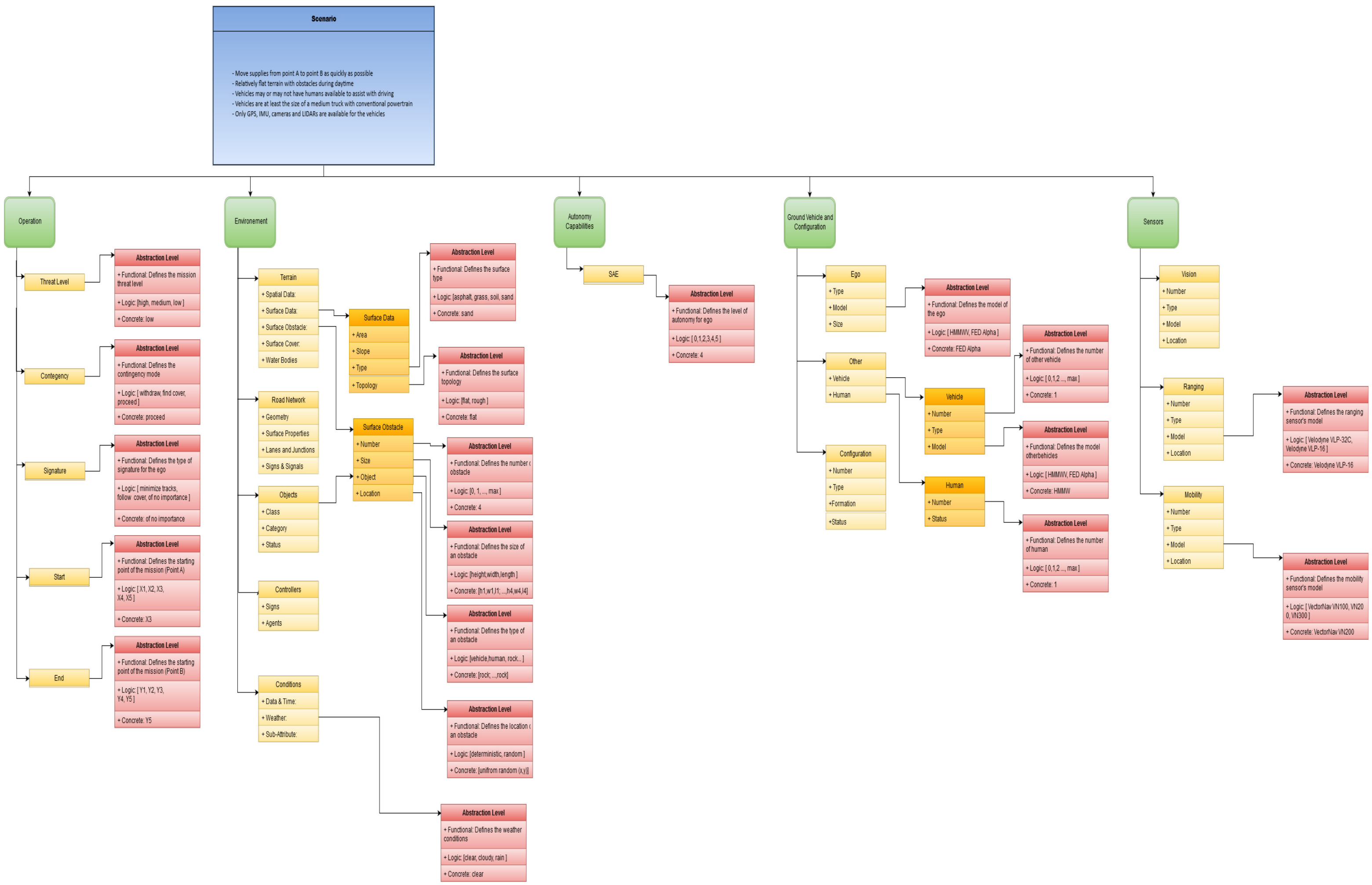
[25] Serban, R., M. Taylor, M., Negrut, D., and Tasora, A., 2016. Chrono: Vehicle-Template-Based Ground Vehicle Modeling and Simulation, University of Wisconsin – Madison, Technical Report TR-2016-10.

[26] Przybyła, M., 2017. Detection and Tracking of 2D Geometric Obstacles from LRF Data, International Workshop on Robot Motion and Control (RoMoCo), 135-141.

[27] Coulter, R.C., 1992. Implementation of the Pure Pusuit Path Tracking Algorithm, The Robotics Institute, Cargenie Mellon University, Technical Report CMU-R1-TR-92-01.

[28] Jayakumar, P., Hoenlinger, M., Mayda, W., and Bradley, S., 2018. Cooperative Demonstration of Technology (CDT) for Next-Generation NATO Reference Mobility Model (NG-NRMM), Technical Memorandum. Available at: https://www.mtu.edu/cdt/downloadable-materials/cdt-technical-memorandum.pdf.

Appendix 1: Example of a Scenario Implemented into Proposed Framework



Chapter 5 – VIRTUAL ENVIRONMENTS, SENSORS, AND UNCERTAINTY QUANTIFICATION

5.1 GOALS AND TEAM MEMBERS

The goal of the Virtual Environments, Sensors, and Uncertainty Quantification team was to evaluate the requirements for representing the operational environment within a modeling and simulation framework for evaluating autonomous mobility of military ground vehicles. The team included consideration of on-road and off-road terrains, structured and unstructured environments, static and moving objects, atmospheric conditions and the digital information layer. The team also investigated the requirements for modeling and simulation of the sensors used by autonomous systems to perceive the environment. The team considered automotive radar, camera, LIDAR, GPS, and other sensors. For each sensor, the team assessed the data generated by the sensor, the applications supported by the sensor, challenges to modeling and simulation, and examples available in current simulation frameworks. As part of our evaluation, the team considered the importance of accurate representations of the variability in the environment and the sensors for uncertainty quantification in analysis of autonomous systems. The objective was to assess the state-of-the-art in environment and sensor representation and to identify current gaps that should be addressed by future work.

The team members included:

Country	Name
Denmark	Balling, Ole
United States	Bradley, Scott
United States	Carrillo, Justin
United States	**Carruth, Daniel: Co-Leader**
United States	Frankenstein, Susan
United Kingdom	Gashinova, Marina
United States	**Gaul, Nick: Co-Leader**
Canada	Hirschkorn, Martin
United Kingdom	Hoare, Edward
Germany	Kluge, Torsten
United States	Negrut, Dan
South Africa	Reinecke, David
Czech Republic	Rybansky, Marian
United States	Serban, Radu
United States	Shoop, Sally
United States	Stawarz, Robert
United States	Wasfy, Tamer

Additional contributions to this report were made by Sean Brennan of Penn State University and Asher Elmquist of University of Wisconsin Madison.

5.2 INTRODUCTION

Uncertainty quantification provides improved understanding of the actual range of performance that can be expected from a system. Uncertainty quantification accomplishes this by describing the output variability in the response of the system to variability in the input. The environment is a significant contributor to input variability to an autonomous system. The environment is an overwhelming, all-encompassing concept for a modeling and simulation framework. In a pure mobility modeling framework, capturing the details of the ground surface and possibly information on obstacles and vegetation is an already monumental task. Autonomous mobility adds the dimension of perception and, with it, many sensors intended to provide that capability. Each sensor provides additional ways for the vehicle to perceive the environment. Some sensors require detailed geometric models. Other sensors require accurately modeled physics-based materials. The ground surface that was sufficient for modeling vehicle-terrain interaction now must also be accurately modeled for the sensors. The ground surface requires physics-based rendering materials that must be consistent with the soil strength properties associated with the surface.

When considering uncertainty, the broad range of operational capabilities of a vehicle produce a range of possible outcomes that is so large that it can seem to defy analysis. However, the boundaries of feasible vehicle behavior are dictated by the constraints imposed by the vehicle and the environment, and the primary constraints that affect off-road mobility are generally well-known. These constraints include: the geometrical limits of vehicles maneuvering around or over obstacles; the vehicle/soil interaction limits that capture the effects of friction, grade, vehicle weights, etc.; the accuracy and range of sensors and/or maps used for maneuvering; and, the typical time delays in processing sensor data, autonomous algorithms, or teleoperation commands which in turn constrain the bandwidth of vehicle guidance. It is thus possible to consider and numerically approximate the effects of these constraints – and their associated uncertainty – on the outcomes of vehicle mobility.

This chapter describes the requirements for representing the operational environment for testing and evaluation of autonomous mobility, perception and mobility, in a comprehensive modeling and simulation framework.

5.3 UNCERTAINTY QUANTIFICATION

Propagation of Uncertainty and Variability. Simulations of a system are used to predict system output responses of interest, given the inputs to the systems. The inputs that help to define the system and the corresponding simulation model are referred to as input parameters or input variables. Once the input parameters for the system are defined and the simulation model of the system is updated accordingly, the simulation is run. The objective of running a simulation is to predict output responses of interest. This simple process is shown in Figure 5-1.

Typically, in real-world systems, the inputs are not deterministic because of aleatory uncertainty. Aleatory uncertainty is defined as the irreducible uncertainty, i.e., the natural variability. Examples of aleatory uncertainty include, but are not limited to, material properties, environmental conditions, operating conditions, loads, etc. Aleatory uncertainty is often referred to as input variability because it is referring to the variability of the input parameters or variables of the system. Uncertainty Quantification (UQ) is a method that can be used to assess the impact of input variability on the output responses of interest. The UQ calculates propagation of input variability through the system and obtains the variability of the output responses, referred to as the output response variability or simply as the output variability. Figure 5-2 shows a simple flow diagram of propagation of uncertainty and variability.

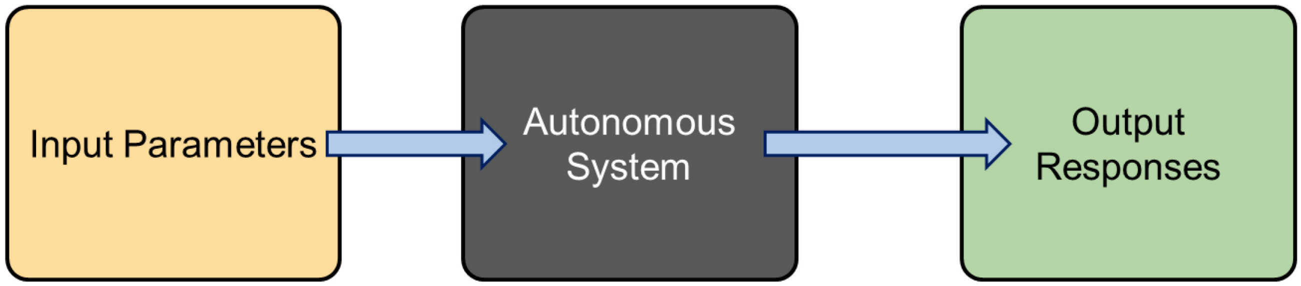


Figure 5-1: Deterministic Simulation Flow.

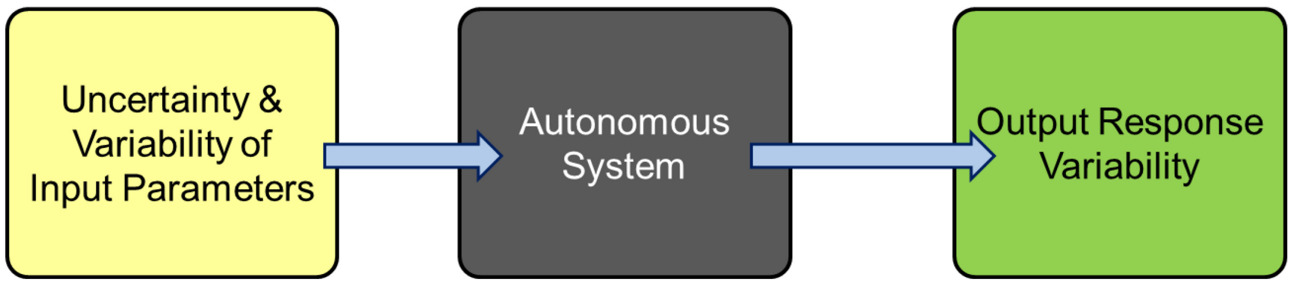


Figure 5-2: Propagation of Uncertainty and Variability.

Every system is different and the effect of input variability on the output variability is difficult to estimate without carrying out UQ. In some cases, the input variability may have a very small effect on the output variability, i.e., small output variability. In other cases, the input variability may have a large effect on the output variability, i.e., large output variability. Thus, it is critical to consider the system's sensitivity to input variability in order to fully understand the expected behavior of the system. Additionally, it is a design goal to choose vehicle designs, routes, operating conditions, and driving algorithms/strategies such that the output response is least affected by the expected sources of variability.

Nominal vs. Mean. Understanding the effect of input variability on the output variability is not always straightforward. One common mistake is to assume that if we evaluate the system at the mean of the input variability by setting the input parameter values to their mean values, the system will respond with the mean values of the output response. However, this is true only if the output responses of the system are linear functions of the input parameters. In most vehicle systems, the output responses are nonlinear functions of the input parameters. A simple illustrative example is a system that simply squares the input parameter as shown in Figure 5-3. In this example, if the nominal input parameter value is zero, then the output response is zero as well. Now consider the input parameter to have variability that is represented by a standard normal distribution. Again, the mean of the input variability is zero and, if one substitutes this mean value into the system, one will get output response that is again zero. The common mistake is to assume the output variability mean is then zero. However, as shown in Figure 5-4, the mean of the output variability of this simple nonlinear system is approximately one. Clearly one is not equal to zero, thus, it is important to correctly propagate the input variability using a correct UQ method in order to obtain the correct output variability.

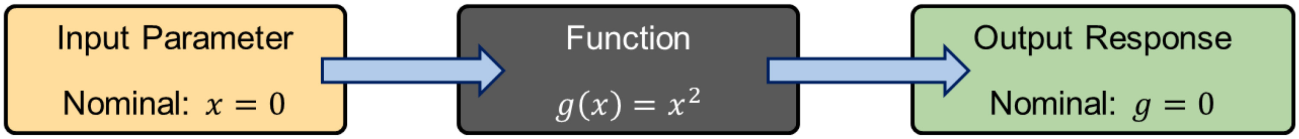


Figure 5-3: Simple Nonlinear System.

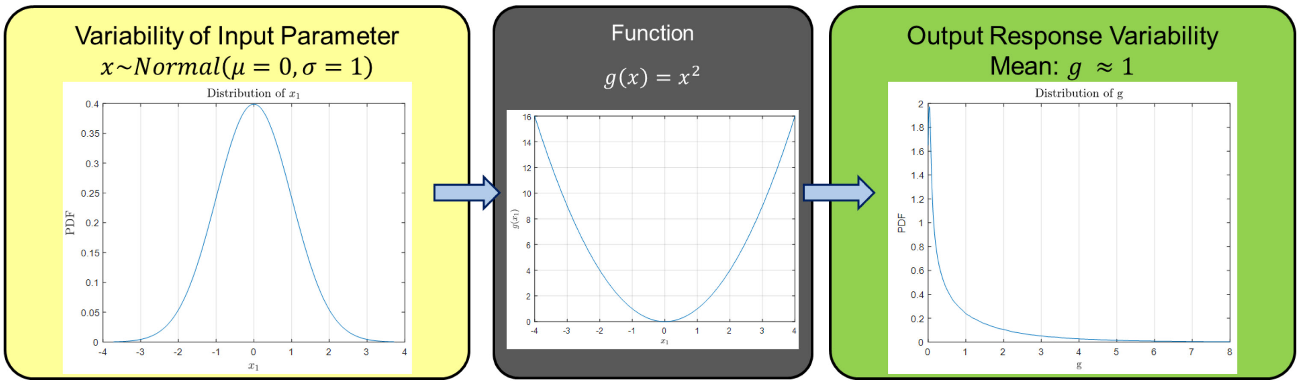


Figure 5-4: Simple Nonlinear System with Input and Output Variability.

Input Variability vs. Output Variability. Another common mistake when trying to understand how the input variability affects the output variability is to assume that, when the input variability is small, the output variability will be small. However, this is not necessarily true for a nonlinear system where small input variability can cause large output variabilities. A system that exhibits high output variability under low input variability is considered to be highly sensitive. A system with low output variability under high input variability is highly insensitive. For example, a tank is equipped with a cannon stabilizing system. The purpose of the stabilizing system is to reduce output variability in the pitch of the cannon. The stabilizer makes the cannon insensitive to variability in the vehicle pitch. A cannon without the stabilizer is highly sensitive to variability in the vehicle pitch. The output variability is not necessarily the same as the input variability, particularly when feedback control algorithms are used to affect vehicle behavior. Therefore, it is important to correctly calculate UQ in order to obtain the correct output variability.

Uncertainty Quantification for Autonomous Vehicle Systems and Mobility Metrics. Autonomous vehicle systems are highly complex systems with numerous input parameters as shown in Figure 5-5. The yellow boxes in Figure 5-5 show the different input parameter categories for an autonomous vehicle system. Each of these boxes represent numerous inputs, e.g., the Environment box might include rainfall, dust, soil type and properties, elevation, vegetation, etc., each with their own variability associated with them. The Sensors used for an autonomous system will have their own variability in terms of accuracy and noise when trying to capture the environmental data. The Stochastic Algorithms used to process and classify the data produced by the sensors have their own variability. This presents a huge challenge, as small changes in these stochastic algorithms can result in different conclusions from the same input data. In addition to that, there needs to be a data fusion step at some point in the process where all the different data inputs and conclusions from that point are combined to reach the final conclusion about what was detected as shown in Figure 5-5. After that, an algorithm then needs to decide what needs to be done in terms of controlling the vehicle, e.g., speed up, slow down, steering, braking, etc. All of this affects the mobility metrics of the vehicle: go/no-go, speed-made-good, efficiency, etc. Figure 5-5 captures the high-level view of an autonomous system with many of the primary mobility variabilities involved.

What is not yet clear is what variabilities have the most significant effect on the mobility metric. While the environment might have the highest number of different inputs and possibly the largest variabilities, it is not clear if they are the most critical ones affecting the mobility metrics. In order to fully understand this, a UQ study would have to be carried out in order to find the effect of the key variabilities expected during operation.

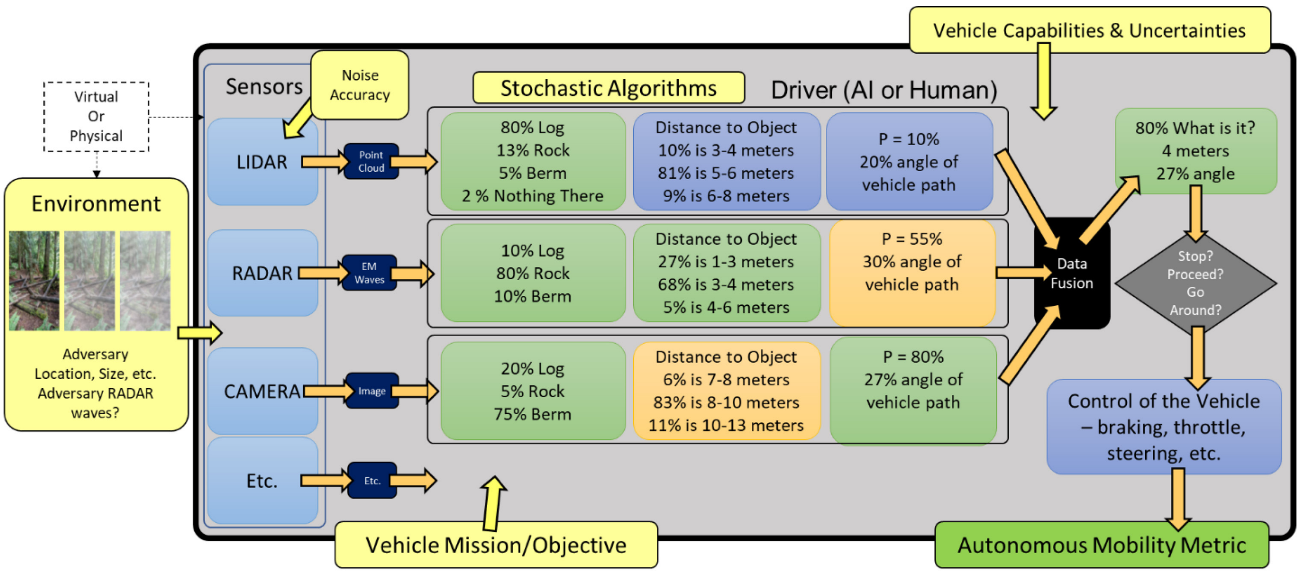


Figure 5-5: Variability in Autonomous Vehicle Systems.

5.3.1 Statistical Assessment of Mobility Uncertainty Using Constraint Analysis

One means to analyze the importance of sensitivity of mobility outcomes to various factors is to study factors one-at-a-time or in careful aggregation using simulations. This methodology allows one to obtain quantitative assessment of the uncertainty related to mobility and can reveal important similarities in the effects of various factors on uncertainty. For example, it is known that, for common ground vehicle models, the dynamics of high-speed operation are mathematically identical to the dynamics of low friction operation, once the models are converted into a dimensionless form. Thus, one can prove that there is a duality between uncertainty in some types of surface friction and uncertainty in vehicle traversal speed. To discover relationships in uncertainty, the use of constraint analysis is particularly useful. Constraints in this context represent factors that are known to limit mobility, with factors including environmental aspects of operation, vehicle design factors, and operational factors such as sensor range and data delays. The use of constraint analysis collapses the dimensions of variables that need to be considered for uncertainty assessment by examining specifically the boundary between feasible/infeasible motion, a boundary that is inferred by activating constraints on the vehicle methodically. For each constraint, one can map these constraint effects to changes in the vehicle's capability as measured in cost curves of important factors, such as the distance the vehicle needs to traverse, time of traversal, fuel use, go/no-go boundaries, etc. It is important to emphasize that the above factors are not comprehensive, and further that the factors may be strongly inter-related. The inter-relationship indeed can be useful, as there are common instances where factors can be combined to abstract the uncertainty analysis to lower dimensional problems.

5.4 VIRTUAL ENVIRONMENTS

The virtual representation of the environment for the assessment of mobility of autonomous vehicles poses a number of challenges, especially as the representation necessary for the environment depends on the usage of data and corresponding inferences used for decision-making. For example, considering the mobility assessment of an operator-driven vehicle, the human operator may be able to correctly digest a poor virtual representation by interpretation of simple 3D geometric shapes or visual representations such as colors, textures and billboards of an environmental challenge. For the human operator to make realistic driving commands, this can be achieved simply by training or other supplemental information such as “wet” or “freezing” conditions without an accurate virtual representation for this other than including the degraded characteristics in the physical modeling of the vehicle interaction with such conditions. The human can often make contextual assessments such as “frozen soil may have low friction” and thus make decisions accordingly. As opposed to closed-loop driving with a human operator, the autonomous system functionality requires significant programming to make contextual inferences from simplistic environment representations. Thus, for autonomy, additional algorithm design may be needed, along with improved sensor/map fidelity, to ensure accurate interpretation of the environments by the sensors as input to the autonomous driving command algorithms.

5.4.1 On-Road and Off-Road Terrain

For on-road driving, the virtual environment represents a generally highly structured, obstacle-free planar environment consisting of the road network, road markings, traffic signs, other vehicles and objects. Less structured elements may include deterioration of the road surface such as potholes, grooves and craters with high enough fidelity that the vehicle mounted sensors will perceive the virtual road in the same manner as the real road. Far more work has been done to develop modeling and simulation frameworks for on-road terrain that support accurate models of perception and sensors as well as models of mobility, and these models can inform mobility assessment for off-road vehicles by defining both the similar and dissimilar characteristics.

In regard to similar characteristics between on-road and off-road environment representations, there are many off-road situations where planar motion is quite similar to on-road mobility in that the vehicle’s route is determined by vehicle maneuvering requirements that are largely planar in nature. As one example, the off-road mobility of a vehicle can often be approximated via friction-ellipse analysis similar to the same friction-ellipse analysis used for on-road mobility estimation, particularly for on-road situations of severe weather, road bank angle, and steep grades. In high-speed on-road operation, the design of the road in terms of curvature, superelevation, and acceptable grade are designed as a function of vehicle operation and friction availability (see Ref. [1] for a discussion of superelevation criteria). Similarly, for off-road operation, the selection of feasible routes is similarly planned either a-priori or in-situ operation in consideration again of vehicle constraints, friction, path curvature, superelevation, and capable operational grade.

Off-road vehicle mobility is similar as well to on-road behavior in that both types of operation must consider obstacle avoidance. On-road networks achieve fixed obstacle avoidance by designing roads to avoid severe obstacles, and consequently road networks are geometrically constrained by the landscape – locations of water crossings, traversable passes through mountains, avoidance of bodies of water, etc. The same constraints, and thus path bottle-necks, occur in off-road mobility, and thus off-road path planning is driven by similar geometric requirements as would be needed for road-building. Indeed, the process of developing on-road networks often starts with off-road traversals that are repeated to the point where dirt, gravel, and eventually paved surfaces are formed, and this process of route selection and optimization implicit in on-road networks is encapsulated in the process of route selection for off-road vehicles.

But off-road mobility encounters many environmental aspects that would not be seen in on-road networks, particularly due to the ability to select paths freely through unstructured environments where mobility assumptions must be made prior to traversal. Thus, there is a long list of environmental representation challenges that must be addressed to generate appropriate simulated sensor data for specific sensor combinations used on an autonomous vehicle. This non-exhaustive list could contain information and challenges such as:

- Topography and surface roughness.
- Layered soil types and depths.
- Moisture content.
- Compaction state.
- Embedded objects (rocks, tree stumps, etc.).
- Vegetation (grass, bushes, trees, etc.).
- Man-made objects (buildings, obstacles, ditches, etc.).
- Dynamic objects (other vehicles, blowing leaves, explosions, etc.).
- Temperature effects (frozen surfaces, snow, etc.).
- Vehicle to Vehicle / Vehicle to Infrastructure (V2V/V2I/V2X).

For the off-road virtual environment, the main challenge is representation of the complex, unstructured environment that the vehicles must operate in, especially because each of the items listed above can have different mobility effects, depending on the off-road vehicle. The objective of the virtual environment is to provide the information needed for the vehicle models and the sensor models to accurately convey the interaction between the vehicle, sensors, and environment to adequately evaluate the autonomous vehicle's perception, planning and control algorithms.

5.4.2 Layers of the Virtual Environment

Since the M&S needs of the user are solely mission dependent, three scenarios were chosen to help focus the efforts of the committee. These scenarios are presented in Chapter 4 and are developed more fully in Chapter 8 on Mobility Assessment Validation and Verification. In Chapter 4, the scenario elements were defined using five categories:

- Operation;
- Environment;
- Ground Vehicle and Configuration;
- Sensors; and
- Autonomy Capabilities.

In this section, we further subdivide the Environment Layer into sub-layers affecting mobility as listed and illustrated in Figure 5-6. These environmental sub-layers aim to incorporate the primary potential factors affecting the mobility environment, and in many cases are reflected in the geospatial input defined in AVT-248 [2]. Our virtual environment layers modify and extend the layers described by the PEGASUS program to support modeling and simulation for off-road autonomy for military ground vehicles. Specifically, we add sub-surface terrain data, ground surface characteristics, topography information, and cover layers. We also define a 'general objects' layer in place of infrastructure and a 'general agents' layer in place of traffic. We describe the virtual environment layers starting underground with sub-surface properties that could impact sensor perception and vehicle mobility. The next several categories describe the surface type and topography. These characteristics are primarily static or unchanging (within months or years), while the next category aims to include the influence of the surface conditions that may change with time seasonally (freeze/thaw, snow, leaf-on, leaf-off) or even daily or hourly changes in soil or vegetation conditions (soil moisture, vegetation health). We then move to discrete items that specifically impact sensors or mobility either as static elements without internal intelligence (roads, obstacles, route restrictions), or "aware" agents with or without some algorithmic or random activity capabilities. Finally, we define the near surface atmospheric conditions of importance for sensor and vehicle operations and communications.

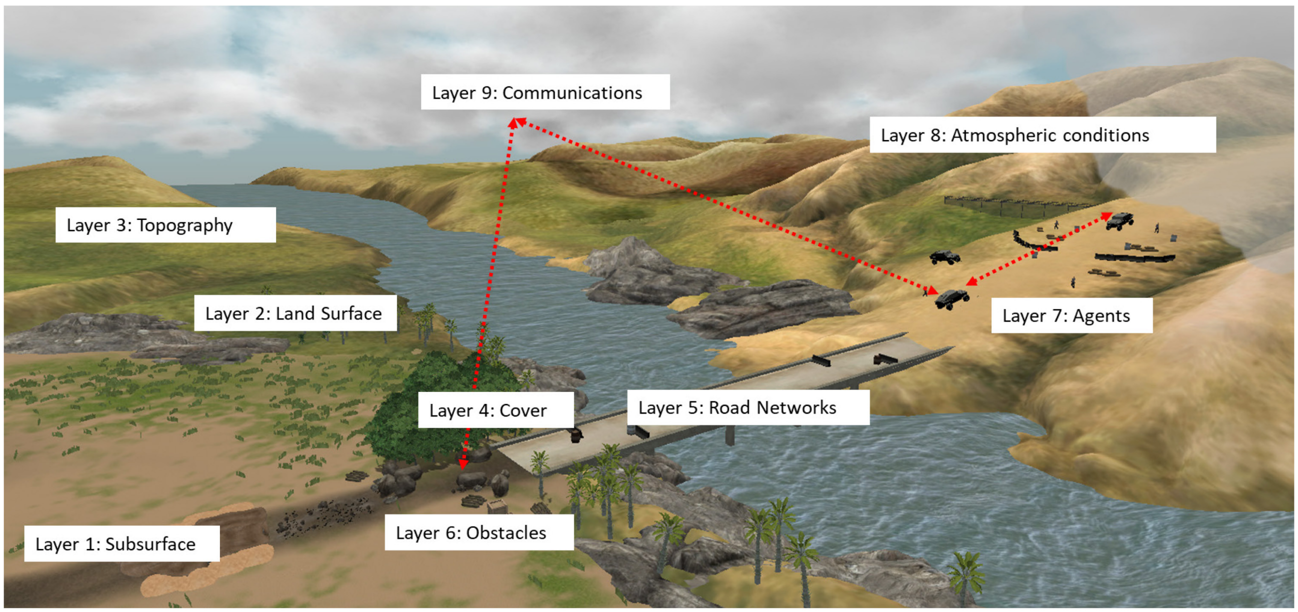


Figure 5-6: Environmental Sub-Layers in a Virtual Environment.

Environment sub-layers:

- Sub-surface: geology, geomorphology, water table depth or geohydrology, depth to bedrock, rock type, soil type, soil strength, significant layering, etc.
- Surface/Land Classification and Characteristics: bare, swamp, forest, urban, farm, etc.
- Topography: elevation, slope, aspect, roughness, etc.
- Surface Condition and Cover: moisture, frost, thaw, snow cover, ice cover, percent vegetation/biomass, leaf-on/leaf-off, vegetation health/greenness, etc.
- Road Networks: LOCs, primary, secondary, roughness, speed restrictions, etc.
- Obstacles/objects: rocks, trees, structures, ditches, etc.
- Agents: vehicles, people, drones; active or static and collaborative or adversarial, etc.
- Near Surface Atmospheric Conditions: dust, rain, fog, smoke, falling snow, etc.
- Communications layer: digital networks, radio, cellular, etc.

5.4.2.1 Sub-Surface Physical Properties

The sub-surface layer defines any applicable geologic or geographic conditions such as surficial geology, soils, magnetism, geohydrology and any sub-surface layering that could impact the perception (via sensors) or vehicle mobility performance. This layer contains the details of the near surface materials. For off-road mobility, the soil type, strength and physical conditions are described in this layer. These attributes can have categorical (e.g., soil type) or quantitative/numerical values. The geospatial qualities and definitions of this layer will be defined and quantified through the AVT-327 STANREC (when complete) to include:

- USCS Soil Type;
- Bulk Density – maximum dry (wet) and in-situ;
- Moisture Content;
- Temperature;
- Depth;
- Bekker-Wong Janosi-Hanamoto coefficients;
- Cohesion;
- Friction Angle; and
- Depth to bed rock or other hard layer.

The list above does not specifically aim to model *dynamic* soil characteristics related to changes in moisture content, frost depth, or thaw depth that are strongly influenced by additional characteristics such as depth to water table, moisture and temperature gradients, moisture and temperature history, etc. Therefore, this list could be considered a snap-shot in time and may not necessarily be applicable to a simulation that aims to consider weather, seasonal or other events.

In addition, attributes important for sensors extend this list to include the visual (if the sub-surface is exposed, or uncovered as in bare soil), geophysical and even geochemical properties of the material, which would include:

- Color (RGB or otherwise);
- Mineralogy (impacts visual, geophysical, and geochemical properties);
- Geochemical spectra;
- Electro-Optical (EO) spectral signature;
- Electro-Magnetic (EM) properties (e.g., conductivity, permittivity, latent magnetic fields, etc.);
- Seismic/Acoustic properties (e.g., wave velocities, attenuation);
- Liquid water content; and
- Ice content.

Because the soil (or rock) moisture content impacts most of the attributes above, defining the hydrological properties of the material could also be important:

- Depth to water table;
- Porosity;

- Permeability;
- Tortuosity;
- Soil-water retention characteristics; etc.

As one can see, the type of environmental data to fully describe the sub-surface and sub-surface processes is not only quite complex but entirely dependent upon the type of sensor and the sensor physics to be modeled. For example, to accurately model dynamic terrain conditions (impact of precipitation, or of freezing temperatures) the processes involved in moisture and heat flow in unsaturated soils may need to be captured or at least understood enough to know the limitations of the environmental model.

5.4.2.1.1 Challenges in Modeling and Simulation

There is limited support in current autonomous vehicle modeling and simulation tools for sub-surface physical properties that are necessary for modeling off-road mobility. For those that do incorporate sub-surface physical properties, high fidelity mobility models are computationally complex and do not run in real-time. In addition, sensor physics are not readily understood or available for surface and sub-surface physical properties. The available physics data does not support unusual or state-of-the-art research sensors. The rapid development cycle of new sensors and sensing technologies is difficult to match in model development for simulation of autonomous mobility.

5.4.2.1.2 Examples in Simulation Platforms

The NATO Reference Mobility Model [3] and the proposed NG-NRMM standards include definitions for sub-surface physical properties. A number of autonomous vehicle modeling and simulation tools provide limited support for definitions of soil properties and models of vehicle-terrain interaction for autonomous mobility (see Chapter 9: Benchmarks for more information on available tools).

5.4.2.2 Surface/Land Classification

The Surface/Land Classification layer aims to capture a bulk description of the surface not captured in the sub-surface layer. Currently, this most commonly would include the land classification or land use classification, such as farmland, urban, wetlands, etc. Other land characteristics are also applicable to this category, such as roughness classification (such as categories related to IRI, RMS or PSD), and vegetation type. While some of these characteristics are coarsely (large grid size) available on a global level, one could image a much more detailed description of the land surface being needed for high fidelity simulations, which might fluidly merge into the cover attributes of sublayer 4.

Statistical variation could also be included in this layer if it is specific to the land surface characteristics, or to the terrain in a broad sense. However, variability of specific physical attributes, such as density, should be included within the same sublayer as that attribute.

5.4.2.2.1 Challenges in Modeling and Simulation

As with sub-surface soil properties, the sensor representations of surface properties should be consistent with the mobility properties. This data may also be redundant if the topography and object data is sufficiently high resolution.

5.4.2.3 Topography

Topography is the representation of the shape of the top surface of the ground. In order to simulate a vehicle, this surface must be represented in some data format that can be localized to a vehicle surface contact area in order to determine the interaction with the wheels of the vehicle. The objective of the topography layer is to represent realistic positive and negative terrain challenges such as cliffs, depressions, cuttings, embankments, pits, slopes, and varying levels of surface roughness. Topographical obstacles should be defined by a height, width, length, and slope.

Some common formats of representing a surface layer are triangle meshes, height maps, and vector or other higher order surface definition.

5.4.2.3.1 Triangle Mesh

In a triangle mesh, the surface is modeled as a set of contiguous polygons (usually triangles, but larger polygons can exist) as seen in Figure 5-7. Each triangle is defined by its three vertices and normal direction. Complex surfaces can be modeled, but the surfaces can never be smooth since there is generally a finite angle between two neighboring triangles.

Figure 5-7: Visualization of a Triangle Mesh Surface.

5.4.2.3.2 Height Map

This surface is represented as the height of a point on a pre-defined grid as shown in Figure 5-8. While this generally results in a surface that consists of triangles, similar to a triangle mesh, the triangle mesh vertices can be in any arbitrary 3-dimensional space, where height map vertices are on the same horizontal grid, and only the vertical height is defined for each point. This restriction on the vertex locations imposes limits on certain functionality (e.g., height maps cannot model vertical surfaces, creates difficulty modeling tunnels or overpasses, etc.), but reduces the amount of data stored, and makes certain operations simpler, such as deforming the terrain.

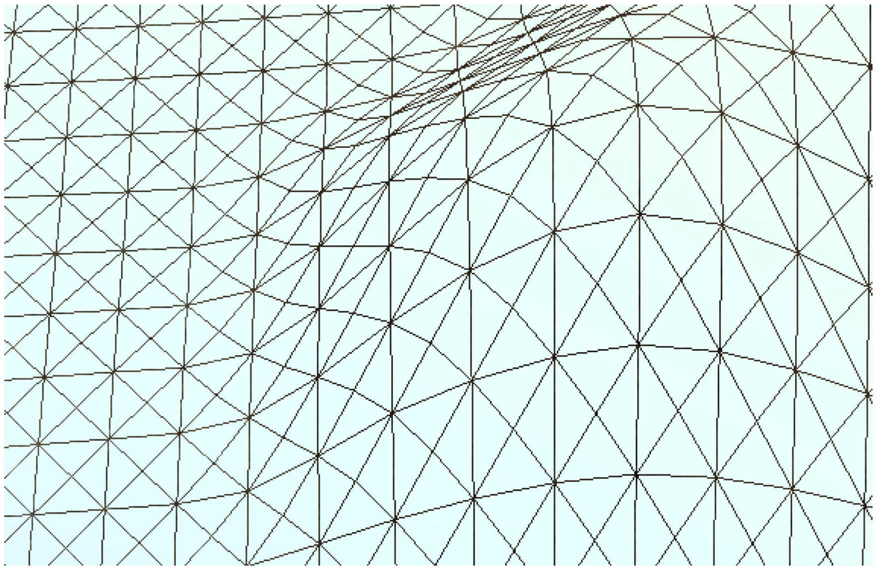


Figure 5-8: A Triangle Mesh Surface Generated from a Height Map.

5.4.2.3.3 Vector of Higher Order Surface Definition

Other methods can be used to represent a surface that can reduce the data or smooth the surface. For example, b-spline surfaces (Figure 5-9) can be used to model continuous, smooth surfaces. Curved Regular Grids (CRG, the basis of the OpenCRG project) can define a road surface relative to the center-line of the road. These grids are commonly used for on-road surface representations and on-road simulations.

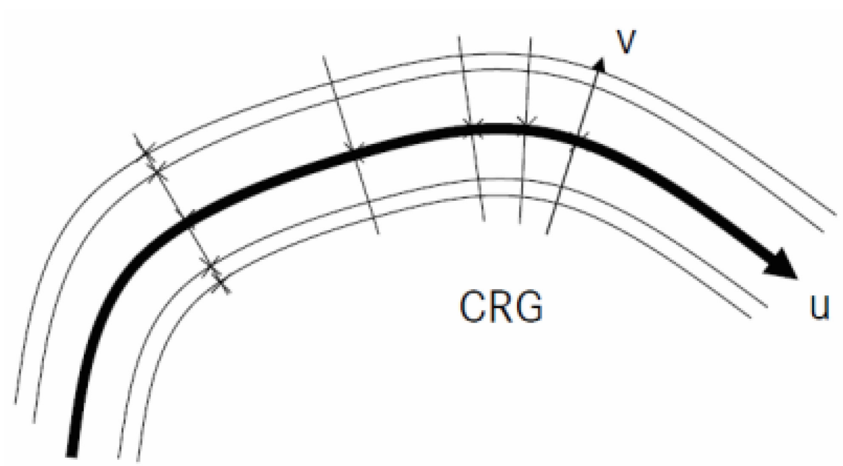


Figure 5-9: Definition of a Road Surface using a B-Spline Surface.

5.4.2.3.4 Scale and Resolution

The terrain surface can be modeled at very different scales. At a scale where the features are larger than the vehicle itself, the detailed shape of the terrain is not considered. This could be the case for NRMM height maps with 10m resolution. In this case, a simulation may only use the height map to estimate the slope of the terrain, but the terrain may otherwise be assumed to be featureless (unless features are included through the Objects layer).

The terrain can be modeled at a much higher resolution. Features of a size comparable to the vehicle would create effects that affect the pitch and roll of the vehicle. Features that are smaller than the tire patch could be used to affect the tire models themselves. Some additional features that could be represented are positive and negative obstacles, which could be modeled by modifying the topography or as an additional modification applied after the topography. In some cases, fixed obstacles that are part of the surface may be modeled using obstacles embedded in and overlapping the topography (e.g., a large rock formation).

5.4.2.3.5 Deformation

Additionally, advanced systems could support deformation of the terrain itself, either from external causes (e.g., mortar strike) or by the vehicle itself due to wheel ruts or digging implements.

5.4.2.3.6 Challenges

Military operations can cover very large areas, up to 100s or 1000s of square kilometers. Representing very large spaces at the resolution necessary may require very large amounts of data. In many cases, the data may not be available at the required resolution. Low resolution height maps (1 m or 5 m) are increasingly available for regions around the world but high resolution height maps (1 – 10 cm) that may be necessary for testing mobility or accuracy of small obstacle detection algorithms are not presently available in many operational environments. The availability of high resolution data is quickly expanding, and many techniques may be employed to impute reasonable high resolution data where none is available.

With larger domains of operation, it becomes more likely that geometric constraints such as rivers, lakes, mountain ranges, etc. that constrain off-road mobility will also constrain the local on-road networks. Thus, off-road mobility analysis over large domains, in some environments, may be expected to converge to common on-road paths. In such situations, off-road mobility analysis must consider as well decision-making on when to use on-road networks, including points of departure and points of return to those networks. These decisions may require special levels of terrain fidelity between off-road and on-road boundaries where there may be sharp geometric discontinuities in the terrain profile due to man-made elements.

There are data representation challenges as well, due to the number of different potential data formats for height maps, triangle meshes, and higher order surfaces. Converting between formats to an internal format supported by a specific modeling and simulation framework may reduce data quality and introduce errors.

5.4.2.3.7 Standards

Triangle meshes and height maps are widely supported in 3D modeling and simulation tools. Other systems (e.g., CRG in OpenCRG) are less commonly used. The Next-Generation NATO Reference Mobility Model (NG-NRMM) recommends use of standard GIS data formats that can be stored in File Geodatabases and then exported into either GeoTIFF or legacy NRMM Code 11 format [3].

5.4.2.4 Cover Layers

Layers above the permanent ground surface that are not individually modeled as objects includes now, vegetation, debris, etc. Many of these characteristics would include transient conditions that change over time such as soil moisture, frost, thaw, snow cover, ice cover, percent vegetation/biomass, leaf-on/leaf-off, vegetation health/greenness, etc. Some of these characteristics could rather be considered within the sub-surface layer, such those relating to the transient soil conditions (moisture, freeze and thaw depths), depending on the purpose and structure of the model.

The cover layer obscures the ground layer and strongly affects sensor perception of the environment, or could be transparent to the sensor, depending on the sensor type. For example, snow would obscure the surface for a visual sensor but not for certain radars. Therefore, the physical characteristics of the cover may need to be captured in some detail, and to include the physical, EO and EM properties listed in Section 5.4.2.1.

The cover layer may impact the objects as well as the ground surface. For example, a snow cover may obscure an object (ditch, bump) visually. In addition, while snow may obscure ground obstacles, it also changes the nature of the obstacle to vehicle movement, such as by increasing ability to cross over obstacles due to low friction, or by "filling in" roughness or obstacles to enable much easier or faster movement. This smoothing of the surface is known to have a strong impact on light-weight robotic vehicles. The cover effect on the obstacles may need to be modeled as condition-specific versions of the objects within the obstacle sublayer, depending on the nature and structure of the simulation.

While bodies of water are usually defined in the surface/land condition sublayer, they may also be defined as a cover layer if these layers are intended to be evaluated for fording or swimming. Water bodies of interest include lakes, ponds, surf zones, streams and drainage areas. For such, the depth and velocity of the water would be attributes. The nature of the water bottom (sub-surface) could fall as an attribute here or within the sub-surface layer.

Attributes:

- Similar to sub-surface layers (see Section 5.4.2.1).
- Other attributes specific to cover types and sensor physics as yet to be defined.

Challenges:

- Complex environments are critically importance for both mobility and sensor performance in natural world, yet the physics and interactions are not necessarily well defined or easily captured in M&S.
- Understanding of the sensor physics is needed to adequately model the cover properties.
- Unknown physical properties of the cover.
- Very high resolution data may be needed.
- Unknown, interactive and complex impacts on vehicle mobility.

5.4.2.5 Road Networks

Modeling of road networks has been relatively well defined by the consumer vehicle industry. A road network consists mainly of roads and junctions. In a modeling environment, a detailed definition of road networks is required to define on-road driving. A dedicated graphical user interface helps when creating road networks and sophisticated road features. Multiple vendors provide tools for defining road networks based on many potential sources. A virtual road can be constructed manually from geometric segments, or complete road networks can be imported from map data (Figure 5-10). Features such as lanes, intersections, height, cross-slope grade, surface condition should be easily addable to a road by editing attributes that are displayed, e.g., in 1-D diagrams. The whole road network might be visualized in a 2-D view (see some example below).

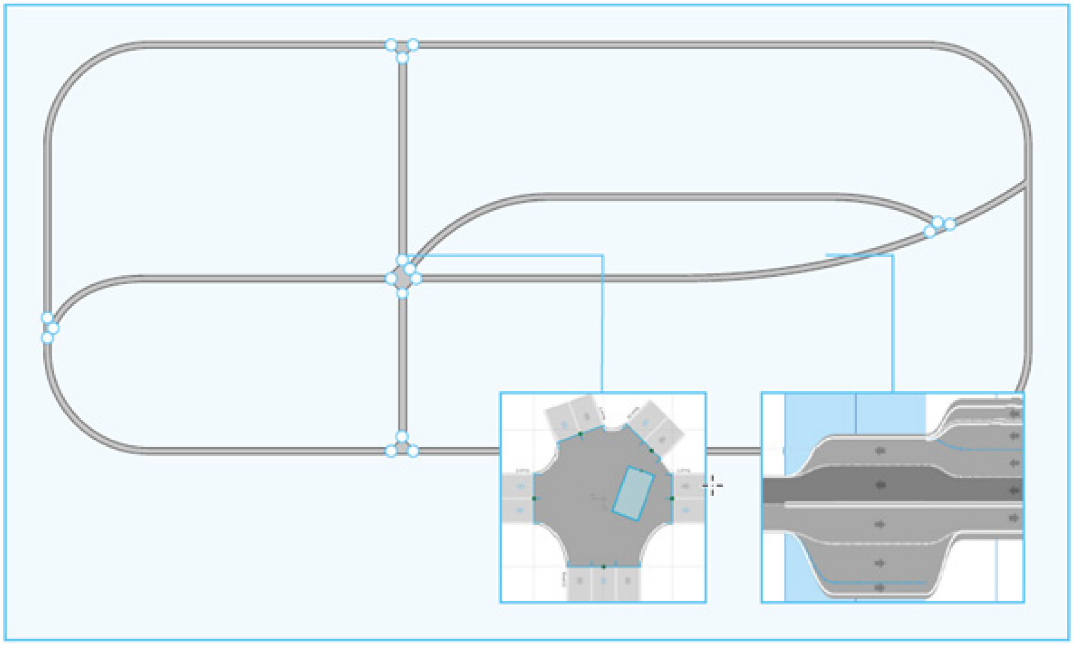


Figure 5-10: Definition of a Road Network with Multiple Lanes and Junctions.

The road design also interacts closely with the 3-D animation software to define the environment (objects, topography, etc.). The road networks serve as the basis for complex traffic scenario creation (ego-vehicle, agents) to develop and test Advanced Driver Assistance Systems (ADAS) or for Automated Driving (AD).

5.4.2.5.1 Attributes of Road Networks

Road designers should be able to specify road geometry including super elevation and lateral profiles. The surface roughness of the roadway should be defined. M&S tools must also support definition of complex road geometry including bridges, tunnels, and intersections with railroads. Bridges should include data on military load classifications.

For each attribute below, the user should be able to define it graphically or by API for conversion from other tools or databases:

- Road geometry (height, super elevation, grade, surface roughness, friction number);
- Lanes;
- Junctions;
- Interconnections of lanes;
- Lane IDs;
- Lane boundaries;
- Traffic signs and lights; and
- Road markings.

For secondary road and trails, the categories and attributes could be quite different than those above and largely relate to the type of surface layer (asphalt, chip seal, unpaved), maintenance level, road geometry alignment, roadside features, and roughness, a primary control on speed and throughput capabilities, especially for military operations. See USDA Forest Service [4], [5] and the Transportation Research Board Low-Volume Road publications for more information on these categories.

5.4.2.5.2 Challenges

The main challenges related to definition of road networks are matching the real-world characteristics of the road, importing and converting from available databases and maps, and the real-time simulation of large road networks. Unlike off-road environments, on-road vehicle operation relies particularly on rules of operation rather than ego-vehicle capability assessment to avoid collisions with nearby fast-moving vehicles. A challenge in autonomous vehicle operation is that these operational rules, either formally declared or inferred by users, will depend strongly on regulations, local conventions, weather, construction, congestion, and operator training.

5.4.2.5.3 Standards and Examples in Simulation Platforms

There are a number of well-known road network standards. These include:

- OpenDRIVE;
- RoadXML;
- High Definition (HD) Maps (e.g., by TomTom, Here);
- OpenStreetMap;
- GoogleEarth and ADAS-RP;
- Analytical definitions of road geometry (e.g., GPS or XYZ data); and
- Many proprietary supplier formats.

OpenDRIVE serves as a common base for describing track-based road networks using Extensible Markup Language (XML). It defines the geometry of roads as well as features along the roads that influence the logics (e.g., lanes, signs, and signals). The goal of this standard model is to describe as many different road networks as possible. The road network is organized in nodes which can be extended with user-defined data. The complex data model allows high flexibility but also has some ambiguity in areas of the model (Figure 5-11).

OpenDRIVE can be extended by the other ASAM standards: OpenCRG, OpenSCENARIO, and Open Simulation Interface. OpenCRG is used to define the surface of the roadway. OpenSCENARIO is used to define behaviors on the road and the Open Simulation Interface (OSI) supports the simulation of environment sensors.

RoadXML is another open data file format for the description of road networks. The RoadXML format includes information on-road topology, road logic (lanes, intersections, etc.), road surfaces and objects, and road geometry [6].

There are several tools available for defining road networks for simulation. One example is Vector Zero's RoadRunner software. RoadRunner provides users with tools to define complex, realistic road networks and export them in a range of proprietary and open data formats [7].

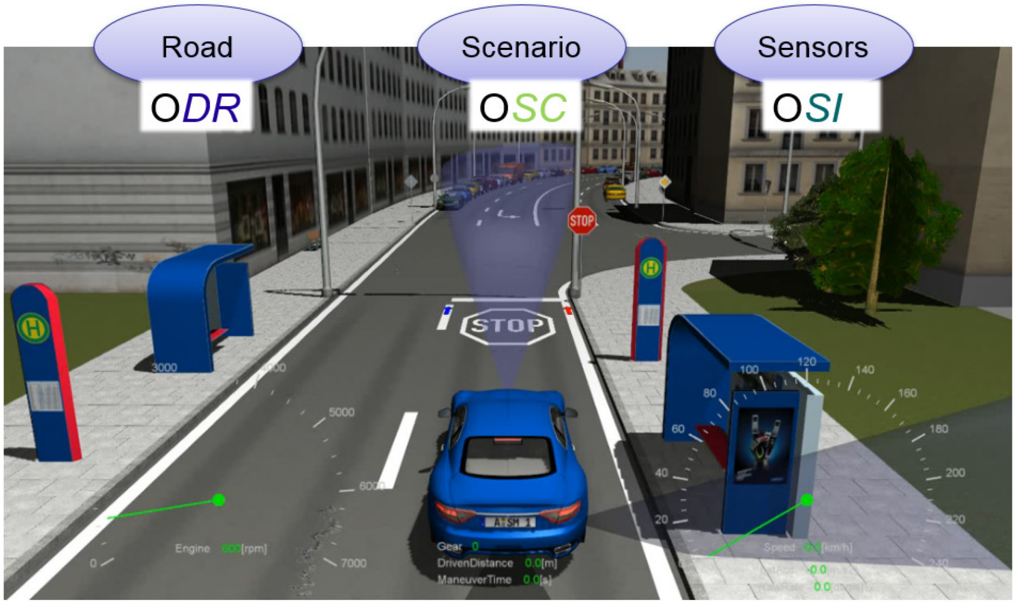


Figure 5-11: Virtual Environment Using OpenDRIVE, OpenSCENARIO, and Open Simulation Interface to Define Road Junction, Behaviors of the Ego-Vehicle and Other Elements of the Scene, and Environment Sensors.

5.4.2.6 Objects

The objects layer includes definitions for natural objects such as trees and boulders and man-made objects such as utility poles, signs, and buildings. While some objects are static and immovable (e.g., buildings), other objects (e.g., rocks, traffic barrels, or logs) may require physical simulations to model their interaction with other elements in the environment and the ego-vehicle (Figure 5-12).

Figure 5-12: Virtual Environment Containing Potential Natural Obstacles (Tree Stump and Log Objects).

We identified three potential classes of object movement: static, kinematic, and physics-driven. Static objects are assumed to never move and can be represented with simplified physics models. While there are no truly static objects in the real environment, there are many objects that can be effectively modeled with a static representation. Kinematic objects have a fixed global position but may have parts that move in response to environmental conditions (e.g., tree limbs in the wind) or based on input from a controller (e.g., lowering/raising of a railroad crossing gate). Physics-driven objects change global position according to the action of external forces on the object (e.g., wind pushing a ball across the road).

Some static objects could be modeled as part of the topography but, given that they might be regular shapes (boxes, cylinders), it can be simpler to model objects using geometric primitives rather than the complex structures used to model the topography.

Object representation is critical for evaluation of both vehicle mobility and vehicle autonomy. Objects in the environment can be physical obstacles that impair or block vehicle movement. An autonomous system must be able to perceive, classify, and update paths to avoid or navigate obstacles. Some objects may provide information to an autonomous system (e.g., roadway signs to give specific directions), and some objects may be contextually inferred (e.g., rocks on the road nearby signage warning of rock-falls).

5.4.2.6.1 Attributes of Objects

Objects can be defined using primitive shapes (e.g., boxes or cylinders) or complex geometric meshes. A position and orientation define the global position of the object in the virtual environment. Materials define the appearance of the object for visualization and for sensor models. The requirements for material definitions may depend on what sensors are modeled in the simulation. The movements of an object may be stored or may be calculated based on physics representations associated with the object. Additional physics information may be required for accurate modeling and simulation of vehicle interactions with the object, particularly colliding with and driving over the object. The definition of an object may include multiple representations for different conditions (e.g., a dry and wet material or a snow-covered mesh and material). Objects may also include definitions of light sources associated with the object. Controller scripts associated with the objects may be used to manage and update the object state (e.g., traffic lights) in coordination with other events in the virtual environment:

- Position and Orientation;
- Dimensions;
- Mesh;
- Material (PBR, spectrum data, thermal data);
- Stored and Kinematic Animations;
- Physics (constituent materials, collider mesh, mass, deformation data);
- Condition Definitions;
- Light sources; and
- Controller scripts.

5.4.2.6.2 Challenges in Representation of Objects

Photorealism in imagery, film, and interactive simulation is difficult to achieve and yet is often the means by which human operators assess fidelity of a scene representation. However, photorealistic surfaces may have little effect on some modes of autonomous sensing (LIDAR does not require photorealistic surface textures) and may confuse or complicate other sensors (mirrored surfaces can confuse camera systems and may be difficult to render). Thus, accurate representation of the full range of physical characteristics that may affect perception of an object by an autonomous system represents a significantly harder challenge. In the natural world, there is enormous variability in essentially all attributes that define an object. Even man-made objects have high levels of variability both by design (e.g., vehicle models and colors) and from wear and tear (e.g., the inevitable dings and bumps to a vehicle surface over 100,000 miles).

In most cases, the objects in modeling and simulation tools are made from exact copies of a representative prototype object. Such reuse of meshes, materials, and animations reduce memory and computation requirements for visualizations. For example, the benches on the left and right of the ego-vehicle in Figure 5-11 use the same mesh and material. The logs in Figure 5-12 use the same mesh and material. Using a scale modifier to shrink the log on the right modifies its appearance slightly but the general shape and the texture are the same.

This reuse of assets artificially reduces variability in the virtual environment. In many cases, this may have no effect on the performance of the autonomous system. However, particularly for autonomous systems leveraging machine learning and neural networks, the lack of variability will affect learning and may affect testing of trained models. For example, a vehicle may be able to push through a decayed log, but may become stuck against a newly fallen tree, but an algorithm could not learn this distinction if the virtual environment represents both via the same log prototype. It is possible to use runtime procedural tools to create unique variations in meshes and materials that more accurately represent the appearance of real objects. However, these methods require novel approaches to object definitions, specialized data formats, and increased computational resources. Users should be aware of potential issues relate to reusing assets, and particularly how reuse of assets may create artificial confidence in learning algorithms that are trained on datasets that are using reduced numbers of assets. Modeling and simulation tool developers should explore methods for improving variability across instances of objects.

In addition to the appearance of the object to modeled sensors, for autonomous mobility, it is critical that physical interactions between the vehicle and the object are accurately modeled. Depending on the vehicle and the object, a collision may damage or destroy the vehicle, the object, both, and have no effect on either. The object may move or be deformed. Vegetation could bend or break. Logs could be crushed. Accurately modeling these dynamic effects, both in terms of physical interactions with the vehicle as well as how these interactions change sensor readings of such objects, is a significant technical and computational challenge.

5.4.2.6.3 Modeling and Simulation Examples

There are many standard methods for representing objects in virtual environments. These standards have been developed for videogames and for modeling and simulation. Common standard data formats include STL [8], OBJ [9], glTF [10], COLLADA [11], IGES [12], STEP [13], and FBX [14]. Different data formats are preferred across different industries. STL, IGES, and STEP files are most often associated with CAD modeling and simulation while OBJ, glTF, and FBX are most often associated with interactive modeling for games and movies. Each data format has different levels of support for the desired attributes of objects. Most modeling and simulation tools provide object representation by supporting one or more common data formats. Modeling and simulation tools may also define proprietary data formats that provide more comprehensive support for desired attributes that are not commonly supported by standard formats.

5.4.2.7 Agents

The Agents layer includes all things that move autonomously, such as humans, animals, and vehicles. Agents are extensions of Objects in that they are physical, interactive objects, and primarily differ in that they are controlled by a complex controller.

5.4.2.7.1 Attributes of Objects

Agents include the attributes associated with the Object layer but are generally more complex and are associated with complex behaviors. An agent is constructed of multiple parts moving in an organized, self-directed motion controlled independently or in coordination with other agents. Agents may be composed of hierarchies of objects, each with their own Object attributes and controllers. An agent senses the virtual environment, processes available information, and, at least, appears to make decisions that drive actions. Animal and human agents' movements give the appearance of self-directed organic movement and may be stored animations, generated at runtime, or a combination of stored and generated movements. Vehicle movements are more likely to be generated at runtime and may use the same physics systems used for the ego-vehicle modeling and simulation.

Agent behaviors may range from simple to extremely complex systems depending on the requirements of the scenario. A scenario that tests an automated emergency braking system and requires a pedestrian to cross the street in front of an autonomous vehicle may require only a simple script that updates the position and animation for a pedestrian agent. A battlefield scenario may include hundreds of human and vehicle agents coordinating movements in response to events across a large area:

- Position and Orientation;
- Dimensions;
- Mesh or Meshes;
- Material(s) (PBR, spectrum data, thermal data);
- Stored and Kinematic Animations;
- Physics (constituent materials, collider mesh, mass, deformation data);
- Condition Definitions;
- Light sources;
- Animation Controllers;
- Complex Behavior Controllers:
  - Simple Scripted Movements;
  - Random Movements; and
  - Obstacle Avoidance.

5.4.2.7.2 Challenges in Representing Agents

The appearance of agents is as complex and as varied as the appearance of objects. The variation just in humans in size, skin tone, and clothing is overwhelming and impossible to fully capture in modeling and simulation tools. Importantly, many of these variations may provide important context (e.g., police uniforms, insignia denoting rank on combatant uniforms, elderly appearance, and presence of weaponry) that an autonomous system may or may not be able to process. In addition, agents may be more likely to have thermal features that may be used to differentiate agents from objects and may need to be represented in modeling and simulation tools.

In addition to basic appearance of the agents, the self-directed nature of agent behaviors adds an additional layer of complexity. Agents must be able to sense the environment and respond with the full range of behaviors that may occur in the real environment. Imbuing agents with accurate and interactive behaviors requires both data describing the desired agent behaviors and complex algorithms capable of creating the desired behaviors under appropriate conditions. Researchers in ADAS and AV technologies are collecting data on pedestrian behaviors and developing methods to predict those behaviors [15], [16], [17]. A simulation environment that can provide realistic pedestrian appearance and behaviors will be invaluable for developing and testing ADAS and AV pedestrian collision avoidance technologies. Military vehicles impose a special challenge with regard to interaction with other agents wherein combatants and non-combatants may be treated differently, rank may affect interpretation of commands, and vehicles may need to accurately classify friend and foe.

5.4.2.7.3 Modeling and Simulation Examples

While there are many examples of standard formats for the representation of objects, there are few standard representations for agents. In most cases, the representation is separated into three parts: an object or hierarchy of objects that represents the form and materials that define the appearance of the agent, a collection of animations and/or physics data for generating movement, and a behavior system that controls the agent's actions.

The definition of the hierarchy of objects often uses the same standard data formats used by objects. Some standard data formats (e.g., FBX, COLLADA, glTF) encode animation along with object data. Behavior systems are custom systems associated with specific modeling and simulation tools.

The ASAM OpenScenario standard provides a data format for describing changes in a scenario including the movement of agents. The OpenScenario definition allows a scenario designer to script actions that agents will take in the scenario but rely on an underlying behavior system to enact the actions in a specific simulation. The M-SDL scenario description language developed by Foretellix also allows users to define actions that define the actions to be performed by an underlying behavior simulation [18]. The MSC Software VIRES Virtual Test Drive (VTD) autonomous driving simulator supports OpenScenario scenario definitions.

Many ADAS and AV modeling and simulation tools allow developers to leverage complex agent behavior models through co-simulation. SUMO and PTV VISSIM are two examples of tools used to model agent behaviors for ADAS and AV testing. The Simulation of Urban Mobility (SUMO) software is an open source tool designed for traffic simulation. SUMO has been used to model both vehicle and pedestrian traffic for autonomous vehicle modeling and simulation (e.g., Ref. [19]). VISSIM is a commercial microscopic traffic simulation tool capable of modeling individual vehicle, cyclist, and pedestrian agents. VISSIM provides multiple interfaces for integration with other modeling and simulation tools. AVSimulation's SCANer Studio simulation software includes integrations with Aimsum's commercial traffic simulator. Many of these traffic simulation tools allow off-line or on-line co-simulation capability via software extensions and scripting. Users should consider the validity and fidelity of modeling and simulation tools used in co-simulation.

5.4.2.8 Conditions

The conditions layer includes parameters that describe the environmental conditions (weather, lighting, atmospheric conditions) in which the scenario occurs. Conditions modify the attributes of the scene as defined in the other layers. Combined with a geo-location, the day and time determine lighting, temperature range, visual state of trees and other vegetation, and seasonal variations in soil strength and soil moisture. Weather conditions define more transient conditions including cloud cover, precipitation, and wind. The conditions interact with each other and the layers, sometimes in complex ways. Many conditions constrain the range of likely values of other parameters. The conditions considered here all have some potential effect on autonomous mobility of ground vehicles. It is reasonable to believe that users will want to repeat test scenarios in many weather conditions.

5.4.2.8.1 Date and Time

Combined with geo-location data, date and time parameters define two conditions that affect a number of environmental factors. First, the position of the sun, moon, and other astronomical bodies can be determined from location, date and time. The sun and moon are significant contributors to lighting levels that are critical to perception of the scene for autonomous systems using electro-optical camera sensors. In addition to providing the primary light source for daytime scenes, the sun also has direct effects on camera sensors. When driving directly toward the sun, sun glare can obscure visibility of critical environmental features in cameras and LIDAR [20].

Location and date also provide seasonal information for scenarios. Season affects the appearance of vegetation which affects the detection range of sensors. The season also affects weather patterns that will affect soil strength and soil moisture content. Season also affects the presence and type of cover layers, surface roughness, and the likelihood of freezing conditions.

5.4.2.8.2 Weather

The weather is a significant factor in autonomous mobility. Rain and other precipitation can degrade sensors ability to detect objects in the scene, increase slip, and reduce soil strength. Across wide ranges of temperatures and in high humidity, sensor performance can be affected. Weather-related conditions include the temperature and humidity, cloud cover, wind speed and direction, precipitation, and certain suspensions.

The date and time can help define reasonable ranges for temperature and humidity. Recorded weather data can be used to provide specific values for testing. Temperature has relatively few effects that directly affect autonomous mobility. In extreme hot or cold, the temperature may affect the operation of sensors degrading sensor data quality or disabling the sensor. At low temperatures, freezing conditions will affect precipitation type and surface conditions. Rapid changes in temperature can cause fogging of lenses on certain sensors if precautions are not made for this effect. Sensor models should incorporate potential failure of systems intended to mitigate weather-related effects.

Cloud cover primarily affects the percentage of sunlight in the scene. Cloud cover also affects the visual appearance of the sky and can strongly affect the performance of an autonomous system in that shadows can be hard to distinguish from obstacles in certain lighting conditions. It is possible that a NN/DL-based algorithm may be adversely affected by atmospheric conditions for which it has not been trained.

Lightning can dramatically change the lighting levels of a scene from one frame to the next. Given the very short duration of a lightning flash, it may be unlikely to have significant effects on perception of the environment. However, it is important to test the effect of a common natural event on an autonomous system.

Wind can be a powerful force acting on a vehicle and the environment in which it is operating. Wind moves objects and vehicles, humans and animals react to the wind, and precipitation is affected by the wind. Wind is characterized by a mean wind speed and a direction (degrees clockwise from north). However, wind is highly variable and may be accompanied by significantly stronger gusts of wind, especially in severe weather [21]. Mean and gust wind speeds can be estimated using various models primarily developed for the wind power industry [21], [22]. For some sensors, wind is a particular factor with precipitation in the design and testing of autonomous algorithms, as the combined effects of wind and precipitation can cause artificial perception of ego-motion in visual systems that rely on optic flow.

5.4.2.8.3 Precipitation

Precipitation is an aspect of weather worthy of a detailed discussion. All-weather performance is an objective for military ground vehicles. Of the environmental conditions, precipitation is second only to lighting conditions in its significance to vehicle operations.

Precipitation has a significant impact on perception of the environment. It can affect sensor surfaces, interfere with sensor performance in the medium between the sensor and an object, and modify the surface of the detected objects. In electro-optical camera sensors, water directly on the lens of the sensor distorts the view of the scene. When sensors are behind glass, the water acts as a reflective lens inverting the image within droplets on the glass. The precipitation in the medium between a camera or LIDAR sensor will reduce the range and detection accuracy of the sensor [23]. A radar sensor on the other hand is largely unaffected by precipitation. Evaluating trade-offs between sensor types, and which sensor to use for decision making during which type of precipitation, requires capturing the different capabilities of the sensors in simulation. On the surface of objects in the environment, wetness will change the visual properties of surface materials [24].

In Figure 5-13, precipitation has created three levels of wetness on a concrete surface: dry, wet, and puddled water. Where the surface is wet, the surface is darker compared to the dry surface and exhibits some specular highlighting. Where water is puddled, we see reflections of the sky and surrounding environment on the surface of the water. The effect of wetness varies according to surface type and sensor (e.g., camera versus lidar; see Figure 5-14). For other surfaces, the lightness, color saturation, and reflectance of the material may be modified by surface wetness [24], [25].

In addition to the visual effects of precipitation and wetness on surfaces, there are also physical effects. Increasing wetness affects soil moisture content and friction – factors that directly affect vehicle mobility. On paved surfaces, the friction value

Precipitation is defined by type, rate, and particle size. The distribution of raindrops by size is commonly described by variants of Marshall-Palmer law [26]. Drizzle is a liquid water precipitation that is smaller than 0.5 mm and falls at a rate of less than 1mm per day. Rain is liquid water precipitation. Rain droplet sizes range from 0.1 mm to 5 mm with a distribution described by Marshall-Palmer law [26]. Sleet is a soft precipitation mix of rain and snow. Freezing precipitation occurs when liquid water precipitation freezes immediately on impact with a surface with a temperature below freezing.

Snow is precipitation of ice crystals. The type of ice crystal will depend on temperature and water saturation levels. Snow size ranges from 0.1 mm to 2.5 mm [27]. Graupel is a soft, small ice pellet less than 5 mm in size. Hail is a large frozen precipitation greater than 5 mm in size.

Figure 5-13: Concrete Surface with Three Levels of Wetness: Dry, Wet, and Puddled Water.

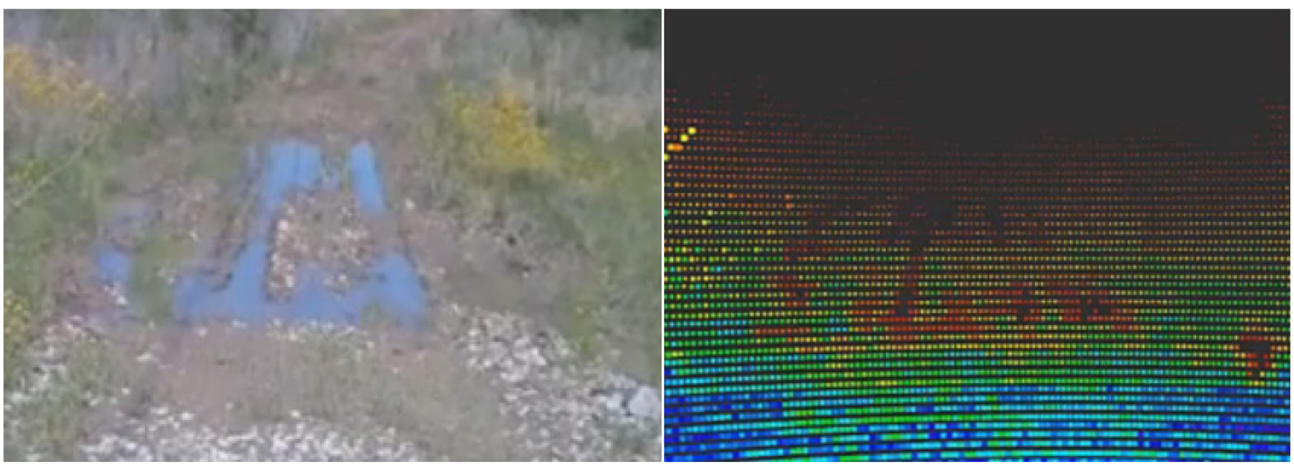


Figure 5-14: Camera (Left) and LIDAR (Right) Data for Dirt and Gravel Trail with Standing Water.

5.4.2.8.4 Suspensions

In addition to falling water particles, the atmosphere also contains suspended particles of various types such as those found in sea salt, mist, dust, smoke, soot, and fog. In the context of conditions, suspensions are like precipitation – particles in the air that may affect sensor data and, under certain conditions, may affect the vehicle, its systems, and its mobility as well as the appearance and behavior of other objects in the scene. Suspensions may also have localized effects generated from a source object and may be affected by the wind. For example, the smoke from a fire or the dust from a passing vehicle. Suspensions can be defined based on the type of particle and the density of the suspension. Turbidity is used as a general measure of the effect of particles suspended in the air.

The primary effect of suspensions is the occlusion or degradation of electro-optical and other sensors due to their inability to penetrate the suspension to detect objects in the scene. The effect of the suspension on sensor performance will depend on the nature and density of the particles and the sensor type. A particularly dense suspension could deposit particles on a sensor or surface that could interfere with sensor performance or affect the surface material properties (e.g., reflectance, color, or wetness). As with precipitation, it may not be necessary or computationally practical to simulate transient changes in surface properties. Instead, the scene could be prepared with material properties that already reflect the impact of the suspension.

5.4.2.8.5 Constraints and Interactions

Many environmental conditions are related to one another. For example, the seasons, depending on geographical location, will define reasonable temperatures, precipitation rates, wetness levels, etc. It is unlikely to have snow in July in the north hemisphere. If it is below freezing, liquid precipitation is likely to be freezing on surfaces and frozen precipitation is likely to be accumulating. It is not necessary and may not be advisable for a simulation framework to strictly enforce constraints and interactions between conditions and the environment. However, it would be helpful for a simulation framework to validate condition settings and notify the user when a scenario is unlikely or impossible. It may be helpful in general for simulation frameworks to support calculation of a reasonability score for scenarios. A reasonability score would indicate how likely a scenario is to occur in the real-world.

5.4.2.8.6 Challenges in Modeling and Simulation

There are numerous challenges associated with modeling and simulation of conditions. Basic modeling of day and night cycles and the position of the sun, moon, and other relevant astronomical bodies is not particularly difficult. However, accurately capturing the lighting effects associated with the sun and the moon for very large and complex geometry is more difficult. The modeling and simulation environment should be able to create soft and hard shadows and the full range of colors observed in the environment including sunrise and sunset. Simulation of sensors should include effects associated with directly facing the sun. There is limited data on the effects of sunlight, precipitation, and suspensions on the performance of camera, LIDAR, radar, and other sensors. For those models that exist, there is limited data on the validity of the models. There has also been limited work on identifying methods for validating models of sensor performance, particularly in adverse weather. First-principles models of sensor interactions with precipitation and suspensions are not computationally feasible. Real-time models that approximate the effects on sensor data quality are needed. While it is not necessary that a modeling and simulation framework enforce consistency across the layers, it should be possible for the modeling and simulation framework to provide sensor properties that match mobility properties. This will require modeling of ground surfaces and objects in the virtual environment in ways that support conditions, e.g., support for simulating wind effects on trees and plants, materials set up for wet surfaces and snow accumulation. An important aspect of condition effects is the modeling and simulation of transitions between states. It is not enough to provide the ability to simulate driving on a dry trail and driving on a wet trail. To be trusted as a surrogate for real-world testing, modeling and simulation tools should be able to simulate driving on a dry trail when rain starts falling, the environment transitions from dry to wet, and the drying process of a wet trail.

5.4.2.8.7 Modeling and Simulation Examples

The legacy NATO Reference Mobility Model includes four season options: dry, average, wet and wet-wet. The seasons are used to apply seasonal differences in soil strength, soil moisture, surface roughness, driver visibility, and freezing conditions [3]. Legacy NRMM also includes soil friction and driving visibility effects to approximate weather condition effects.

Most simulation platforms provide the ability to specify the time of day and basic weather parameters such as cloud cover, precipitation rate, and fog (e.g., Ref. [23]). However, many tools offer little to no validation of their models, allow arbitrary setting of values, and are largely limited in the scope of effects captured by the models. Few model direct effects on simulated sensors (e.g., lens glare, raindrops on camera lens). Fewer model ground surface effects on mobility related to weather conditions.

5.4.2.9 Digital Information Networks

Modern vehicles are increasingly connected via communication networks to local and global digital information networks. Global networks provide autonomous vehicles with continuous access to updated 3D maps and route information. Vehicle-to-Infrastructure (V2I) local networks can provide real-time route and traffic management data to autonomous vehicles, as well as real-time updates to maps such as obstacles to be expected in the environment and changes to the road network itself. Vehicle-to-Vehicle (V2V) networks allow vehicles to communicate directly with each other. In military applications, communication networks provide critical capabilities related to C4ISR. To fully capture the operational environment of military ground vehicles, the virtual environment should include models of the communication networks that connected and automated vehicles rely on. There are many types of digital information networks including radio and cellular networks, mesh networks, satellite communication, V2I and V2V (V2X).

5.4.2.9.1 Attributes

Vehicle networks depend on three components: the movement of the vehicle, the surrounding traffic and environment, and the communication network [28], [29]. Modeling of the communication network requires definition of the data to be transmitted, the message frequency, the communication protocol, and the communication channel. Communication parameters include channel frequency, transmission power, receiver sensitivity, and loss models as a function of terrain and environmental characteristics, for example the possible loss of reception in vehicles operating within deep canyons.

5.4.2.9.2 Examples in Simulation Platforms

There are multiple examples of modeling and simulation of communication and digital information layers. Communication is often modeled separately from other aspects of autonomous vehicles and integrated into a larger simulation using co-simulation.

Plexe is a platooning simulation tool that presents itself as an extension of the Veins simulation environment [30]. As such, users can exploit Veins' fully detailed IEEE 802.11p and IEEE 1609.4 DSCR/WAVE network stack for realistic simulation of vehicular networks [31]. Plexe is meant to assist researchers both in the control theory and in the vehicular networking fields. Lastly, Plexe extends SUMO by implementing several state-of-the-art cruise control models and realistic engine dynamics. More precisely, Plexe-Veins targets network simulation while Plexe-SUMO aims at road traffic simulation. SUMO, from "Simulation of Urban MObility", is an open source, microscopic, multi-modal traffic simulation [32]. It allows users to simulate how a given traffic demand which consists of single vehicles moves through a given road network. The simulation allows users to address a large set of traffic management topics. It is purely microscopic: each vehicle is modeled explicitly, has its own route, and moves individually through the network. Simulations are deterministic by default but there are various options for introducing randomness. These packages and the packages they draw on are typically open source and free for academic research and other non-commercial pursuits. The V2X Simulation Runtime Infrastructure (VSimRTI) is a comprehensive framework for the assessment of new solutions for Cooperative Intelligent Transportation Systems [33], [34]. Vehicle movements and communication technologies like V2X communication and cellular networks can be modeled in detail. VSimRTI seeks to simulate Smart Mobility applications and to assess their impacts and benefits.

The ns-3 network simulator is a discrete-event network simulator, targeted primarily for research and educational use. ns-3 is free software, licensed under the GNU GPLv2 license [35]. Unlike VSimRTI, which targets the Smart Mobility applications and V2X market, ns-3 is a general purpose discrete-event network simulator that can also be used for AV simulation. As such, compared to other dedicated tools, more prep work is necessary to establish an AV simulation solution whose needs are anchored by ns-3. The ns-3 simulation core supports research on both IP and non-IP-based networks. However, the large majority of its users focuses on wireless/IP simulations which involve models for Wi-Fi, WiMAX, or LTE for layers 1 and 2 and a variety of static or dynamic routing protocols such as OLSR and AODV for IP-based applications. ns-3 also supports a real-time scheduler that facilitates a number of "simulation-in-the-loop" use cases for interacting with real systems. For instance, users can emit and receive ns-3-generated packets on real network devices, and ns-3 can serve as an interconnection framework to add link effects between virtual machines.

5.4.3 Gaps

We reviewed types of information that must be included in a comprehensive virtual environment for modeling and simulation of off-road autonomous mobility. In considering the required information and the state-of-the-art in virtual environments, we have identified several gaps in the definition of the layers. Most critically, there is a lack of information available on relevant parameters for attributes and the realistic ranges and distributions of parameter values. Even when data is available, it has not been organized for environment modeling and simulation. Another significant issue is the uncertainty regarding the sensitivity of autonomous vehicle systems to variability in specific attributes. A comprehensive physics-based model of the virtual environment is computationally expensive. In many cases, it may be sufficient to use a reduced order model of the environment and ignore certain attributes. However, at this time, there is insufficient data available to determine which attributes of the environment are critical to modeling a scenario and which have limited relevancy. The importance of an attribute and the required fidelity and resolution of data likely depends on a combination of the scenario objective, the vehicle's sensors, and the data processing algorithms used by the autonomous vehicle system.

The layer model is a convenient method for organizing the information that constitutes a model of the operational environment. However, the layer model makes abstract the complex interactions between layers, e.g., weather condition effects on moisture content, surface appearance, object appearance, and agent behaviors. Further, representations can be confused between layers; for example, is a large boulder better represented as a terrain feature or as an obstacle, will the simulation behave differently if it is represented in one or the other, and will the simulation break if it is accidentally represented in both layers? Many modeling and simulation tools for autonomous vehicles have limited physics models, particularly for vehicle-terrain interaction. Off-road autonomous mobility modeling and simulation requires more advanced representations of the vehicle and soil properties that define those interactions. In addition, the physical properties of the vehicles and the environment should be consistent with the simulated sensor data. If the soil properties represent a wet, soft soil, then the camera sensor should perceive darker soil with specular highlights, the LIDAR sensor should perceive lower reflectance, etc. There is a need for both new data on the relationships between environment parameters and vehicle-environment interactions and sensor-environment interactions and organization of currently available data. Current standard data formats store limited representations of terrain, object, and agent properties – particularly physical properties for physics simulations and for sensor models.

Finally, modeling and simulation of autonomous vehicle technologies, particularly for off-road autonomous mobility in unstructured environments, is still in early stages of research and development. There are relatively few tools for modeling both physical mobility and sensor perception for off-road environments. The tools that exist do not capture all relevant aspects of the environment or the vehicle. There are also limited examples of applications of modeling and simulation for development or evaluation of off-road autonomous vehicles. Therefore, there is limited information on best practices for developing and testing AV systems. As the tools mature, it will be important to consider how best to use the tools, how to determine what is and is not relevant, how to assess uncertainty in systems, etc. Further, there is need for the development of these simulation tools to enable co-simulation, e.g., the live updating of simulation features using real-world measurements, and as well a need to enable forecasting via simulation tools that are purpose-built to enable concurrent simulations into the future from perturbations around the same starting inputs. As developers and evaluators leverage co-simulation to piece together complete simulations of autonomous systems, it is critical that each component simulation provide information on model fidelity, appropriate applications, constraints, pitfalls, and limitations to avoid misuse of simulation tools by well-meaning modelers that may not be fully aware of the technical details of every aspect of the modeling and simulation toolkits.

5.5 SENSORS

Autonomous mobility has two components: the ability to perceive and understand the environment and the ability to move and act in order to complete a mission. Sensors are used to perceive the operational environment. Common sensors for autonomous vehicles include automotive radar, electro-optical cameras, LIDAR, GPS, and IMU. Sensors are used to detect objects in the environment, determine vehicle position and status, and assess environmental conditions. In a modeling and simulation environment, sensor models should provide data that is representative of data that a physical sensor would provide in the real operational environment. Ideally, the sensor model should include noise and errors that normally affect sensor operation in the real-world. Sensor performance should be degraded due to environmental conditions, vehicle dynamics, and other effects. The sensor models should include models of failure states. The sensor data interfaces should match real sensor interfaces, as data compression and data transfer can further degrade sensor fidelity. Data formats and communication details should be accurately modeled, including any on-board or external communication latencies. Any relationship between vehicle state and sensor performance should be reflected in the vehicle and sensor simulations. Accurately capturing not only ideal performance but realistic performance is critical to using modeling and simulation to evaluate autonomous vehicle system performance.

5.5.1 Approaches to Sensor Models

There are multiple approaches to modeling and simulation of sensors. The selection of models is often related to a trade-off between fidelity, complexity, and computational performance. First principle models properly account for every aspect of the sensor and the factors that affect the sensor data. While this has significant value in design and evaluation of sensors, it has high costs in complexity and computational performance. Physics-based models reduce the model to capture the aspects of the sensor and the environment with the most significant impact on sensor performance. These models still require high quality environment characterization and some individual sensor parameters but have reduce complexity and moderate computational requirements. Simulators that leverage game technologies typically have lower computational requirements and are easier to use. However, the sensor data results are designed to 'look good', not to be physically correct. Another strategy for modeling sensors is to develop empirical models based on measured data. Empirical models trade data collection efforts for much lower computational requirements.

In addition to high fidelity models of actual sensor performance, there are two additional types of sensor models to consider: ideal sensors and bypass sensors. Ideal sensors perform perfectly within the constraints of parameters defining the sensor. For example, an ideal LIDAR sensor will return perfectly accurate distances for every beam projected into the environment regardless of environmental conditions, vehicle movement, noise, etc. The purpose of an ideal sensor is to identify the best possible performance under perfect conditions. An ideal sensor also simplifies the model and reduces computational requirements by reducing the number of factors considered in the model and removing variability in the data. A bypass sensor provides the results of an analysis of sensor data without modeling the sensor data itself. In other words, a bypass perception sensor might generate obstacle data or an occupancy map directly from environment data without modeling the LIDAR, radar, or camera that capture the data or the algorithms used to interpret the data. Using a bypass sensor can significantly reduce complexity of models in situations where the details of how the data is captured is not critical to modeling and simulation of the portions of the framework that are of interest. For example, when testing a path planning algorithm, a bypass sensor could be used to generate the occupancy map without the computational costs associated with rendering the environment from the perspective of particular sensors on-board a vehicle.

5.5.2 Automotive Radar

Automotive radar uses millimeter-wave technology to detect range, angle, and velocity information for objects and obstacles in the area surrounding the vehicle [36]. Radar works by emission of electro-magnetic waves and processing of the signal in reflections of the waves from the environment. Current automotive radar typically operates in 24 GHz and 77 GHz frequency bands. Radar is primarily an active sensor that emits energy and detects reflections. It is possible to develop passive receivers that use illuminators of opportunity (e.g., satellite and cellular signals). Automotive radars are available in multiple configurations: single or multi-antenna, synthetic aperture radar, etc. Advanced imaging radar technology can provide high resolution data similar to optical video. Typically, ‘clutter’ in reflectance is discarded but state-of-the-art techniques can extract meaningful information including texture and shape from contrast in the intensity of the return signal. Multiple receivers can support height profiling of elements in the environment. However, radar does not have the precision of LIDAR or the field of view of electro-optical systems [37].

5.5.2.1 Data

Automotive radar sensors provide range and angle (position), velocity, acceleration, and radar cross section of targets within range of the sensor. While range estimation is critical data that automotive radar can provide, the ability to directly provide velocity estimation for objects is unique to automotive radar. The sensor may also provide signal-to-noise ratio data. This data can be difficult to fuse with other sensors but is often used to update occupancy maps. Sensor data from different vendors and models may have different update rates, different data formats, etc.

5.5.2.2 Applications

Radar sensor data is used for adaptive cruise control, obstacle detection, side and rear crash and crossing traffic alerts, parking assistance, lane-change assistance and blind spot checking. Radar sensor data is used to detect and estimate the speed of objects in front of the vehicle at ranges from 60 to 200 m. There is a trade-off between range and resolution: as range increases, the resolution and/or field of view is reduced.

5.5.2.3 Modeling and Simulation Data

In order to model automotive radar, a combination of sensor data and environment data is required. For the sensor, generic transmission and receiver antennas definitions and signal models (FMCW, doppler). For the environment, the reflection, diffraction, and scattering information for high frequency waves. Ideal models of radar data can be quickly estimated based on general radar system performance metrics: range resolution + noise, velocity resolution + noise, angular direction, signal-to-noise ratio, and probabilities of target detection. More accurate models of radar may leverage ray tracing to estimate emission and reflectance paths. However, producing a high fidelity, simulated radar image requires multiple distributed rays interacting and scattering in the scene including full electro-magnetic descriptions of the elements of the scene. This is not feasible for real-time modeling and simulation of radar for autonomous mobility.

5.5.2.4 Conditions

Automotive radar is commonly used because it is less expensive than other sensors and is generally not affected by weather conditions (e.g., fog, rain, or snow). Water does attenuate the radar signals, but the effect is small at ranges of 150 – 200 m. Radar is also not affected by solar lighting or nighttime conditions. However, contaminated radome can lead to signal reductions and electro-magnetic distortions will affect the signal. Radar units will typically be calibrated for the system configuration. Radar can also be affected by the presence of other signals in a crowded electro-magnetic environment. This may be direct interference where an incoming signal is directly received by the antenna from another transmitting system. Multi-path interference is an indirect form of interference which occurs when signals bounce off objects in the environment and are received by the antenna. Interference can overpower the actual signal of interest.

Jamming is a form of purposeful interference that occurs when an adversary is transmitting a signal with the intent of overpowering a receiver and masking real signals. Spoofing is a complex form of interference where an adversary transmits a signal with the intent of tricking a receiver.

5.5.2.5 Challenges

There are many vendor- and model-specific attributes that make it difficult to provide a simulated radar model that accurately reflects the performance of a radar in real-world conditions. Simple object detection models are easy to implement and are computationally performant but have limited accuracy. Physics-based EM simulation is needed to train detector algorithms, but EM models are complex and computationally expensive. Modeling and simulation tools can provide empirical and analytical models of reduced complexity. Commercial packages (e.g., FEKO) can provide EM models that can be used to generate parameters for real-time approximations of radar performance. There is a need for real-time models for radar interference.

5.5.3 Camera

Cameras typically are passive sensor systems that provide a 2D sensed image of the ambient electro-magnetic waves in the visible spectrum from the environment that are incident on the sensor. The primary cameras used for automotive applications are RGB cameras that provide a 2D array of pixels, each containing a red, green, and blue component. These cameras use an optical lens system to focus light onto an array of diodes that measure the intensity of a given wavelength (red, green, blue). This data is converted to a digital signal and processed through an image processing pipeline. This pipeline introduces one potential modeling challenge in that the exact pipeline and set of processing algorithms are typically proprietary. The processing pipeline serves to interpolate the color array, make color corrections, feedback exposure changes, and reduce image noise before sending the final image over a standard data connection to be used. While there are many automotive camera systems and manufacturers, Bosch [38] and Panasonic [39] are representative examples of such systems.

5.5.3.1 Data

The data can be sent over such connections as Gigabit Multimedia Serial Link (GMSL), Ethernet, CAN, coaxial cable, and low voltage differential signaling. When image data is being transferred, it is typically encoded in either a known image format (usually for internal communication in a control algorithm) such as an ROS message or encoded and streamed in a video format such as H.264 or MPEG (typical for streaming from a camera to a vehicle). In video mode, the acquisition process takes the form of a processing pipeline meaning that any color or exposure corrections can experience a small lag before being evident on a single frame from the camera. Beyond standard RGB cameras that mimic the human eye, a stereo camera system can be used to replicate a 3D version of the surroundings by using a disparity map of the images taken by two cameras with known spacing that are typically rigidly mounted together. Additionally, some systems can also operate in the near-Infrared spectrum (IR cameras), or far-infrared (thermal cameras).

5.5.3.2 Applications

In automotive applications, cameras are often used to perform object detection/classification, image segmentation, and visual odometry. The challenge of camera systems is that the camera images compress 3D information into a 2D image plane, and thus inference, processing, or the use of multiple data sources is necessary to recover the 3D world view. Additionally, cameras are largely sensitive to changes in ego- or object angular position but can be very insensitive to changes in range.

To recover information about the environment, images are often processed by deep learning algorithms running on central hardware, but some sensor systems provide processing on the sensor module to perform initial perception. In the case of object detection, the purpose is often to identify objects by class (car, pedestrian, bicycle, etc.) and estimate a pose and bounding box. Those estimations are then used in path planning. Image segmentation, which is a process that seeks to classify all pixels in an image, is also done through deep learning algorithms as well as physics-based processing, and this information can be used to assist in object detection or can be fed directly into the path planning stage. Camera data can also be combined with information from other sensors including GPS, LIDAR, and radar through sensor fusion to create a composite understanding of the environment.

5.5.3.3 Parameters

Standard camera parameters include:

- Vertical and Horizontal Field of View;
- Vertical and Horizontal Resolution;
- Vertical and Horizontal Pixel Size;
- Gamma;
- Gain;
- Focal Length;
- Frame Rate; and
- Data Format.

5.5.3.4 Conditions

The acquired image can differ significantly from the ground truth environment due to environmental conditions, distortion, and sensor noise. Environmental conditions that can affect a camera system include:

- Lighting conditions:
  - Direct sunlight, lens flare, low light, shadows.
- Particulate matter:
  - Turbidity;
  - Precipitation:
    - Rain, snow, freezing rain, sleet, hail.
  - Suspensions:
    - Sea salt, mist, fog, dust, dirt, soot, smoke.
  - Accumulation on sensor:
    - Snow, water droplets, dirt, dust, bugs.
- Movement:
  - Vibration;
  - Motion blur;
  - Shock;
  - Object motion.
- Temperature and humidity; and
- Failure modes:
  - Complete failure, data corruption, connection failure, partial diode failure.

While some environmental conditions are independent of the camera, many, including light, interact with the sensor system itself. Direct light on the lens can generate lens flare and can saturate the image. While white balance correction is designed to prevent this and the processing pipeline can accommodate for changing light, the lag in correction can result in low quality frames. Other lens and sensor distortions can include:

- Lens:
  - Vignetting;
  - Radial lens distortion (wide-angle effects);
  - Lens dust;
  - Chromatic aberration;
  - Focal distance;
  - Depth of field.
- Sensor array + processing distortion:
  - Demosaic pattern;

- Pixel saturation;
- Color correction;
- Autofocus;
- Exposure rate;
- Motion blur;
- Color correction;
- Bias from calibration.

Along with distortions, the image acquires noise during the light acquisition and processing stages. The following is a list of potential sources of noise, but the relative effects depend on the quality of the sensor and the sophistication of the image processing pipeline:

- Fixed pattern noise;
- Dark current noise (thermal noise);
- Shot noise (electron measurements);
- Quantization noise;
- Background radiation on chip; and
- Photo response non-uniformity.

5.5.3.5 Challenges in Modeling and Simulation

A camera model should be able to account for various parameters that differentiate the sensors such as field of view, precision, sensitivity, accuracy, noise levels, image resolution, repeatability, update frequency, and depth of field. The primary challenges in modeling camera sensor systems come from three main sources: complexity and variance of the virtual environment, simplification of the lens system, black box behavior of the image processing pipeline.

While game developers have generated increasingly complex open-world scenarios, their representation of the real-world is still limited and often simplified in favor of human perception rather than sensor accuracy. For example, 3D texture details in rendering engines are often emulated to human users by surfacing a flat plane with visual features that appear 3D in nature. While a game may have hundreds or thousands of models and details, the real-world has millions and billions of different objects and scenarios that can significantly alter an image. This is most notable in the fact that a game seeks to appear visually realistic to a human while a camera model must be realistic to an object detection algorithm and thus various complexity deep neural networks. The second limitation, due to individual sensor systems, arises in the physical and computational complexity of modeling the interaction between the light/environment and the lens characteristics. While we have simple models that can often be visually appealing and, in some cases, accurate enough for the application, many do not seek to physically represent the lens characteristics. Furthermore, physical representation of the lens parameters and characteristics can become intractable.

In addition to the lens and environment, there are a simple set of noise models that can closely represent that noise incurred from data acquisition. As camera systems become more complex and deblurring and denoising algorithms are added to the image processing pipeline, the challenge in representing the augmented image increases.

5.5.3.6 Modeling and Simulation Examples

There are a host of simulation platforms that provide at least a minimal level of camera sensor support. These can range from idealistically rendered pinhole cameras to physically based virtual environments with noise characteristics of the sensor. As many companies and institutions continue to conduct research in this field, additional simulation frameworks are continually developed and the capabilities of each framework changes rapidly as the needs evolve, it would be difficult to compile a comprehensive list. The following is a set of the more common simulations platforms that currently support camera simulation for robotic or autonomous vehicle applications: Gazebo, Carla, Udacity, AirSim, Unity SimViz, NVIDIA DRIVE, VIRES Virtual Test Drive, rFpro, VANE, MAVS, DeepDrive, DeepRoad, DeepTest, Aureate, USARSim, Roadview, Unreal Engine 4, Matlab, SynCity, AutononoVi-Sim, MORSE, ASM Traffic (dSpace), CarMaker, DYNA4 (TESIS), Aimsun, Prescan, PTV vissim, SCANeR studio, and CoppeliaSim.

5.5.4 LIDAR

LIDAR, Light Detection and Ranging, is a sensing method used primarily for measuring distance to a target. LIDAR uses pulses of light and measures the reflected energy. There are multiple types of LIDAR. The most common form of LIDAR is electromechanical LIDAR. Lasers are emitted from the LIDAR unit in a circle using a spinning mechanical element. The distance from the unit to an object is measured based on how long it takes from emission of the pulse to detecting a reflection of the emitted beam from an object. For each emitted beam, the sensor reports a distance from the LIDAR unit to an object and the intensity of the return. Multiple returns can be detected for a single emitted beam. Data is returned in the form of an array of returns with distances and intensities at regularly spaced angles. Distances are often converted to 3D point clouds for processing. Mechanical components limit lifetimes to 1,000s of hours.

A 3D flash LIDAR camera works like a camera sensor but adds depth and intensity data. A 3D flash LIDAR emits a laser flash pulse. Each pixel of the flash LIDAR camera records the time it takes a reflection of the flash to reach the sensor. Flash LIDAR cameras do not rely on moving mechanical parts reducing power consumption and increasing reliability.

A solid-state LIDAR has no moving parts. A solid-state LIDAR is typically smaller, lighter, and is less impacted by shock and vibration than an electromechanical LIDAR.

Parameters:

- Range;
- Range Accuracy;
- Vertical and Horizontal Field of View;
- Vertical and Horizontal Angular Resolution;
- Number of Beams;
- Number of Samples;
- Scan Rate; and
- Beam Wavelength.

5.5.4.1 Data

LIDAR typically provides data in the form of an array of distances and intensities. This scan data is often converted to an XYZ Intensity point cloud. LIDAR units may also report multiple returns – detection of multiple reflections of a beam. Multiple returns can occur in various conditions, but an example is a beam passing through the branches of a tree. As the beam passes through the tree's branches, reflections may return from multiple leaves or branches along the path. LIDAR units may provide configuration options for return selection (e.g., first, last, strongest, etc.). LIDAR units are often integrated with GPS and/or IMU units to synchronize point cloud data with vehicle pose and position. The Robot Operating Systems (ROS) is a middle-ware open-source software environment that provides standard data formats for incoming scan and point cloud data. The LaserScan message is used to encode a scan by a laser scanning device. LaserScan messages report distances and intensities for readings between a given minimum and maximum angle at a specified increment and recorded over a specified length of time [40]. ROS also provides higher level PointCloud and PointCloud2 messages that encode laser scans as 3D point cloud data [41], [42]. Other autonomous vehicle development platforms provide libraries for capturing and converting laser scan data to point cloud data. LIDAR is usually connected to a local area network on a vehicle over gigabit Ethernet.

5.5.4.2 Applications

LIDAR is primarily used to measure distances to objects in an environment for the detection of objects. LIDAR can be used for adaptive cruise control, terrain characterization (shape and properties), object detection, classification, and avoidance. LIDAR data is often converted to point clouds that are used to generate maps of the environment and to determine geometric shapes of objects. Surface properties can be extracted from intensity return data. Multiple return data can provide insight into presence of suspended particles (e.g., smoke) or collections of small objects (e.g., vegetation).

5.5.4.3 Conditions

Beam reflections and the data detected by the LIDAR are affected by environmental conditions including ambient light, surface material (surface reflectance), and temperature. Particulates suspended in the air and precipitation can also significantly affect LIDAR data. The effects of environmental conditions can depend on the wavelength of the LIDAR beam (e.g., 1550 nm LIDAR is more effected by suspended water or precipitation). LIDAR is also affected by shock and vibration from the movement of the vehicle. LIDAR is also often tightly coupled with GPS and inertial navigation data. Errors in GPS and inertial navigation systems will contribute to errors in LIDAR data. Accuracy of returns diminishes as range increases.

- Surface Material;
- Thermal Range;
- Precipitation;
- Suspensions;
- Shock and Vibration; and
- GPS/INS integration.

5.5.4.4 Challenges in Modeling and Simulation

A basic LIDAR model that provides ideal simulated range data is not particularly difficult given a virtual environment containing geometric representations of objects and terrain. A complete model of LIDAR reflectance includes laser pulse energy, receiver area, transmitter and receiver efficiencies, reflectance data for target materials, scattering coefficients for the air, and should consider interactions with multiple objects along the beams path. However, few LIDAR models consider all factors due to the computational cost, the relative contribution of the parameters, and the availability of accurate data. In order to maintain real-time performance, LIDAR models are typically reduced in complexity by approximating or neglecting some aspects of the complete model. Accurate modeling of intensity returns is primarily a data challenge. Surface material data associated with 3D objects most often does not include complete physics-based rendering information for visible light and very rarely includes reflectance data for LIDAR wavelengths. Increasingly, LIDAR intensity of return is being used as a component of object classification. Accurately modeling intensity of return for classes of objects will be important for evaluating these object classification algorithms. In real-world data, the reflectance data will vary in non-repeating ways that is not typical of stored material data for 3D objects in games and simulations. Another challenge for modeling vendor-specific LIDAR units is that each LIDAR unit performs signal processing using vendor-specific software. It is often not possible to incorporate the vendor processing in a modeling and simulation framework.

5.5.4.5 Modeling and Simulation Examples

Most autonomous vehicle modeling and simulation tools provide a LIDAR sensor model. However, the level of detail of the model varies significantly across different modeling and simulation tools. Many LIDAR sensor models provide only range data and are not intended to mimic the performance of vendor-specific LIDAR units. Gazebo is a popular simulation tool that is tightly integrated with ROS. Gazebo provides a LIDAR model, but environments tend to be simplistic. Udacity provides a Unity-based simulator that includes a LIDAR simulation. Carla and NVIDIA’s DriveSIM provide Unreal-based LIDAR simulation. VANE is a U.S. DoD model optimized for high performance computing platforms [43]. The Mississippi State University Autonomous Vehicle Simulator (MAVS) provides a physics-based LIDAR model that provides range, intensity, and return data and includes effects of rain on LIDAR accuracy [23].

5.5.5 GPS

5.5.5.1 Data

GPS, or more broadly, Global Navigation Satellite System (GNSS), is an inertial sensor that uses signals from satellite constellations to trilaterate the receiver’s position in space. The essential data provided by these systems are latitude, longitude, and altitude with certain sensors providing additional data including position uncertainty, number of satellites locked, velocity, heading, etc., [44]. Example GPS systems for autonomous vehicles include Refs. [45] and [46].

Because a simple GPS system suffers from significant lack of accuracy (order meters), additional techniques can be used to improve accuracy and reduce uncertainty. Some of the correction techniques included Real-Time Kinematic (RTK), Precise Point Positioning (PPP), and Inertial Navigation System (GPS/INS). RTK makes use of signal phase as well as a reference receiver to improve the accuracy of the measurements from the satellites. PPP also takes into account the phase and uses a reference station network to provide precise orbit information. To further improve the precision of a GNSS, it can be combined with inertial data to make mutual corrections between positional, velocity, and acceleration level information. By including correction methods, automotive GPS can typically perform global positioning reliably within order centimeter accuracy. GPS is commonly used in localization in combination with mapping and planning.

5.5.5.2 Conditions

Depending on the specific GPS and corrections, various effects can be observed. These effects include:

- Occlusion;
- Multi-path;
- Atmospheric:
  - Ionosphere distortion;
  - Troposphere distortion;
  - Air pressure, humidity, signal angle.
- Satellite Error;
- Shock;
- Failure Modes;
- Accuracy and Error; and
- Dynamic characteristics of transient response.

5.5.5.3 Challenges in Modeling and Simulation

The primary challenges arise from two sources. First, the GPS signal must be modeled to understand the satellite visibility as well as the signal path to the receiver as much of the error is introduced because of lack of signals, or distorted arrival signals (multi-path and atmospheric distortion). Second, if the system includes correction techniques, the model must account for these potentially proprietary data augmentations to produce realistic data. Mimicking this black box behavior can provide a significant challenge in the modeling process.

5.5.5.4 Modeling and Simulation Examples

The most comprehensive GPS model used for autonomous simulations found in literature includes atmospheric effects and predicts multi-path received signals. It uses the modeled signals as input to a generic trilateration algorithm to produce a simulated signal [47], [48]. While this method seeks to replicate much of the sensor noise, it may not be as applicable to modern GNSS used for autonomous navigation. In many cases, simulation platforms support GPS sensors but reduce the noise to either a small gaussian noise on the position or provide ground truth position from the simulation framework. Some example simulation platforms include: Gazebo, VANE, Carla, AirSim, Unity SimViz, NVIDIA DRIVE, and rFpro.

5.5.6 Other Sensors

Automotive radar, camera, LIDAR, and GPS are some of the primary sensors used for ADAS and autonomous vehicle systems. However, other important and useful sensors include thermal imaging (SWIR, MWIR, LWIR), hyperspectral imaging, ground-penetrating radar, ultrasonic, and miscellaneous other sensors (light sensor, compass, temperature/humidity/pressure sensors). These sensors have received limited modeling and simulation attention compared to the primary sensors. However, thermal imaging, hyperspectral imaging, and ground-penetrating radar have clear applications to military operations: enhanced human, animal, and vehicle detection, improved material detection and classification, soil moisture content analysis and detection of buried objects.

5.6 SUMMARY

This chapter reviewed requirements for representing virtual environments and sensors for evaluation of autonomous mobility of military ground vehicles. The chapter also discussed the importance of considering uncertainty quantification in modeling and simulation of autonomous systems. Our review of current capabilities and requirements identified a number of gaps:

- There is a need for development of shared libraries of scenarios that provide effective challenges for autonomous mobility and exercise the scenario description formats/languages, particularly for representation of complex, unstructured, and dynamic environments.
- Current work in virtual environment and scenario representations has focused primarily on requirements for representing on-road environments. There is a need for extensions to the open data format standards to support the requirements of off-road scenarios (terrain representation, path and trail networks and geometry, vegetation, animals, etc.).
- Current object and agent model representations are often limited to static models or models with limited stored animations. There is a need for libraries of object and agent models that support complex vehicle-object and vehicle-agent interactions (e.g., collisions, crushing). Additionally, object and agent models should support representations of the effects of environmental conditions (e.g., moving in the wind, changes in gait in wind and rain, etc.).
- In order to improve representation of surfaces for sensor models, there is a need for libraries of surface material property distributions required for accurate modeling of camera, LIDAR, radar, thermal, and other sensors. Distributions should include variations within-object (e.g., variation observed on a single plant) and within-class (e.g., variation observed across a species of plant).
- Current efforts to model micro-behaviors for vehicles, pedestrians, and animals tend to use co-simulation with traffic models that are not designed to represent detailed interactions between agents and their environment. There is a need for nano-behavior models for human and animal agents that can generate the enormous range of intelligent, complex, and interpretable behaviors of humans and animals.
- In addition, there is a need for increased variation in human and animal appearance. Models available in most tools do not capture the diversity in culture, race, age, weight, height, clothing, activities, and accessories (e.g., phones, shopping carts, strollers, bikes, etc.) observed in the populations of interest.
- In order to support variation in appearance and behavior, new tools need to be devised for defining and modeling agents.
- Much of the work on vehicle-terrain interaction models has been separate from the work on modeling sensor perception of the environment. For autonomous mobility, it is important that the appearance of the soil to sensors matches the soil properties used for vehicle-terrain interaction. In other words, if the soil properties represent wet soft soil, the camera and LIDAR sensor data should indicate a wet soft soil surface.
- While many modeling and simulation tools provide some representation of precipitation, most are limited to an approximation of the effects of precipitation in the medium on sensor data. Fewer tools provide realistic models of precipitation that include effects on the surfaces of sensors (blurring, distortion) and effects on the environment (changes in color and reflectance, movement of objects).

- Reduced fidelity models are often used for sensor simulations to avoid computational complexity and cost. In some cases, the reduced models cannot provide sensor data and meta-data that may be used by intelligent algorithms (e.g., LIDAR potential use of multiple returns and intensity data).
- Similarly, the real-time models provided for automotive radar provide ideal sensor data potentially adjusted with a noise model. Physics-based models are computationally complex and resource intensive, but there is a need for reduced order models for radar that can achieve real-time performance but still provide a more accurate representation of real-world performance. As new, advanced imaging radar techniques become available, new models for M&S tools will be required.
- Many commercial sensors are complex sensing systems that incorporate vendor-specific, proprietary data processing. More work is needed to address development and validation of vendor-specific sensor models.
- There are two groups of sensors that have received less attention than the primary sensors: secondary and on-board sensors (e.g., compass, temperature, light meter, contact sensor, etc.) and more complex specialty sensors (e.g., hyperspectral imagers and ground-penetrating radar). Secondary and on-board sensors are more often found in robotics but may be critical components of off-road vehicles that should be incorporated into modeling and simulation tools. Hyperspectral imaging and ground-penetrating radar are currently used for special applications but may see broader use as technologies develop and applications are identified.
- On-board, V2V, and V2I communication are critical components of autonomous systems with multiple sources of noise and potential points of failure. Failing to model communication systems and potential system latencies will obscure issues that will affect real-world performance.
- There is a need for evaluations of the sensitivity of sensors, algorithms, and system performance to variations in environment parameter values. This data would allow environment modelers to prioritize parameters to achieve desired fidelity and make informed trade-offs between computational cost and model fidelity.
- There is a related need to determine fidelity requirements for camera models. Some camera models are based on technology developed to generate images that are attractive or compelling to the viewer and are not designed to produce physically correct images. Research is needed to investigate what level of image fidelity is required to accurately model system performance.
- Increasingly, autonomous mobility modeling and simulation tools are being used to train and evaluate neural network, machine learning, and deep learning models. Research is needed to determine the sensitivity of NN/DL models to fidelity of the virtual environment. The reuse of models and material data in virtual environments may limit transfer from the virtual tests to real-world applications. Understanding and addressing the factors that affect sim2real transfer will be critical for future use of simulation for evaluation of NN/DL algorithms.
- There is currently limited data on the fidelity and limitations of sensor and environment models as well as limited information on verification and validation of models. There is a need for standard benchmarks at the component and system level that produce quantitative metrics that allow comparison of models.

For future work, we recommend that research groups work to create a series of quantitative benchmarks that not only will provide metrics for the assessment and validation of the models incorporated into the simulation tools but also will exercise the data formats used to define the environments and the sensors lea2ding to better representations of scenarios. Future work should consider how to define, validate, and use sensor models of varying levels of fidelity. M&S tool users would benefit from prescription of best practices for testing systems.

5.7 REFERENCES

[1] Torbic, D.J., O'Laughlin, M.K., Harwood, D.W., Bauer, K.M., Bokenkroger, C.D., Lucas, L.M., Ronchetto, J.R., Brennan, S., Donnell, E., Brown, A., and Varunjikar, T., 2014. Superelevation Criteria for Sharp Horizontal Curves on Steep Grades (Project 15-39). Available at: https://trid.trb.org/view/1322919.

[2] Balling, O., Bradbury, M., Bruce, J., Cammarere, M., Choi, K.K., Dasch, J., Foster, C., Funk, M., Gaul, N., Hodges, Jain, A., Jayakumar, P., McCullough, M., Niemann, J., Ramyar, E., Scalia, J., Wasfy, T., and Wojtysiak, B., 2019. AVT-248 Next-Generation NATO Reference Mobility Model (NRMM) Development, NATO-STO-AVT-248 Technical Report. AC/323(AVT-248).

[3] Ahlvin, R.B., and Haley, P.W., 1992. NATO Reference Mobility Model Edition II, NRMM II User's Guide. US Army.

[4] USDA Forest Service, 2005. Guidelines for Engineering Analysis of Motorized Mixed Use on National Forest System Roads (EM-7700-30). Available at: https://www.fs.fed.us/eng/pubs/pdf/EM7700-30.pdf.

[5] USDA Forest Service, 2012. Guidelines for Road Maintenance Levels. Available at: https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3793545.pdf.

[6] Ducloux, P., 2016. RoadXML 2.4.1 Road Network Description XML Format Specification. Available at: https://www.road-xml.org/download/roadformatspec/RoadXML_FormatSpecification2.4.1.pdf.

[7] VectorZero, 2020. RoadRunner. Available at: https://www.vectorzero.io/.

[8] 3D Systems Inc., 1988. (June). Stereolithography Interface Specification. Valencia, CA.

[9] Wavefront Technologies, 1992. Appendix B1. Object Files (.obj). Advanced Visualizer 3.0 User Manual.

[10] Khronos Group, 2017. glTF Version 2.0. Available at: https://github.com/KhronosGroup/glTF/blob/master/specification/2.0/README.md.

[11] Khronos Group, 2008. COLLADA – Digital Asset Schema Release 1.5.0 Specification. Retrieved from: https://www.khronos.org/files/collada_spec_1_5.pdf.

[12] Smith, B., Rinaudot, G.R., Reed, K.A., & Wright, T., 1988. Initial Graphics Exchange Specification (IGES) Version 4.0 (NBSIR 88-3813. US Department of Commerce National Bureau of Standards.

[13] ISO, 2016. Industrial Automation Systems and Integration – Product Data Representation and Exchange – Part 21: Implementation Methods: Clear Text Encoding of the Exchange Structure. (ISO 10303-21:2016). International Organization for Standardization, Geneva, Switzerland.

[14] Autodesk, 2020. FBX: Adaptable File Format for 3D Animation Software. Available at: https://www.autodesk.com/products/fbx/overview.

[15] Nedevschi, S., Bota, S., and Tomiuc, C., 2009. Stereo-Based Pedestrian Detection for Collision-Avoidance Applications. IEEE Transactions on Intelligent Transportation Systems, 10(3), 380-391.

[16] Saleh, K., Hossny, M., and Nahavandi, S., 2018. Intent Prediction of Pedestrians via Motion Trajectories Using Stacked Recurrent Neural Networks. IEEE Transactions on Intelligent Vehicles, 3(4), 414-424.

[17] Rasouli, A., Kotseruba, I., and Tsotsos, J.K., 2018. Understanding Pedestrian Behavior in Complex Traffic Scenes. IEEE Transactions on Intelligent Vehicles, 3(1), 61-70.

[18] Foretellix, 2020. Open M-SDL: Measurable Scenario Description Language. Available at: https://www.foretellix.com/open-language/.

[19] Artal-Villa, L., Hussein, A., and Olaverri-Monreal, C., 2019. Extension of the 3DCoAutoSim to Simulate Vehicle and Pedestrian Interaction based on SUMO and Unity 3D. 2019 IEEE Intelligent Vehicles Symposium (IV), 885-890.

[20] Paul, N., and Chung, C., 2018. Application of HDR Algorithms to Solve Direct Sunlight Problems when Autonomous Vehicles Using Machine Vision Systems are Driving into Sun. Computers in Industry, 98, 192-196.

[21] Seregina, L.S., Haas, R., Born, K., and Pinto, J.G., 2014. Development of a Wind Gust Model to Estimate Gust Speeds and their Return Periods. Tellus A: Dynamic Meteorology and Oceanography, 66:1.

[22] Naimo, A., 2014. A Novel Approach to Generate Synthetic Wind Data. Procedia – Social and Behavioral Sciences, 108, 187-196, Jan. 2014.

[23] Goodin, C., Carruth, D.W., Doude, M., and Hudson, C., 2019. Predicting the Influence of Rain on LIDAR in ADAS. Electronics, 8(1), 89.

[24] Jensen, H. W., Legakis, J., and Dorsey, J., 1999. Rendering of Wet Materials. In Rendering Techniques '99, D. Lischinski and G. W. Larson, Eds. Springer, 273-281.

[25] Sawayama, M., Adelson, E.H., and Nishida, S., 2017. Visual Wetness Perception Based on Image Color Statistics. Journal of Vision, 17(5), 7.

[26] Marshall, J.S., and Palmer, W.M., 1948. The Distribution of Raindrops with Size. Journal of Meteorology, 9, 327-332.

[27] Gunn, K.L.S., and Marshall, J.S., 1958. The Distribution with Size of Aggregate Snowflakes. Journal of Meteorology, 15(5), 452-461.

[28] Schiegg, F.A., Krost, J., Jesenski, S., and Frye, J., 2019. A Novel Simulation Framework for the Design and Testing of Advanced Driver Assistance Systems. 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), 1-6.

[29] Teixeira, F.A., and Oliveira, R.A., 2019. Survey of Vehicular Network Simulators: A Temporal Approach. Enterprise Information Systems: 20th International Conference, ICEIS 2018, Funchal, Madeira, Portugal, March 21-24, 2018, Revised Selected Papers, 363, 173. Springer.

[30] Segata, M., Joerer, S., Bloessl, B., Sommer, C., Dressler, F., and Lo Cigno, R., 2014. PLEXE: A Platooning Extension for Veins. Proceedings of the 6th IEEE Vehicular Networking Conference (VNC 2014), 53-60.

[31] Sommer, C., 2020. Veins: Vehicles in Network Simulation. Available at: http://veins.car2x.org/.

[32] German Aerospace Center, 2019. SUMO at a Glance. Available at: http://sumo.sourceforge.net/userdoc/Sumo_at_a_Glance.html.

[33] Daimler Center for Automotive Information Technology Innovations, 2020. VSimRTI – Smart Mobility Simulation. Available at: https://www.dcaiti.tu-berlin.de/research/simulation/.

[34] Robert Protzmann, Björn Schünemann, and Ilja Radusch. Simulation of Convergent Networks for Intelligent Transport Systems with VSimRTI. In Benoit Hilt, Marion Berbineau, Alexey Vinel, and Alain Pirovano, editors, Networking Simulation for Intelligent Transportation Systems: High Mobile Wireless Nodes, chapter 1, 1-28. John Wiley & Sons, 2017. ISBN: 978-1-119-40745-4

[35] Riley G.F., and Henderson T.R., 2010. The ns-3 Network Simulator. In: Wehrle K., Güneş M., Gross J. (eds) Modeling and Tools for Network Simulation. Springer, Berlin, Heidelberg.

[36] Patole, S.M., Torlak, M., Wang, D., and Ali, M., 2017. Automotive Radars: A Review of Signal Processing Techniques. IEEE Signal Processing Magazine, 34(2), 22-35.

[37] Rosique, F., Navarro, P. J., Fernández, C., and Padilla, A., (2019). A Systematic Review of Perception System and Simulators for Autonomous Vehicles Research. Sensors, 19(3). Available at: https://doi.org/10.3390/s19030648.

[38] Robert Bosch GmbH, Multi Purpose Camera, 2019. Available at: www.bosch-mobility-solutions.com/en/products-and-services/passenger-cars-and-light-commercial-vehicles/driver-assistance-systems/lane-departure-warning/multi-purpose-camera.

[39] Panasonic Automotive, Cameras, 2019. Available at: https://eu.automotive.panasonic.com/solutions/components/cameras.

[40] LaserScan Message, 2019. Available at: http://docs.ros.org/melodic/api/sensor_msgs/html/msg/LaserScan.html.

[41] PointCloud Message, 2019. Available at: http://docs.ros.org/melodic/api/sensor_msgs/html/msg/PointCloud.html

[42] PointCloud2 Message, 2019. Available at: http://docs.ros.org/melodic/api/sensor_msgs/html/msg/PointCloud2. html.

[43] Goodin, C., Carrillo, J.T., McInnis, D.P., Cummins, C.L., Durst, P.J., Gates, B.Q., and Newell, B.S., 2017. May. Unmanned ground vehicle simulation with the Virtual Autonomous Navigation Environment. In 2017 International Conference on Military Technologies (ICMT), 160-165, IEEE.

[44] Madry, S., 2015. Global Navigation Satellite Systems and their Applications. Springer, New York.

[45] Hexagon. High-Precision GPS for Autonomous Vehicles, 2019. Available at: https://www.novatel.com/industries/autonomous-vehicles/#technology.

[46] Septentrio, Automotive ADAS, 2019. Available at: https://www.septentrio.com/en/industries/automotive-adas.

[47] Goodin, C., Durst, P.J., Gates, B., Cummins, C., and Priddy, J., 2010. November. High Fidelity Sensor Simulations for the Virtual Autonomous Navigation Environment. In International Conference on Simulation, Modeling, and Programming for Autonomous Robots, 75-86, Springer, Berlin, Heidelberg.

[48] Durst, P.J., and Goodin, C., 2012. High Fidelity Modelling and Simulation of Inertial Sensors Commonly Used by Autonomous Mobile Robots. World Journal of Modelling and Simulation, 8(3), 172-184.

Chapter 6 – VEHICLE SYSTEM MODELS

6.1 THRUST OBJECTIVE AND TEAM MEMBERS

The *objective* of the Thrust Area 3 Vehicle System Models is to develop requirements for:

1) Autonomous vehicle models needed for virtual assessment of vehicle mobility.
2) Discussion of capabilities needed for simulating the autonomous vehicle models and assessing vehicle mobility at a level of accuracy and computational time appropriate for both operational tools and design and procurement tools.

The requirements identified as part of this thrust area pertain to:

1) The modeling of vehicle dynamics, vehicle systems, vehicle sensors, and vehicle-operator and vehicle-terrain interaction while the vehicle models interface with other components of the virtual mobility assessment framework, including virtual environment, autonomous mobility sensor models, planning and control sub-systems.
2) Capabilities and simulation performance of software products.

The team members included:

Country	Name
Turkey	Özgen Akalin
Canada	Martin Hirschkorn
Germany	Torsten Kluge
South Africa	Dithoto Modungwa
South Africa	Phumlane Nikosi
South Africa	David Reinecke
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United States	Robert Stawarz
United States	**Vladimir Vantsevich: Leader**
United States	Tamer Wasfy
United States	Xiabo Yang

6.2 BASIC REQUIREMENTS OF AUTONOMOUS VEHICLE MODELS AND AUTONOMOUS MOBILITY ASSESSMENT

To identify distinctive features of the modeling and simulation of autonomous mobility and to formulate requirements for autonomous vehicle models, which could be common or different as compared to the requirements for conventional (with a driver) vehicle models, the following tasks should be discussed and addressed:

1) Understand the reason and the purpose of transition from conventional to Autonomous Vehicles (AVs) and, thus, formulate requirements for functional features and operational properties that AVs and AV systems should demonstrate in combat and tactical conditions.

2) Analyze mobility assessment methods for their compliance with the functional features and operational properties of autonomous vehicles, and, thus, for being suitable to assess autonomous mobility in the process of vehicle movements.

Indeed, setting up distinctive functional features and operational properties of autonomous vehicles will certainly lead to requirements for their mathematical models to simulate AVs for the purposes of vehicle design, marketing, procurement, etc. On the other hand, studying the existing mobility assessment methods for their applicability to autonomous mobility can result in a necessary I/O interface between the models of the assessment methods and the AV models, or even give rise to never-existed-before methods for assessing autonomous mobility if the existing mobility assessment methods are not suitable to the AV models.

6.2.1 Autonomous Vehicle Models

The US Army Robotic and Autonomous Systems Strategy established five capability objectives to guide technology development in unmanned systems [1], including:

1) Increase situational awareness;

2) Lighten the Soldiers' physical and cognitive workloads;

3) Sustain the force with increased distribution, throughput, and efficiency;

4) Facilitate movement and maneuver; and

5) Protect the force.

For the autonomous mobility modeling and simulation, the most important to discuss is vehicle capabilities given by Objectives 1, 2, 3, and 4. Objective 5, which does not directly relate to vehicle mobility, enhances Soldiers' survivability by providing greater standoff distance from enemy formations, rockets, artillery, and mortars as well as placing less Soldiers at risk during convoy operations. The increase in *situational awareness* (Objective 1) is based on anticipation of a much better capability of autonomous vehicles to operate over wide areas of complex terrain, often going where manned vehicles cannot. Thus, the modeling and simulation of autonomous vehicles should target terrain conditions that are much more severe than dirt roads and unprepared terrain conditions where manned systems cannot operate. The *Soldiers' cognitive load* (Objective 2) is expected to be reduced by AI-based decision-making, which should also improve tactical mobility and reduce cyber, electronic, and physical signatures. It is clear that the usage of AI-based on-board technologies is to be implemented in real time. Thus, the models of autonomous vehicles should be able to run in real time and even faster than real-time to enable the AI- and model-based decision-making process. To *sustain the force with increased distribution, throughput, and efficiency* (Objective 3), i.e., to enhance logistics by adopting autonomy-based capabilities requires models to simulate the AI-based mission planning and implementation with interface to vehicle system controls. Thus, the models of autonomous vehicles should be suitable for both simulating model-based vehicle system controls and interfacing with the AI-based mission planning and implementation. Additionally, the autonomous vehicle models should be capable to adequately simulate power losses in the vehicle systems and vehicle-terrain interaction and, hence, to assess vehicle energy efficiency.

Joint Combined Arms Maneuvers in the 21st Century requires ground combat forces to be capable of outmaneuvering adversaries *physically* and *cognitively* in all domains [2]. In this regard, Objective 4, *Facilitate movement and maneuver*, targets to ensure freedom of maneuver of autonomous vehicles on battlefields, to guarantee functioning and maneuvering across variable and rough terrain under combat conditions, to improve agility and tactical mobility, and to sustain high tempo operations (automated ground re-supply convoys). Clearly, the key property of autonomous vehicles, which is the basis of the capability to function and maneuver on across variable and rough terrain under combat, tactical and operational conditions, is *agility*. The fundamental concept of vehicle agility is by no means a novelty. In 1965, M.B. Bekker defined agility as an operational requirement of acceleration, turning radius, stability and maneuverability through lateral impenetrable obstacles which demand a special vehicle configuration, such as articulated vehicles [3]. In the late 1970s, US Army research centers began analyzing mobility, agility, and survivability of ground combat vehicles of which the results led to a conclusion that mobility and agility have a substantial impact on the vehicle's performance [4]. Researchers then understood that the vehicle's survivability was increased through agility. For a number of years, straight-ahead acceleration was the focus [5]. Later, steering behavior prediction was included due to its complexity and the considerable attention given toward agility for increased battlefield survivability through avoiding projectiles and missiles by high-speed and violent maneuvers [6]. DARPA considers agility to be a vehicle's ability to quickly react. In an example, a rapid change in speed or acceleration (burst acceleration) or an ability to "dodge" through advance suspension control [7]. The intent and benefit for the development of advanced vehicle agility for military vehicles is to reduce the requirement of armor-based survivability and to increase efficiency through vehicle weight reduction, thus increasing the vehicle's ability to effectively move across severe terrain conditions. It is clear, that although advancements in technology for agile vehicle dynamics have been accomplished, nothing has been done to develop agility for off-road mobility, or military operations that function at millisecond and tens-of-milliseconds levels. The above-presented brief analysis illustrates the importance of agility as a research topic of the future RTG to study agility as a distinctive feature of autonomous vehicles and to research requirements for mathematical modeling and computer simulation of agile autonomous vehicles. In this ET-194 report, agility is termed as extremely fast, precise and pre-emptive parameter identification, decision-making, and control of autonomous vehicles [8]. Thus, mathematical models of autonomous vehicles and vehicle systems should be capable to sufficiently simulate agility as defined. Additionally, and importantly, introducing various levels to vehicle autonomy by establishing a balance and relationship between human and artificial intelligence undoubtedly leads to new requirements for modeling autonomous vehicles and vehicle systems. It is clear from the above-considered features of autonomous vehicles that autonomous vehicle models and vehicle system models should be considered as an integrative part of autonomous and agile decision making and controls, which include:

1) Sensing and observing states of the vehicle system models.
2) Interfacing with autonomous movement sensors (navigation, localization, dynamic changes of terrain conditions, etc.).
3) Vehicle sensor signal processing and sensor fusion.
4) Decision-making on vehicle system controls (with or without human inputs).
5) Actuating on vehicle system models to respond to the control inputs.

In conclusion, Table 6-1 presents distinctive features of autonomous vehicle models and vehicle system models that are further detailed in the following sections of this chapter.

Table 6-1: Distinctive Features of Autonomous Vehicle Models and Autonomous Vehicle System Models.

Nº	Short Name	Definition
1	Environmental and Terrain Conditions	Simulate vehicles and vehicle systems in terrain conditions that are much more severe than dirt roads and unprepared terrain conditions where manned systems cannot operate.
2	Run Time	Run in real time and even faster than real time to enable AI- and model-based decision-making process with or without human inputs to comply with different levels of autonomy.
3	Mission and Control	Suitable for both simulating autonomous model-based vehicle system controls and interfacing with the AI-based mission planning and implementation.
4	Energy Efficiency	Capable to adequately simulate power losses in the autonomous vehicle systems and the vehicle-terrain interaction and, hence, to assess and autonomously control vehicle energy efficiency.
5	Movement and Maneuver	Capable to simulate and assess autonomous agile maneuvering and mobility on battlefields in hyperactive conditions and in tactical and operational conditions.

6.2.2 Autonomous Mobility Assessment, Framework for Modeling, Complexity and Accuracy

Conventionally, vehicle terrain mobility is considered as the overall capability of a vehicle to move from place to place while retaining its ability to perform its primary mission. There are two major elements in the above-given definition that autonomous vehicle models should demonstrate the following features during their simulation for the purpose of mobility assessment:

a) The capability to move from one place to another place in principle; and

b) The ability to perform a primary mission/task.

To assess the vehicle capability to move in principle and the ability to perform a task, mobility assessment methods should be functional for:

a) Predicting *terrain mobility margins* of a vehicle during its motion, i.e., assessing the mobility state of a vehicle with regard to its immobilization state; and

b) Estimating *terrain mobility performance* while the vehicle still maintains certain mobility margins.

According to the above-given definitions and overall requirements to the vehicle models and mobility assessment methods, vehicle models' outputs should be considered as inputs in mobility indices to assess terrain mobility margins and mobility performance of vehicles. Autonomy in the long run should bring new qualities to the vehicle operational functioning by not only replacing a driver or a remote operator, but making autonomous vehicles safer, more agile and maneuverable, more energy efficient, and more effective in mission fulfilment. For the same purpose, autonomous mobility should be properly modeled, and computer simulated by the means of adequate mathematical models. Autonomous vehicle models should be capable of assessing the mobility of the vehicle model in real time and, thus, to facilitate adequate decisions on vehicle system controls. In this regard, this Section 6.2.2 provides a brief analysis of mobility assessment for their functionality and sufficiency in the autonomous vehicle modeling.

6.2.2.1 Mobility Margins Assessment

The mathematical appearance of the indices should be light enough to make their components easily determined and, thus, provide a potential for real-time control of autonomous vehicle applications. A set of wheel mobility indices that can satisfy these requirements is the *Wheel Mobility Index* and *Vehicle Mobility Index* [9], [10]:

$$WMI_{\mu i} = 1 - \frac{F_x}{F_{x\,max}} = 1 - \left(\frac{\mu_{xi}}{\mu_{pxi}}\right) \tag{6-1}$$

$$VMI_{\mu} = \sum_{i=1}^{n} \frac{WMI'^{('')}_{\mu i}}{2n} = 1 - \frac{1}{2n}\sum_{i=1}^{n} \frac{F'^{('')}_{xi}}{F^{max'('')}_{xi}} = 1 - \frac{1}{2n}\sum_{i=1}^{n} \frac{\mu'^{('')}_{xi}}{\mu'^{('')}_{pxi}} \tag{6-2}$$

here, $F_{xi}^{max\,'('')}$ is the maximum circumferential force determined by the gripping properties of tires, $F_{xi}^{max\,'('')} = \mu'^{('')}_{pxi} R'^{('')}_{zi}$, $\mu'^{('')}_{pxi}$ is the peak friction coefficient, $R'^{('')}_{zi}$is the wheel normal reaction, $F'^{('')}_{xi}$ is the current circumferential force of a wheel that is linked to the current friction coefficient, $\mu'^{('')}_{xi}$, $\mu_x = \frac{F_x}{R_z}$, signs $'('')$ are for the right and left wheels, and i is the drive axle number, $i = 1, n$.

In this approach, vehicle mobility is estimated by an index, which counts the mobility indices of all wheels, i.e., the method values contributions of all and every wheel. The variables in Equation (6-1) and Equation (6-2) are able to be determined and estimated in real time. Indeed, the current friction coefficient of a driving wheel can be computed from the circumferential wheel force that, in turn, results from the wheel torque and the tire rolling radius in the driven mode. This rolling radius is not constant and usually depends on the wheel normal reaction and the inflation pressure [11]. Several methods are known to determine the dynamic normal reactions of the wheels in real time; one of them is a model-based approach that involves the measurement of suspension travel characteristics [12]. The wheel torque can be obtained by integrating the wheel angular acceleration when an inverse dynamics-based control is employed [11]. For the estimation of the peak friction coefficient, an observer-based method can be used, which does not require direct measurements of this coefficient.

Index WMI_{μ} in Equation (6-1) estimates the mobility potential of a driving wheel loaded with a positive drive torque that generates the circumferential wheel force, F_x. The upper boundary of the mobility potential is established by the maximum value of the circumferential wheel force, F_x^{max}, which is constrained by the gripping properties of the tire and terrain, i.e., by the peak friction coefficient. As seen from a technical literature analysis, the peak friction coefficient is a random variable with a certain distribution [13]. Figure 6-1 illustrates a distribution of the peak friction coefficient, which stochastically changes between its minimum to maximum values. These values pre-determine the maximum circumferential wheel force that can be developed by a wheel.

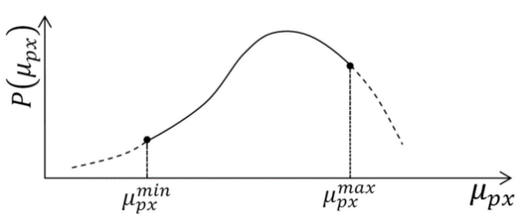


Figure 6-1: A Distribution of Peak Friction Coefficient.

When a wheel runs, both the peak friction coefficient and the current friction coefficient stochastically vary due to changes of the terrain properties and wheel dynamic loadings. Stochastic variations of the two friction coefficients are illustrated in Figure 6-2.

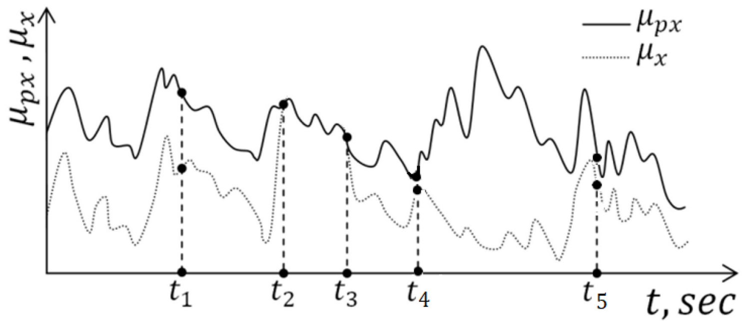


Figure 6-2: Stochastic Variations of the Peak (μ_{px}) and Current (μ_x) Friction Coefficients.

The wheel movement occurs when the current friction coefficient is less than the peak friction coefficient (e.g., at time moment t_1): $\mu_x < \mu_{px}$, and the circumferential wheel force is less than its maximum value: $F_x < F_x^{max}$. The difference $(\mu_{px} - \mu_x)$ represents the mobility margin. When the wheel and vehicle mobility indices are utilized for computational estimation of mobility margins, mathematical models of the vehicle and vehicle systems should be capable to simulate the dynamic interaction of the terrain – locomotion system with the vehicle powertrain/chassis systems that results in the parameters used in Equation (6-1) and Equation (6-2). Computational simulations can run in either non-real time or real time depending on a particular application of the vehicle and system mathematical models.

6.2.2.2 Mobility Performance Assessment

Mobility performance of a vehicle is demonstrated as a vehicle capability to move from place to place in terrain conditions while retaining an ability to perform effectively the vehicle's mission or task (e.g., a payload transportation task). In this regard, to maximize the productivity of the transportation task, the vehicle also needs to be able to operate with maximum mobility. Thus, the wheel and vehicle mobility assessment needs to combine and analyze the wheel traction with the velocity to increase and then to maximize the effectiveness of the movement, i.e., to maximize mobility. Since the wheel traction is mathematically linked to tire slippage, which relates the actual and theoretical velocities to each other, the mobility performance analysis is often based on estimating the actual vehicle velocity that could be achieved without losing mobility, i.e., while maintaining certain mobility margins. Thus, the actual vehicle velocity has always been an obvious index of the effectiveness of vehicle movement and vehicle mobility. In particular, the *average actual vehicle velocity* is an important index of vehicle mobility. In technical literature, various mathematical methods have been established to determine the average actual vehicle velocity. As an example, Equation (6-3) presents an approach to compute the average velocity using probabilities of movements, p_i, at different average velocities, v_{avg_i}, on surfaces with the resistance to motion given by the rolling resistance coefficients, f_{mi}:

$$v_{avg} = \frac{1}{\sum_{i=1}^{n} \frac{p_i}{v_{avg\_i}}} \tag{6-3}$$

The probabilities of motion at different velocities are typically determined by using the traction characteristic and stochastic changes of the resistance to motion in different terrain conditions. In simulations of vehicle movements, the average velocity of a vehicle can be obtained from the actual travel, S_a, and the time of actual motion, T_m:

$$v_{avg} = \frac{S_a}{T_m} \tag{6-4}$$

It is clear that a computational model of a vehicle should be capable of computing the time needed to cover a given travel distance with a given average velocity or with its distribution along the travel distance. In this regard, the vehicle model should allow for computing the rotational velocity of the locomotion system and the rolling radius (tire slippage). To simulate the above-listed vehicle characteristics, the dynamic interaction of the terrain – locomotion system with the vehicle powertrain/chassis systems should be modeled appropriately. Again, the computational simulations can be done either in real time or in non-real-time depending on the model application and simulation tasks. In particular, real-time and non-real-time simulations are determined by a framework that should be assigned for modeling an autonomous vehicle and its systems. The *framework for both simulations* should be established for the vehicle movement scenarios by setting up combinations of vehicle and terrain models, including:

- Different environments: simple vs. complex terramechanics.
- Structure and ability impact.
- Movement classification: Pure braking and accelerating, pure cornering at constant speed, cornering and braking and accelerating, off-road steady and transient dynamics, etc.
- Model Architecture: Single-domain vs. Multiple domains, Multi-body vs. Single body, Module based model vs. centralized vehicle architecture model (e.g., ADAS is an example of integrative approach to automation of vehicle sub-systems), Code based vs. Graphic based.
- 1-D and 3-D models.
- Physics vs. Data Based Models.

The *complexity* and *fidelity of autonomous vehicle models* that can be computed in non-real-time, real-time, or faster than real-time is determined by an appropriate/acceptable level of the accuracy and a computational time to provide autonomous control of mobility in real time. Technical approaches to modeling vehicle systems at appropriate levels of complexity and accuracy are considered in the following sections of this chapter when the models of the vehicle systems are analyzed.

6.3 VEHICLE – AI – OPERATOR INTERFACE MODELING

The outcome of this section is an analysis of approached to modeling interface between the operator model and AI-based algorithms to control vehicle steering, throttle, and brakes. The analysis does not concentrate on estimating advantages and disadvantages of the operator models, which are taken as a black box. The analysis is mostly concerned with the interface that should be present in any operator model to get it linked to autonomous vehicle models with various degrees of autonomy.

Different levels of autonomy require different types of information (feedback, data) that is of relevance to/between the driver/operator, vehicle models and the AI system. The role of the interface (whether with a human-in-the-loop or simulation models) is to facilitate this process ensuring relevant and accurate date data/feedback (driver/operator-to-vehicle state, AI-to-driver/operator in the shared control case and vice versa) is communicated across, depending on the level. A generic overview of the interface and flow of information between these components is illustrated in Figure 6-3.

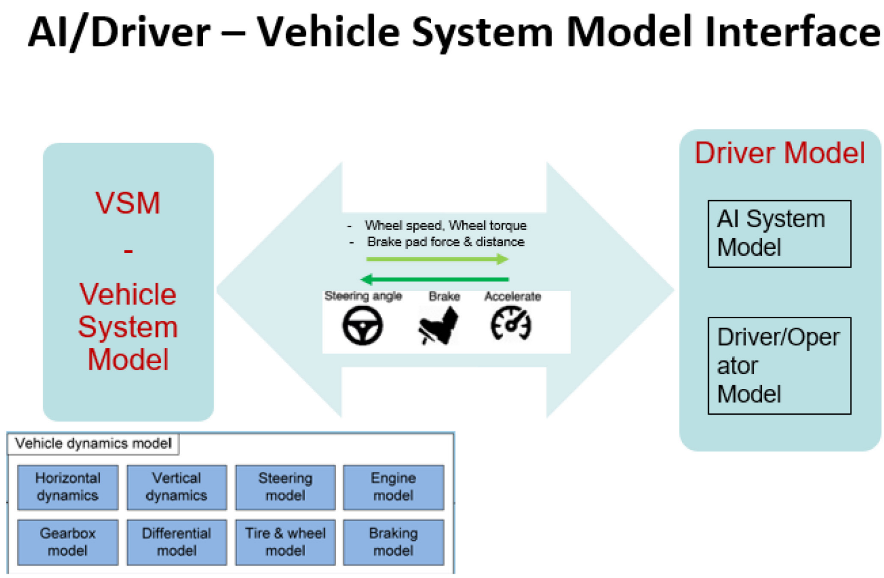


Figure 6-3: Generic AI/Driver Vehicle System Model Interface.

6.3.1 Shared Control

With a human-in-the loop system, the interface incorporates driver/operator, vehicle, and environment data with user interfaces to act as a communication medium between the driver and autonomous systems. One of the major difficulties particularly with semi-autonomous systems is the interaction with the human driver, as there is often disparity between how the system functions and how the human expects the system to perform. The User Interface (UI) must satisfy the following criteria:

- Meet the expectations of the driver:
  - Avoid mode confusion by displaying the correct data for a given driver state (i.e., provide the drivers insight to the autonomous system's intent without overloading them with unnecessary information) [14].
  - Display concise and informative data.
  - Present information in a user-friendly manner.
  - Accommodate driver/operator-autonomous (AI system) handover.
  - Accommodate communication delays.

In a similar manner modeling of such an interface would have to consider and include framework of simulating some of these situations. Furthermore, the modeled interface would have to accommodate different modes for different levels of autonomy, different vehicle and driver/operator models, as shown in Figure 6-4 presenting high-level principles of shared control and as it applies to different vehicle models as well. How to verify and validate these interfaces still remains an open research question [14], [15].

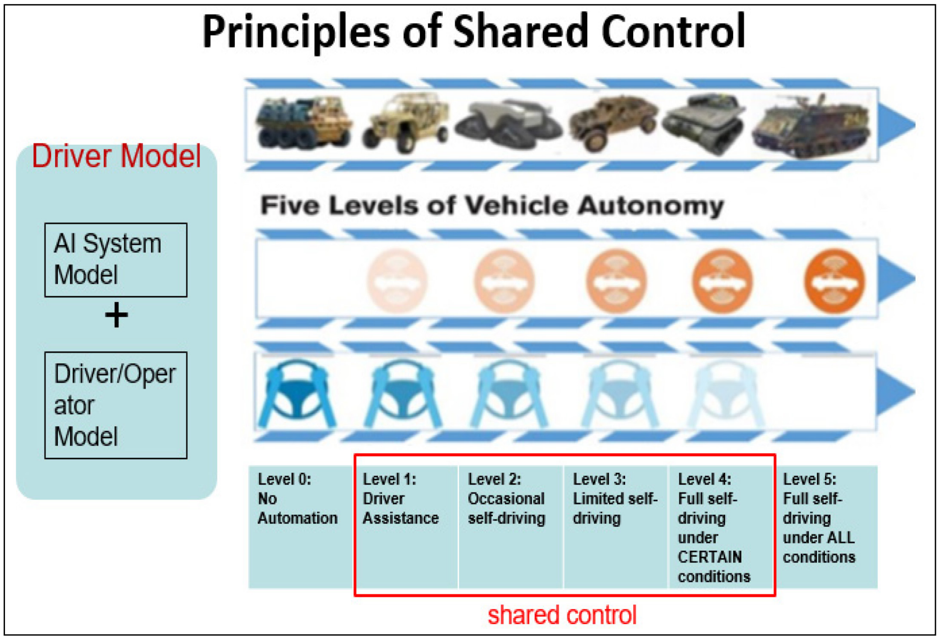


Figure 6-4: Principles of Shared Control.

According to literature, another Human-Machine Interface (HMI) in the area of shared control challenges is at level 3 and 4 automation. Figure 6-5 illustrates some of the parameters or data interchange required at some of these levels between the driver/operator and AI navigation system for shared control. The driver/operator and AI system need to have a mutual understanding; otherwise, they will not be able to grasp the intensions of each other [16], [17]. This prompted research and development interest in AI-Driver/Operator Handover systems [14], [15], [16].

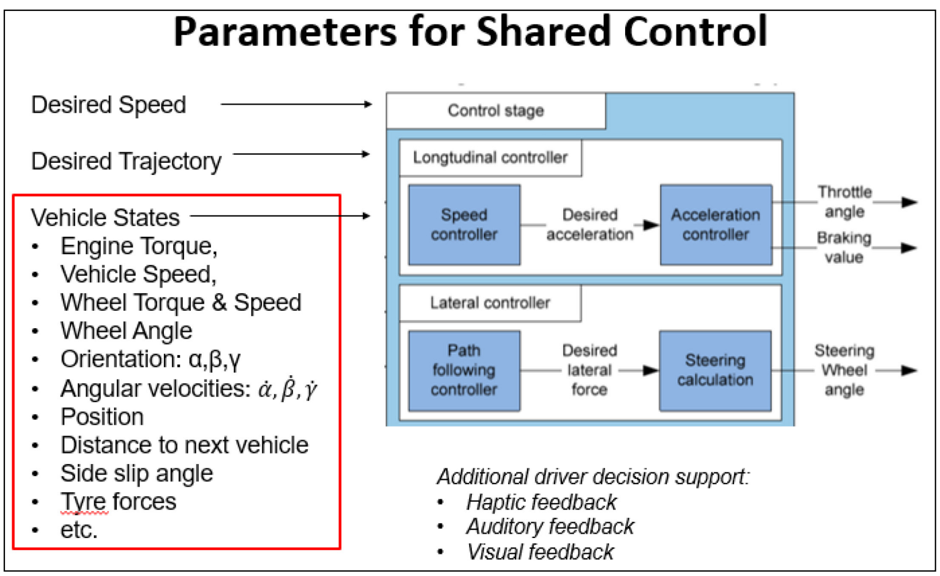


Figure 6-5: Some of the Parameters Inputs and Outputs for Shared Control.

6.3.1.1 AI-Driver/Operator Handover

Some of the research efforts related to the topic of AI-Driver/Operator handover in shared control of semi-autonomous driving includes Gold and Bengler [18], who defined a generic procedure for take-over situations in which: System boundaries are defined and when the autonomous system detects these, it requests the driver/operator to take-over via a Take-Over Request (TOR). As soon as the driver gazes on the traffic scene, the self-driving automation or on-board AI system is shifted to manual driving within a transition area that begins when the driver/operator starts to steer. The time period between the TOR and the moment when the vehicle reaches the system boundary is called time budget. As a consequence of autonomous driving, drivers/operators tend to engage in non-driving related tasks and thus should be considered to be “out of the loop” [19]. It has been shown that with shared control, distracted drivers/operators are capable of taking-over control within a time budget of 4 to 8 seconds, depending on the complexity of the situation [20]. If drivers/operators are provided with a longer time budget, they brake less and intervene later [21]. Furthermore, the length of the time budget has an impact on the error rate – drivers/operator make less errors in take-overs with a larger time budget [20]. Damböck et al. [20] undertook a study in which it was also discovered an impact of the varying time budgets on the driver/operators’ perceived comfort during the take-overs.

Walch et al. [22] investigated the feasibility of car-driver/operator handover assistance in autonomous driving. The evaluation in this study showed that car-driver handovers prompted by multimodal (auditory and visual) warnings are a promising strategy to compensate for system boundaries of autonomous vehicles. The study presents a generic handover framework from full automation to manual driving as illustrated in Figure 6-6. While the system sends out an alert along with the reason for system behavior, it interrupts secondary tasks and starts deceleration. After the system has gained the driver’s attention, it can request them to take over. Finally, the handover of control can proceed. Should the driver/operator not take over, the autonomous system has to manage the situation on its own. There may be different de-escalation strategies that can be implemented depending on the situation, e.g., driving at a lower speed, or an emergency stop on the side of the road.

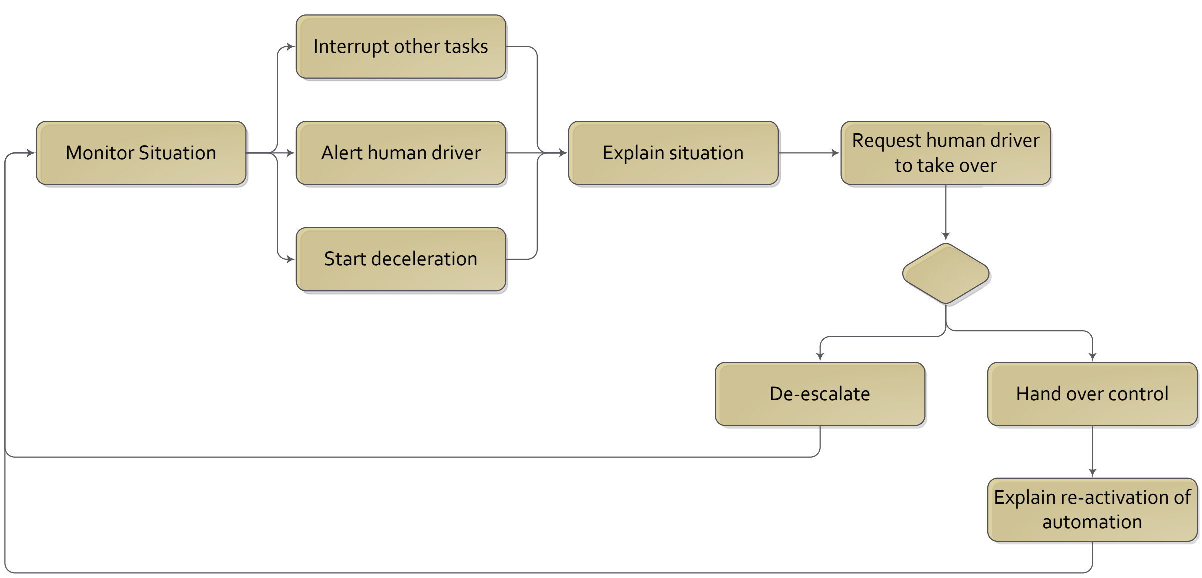


Figure 6-6: Procedure of a Generic Handover Process from Full/Semi-Autonomy to Manual Driving [22].

Examples of the different possibilities for the implementation of the actual handover of control can include [22]:

- **Immediate Handover:** Complete shift of control from one second to the other, e.g., when drivers grasp the steering wheel.
- **Stepwise Handover:** Control is handed over step by step, e.g., first longitudinal control followed by lateral control, or vice versa.
- **Driver Monitored Handover**: Drivers monitor the system behavior, e.g., by grasping the steering wheel (force feedback). After a certain period of time (countdown), the control is handed over.
- **System Monitored Handover:** The system monitors the inputs of the driver for a certain period after the handover. In cases wherein the driver input may result in an unsafe situation, e.g., too harsh braking that threatens to result in a rear-end collision, the system can adjust the inputs.

6.3.2 Possible Direction for RTG that Utilizes Technology-Based Approach

- Vehicle sensor and observer information processing in decision-making.
- Interface between autonomy/environment sensors and vehicle sensors.
- Interaction between the higher and lower levels of control (autonomous vehicle dynamics control and autonomous vehicle system control).
- VSM only concerned with the data it needs to supply outputs received from the Controller (AI-Driver/Operator) model. Therefore, data formats (e.g., should be in the format expected by the controller) and timing of the signals should be considered.
- How VSM handles the demands/requirements for low-level to high-level/advanced controllers in the different levels of autonomy. Modifications required for/from the VSM when dealing AI-based controllers (but maybe the current VSMs are already able to or dealing with such), which would not warrant any further exploration.
- Human Driver Models for validation purposes.
- Simulation requirements for hand-over strategy (in shared control) from the VSM.
- Consider delays in taking-over in shared control.
- Consider faster than and slower than real-time (i.e., independent of real-time) in this area.
- Interface Standards if any.

6.4 VEHICLE DYNAMICS MODELING

A vehicle dynamic model needs to adequately represent the system response and resultant mobility achieved over varying terrain and conditions. Mobility models range from the Two-Dimensional (2D) bicycle model through to the three-dimensional Multi-Body-Dynamics (MBD) model with selected components being represented by simple finite element models commonly called flex-bodies. The high fidelity, more complex models require exponentially longer computational solving times. A conventional vehicle system generally comprises a power source, a transmission, a drive line, various reduction gearboxes located either within the drive line system or within the wheels and tracks. In most vehicle models the body is modeled as a rigid mass with inertia which is generally suitable for military vehicles that are hardened for protection, however, for vehicle systems which have thin-walled bodies such as commercial passenger vehicles this assumption may not be acceptable. In some military vehicles where a separate chassis is used, a flexible body model of the chassis may be needed to address the effects of compliance of the chassis on the vehicle response. Multi-Body Dynamics (MBD) formulations can be categorized into two main groups, based on the set of coordinates used to describe the state of the system.

The *Cartesian coordinate* formulation – also known as global approach, or full coordinate approach – uses a set of coordinates that can independently define the position and orientation of each body, with algebraic constraints introduced to model joints and other body connections. The resulting Equations Of Motion (EOMs) typically take the form of so-called Differential Algebraic Equations (DAEs), are relatively easy to assemble, and are characterized by a large number of redundant states and very sparse data structure. On the other hand, the *relative coordinate* formulation – also known as topological approach, or recursive approach – uses a minimal set of coordinates which correspond to degrees of freedom in the mechanism joints. For open-loop mechanisms, the EOMs take the form of Ordinary Differential Equations (ODEs). The presence of closed loops, a common occurrence in ground vehicle models, can be treated with various approaches (e.g., cut-joint or cut-body) and implies the introduction of algebraic constraints and hence a DAE representation. Salient features of these formulations include a significantly more complex process for assembling the EOMs which typically involve recursive traversals of the mechanism topological graph, a small (effectively minimal) number of states, and dense data structures and matrices. In general, except maybe for efficiency considerations, a particular choice of MBD formulation is not expected to be dictated by the type of ground vehicle – conventional or autonomous – being modeled. It is much more likely that the modeling choice in any given simulation package will be guided by other considerations.

Selection of a particular formulation takes into account many factors, especially for MBD simulation tools that are general purpose and not tailored specifically to vehicle systems. Such considerations take into account ease of modeling and extensibility, ability to include additional physics, ease of interfacing with external tools, etc. Important considerations relate to efficiency of the solution scheme, including problem size, problem type (DAEs vs. ODEs), choice of integration and solver (linear and/or non-linear) techniques. Finally, this choice is dictated by the actual computer implementation adopted and the use of techniques such as automatic differentiation, sparse linear algebra, and parallelization methods, as well as the hardware platform targeted. In general, an accurate mathematical model of a vehicle would incorporate body flexibility. This is especially true for off-road multi-wheel vehicles with long frames operating on unprepared terrains.

However, following the precept that a model should not be more complex than necessary for the particular application at hand, it is expected that flexible body dynamics in (conventional or autonomous) vehicle mobility assessment may need to be considered only for very specific components, such as tires and flexible (rubber) tracks, which are characterized by large displacements and large deformations. Common approaches to accommodating flexibility in multi-body dynamics include simplified lumped-parameter models, as well as various formulations based on the Finite Element Method (FEM). Special FEM formulations appropriate in this context must account for the large relative motions that occur in multi-body systems and for the possibility of large deformations of the flexible bodies (as in the case of a deformable tire model). A requirement of flexible body formulations in multi-body applications is that they must not exhibit any strain when undergoing rigid body motion. There are three formulations often used in such applications that are mentioned below.

The *Floating Frame Of Reference* Formulation (FFRF) is a common FEM-based approach in which large relative body displacements and rotations are described using a moving non-inertial reference frame and deformations of the finite elements are described relative to this reference frame [23]. The main advantage of the FFRF lies in the simple definition of the strain energy and in the possibility of reducing model complexity through modal reduction techniques [24]. On the other hand, this formulation leads to a complex definition of the kinetic energy due to the coupling between inertial and non-inertial reference frames; as such, inertial force terms and quadratic velocity-dependent terms must be explicitly taken into consideration and the system generalized mass matrix is non-constant. Furthermore, the FFRF has the same challenges as full-coordinate MBD formulations in terms of selecting parameterization of rotation.

The *Large Rotation Vector* Formulation (LRVF) employs positions and rotations as nodal coordinates and uses two independent interpolations for its finite elements, one for the position field and the other for the rotation field [25]. Elements based on LRVF also lead to a non-constant generalized mass matrix which, combined with the complexities stemming from the rotation parameterization and interpolation, makes them relatively computationally intensive.

The *Absolute Nodal Coordinate* Formulation (ANCF) is a FEM-based approach specifically developed for use in multi-body systems [26]. In ANCF, all generalized coordinates are defined in the global inertial reference frame and no rotation parameterization is explicitly used, instead relying on position gradient vectors to describe rotation. These characteristics of the ANCF result in a constant generalized mass matrix and vanishing of quadratic velocity-dependent terms. While these features have a positive impact on computational efficiency, the ANCF formulation has the drawback that, while the description of kinetic energy is very simple, the internal elastic forces are highly non-linear and potentially expensive to evaluate. Furthermore, ANCF-based formulations using full three-dimensional elasticity are known to suffer from so-called locking issues (caused, for example, by the inability of the element to reproduce exact deformation shapes resulting in artificial stiffening) [27]. Locking-alleviation can be addressed using various numerical techniques or else by employing higher-order derivatives as additional nodal coordinates [28].

In general, the choice of including body flexibility in multi-body simulations is primarily dictated by the balance between the necessary/desired accuracy for a given type of analysis and the ensuing (potentially significant) increased computational effort. As already mentioned, for vehicle modeling in the context of mobility studies, inclusion of flexibility is expected to be necessary only for specific parts of the model and only for certain types of scenarios. Even in these cases, other less computationally intensive approaches (such as simplified lumped-parameter models or phenomenological models) may very well provide the level of accuracy necessary for useful mobility predictions. Either way, it is not expected that modeling conventional or autonomous vehicles is a deciding factor on including flexible dynamics in the vehicle models or, if included, on the choice of flexible body formulation. As a significant component of real-time mobility control technologies, real-time computer simulation methods of vehicle dynamics have been in the development for a long while. In technical literature, a real-time simulation is usually defined as an imitation of the operation of a real-world process or a system, in which the system's resulting performance depends not only on the adequacy of the mathematical model and computational accuracy of the system's states, but also on the time period required to produce computational results. A real-time simulation should demonstrate characteristics of synchronization, timing, predictability, robustness and fault tolerance. The listed characteristics needs to be analyzed as a property of both vehicle dynamics models and a software product that is used for computer simulations.

6.5 MODELING OF INTERNAL COMBUSTION ENGINES

An engine model needs to be chosen to adequately simulate vehicle mobility. The engine model will have to serve two primary purposes: provide torque to power the drive train and report the amount of fuel used during operation. Models can be chosen to simulate a wide range of complexity and fidelity. The most sophisticated could consider all mechanical components (pistons, valves, crank shafts) and combustion modeling, and the least sophisticated could be look-up tables based on empirical measurements. While different applications could require different modeling fidelity levels, simple empirical models are generally adequate to model mobility performance of a vehicle, so sophisticated multi-body or combustion models are not considered for this initiative. Empirical models can generally be simulated very efficiently, since they are a single table look-up for a given throttle position and engine RPM state. An example of such a table can be seen in Figure 6-7.

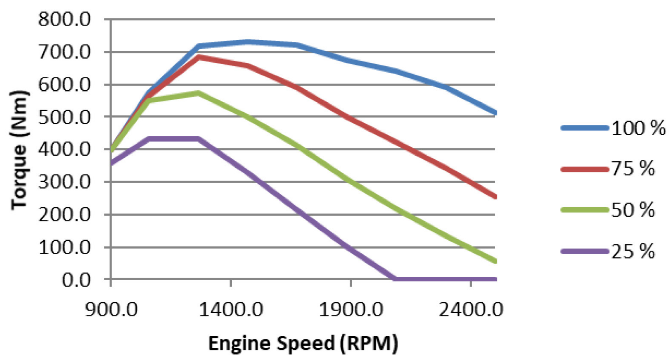


Figure 6-7: Sample Engine Torque Table at Various Throttle Positions.

The simplest of these models might include only the maximum torque available at full throttle for the RPM range of the engine. But if efficiency and fuel economy are to be considered, the model must also include fuel efficiency data, and performance data for the full range of throttle positions as well. The engine inertia and reaction times are of importance to enable control effects of autonomous vehicles to be simulated. While simple models based on maximum torque available provide accurate steady-state torque, transient effects can be significant and important in many modeling scenarios. Models may need to consider inertial effects of the engine crank shaft and flywheel, and lags in torque due to response times of the fuel and air supply systems. It is not expected that the modeling fidelity requirements for engines will differ significantly between autonomous vehicle and traditional vehicles. However, simplicity and fast simulation are particularly important for autonomous vehicle simulations in order to perform a large number of trials. Many modern autonomous vehicle control systems make use of engine CANBUS data. This requirement is addressed in Section 6.12 as on-board autonomous sensors. The engine model should ensure that data provided by the vehicle system CANBUS is drawn from the engine performance and partial load maps.

6.6 MODELING OF DRIVETRAIN

6.6.1 Terms and Definitions

The primary function of the drivetrain is to:

- Change the torque and speed of one or more power sources (which can be internal combustion engines, ICE, or electric motors, EM) at the driving wheels of wheeled vehicles or drive sprockets for tracked vehicles.
- Distribute mechanical power to electric generators, which convert it in electric power that can be stored in a battery.
- Reverse the direction of motion.
- Redistribute power between the driving wheels and sprockets depending on conditions of movement.

Components of the drivetrain can comprise one or more of the following components arranged in a tree-like configuration from one or more power sources to the driving wheels or sprockets:

1) Mechanical couplers (to couple the further-listed components to each other and to the power sources);
2) Main clutch;
3) Torque converter;
4) Gear box or transmission (gear boxes integrated with turning mechanisms in tracked vehicles);
5) CVT (Continuous Variable Transmission);
6) Transfer case;
7) Open differentials, locking differentials, limited slip differentials, etc.;
8) Final drive gear sets (to re-direct the power flow from the longitudinal direction to the lateral direction of the vehicle);
9) Geared wheel hub (gear sets installed in the wheel hub);
10) Simple and telescopic drive shafts, axle shafts;
11) U-joints and double U-joints;
12) CV-joints;
13) Electric Generator (EG); and
14) Electric Motor Generator (MG). An MG can be a power source or a generator (which converts the rotary mechanical power to electric power).

A part of the drivetrain, which is located between the output shaft of the transmission and the driving wheels, is named the driveline (see more in Section 6.6.3).

6.6.2 Torque Converter and Transmission

A torque converter is used to transmit power from the engine shaft to the transmission shaft either by initially dynamically multiplying the engine torque and then by rigidly coupling the engine and transmission shafts. The torque converter is a critical element in the automatic driveline, and it affects the vehicle's fuel consumption and longitudinal dynamics. The fundamental purpose of the torque converter is to dampen the driveline vibrations as it is a fluid coupling that connects the engine to the transmission and vehicle. The torque convertor also will not stall the engine if matched correctly and enables an almost correct match torque-speed characteristic for the vehicle system. Generally, a torque converter may have three components: the impeller or pump, the stator, and the turbine. The pump side of the torque converter loads the engine and rotates at its speed. It pushes the fluid to the turbine side and rotates it. The turbine finally drives the load. The fluid is recirculated back to the impeller through the stator which guides it appropriately. The torque converter operates under two modes, converter and fluid-coupling. In the converter mode, the pump and turbine operate separately, while in the fluid coupling mode, the pump and turbine are locked down and rotate together. The torque convertor generates inertia which differs for each mode and affects the model response times. The locking and un-locking is normally governed by speed ratio and gear number. Lock-up starts when the stator starts to rotate and lock-up is when the torque convertor components are mechanically linked. The lock-up and un-lock control schedule is required and can be defined as percentage of Wide Open Throttle Torque and either engine speed, speed-ratio or turbine speed. The torque converter model should be able to capture both transient and steady-state characteristics in terms of the coupling between the engine and transmission through the torque converter. All operating modes should be included in the model. The basic input signals to the torque converter are the engine output shaft torque and rotational speed, the output signals of the torque converter are the torque and rotational speed that will be served as the input signals to the transmission. The basic assumption for the autonomous vehicle is that an automatic transmission is used for the vehicle. The transmission is used to vary its input torque, speed and the direction from the torque converter by changing the transmission ratios and enables the vehicle to start with a high torque. An automatic gearbox, or automatic transmission system, is a gearbox which, after switching on the gear, does not require manual switching. The transmission model is usually composed of planetary gears and clutches. Control logic for the clutches can be modeled as a state machine. There are three widely used methods for modeling automatic transmissions, namely algebraic equation method, lever analogy, and matrix methods. While the first two are handy for transmissions with fewer (one or two) number of planetary gear sets, the matrix methods are prioritized for larger transmissions. Some vehicles may have a connecting or drop-down gearbox between the engine and torque convertor. These should be included as part of the transmission system model. This gearbox introduces additional inertias and losses. As with conventional vehicle models the accessories that absorb engine generated engine power must be accommodated in the model. These include alternators, power steering, air conditioner, in-line generator, etc. Each of these sub-systems have efficiencies and inertias that affect both available engine power for mobility and response time of the system to control inputs.

6.6.3 Modeling of Driveline

The main function of the driveline is to distribute power between the driving wheels and to change the torque and speed that goes from the transmission via the transfer case and the final drive gear sets to the driving wheels. The driveline system is comprised of power-dividing units and other gear sets installed in the transfer case and drive axles and connected by shafts and joints. A Power-Dividing Unit (PDU) is a mechanism with one input and two outputs, which splits the input power between the two outputs. Figure 6-8 illustrates major types of PDUs that are utilized on wheeled vehicles and some tracked vehicles.

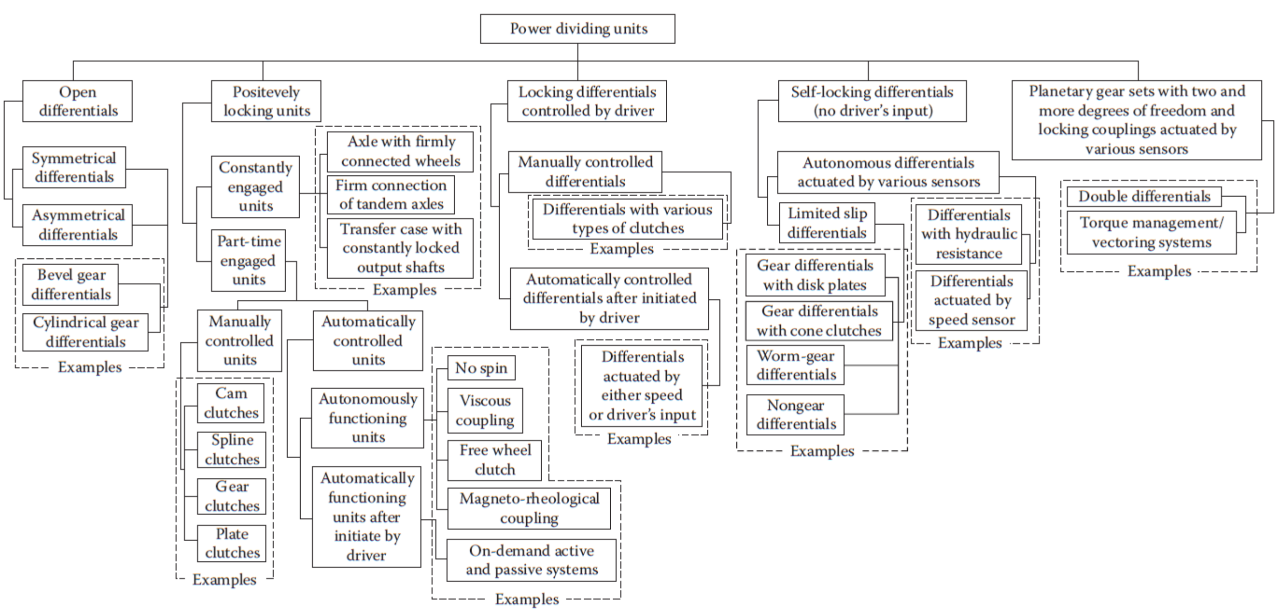
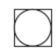
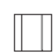


Figure 6-8: Major Types of Power-Dividing Units [29].

Table 6-2 presents graphical designations of various power-dividing units. By comprising different PDUs, driveline systems with different characteristics of power distribution between the driving wheels can be arranged. The number of PDUs in a vehicle with an axle-type configuration is the number of the driving wheels minus unity. For example, 4x4 vehicles with 4 driving wheels have three PDUs, and 16x16 vehicles – 15 PDUs. Conditionally, all combinations of various PDUs can form three types of driveline systems shown in Figure 6-9, including simple, combine, and integrated driveline systems.

Table 6-2: Graphical Designations of PDUs [29].

Mechanism in PDU	Designation
Symmetrical open (free) differential	
Symmetrical locking differential	
Asymmetrical open (free) differential	
Asymmetrical locking differential	
Symmetrical limited slip differential	
Asymmetrical limited slip differential	
Symmetrical differential with viscous or rheological clutch	
Asymmetrical differential with viscous or rheological clutch	
Overrunning self-locking differential (similar to NoSPIN)	
Automatic engagement/disengagement of one of the output shafts (e.g., on-demand systems)	
Freewheel (overrunning) clutch	
Constantly locking engagement of the output shafts	
Nonconstant engagement with manual disengagement of one of the output shafts	
Torque vectoring (torque management) device based on planetary gear sets with two and more degrees of freedom and locking couplings/mechanisms	T

Notes:

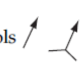
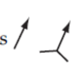
1. Intelligence symbols  (SAE J1952 Standard) may be added to the basic symbol to indicate that the PDU responds automatically to signals from one or more external control systems.
2. Additional abbreviations explains  symbols. Examples: AL/AS, antilock and antispin brake; IA/IW, interaction between interaxle and interwheel PDUs. The following abbreviations describe an interaction between driveline system (DL) and other vehicle systems and sensors: DL/DT, drivetrain (engine and transmission) system; DL/ST, steering system; DL/SS, suspension system; DL/BR, brake system; DL/LoA, longitudinal acceleration sensors; DL/LaA, lateral acceleration; DL/YAW, yaw (rate) sensors; DL/RO, rollover sensors.

Figure 6-9 shows diagrams of 4x4, 8x8, 12x12, and 16x16 vehicles with different sets of PDUs in the drivelines.

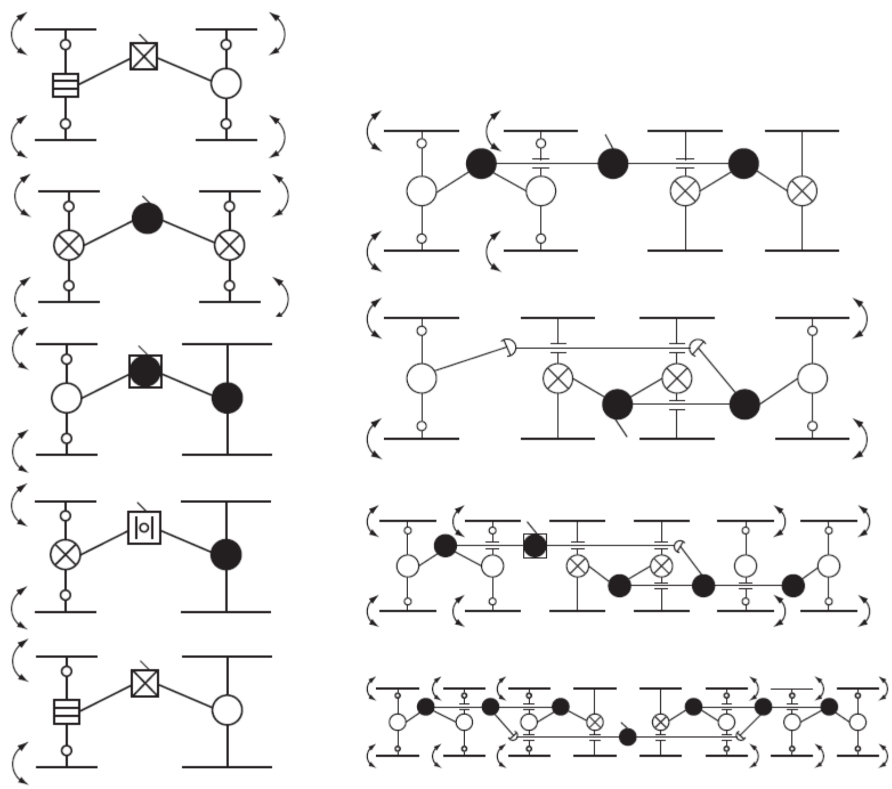


Figure 6-9: Diagrams of Various Driveline Configurations [29].

Figure 6-10, Figure 6-11 and Figure 6-12 give examples of some driveline schematic diagrams as components of drivetrains and powertrains.

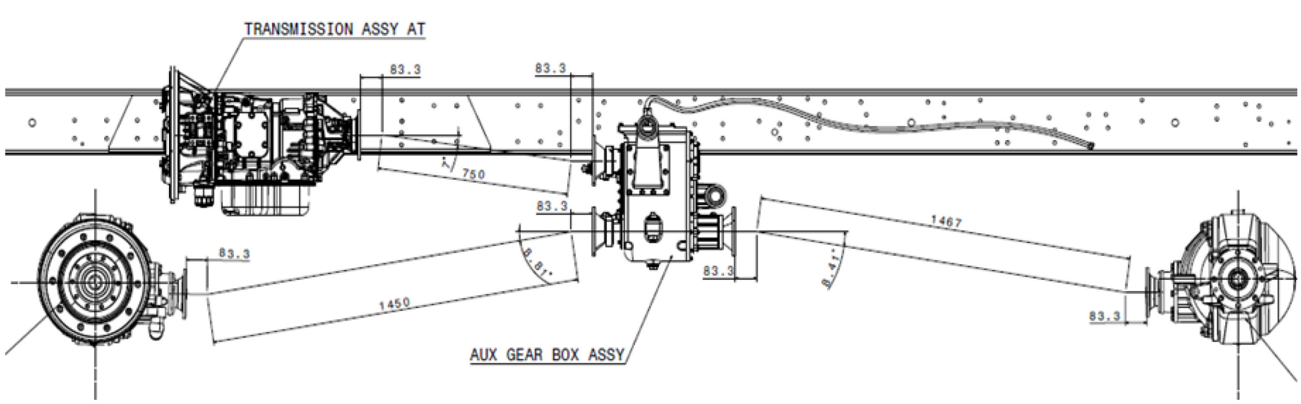


Figure 6-10: 4 Vehicle Drivetrain.

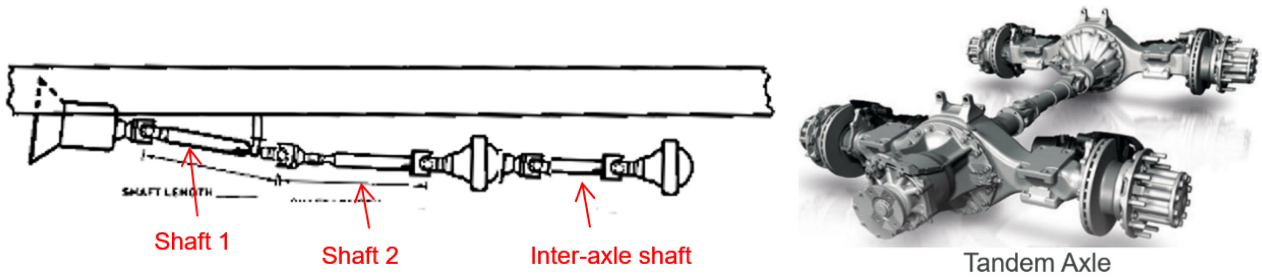


Figure 6-11: 6x4 Vehicle Drivetrain with a Tandem of Two Axles.

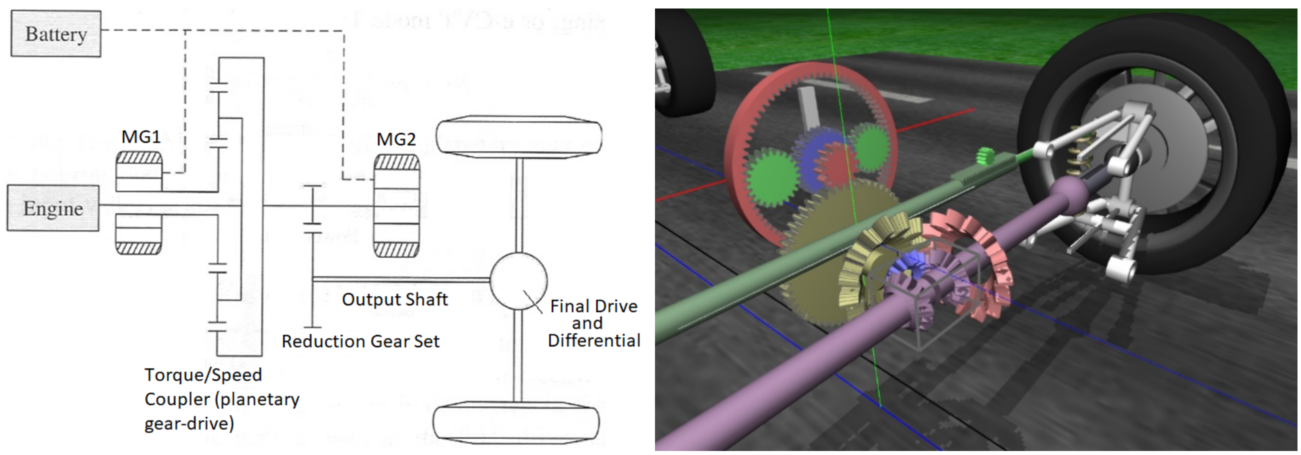


Figure 6-12: Powertrain of a 4x2 Series-Parallel Hybrid Vehicle with a Mechanical Speed/Torque Coupler and Two Separate MGs.

The main requirement of modeling drivelines of conventional (with a driver) vehicles and autonomous vehicles is that driveline models should be based on a mathematical method(s) that is capable to effectively model characteristics of various power-dividing units. The PDU characteristics mathematically link the torques and rotational velocities at the two output shafts of a PDU. The characteristics of PDUs may vary in time depending on vehicle maneuvers and terrain conditions. PDU characteristics can be influenced by the input torque, by the difference of the output torques and the rotational velocities at the output shafts. In some PDUs, the characteristics are dependent of the tire-terrain longitudinal stiffness, the rolling radii of the vehicle tires in the driven rolling mode (i.e., at zero wheel torque), and the gear ratios between the transfer case and the drive axles, which can be either controllable or non-controllable [29]. The number of PDU characteristics is obviously equal to the number of PDUs, which is one less than the number of the driving wheels. For example, in a 4x4 vehicle, three characteristics of three PDUs provide three equations, which being solved together with the equations of vehicle motion allow for determining the torques at all four wheels.

In the simple and combined driveline systems (see Figure 6-13), the PDU characteristics can have open-loop controls, e.g., a torque bias factor that depends on the input torque (employed in some limited slip differentials with disk clutches and springs). In some simple and combined drivelines, a time meter can be used, e.g., to keep a differential locked for a certain time period. In the integrated drivelines (see Figure 6-13), the PDU characteristics can change depending on signals of sensors in the steering system, the yaw sensor and the lateral acceleration sensor, sensors in brake mechanisms (indicating if a brake is engaged), the wheel rotation sensors, and the suspension travel sensor. The integrated driveline systems are most likely candidates for the employment at autonomous vehicles with autonomous controls of the power split between the driving wheel to improve vehicle terrain mobility, maneuverability, and energy efficiency. Thus, there should be an interface model between the virtual signal of a sensor model(s) and the models of the PDU characteristics. The modeling of the PDU characteristics does not require much computational power and the characteristics can be simulated in real time. The real-time modeling of the above-listed sensors that interface with the PDU characteristics needs to be accomplished at a level of fidelity that does not compromise the power distribution between the wheels. The adequate level of fidelity can be determined by comparing the wheel torques computed in non-real-time and real-time simulations.

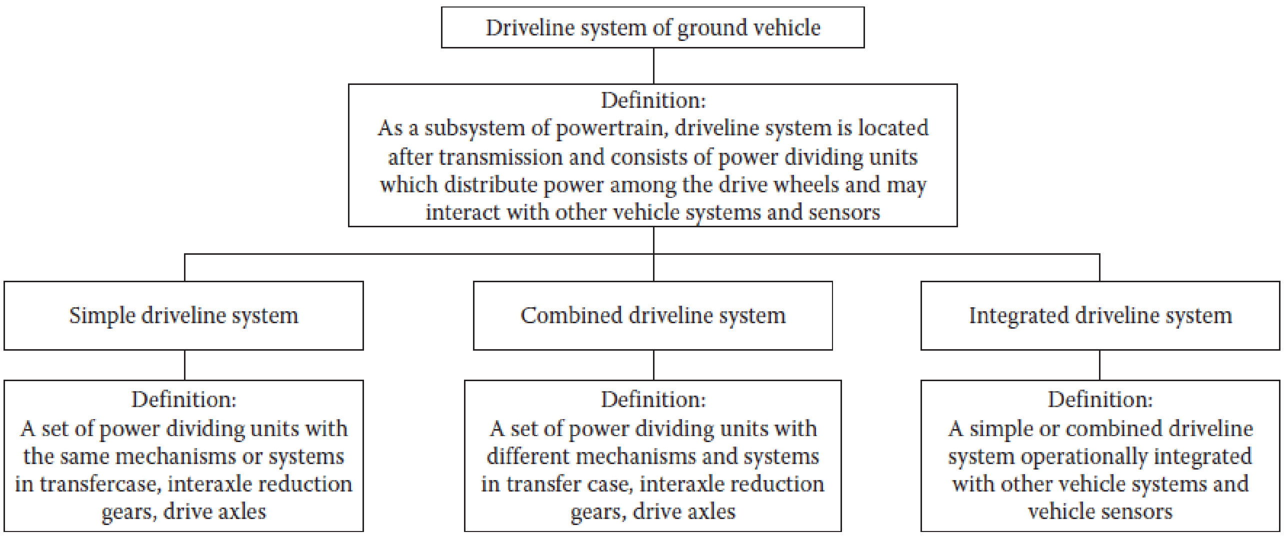


Figure 6-13: Simple, Combined, and Integrated Driveline Systems [29].

The U-joints, CV-joints, shafts, and the drive axle housings with PDUs and other gear sets require adequate modeling of their inertia and friction in the joints, splines and bearings, which influence the normal movements of the unsprung masses and, thus, impact the dynamic normal reaction at the wheels, the reactive moment that redistribute the weight between the wheels, and the vibrations of the sprung mass. The fidelity of the model depends on the purpose of an autonomous vehicle. For autonomous battle vehicles, the absorbed vibrations power and peak accelerations of the sprung mass should be high to guarantee a required lethal capability of the vehicle (e.g., a small roll angle of a vehicle can result in a 100 m and more lateral deviation of the bullet from a target that is about 500 m far from the vehicle). Figure 6-14 illustrates a multi-body diagram that can be used to study the driveline rotational dynamics. The number of rotational masses (i.e., the fidelity level of the model) is determined by the purpose of a research study. The model should have all masses included for studying resonant rotational velocities and excessive torques in the driveline itself and supporting frame structures to predict their durability and fatigue/reliability. When modeling vehicle performance, mobility and maneuverability, the multi-body diagram in Figure 6-14 can be reduced to a smaller number of rotational masses without much loss of accuracy and, thus, saving computational time. In real-time simulations of autonomous vehicles, the multi-body rotational dynamics can be compensated by including the rotational inertia factor as a multiplier of the linear acceleration of the vehicle. The rotational inertial factor represents the impact of the rotational inertia of the powertrain and the wheels on the vehicle linear acceleration.

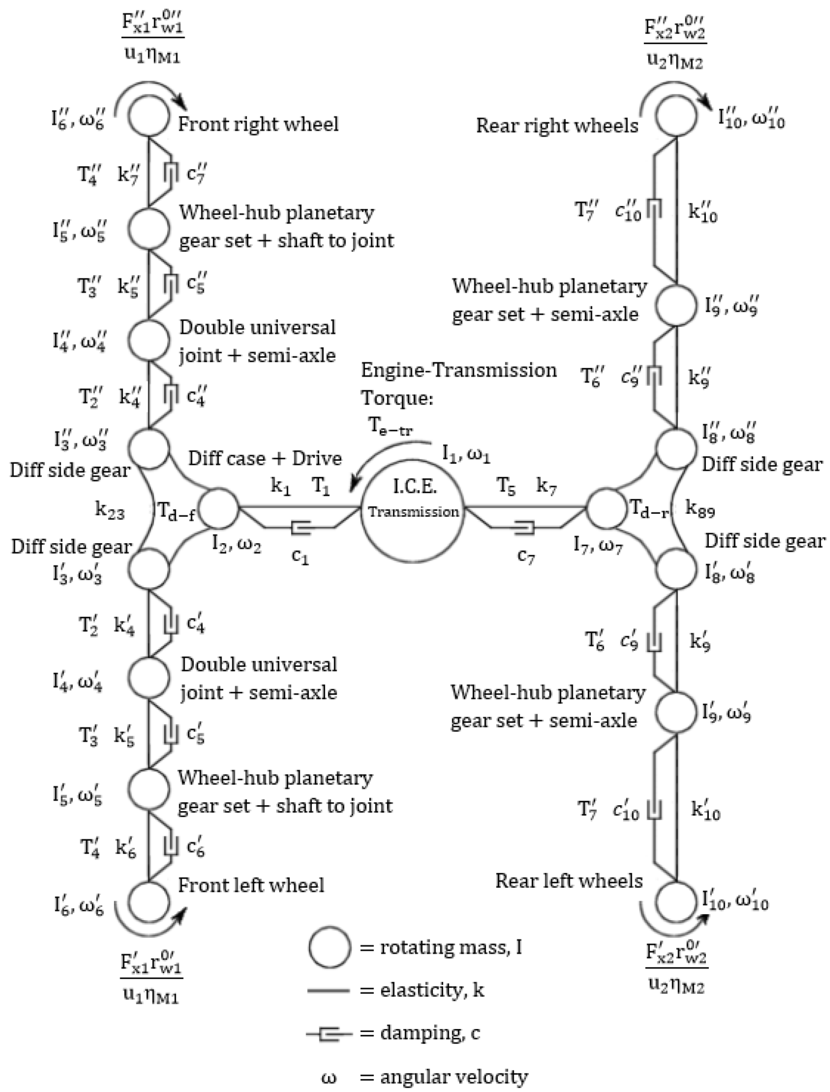


Figure 6-14: Diagram of a 4x4 Vehicle Driveline to Study Rotational Multi-Body Dynamics.

To summarize Section 6.6, the models of the drivetrains of autonomous vehicles can be grouped as follows:

1) **Very high fidelity detailed models of sub-components and parts.** These models can be developed as finite element models of the various solid parts such as gears, shafts, and bearings along with detailed modeling of the contact geometries and effects of fluid flow such as lubrication or flow inside torque converters.

2) **Multi-body dynamics models of sub-components and parts.** In these models each part is modeled as rigid body which is connected to the other rigid bodies using joints or contact. Compliance effects can be incorporated into the joint and/or contact models.

3) **Zero or one dimensional analytical algebraic and differential algebraic equations models of sub-components.** These drivetrain models can be integrated with vehicle dynamics models by using a block diagram/transfer function approach.

The computational power requirements decrease significantly from type 1 to 3 model. As the above-given analysis showed, mathematical models of autonomous vehicle mobility can integrate elements of types 2 and 3 models. This approach would allow for real-time simulating the drivetrain that might be needed for using the models in on-board real-time models for mobility assessment and controls.

6.7 MODELING OF ELECTRIC AND HYBRID-ELECTRIC DRIVES

Electric and Hybrid-Electric vehicles have been used in the military for decades [30]. Electric and hybrid-electric drives offer advantages of better integrated design (reduced or removed drive lines), lower mechanical complexity with reduced noise, and greater efficiency over mechanical systems and enhanced traction control.

Electric and hybrid-electric drive vehicles differ primarily in terms of the energy source, for electric drive it is an on-board power storage typically batteries fuel cells whereas hybrid-electric vehicles use an on-board mechanical power generation source that must be converted to electricity. Electric and hybrid-electric drives directly influence the design of the suspension and steering systems but can be accommodated in multi-body-dynamics. Electric drives provide additional vehicle control capabilities vested in the power and electric motor controllers and software.

Currently hybrid-electric and electric drives are becoming common in commercial vehicles however their broad application in military environment has not materialized. Military research into hybrid and full electric drives has accelerated in the 1990's due to rapid improvements in electric motor technology including the motors, power electronics and in particular Isolated Gate Bipolar Transistor), magneto-dynamic storage. Electric drives provide advantages in delivery of power to the locomotion system; however, they have a direct impact on the suspension and steering systems. For electric drive and series hybrid-electric drive vehicles the motors can be placed within the wheel hubs and thus add bulk and weight to the un-sprung mass but provide lower drive line losses.

The modeling of hybrid-electric drives can be incorporated quite easily into existing vehicle dynamics models through the substitution of the appropriate power and loss models within the drive train and locomotion system models. Modeling of the electric vehicle control's is not as simple as it is critical for autonomous vehicle modeling in how the autonomous vehicle driving strategy will use the capabilities offered by electric and hybrid-electric drive systems competent to execute the autonomous driving strategy in addition to the various standard vehicle and autonomous control system sensor inputs and outputs.

Most of the approaches and key aspects to modeling noted previously regarding vehicle system modeling remain valid. Modeling is a critical step not only in terms of vehicle system performance but also in designing the system by ensuring the correct match of components in terms of efficiencies, power supply, power usage etc.

6.7.1 Modeling of Electric Drives

Electric Drive systems are drive solutions that are completely electrically implemented and therefore do not draw any energy from a combustion engine at all. In addition to the electric motor and various drive components, all electric drive systems mainly consist of an electrical energy store – in most cases, a battery is used, but supercapacitors and fuel cells are also possible here. The inverter, which is located between the energy store and the electric motor and which always supplies the electric motor with the current frequencies adapted to the particular driving situation, is of central importance – this is also the essential efficiency advantage of electric motors over internal combustion engines. In combination with high-performance inverters, electric motors can achieve extremely high efficiency levels of well over 90%. Electric drive systems can be either be directly mounted on the locomotion system such as wheel or can use a conventional power train system to transfer the torque to the locomotion system. The modeling of electric drives is mature ant there are various software solutions available addressing mechanical as and electrical power aspects of electric motors and stored battery options such as batteries and fuel cells such as MATLAB®, Maplesoft and ANSYS®, etc.

In addition to the mechanical components data listed above the electric drive vehicle model requires the efficiencies, power performance parameters for the motor, the controller with power electronics and the energy store. The controller model should include the strategy for braking and energy storage as per the system design requirements. The electric drive models can be mapped output plots and look-up tables or can be temporally simulated using physics based models. In most cases highly detailed physics based models can be used to model the performance and control outputs that can then be used by the vehicle model. As noted previously temporal models take exponentially longer to run however may provide high resolution response models for autonomous vehicle control model.

Simulation models for electric drives should simulate realistic electric system behavior in real time or offline. The models should be chosen for function design and controller testing in model-based development processes. The possible applications vary from electric drives and inverters for very fast closed-loop simulation with an electric drive controller to complete vehicle electrical systems including a very detailed battery model. For real-time applications, it is important to prevent an extensive tire slippage requires an extremely fast, exact and pre-emptive response of a wheel control system to dynamic changes of terrain. The managing of the wheel torque within the time interval that would be close to the tire-terrain relaxation time constant could allow for a significant improvement of vehicle mobility [31], [32]. However, the reduction of the response time of control systems to that time interval can be limited by characteristics of actuators that can substantially affect the response time.

In this regard, there is a need in analytical studies for the response time of electric driveline systems. An open-loop-model of the rotational dynamics of the locomotion module was simulated in Ref. [33], and the response time was analyzed in severe terrain conditions under different combinations of the electric, magnetic, and mechanical parameters and characteristics of the electric driveline. The response time of the electric wheel drive of 10-ton tactical vehicles ranged from 18 to 170 $msec$ when the characteristics of the driveline significantly vary, including change of the electrical resistance (R_a) from 0.25 to 0.5 Ω , the motor inertia (I_m) from 0.2 to 0.4 $\frac{kg.m^2}{rad}$, the motor back emf constant (K_b) from 1 to 4 $\frac{N.m}{A}$, the armature electric inductance (L_a) from 0.00012 to 0.003 H, the motor damping coefficient (c) from 0.2 to 0.4 $\frac{N.m}{rad}$. By eliminating combinations of the parameters with higher response time, the best feasible combination, which provided the response time within 30 $msec$, was proved at $R_a = 0.25\,\Omega\,, c = 0.3\,\frac{N.m}{rpm}, I_m = 0.2\,\frac{kg.m^2}{rad}$, $K_b = 2\,\frac{N.m}{A}\; and\; L_a = 0.0012\,H$. As illustrated in Ref. [33], such considerable reduction of the response time results in substantial drop of the tire slippage and improves the tire dynamics in terrain conditions.

Another important requirement would be fast variant handling for different drivetrain scenarios such as FWD, RWD, and AWD with 1or 2 electrical motors, or individual motors in the wheel drives. For simulating the charging process an emulation of a charging unit with tailored interfaces for coupling scenarios with real charge controllers could be helpful.

In-wheel electric motors open up new prospects to radically enhance the mobility of autonomous electric vehicles with four or more driving wheels. The flexibility and agility of delivering power individually to each wheel can allow significant mobility improvements, agile maneuvers, maintaining stability, and increased energy efficiency. However, the fact that individual wheels are not connected mechanically by a driveline system does not mean their drives do not impact each other. With individual torques, the wheels will have different longitudinal forces and tire slippages. Thus, the absence of driveline systems physically connecting the wheels requires new approaches to coordinate the wheel power distribution. This problem can be solved by introducing Virtual Driveline Systems (VDS) to emulate a mechanical driveline system virtually connecting the e-motor drive shafts and providing coordinated driving wheel power management [34]. The VDS simulates power split between driving wheels. Conceptually, VDS is founded on generalized tire and vehicle parameters. Generalized slippages are utilized to determine virtual gear ratios from a virtual transfer case to each wheel. The virtual gear ratios serve as signals to the electric motors. Computer simulations of a 4x4 tactical vehicle in stochastic soil conditions demonstrated a 17% increase in mean values of the velocity-based mobility performance index when the vehicle is electrically driven by the optimal virtual gear ratios as compared to the mechanical driveline system with non-controlled differentials [34]. The concept of the virtual driveline systems is proposed for the AVT-341 study.

6.7.2 Modeling of Hybrid-Electric Drives

Hybrid-Electric Vehicle (HEV) drives differ from pure electric drives by having a conventional power source such as a combustion engine providing mechanical power that is converted to electrical power. There are two primary HEV layouts; these are Parallel and Series. Parallel layout allows for direct transmission of engine power through the mechanical transmission and drive line to the locomotion system and a parallel system that converts mechanical energy to electric energy and storage that is able to drive the mechanical system when required. The parallel system uses a mechanical coupling to an electric motor that converts the mechanical energy to electric energy that is transferred to the power control and battery storage system. Series HEV layout allows for the direct conversion of the engine mechanical energy to electric energy and then using this electric energy to drive the system with an electric storage capacity. The mechanical power is converted using a generator, rectifier and other power electronics sub-systems to provide power to a traction motor.

A parallel HEV system will require many of the same mechanical components as found on conventionally drive vehicles such as engine, automatic transmission, torque convertor and transmission systems. In this case the engine accessories should include the power take off to the electrical motor. Series HEV model requires additional electrical components, these are the generator, energy store and electric motors. The generator and drive motors are similar in that they introduce inertia and efficiency losses to the power train but are normally modeled in a similar manner to combustion engines with operating power vs. rotational speed maps. In addition to the electrical power input and output capabilities, these components also require power electronics to be defined in terms electrical efficiencies and cooling requirement power maps. As with the combustion engine, the HEV generators and electric motors can be dynamically modeled at a component level however this will exponentially increase the solving time for the model. In addition to the generator power characteristics, the controller also has power storage and can have electrical braking capabilities that affect the system model and must be defined in look-up tables or modeled. The energy store has both charging and discharge efficiencies that will impact the system model and power electronics that require cooling and have efficiency losses thus must be defined or modeled.

Hybrid-electric drivelines offer an opportunity to improve autonomous vehicle mobility, maneuverability and energy efficiency by decoupling the dynamic interference of the driveline system with the steering system [35], [36], [37], [38], suspension [39], and brakes [35]. The decoupling of the autonomous vehicle systems and the establishing of the interactive and collaborative dynamics between the systems offers opportunities for designing advanced vehicle platforms that can meet expectations of AI-based autonomous controls of vehicle systems [40]. Modeling and simulation of coupled and de-coupled dynamics of autonomous vehicle systems can be considered as a research direction for AVT-341.

6.8 MODELING OF LOCOMOTION SYSTEMS

A locomotion system refers to how the energy generated by the vehicle engine and distributed by the transmission and driveline is converted into displacement of the vehicle. Although there have been a number of technology demonstrators using what are considered unconventional such as legged or combined wheel-leg means of locomotion, this assessment focusses on wheeled and tracked locomotion.

6.8.1 Tire Models

Vehicle dynamics simulation tools have shown significant improvement over the years enabling early phase design changes and reducing the number of tedious proving ground tests. Also, validated simulation tools have key role in the development of driver assistance systems and autonomous vehicles improving active safety, performance and energy efficiency. Modern vehicle dynamics tools rely on high fidelity tire models to predict forces and moments generated in the contact patch. Tire characteristics have significant impact on handling, braking, acceleration and ride, thus use of accurate tire models that represent dynamic interaction with the ground is crucial. Typical forces and moments acting on a tire is shown in Figure 6-15 according to SAE convention.

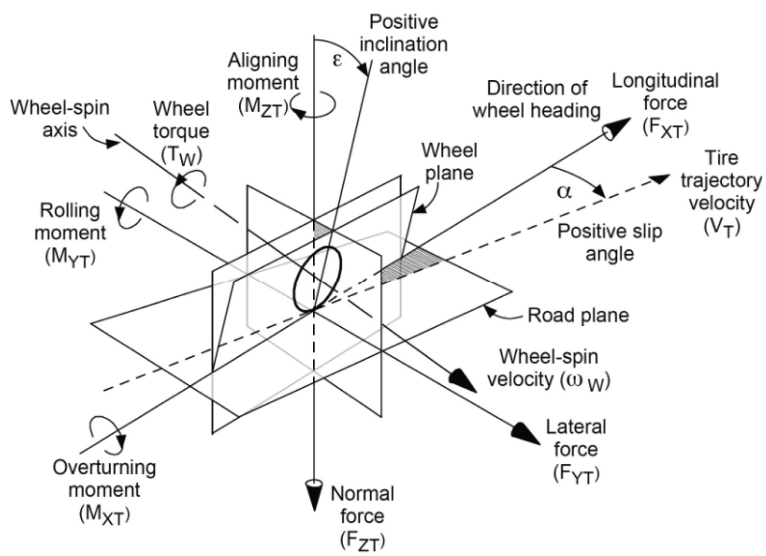


Figure 6-15: SAE Tires Axis System [41].

Typical inputs of a tire model are radial deflection, longitudinal slip, speed of revolution, lateral slip angle, spin, camber angle and temperature; whereas typical outputs are normal load, longitudinal force, rolling resistance moment, cornering (side) force, self-aligning torque and overturning couple. Tire models ranges from simple curve-fitted experimental results to detailed finite element models where usually a compromise is necessary between accuracy and complexity [42]. Four categories of possible types of approach to develop a tire model is shown in Figure 6-16. Pure experimental models require large tire datasets collected at various operating conditions such as load, slip angle, speed, inflation pressure and camber angle, and extensive curve fitting processes increase the solution times significantly. Prediction of tire characteristics outside the test matrix is not possible using this type of models. The empirical models are commonly used in mobility and real-time simulations. One of the most important empirical models is the NATO Reference Mobility Model (NRMM).

This is a “Go/No-Go” model that uses an instrument called a cone penetrometer to determine a cone index, which is then compared to a mobility index of a vehicle. The vehicle mobility index is computed based on vehicle characteristics such as vehicle weight, contact area, size of grouser, engine power, and type of transmission. If the vehicle mobility index exceeds the cone index, then motion is possible; otherwise the vehicle is stuck. Empirical traction models should be used with caution for new scenarios.

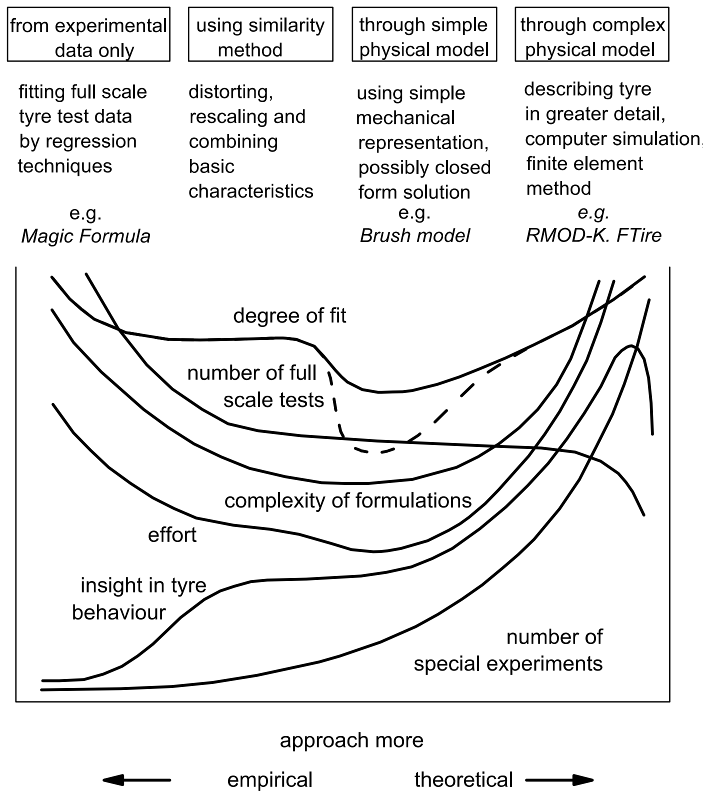


Figure 6-16: Four Categories of Possible Types of Approach to Develop a Tire Model [42].

A non-linear, semi-empirical function developed by Hans Pacejka, referred to as “Magic Formula”, is widely used in vehicle dynamics simulations for characterizing tire cornering behavior using test data [43]. This formula is comprised of terms corresponding to real life tire properties and can be used to represent relationships such as cornering force and aligning moment versus slip angle, and longitudinal force versus slip or skid. Each term can be written in a polynomial form as a function of normal load where empirical coefficients can be obtained from experimental data. The empirical coefficients can be easily exchanged between tire and vehicle manufacturers. Combined steering and braking/traction scenarios are defined using additional terms. Due to its simplicity and practicality, the “Magic Formula” has become a common method in tire modeling. Initially, the transient effects were not considered in the Magic Formula. However, when a step-steer or sweep steer is applied to a tire, a finite distance must be traveled before the tire forces and moments reach their steady state condition. Gradually, the formula has been improved by adding second order transient terms simulating the time lag and relaxation lengths [44]. Later, the normalized form of equation was published where physical terms are defined as a function of tire pressures [45]. Since then, the formulation has been improved and commercialized by several groups and companies such as TNO, Smithers Scientific Services Inc., and MSC Corp. adding new features

[46], [47]. Due to large number of data sets and high non-linearities, calculation of the empirical parameters from test data has been challenging. Regression techniques, evolution algorithms, interpolation and non-linear curve fitting methods have been used to calculate empirical parameters from the experimental data which is usually obtained by rolling drum or flat track type of test systems. On the other hand, advanced driver assistant systems and autonomous systems should adapt to the fast-changing operating and environmental conditions and in situ calculation of the empirical parameters can be obtained in real road conditions. Kalman or Extended Kalman Filter type of approaches have been adopted in several studies for online calculation of the Magic Formula parameters comparing experimental road data such as lateral acceleration, yaw rate and side slip angle to those obtained by vehicle model numerical simulations [48].

Similarity approaches and simple physical tire models are based less on full-scale experiments and more on the theory of the behavior of the physical tire structure compromising the accuracy of the model. In a simple similarity model [49], the tire tread in the contact patch is represented by a stretched string connected to a rigid wall by means of a number of lateral springs representing the sidewall where wheel rim is acting as a rigid support. In another similar approach the tread is considered as an elastic beam as shown in Figure 6-17. If there is sliding between the tire tread and ground, the equatorial line in the contact patch cannot be assumed as a straight line. Therefore, the use of this type of models is limited for small slip angle values only.

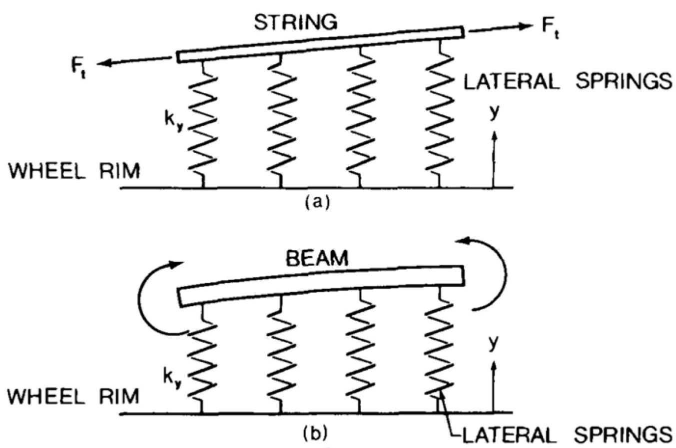


Figure 6-17: Stretched String and Elastic Beam Type of Similarity Models [49].

In Fiala's model, the tire tread is modeled using an elastic beam connected with flexible elements and tire slip is also considered in the model. This model later improved by software developers such as MSC ADAMS calculates expressions for all tire forces and moments except for the overturning moment. The effects of camber angle on tire forces are not included, and slip during combined cornering, braking, and traction is not considered. Therefore, its application is only limited to zero camber and small slip angles [50]. The brush tire model (initially developed by De Carbon) is an example for a simple physical model, where the tire tread, belt and carcass structure are represented by a row of elastic bristles that can deflect in a direction parallel to the road surface as shown in Figure 6-18 [42]. When there is a slip angle between the speed vector and the wheel plane, elastic elements deflect horizontally, and corresponding forces and moments are generated. Pure side slip, pure longitudinal slip and combined slip scenarios including parabolic pressure distribution and camber effects is considered in this model. Brush type tire model is useful to acquire good understanding of tire behavior on rigid ground. However, obtaining model parameters for vehicle simulations is very difficult.

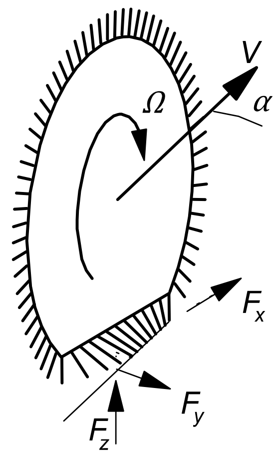


Figure 6-18: Brush Tire Model [42].

The TameTire model developed by Michelin is based on three different models which is a mechanical tire model-based on a "brush element" approach. The carcass and belt deformations define the boundary conditions for the brush element at the tread-belt interface, whereas the boundary conditions of the brush element at the ground level are governed by the frictional characteristics. The rubber compound descriptions are considered when calculating the friction coefficient between tire tread and ground. In addition, the thermal model calculates the contact temperature at the rubber-ground interface in the contact patch and calculates the temperature distribution through the tread thickness around the tire circumference [51]. There are several multi-body-dynamics-based tire models available for ride and durability simulations considering the tire structure and terrain interaction such as F-Tire, CD-Tire, and MF-SWIFT. The F-Tire model developed by "Cosin Scientific Software" contains a rigid mounting rim surrounded by 50 – 100 lumped masses with non-linear elastic interconnections and dampers that form a surrounding flexible belt or ring and can deal with frequencies of up to 120 Hz to encompass obstacles in the longitudinal direction of rolling with wavelengths half the length of the tire contact patch as shown in Figure 6-19. In the transverse direction the model can handle inclination of the road surface and also obstacles that vary across the tire lateral footprint, hence the model is considered as a non-linear vibration model. The model can also accommodate the effects of stiffening and radial growth associated with high angular spin velocities. Frictional forces can be transmitted through the shear forces acting on the mass-less tread elements in both longitudinal and lateral directions. More elements increase the compliance in a convergent way until something resembling the 'real' answer is reached. But this leads to a large increase in the number of computations required. Advanced DEM soft soil models and Becker-Wong type of simple terramechanics models can be integrated to the tire model [52].

CD Tire is a physical tire model family developed by Fraunhofer Institute, Germany having different physical models for belt, sidewall and tread to balance accuracy and performance for different applications as shown in Figure 6-20. CD Tire 3D is shell based model of sidewalls and belt, flexible rim support; CD Tire RealTime is local brush type contact model having scalable belt discretization for real-time calculations. It can be used in frequency ranges up to 150 Hz for applications on arbitrary longitudinal wavelength road surfaces such as cleats, curbs and 2D road surfaces; CD Tire/MF++ is a temperature enhanced Magic Formula for coupling to CDTire/Thermal in advanced handling applications; CD Tire Thermal is a detailed thermo-dynamical model to predict temperature creation and propagation in a tire; CD Tire NVH is a software toolbox to derive a linear model from CDTire/3D for a rolling preloaded tire [53]. RMOD-K is another flexible structure tire model which is particularly developed for ride and durability analysis in on road and off-road simulations [54], [55].

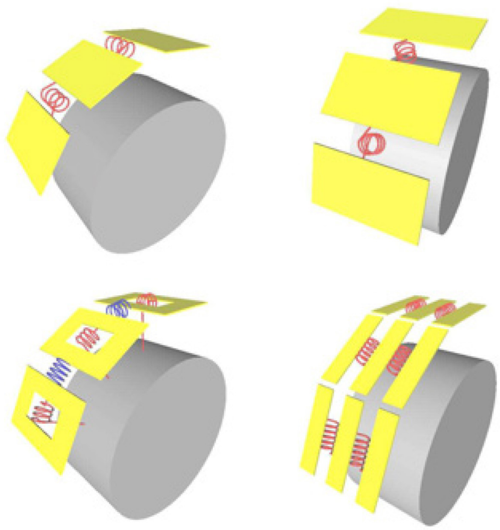


Figure 6-19: Multi-Body-Dynamics Tire Model (F-Tire).

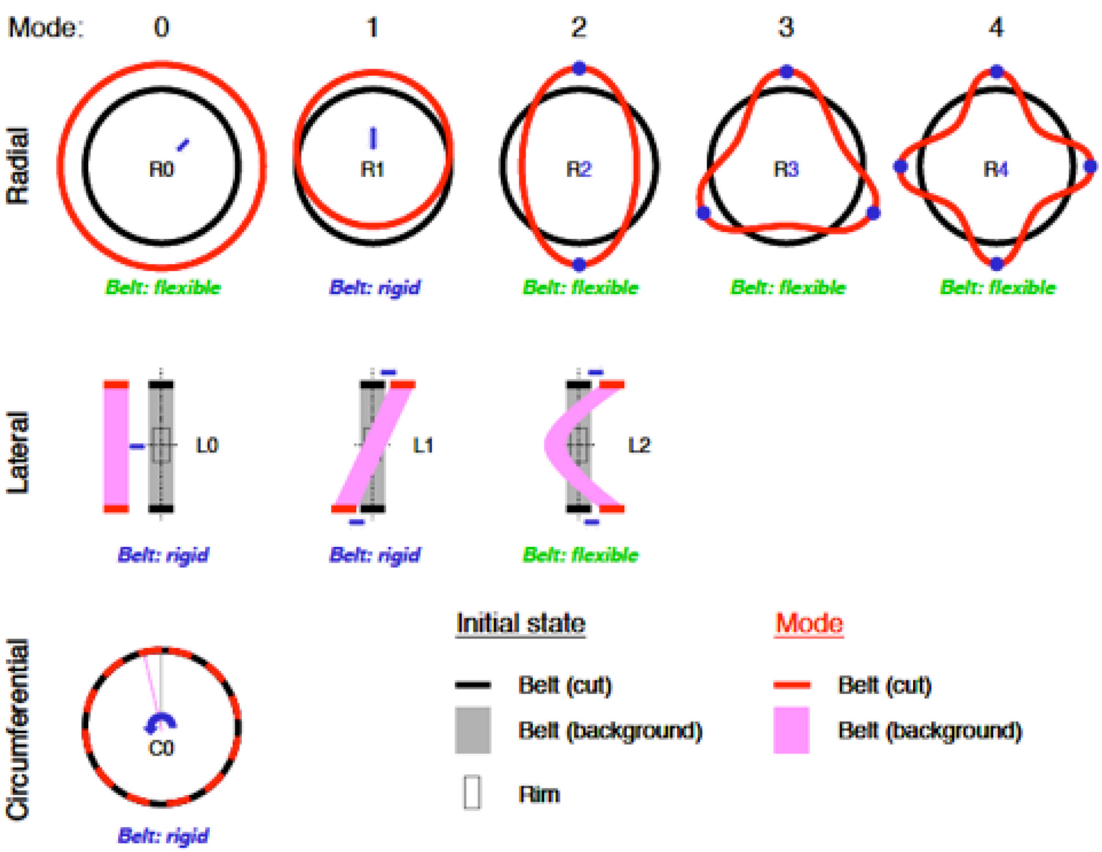


Figure 6-20: Elastic Tire Modes (CD-Tire).

MF-Swift is a high frequency extension of MF-Tyre for ride comfort, road load, and vibration analysis. MF-Swift adds generic 3D obstacle enveloping and tire belt dynamics to tire-road contact force and moment simulations [45].

High fidelity finite element tire models enable modeling of tire structure and uneven ground interaction with a great detail and experimentally validated, high fidelity finite element tire models have proved to be beneficial in the tire design phase. Also, use of finite element tire models is beneficial for discrete-element soft soil simulations where high-performance computing is available. However, it is not practical to use these types of models in near real-time simulations due to required computational burden. Usually, experimentally validated finite element tire models are used offline to generate Multi-Body-Dynamics tire model parameters that can be used in real-time simulations. Modern vehicle dynamics tools usually have a number of interfaces for various tire models. It is not easy to say that one tire model is better than the other one. Each tire model has different analysis focus such as comfort and vibration analysis, durability analysis, vehicle dynamics, driving safety, driving test support and control system design, and has advantage and disadvantages. Usually, a compromise is necessary between fidelity and simplicity. Figure 6-21 shows various types of tire models in terms of analysis focus and their frequency range. A data exchange standard "TYDEX" has been developed and unified in order to use different tire models in various simulation environments and enable the comparison of results with each another. TYDEX includes norms for parameters such as the units used in measurement results and standardized measurement coordinate systems, which enable the comparison of simulation and experimental results.

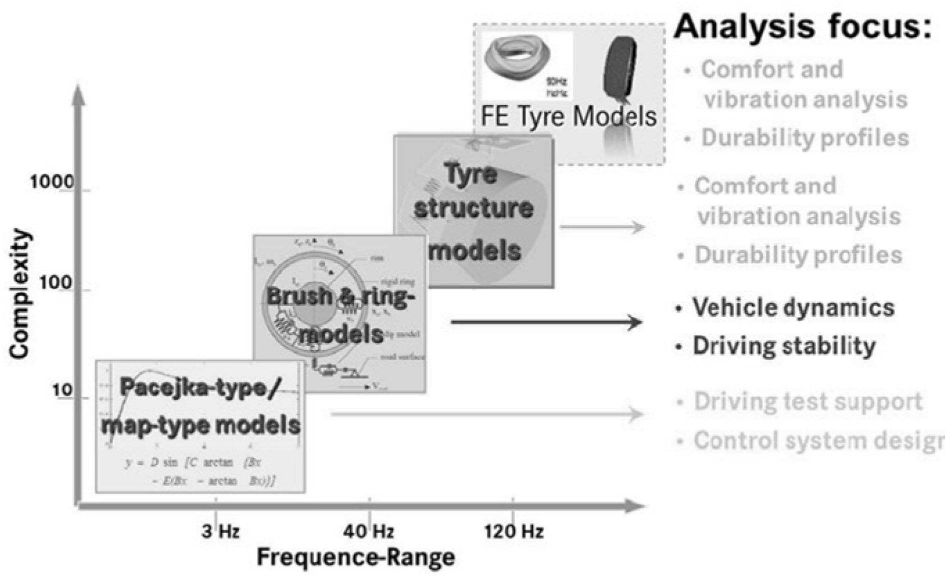


Figure 6-21: Complexity and Frequency Range [55].

6.8.1.1 Tire Model Challenges in the Mobility Assessment of Autonomous Vehicles

Similar to conventional vehicle dynamics tools, mobility assessment tools used to evaluate autonomous vehicles should also have interfaces for different tire models for different analysis objectives. Although, mobility assessment tools used to simulate autonomous vehicles do not require special tire models, model-based control systems used in autonomous vehicles should be able to operate real-time and even faster than real-time. Therefore, a good balance between the complexity and fidelity should be obtained. In conventional vehicle dynamics simulations, tire data is usually obtained using dedicated test systems such as flat-belt or drum type of test systems, laboratory cleat tests and modal tests are performed and intensive regression and optimization techniques are used for offline generation of model parameters. However, in autonomous vehicles, tire models used in control systems should adapt to various operating conditions such as load, inflation pressure, temperature, coefficient of road adhesion, etc. and on-board generation of tire model parameters provide valuable information.

Recently, development of online tire model parameter estimation algorithms is attracting considerable interest. Various online optimization techniques as well as Kalman or Extended Kalman Filter type of approaches are used to estimate tire model parameters. Using a reliable vehicle dynamics model along with sensor data that can be obtained using conventional sensors such as yaw rate and lateral acceleration, tire model parameters can be predicted for autonomous drive. On the other hand, sensing tire-terrain conditions are of great interest for autonomous vehicles from the mobility, vehicle dynamics control, vehicle safety and vehicle performance evaluation perspectives. Commercially available wheel force transducers can provide information about forces and moments generated in the contact patch. However, development of low cost and lightweight wheel force transducers are crucial for their widespread application in autonomous systems. Most common methods in tire sensing are accelerometers, optical sensors, strain sensors and Polyvinylidene Fluoride (PVDF) sensors. Data transmission and power management are major challenges for tire sensors. Effective estimation algorithms are required for online estimation of tire model parameters using tire sensor data.

6.8.2 Track Models

Tracked vehicles are used in civilian and military ground vehicles, especially vehicles which are intended to operate mostly off-road. Tracks have better mobility characteristics than tires on soft soil terrains, steep slopes, slippery terrains, and/or obstacle laden terrains. This is due to the fact that tracks distribute the weight of the vehicle over a large contact area thus reducing ground contact pressure and allowing the vehicle to cross larger positive/negative obstacles. In addition, a major advantage of tracks over pneumatic tires which is especially critical in military applications is that they cannot be punctured. The main disadvantages of tracked vehicles is that their maximum speed is typically lower and fuel consumption is higher than equivalent wheeled vehicles. Tracks can be used on vehicles of various sizes ranging from large tractors, excavator, and tanks to small unmanned ground vehicles. In some vehicles, tracks are used in conjunction with tires or skis. Tracks can be divided into two types:

- *Continuous belt tracks*. The cross-section of a continuous belt track is similar in construction to a tire. It consists of a rubber matrix reinforced with steel, kevlar and/or polyester wire/ply along the length and width of the track. The outer track surface in contact with the ground can have a deep tread pattern similar to a tire in order to improve traction over soft soil and flooded terrains. The inner surface of the track typically has teeth/grooves which engage with the drive sprocket in order to drive the track without slip.
- *Segmented tracks*. The track consists of a large number (~ 100) of relatively stiff identical segments/units connected using revolute joints into a closed-loop. The segments are usually made out of steel. A rubber layer, called track shoe or pad, can be used as the track segment road contact surface in order to enable tacked vehicles to operate on hard surfaces (such as pavement) without damaging the surface and without excessive noise/vibrations. Grousers and/or deep track shoe patterns are used to improve soft soil traction. The revolute joints connecting the segments typically have rubber bushings which provide longitudinal flexibility for the track in order to absorb and damp sudden track tension forces. The inner surface of the track is in contact with the road wheels, idlers, and the driving sprocket. Two types of segmented tracks are typically used: single-pin (Figure 6-22) and double-pin (Figure 6-23) tracks. In single-pin tracks one track segment/unit type is used. In double-pin tracks two track segments/unit types are alternately used in the track.

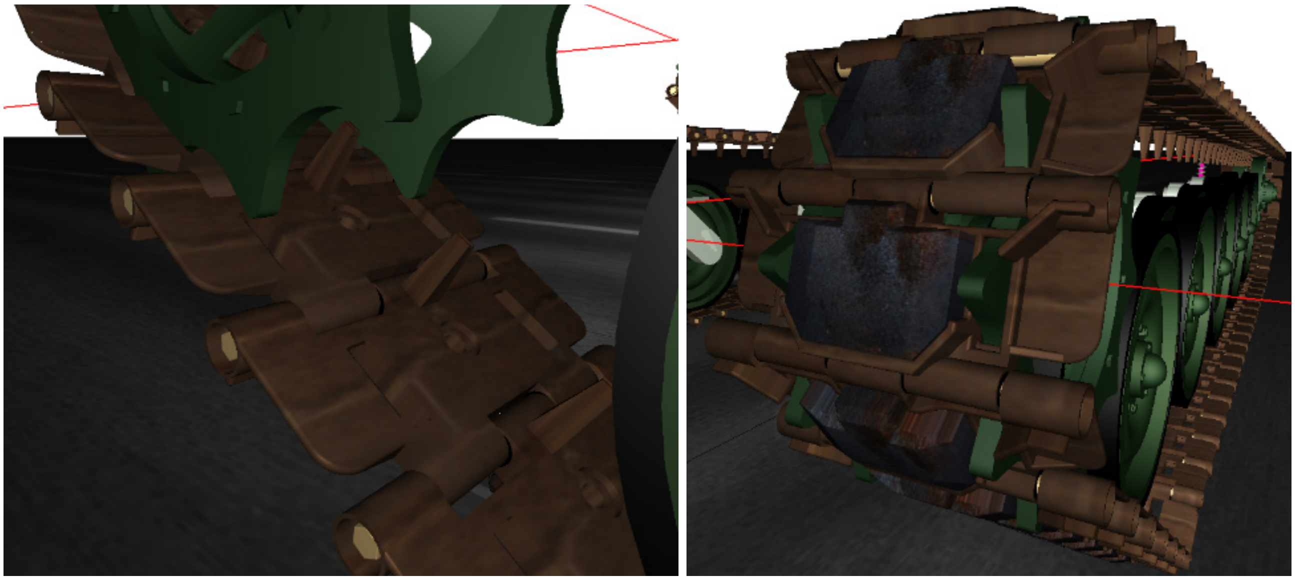


Figure 6-22: Typical Single-Pin Segmented Track with One Track Segment/Unit Type Used Throughout the Track.

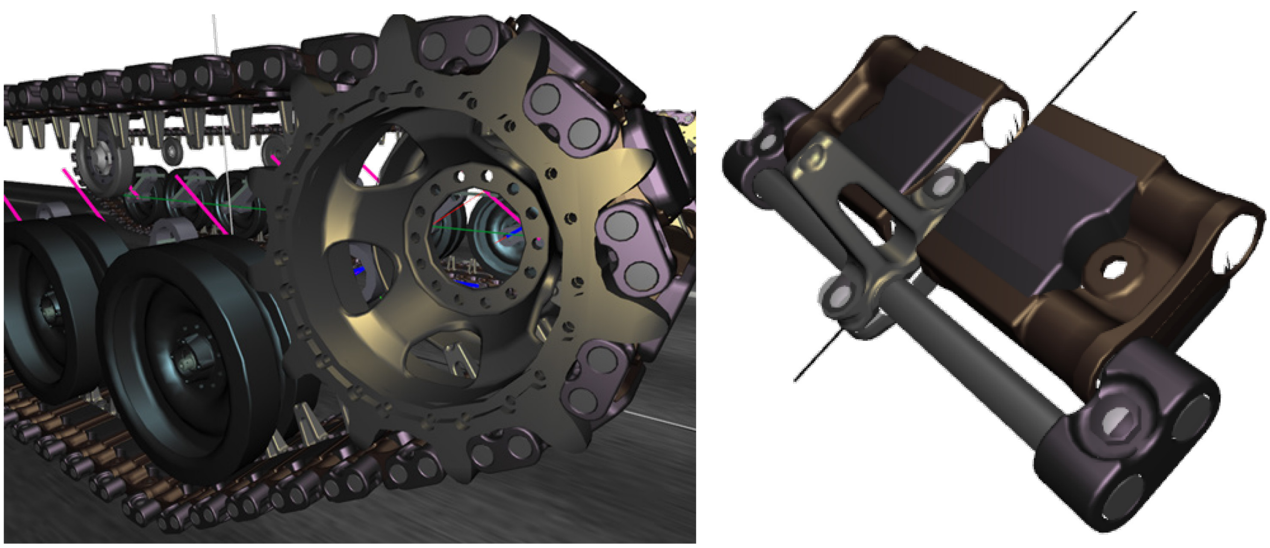


Figure 6-23: Typical Double-Pin Segmented Track with Two Track Segments/Units Types.

A track system typically consists of the following components (Figure 6-24):

- *The track* which can be continuous or segmented (single or double-pin).
- *Drive sprocket* is typically directly mounted on the vehicle frame and is connected through the vehicle driveline to the drive motor thus providing the power (torque and angular velocity) necessary to drive the track. The sprocket has teeth and grooves which engage with the inner surface corresponding grooves in the track in order to drive the track without slip.

- *Road wheels* provide support for the track span which is in contact with the ground. The road wheels can be mounted to the vehicle frame directly or through a suspension system. The most common suspension system used in tracked vehicles is the torsion bar suspension with road arms and rotational spring-dampers at each road wheel. Road wheels are typically covered with a rubber layer in order to soften the contact with the inner surface of the track.
- Idlers are the rollers that do not provide support for the weight of the vehicle on the ground. They are typically mounted directly to the vehicle frame and present at the front, rear, and/or top part of the track in order support the track and maintain the track tension.
- *Tensioner.* At least one of the track wheels (idler, sprocket, or road wheel) has to be movable to enable setting the proper tension for the track. The track tensioner can also include a spring-damper to enable smoother absorption and damping of sudden track tensions.

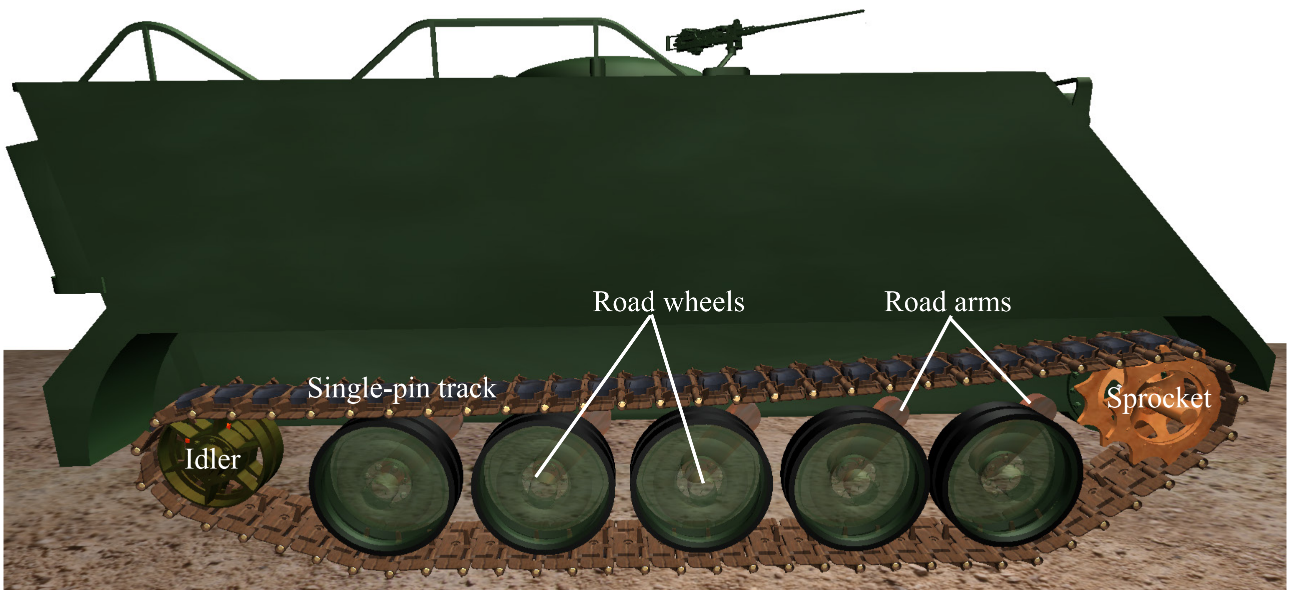


Figure 6-24: Typical Components of a Track System.

There are currently three main approaches used in commercial simulation software for modeling tracks going over arbitrary topography terrains: the track super-element method, the multi-body dynamics approach for modeling segmented tracks, and the finite element method for modeling continuous belt-type tracks. In the track super-element method [56], [57], [58] a specially formulated super-element representing the track that is in contact with the terrain and the road wheels is employed (Figure 6-25). The model can be used for both continuous belt-type tracks and segmented tracks. The model accounts for the tension variations, axial deformation, and transverse deflection of the track. Adaptive meshing can be used to capture high frequency content of the track-wheel-terrain interaction and the rough terrain geometry. The track-wheel-terrain model combines approximate constitutive laws for terrain with the track representation, which allows the computation of the normal and shear forces at the track-terrain interface. The main simplifying assumptions in the super-element method are that there, the effects of sprocket-track clearances and engagement and disengagement of the track grooves with the sprocket teeth are not included. Another assumption is that the first and last road wheels remain in contact with the track.

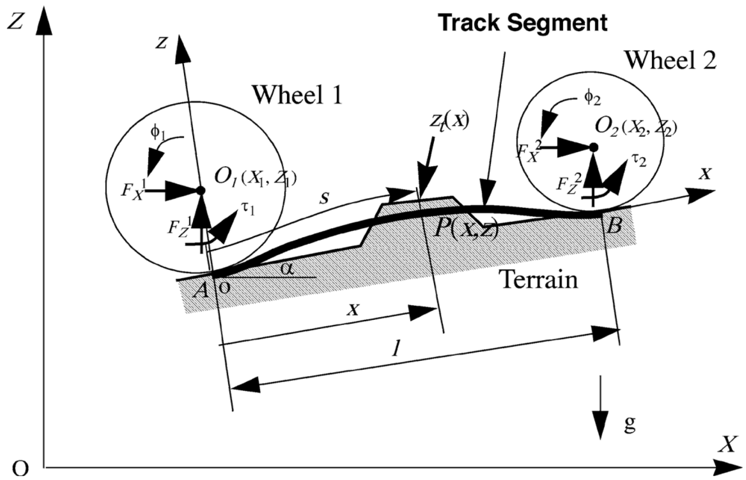


Figure 6-25: Force Super-Element for Track-Wheel-Terrain Interaction [56], [57].

In the multi-body dynamics approach [59], [60], [61], [62] for modeling segmented tracks, all track links, track wheels/rollers, and sprocket are modeled as rigid bodies. The revolute joints connecting the track segments include the effects of axial compliance (stiffness and damping) of the track bushings. The actual contact surfaces are used for the sprocket, wheels, and track segments (Figure 6-26). The contact model includes the effects of friction and normal compliance between the track and the wheels/sprocket, and geometry/clearances of the sprocket teeth and track grooves. Contact between the track and ground can be modeled using a stiff terrain with a friction coefficient, a Bekker-Wong terrain model, a finite element soft soil model, or a Discrete Element (DEM) soft soil model (e.g., Figure 6-26). This model can accurately predict tension variations along the track, transverse vibrations of track, and suspension system/road wheel motion. Many commercial multi-body dynamics codes such as ADAMS [63], Recurdyn [64], Simcenter 3D [65], Chrono [66], and DIS [67] use this approach for modeling segmented tracks.

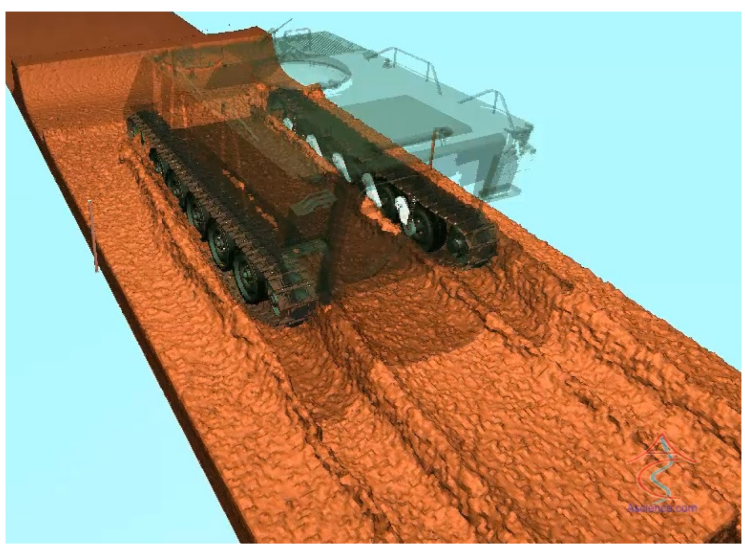


Figure 6-26: Full Multi-Body Dynamics DIS [66] Model of the M113 Single-Pin Segmented Track Vehicle Undergoing a Braking Maneuver on a Soft Soil DEM Terrain.

In the finite element approach for modeling continuous belt-type tracks [61], [68], the track is modeled using brick elements representing the rubber matrix with embedded thin beam elements along the width and length of the track representing the track reinforcements (Figure 6-27). The top and bottom contact surfaces of the track's brick elements are used as the contact surfaces for the wheels/sprocket and ground. Proxy contact surfaces attached to the top and bottom brick contact surfaces can be used to representing the actual track tread outer surface and inner surface tooth/groove profile. This enables accurately modeling of the effects of geometry and clearances of the sprocket teeth and track grooves as well as the interaction between the track's tread and soft soil. This finite element track model can accurately predict the track internal stresses (including axial, radial, and shear stresses), transverse vibrations of track, and suspension system/road wheel motion. The DIS [67] multibody dynamic code supports this approach for modeling belt-type tracks (Figure 6-28).

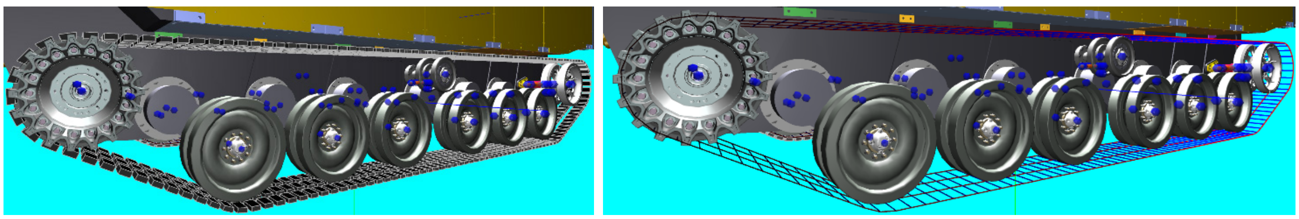


Figure 6-27: Exploded View of the Brick Elements for Modeling the Track Rubber Matrix (Left) and Beam Elements for Modeling the Track Reinforcements Along the Track's Width and Length (Right) [61].

Figure 6-28: Tracked Vehicle w/ a Belt Track Simulated Using the DIS Code [66] Going Over Semi-Circular Bumps [61].

6.9 MODELING OF SUSPENSION SYSTEM

The main objective of vehicle suspension systems is to modulate the vibration of the vehicle sprung mass to terrain/road disturbances. The primary functions of the suspension system are to:

- Isolate the vehicle's body from road inputs for improved vehicle ride and comfort characteristics considering human response to mechanical vibrations.
- Reduce dynamic tire vertical load variations for desired performance and handling by proper spring / damper / unsprung mass / tire combinations.
- Transmit tractive and braking forces by control arms.
- Transmit lateral forces by control arms, struts and leaf springs.
- Carry normal loads by suspension springs and dampers.
- Control body roll stiffness and lateral load transfer by suitable anti-roll/anti-sway bars for desirable handling characteristics.
- Minimize excessive squat/pitch/dive motions by proper suspension kinematics.
- Define bump-steer, roll steer and compliance steer characteristics by suspension geometry for desired handling characteristics.
- Define proper roll centers and roll axis position affecting roll rate and lateral load transfer for desired handling characteristics.
- Control wheel plane geometry due to compliant and kinematic effects.
- Support vehicle's motion direction control.
- Maintain the durability of vehicle components and payload against shocks and vibrations.
- Maintain the tire-terrain contact and the desired ground clearance for optimized off-road mobility, accessibility (kneeling, etc.) and reduced aerodynamic resistance.
- Stabilize the vehicle's body in military operations such as turret stabilization, radar, etc.

There are various suspension systems used on vehicles. Suspension systems are classified into two main categories as dependent suspensions and independent suspensions. For dependent suspension, it may be differentiated by the system of linkages used to locate them longitudinally and/or transversely. Examples of location linkages include Satchell link, Panhard rod, Watt's linkage, WOBLink, Mumford linkage, Hotchkiss suspension, Leaf springs used for location (transverse or longitudinal). The dependent suspensions are good for heavy load carrying; however, they provide limited packaging room and poor road isolation. Independent suspension systems permit one wheel to move without affecting the others and provide packaging space and allow the control of roll steer. Independent suspension systems have many variations such as short-long-arm (double wishbone), MacPherson strut/Chapman strut, multilink, torsion bar, twin-I-beam, sliding pillar, etc. Whereas mechanical systems having bushings, coil, leaf, torsional springs and hydraulic dampers which are sufficient for lightweight vehicles, air springs requiring an external pressure supply is commonly used for heavy duty vehicles. Also, hydro-pneumatic suspension systems use nitrogen accumulators as springs and hydraulic cylinders for body control. In conventional suspension systems, an optimum balance between the ride quality and the handling is usually achieved by proper selection of spring stiffness and damping rates.

Depending upon the method to control the wheel motion relative to vehicle chassis, there are three types of suspensions:

- Passive suspension, where its elements cannot provide any external energy to the suspension system. It only limits the motion of the vehicle chassis/body and wheel by limiting their relative velocities to a rate that gives the required ride comfort.
- Semi-active suspension, where it can only change the viscous damping coefficient of the shock absorber or damper, and do not add external energy to the suspension system. Usually, it has a limited number of damping coefficient values used for different riding modes (comfort, normal or sport).
- Active suspension, where it uses separate actuators which can exert an independent force on the suspension to improve the ride and handling characteristics, in other words, external energy is added to the suspension.

In active suspension systems, mechanical springs and dampers are replaced by force actuators to apply correct stroke according to the road profiles. However, active suspension systems require a significant power source, and they are not practically viable. Semi-active suspension systems, where damping rate is automatically modulated according to body amplitudes and road profiles by means of mechanically or magneto-rheological, etc. variable dampers, require very little power and are viable alternatives for active suspension systems. Depending upon the purpose of the simulation task, the suspension model may be established differently. If the simulation is tasked to perform the whole vehicle system dynamics mobility simulation, the suspension model may be established with focus on the high-level relationship between the input and output variables. The input variables can be the wheel motion states (position and velocity in local or global reference frames) with 6 degrees of freedom. The output variables can be the lumped and/or individual component forces/moment vectors acting on the vehicle chassis, depending upon how the suspension model is attached with the chassis structure and how the assumptions are made. Such input and output variables relationship can be established with experimental method (typically called a suspension Kinematics and Compliance test rig) or analytical method (typically the Multi-Body-Dynamics modeling and simulation approach). If the suspension is semi-active or active, the controlled component may be included in the suspension input and output relationship model or separately integrated with whole vehicle system model. General purpose simulation tools provide templates with preprogrammed configurations of suspension systems commonly used in the automotive design. Typically, simulation of active and semi-active suspension control systems, and pneumatic and hydro-pneumatic plumbing systems are modeled using multi-physics and co-simulation techniques. In Multi-Body-Dynamics simulation tools, each suspension component is modeled as a rigid (or flexible) body with boundary conditions connected by joints, bushings, etc. Wheel plane motions are calculated at each time increment in this case. However, increasing the number of degrees of freedom adds significant complexity to the mobility model where real-time simulations are necessary. In real-time or near real-time simulation tools wheel kinematics is defined as a function of suspension travel, roll, etc. and spread-sheets, look-up tables and equations are used to define suspension kinematics.

6.9.1 Suspension System Model Challenges in the Mobility Assessment of Autonomous Vehicles

Suspension system models for conventional vehicle dynamics tools and for mobility assessment tools used to evaluate autonomous vehicles are not different since there is no significant difference in the autonomy case. In conventional vehicle simulations, human perception to mechanical vibrations and handling are primary concerns. However, there are several issues that are more critical or less important in the case of autonomous mobility. In passenger carrying vehicles, human perception to mechanical vibrations is the primary issue in the selection of suspension system components such as springs and dampers. However, an autonomous vehicle does not have to be manned, and human perception is not the priority concern for unmanned vehicles.

On the other hand, in an autonomous vehicle, the occupants/driver can perform other tasks while driving such as working on computer, reading, mission planning, etc. so that motion sickness can be a more critical issue to be considered. For remotely controlled vehicles, the ride quality is important if the vehicle mission/task requires a certain smoothness of ride. It is also essential to maintain a considerable tire patch for assuring high mobility and traction of autonomous vehicles.

Typically, the driver avoids the obstacles on the road such as rocks and vegetation and chooses the most traversable path on the way. In an autonomous vehicle, the driver is replaced by the vehicle control system. Therefore, path planning algorithms must be programmed considering the vehicle suspension system model and potential effects of obstacles and road profiles. Since an autonomous vehicle should plan its path in real time, the balance between suspension system model complexity and fidelity is also critical. LIDAR, camera systems and other vehicle system sensors can be used for in-situ measurement of surface profiles to model autonomous vehicles.

In an autonomous vehicle, radars, GPS, LIDAR and cameras are widely used for perception purposes. However, these sensors are typically mounted on the vehicle's sprung mass and suspension travels affects their performance. Therefore, vehicle bounce, roll and pitch motions are more critical for autonomous vehicles compared to conventional vehicles. The suspension system kinematics should be designed to minimize excessive body motions. However, eliminating body motions completely may not be achievable. In this case, proper image stabilization techniques can be used for path planning. At the same time, image and position information acquired in an autonomous vehicle can be used to actively control vehicle body motions on an active suspension system. Vehicle suspension travels can also be used as a road sensor. Mobility assessment tools designed for the simulation of autonomous vehicle should have proper interfaces and co-simulation possibilities for potential advancements in this field. An autonomous vehicle might require different control strategies that need suspension intermediate variables responses, such as the shock absorber temperature (which may affect the damping) response as well as different ways and frequency bandwidth to sense the wheel motions relative to chassis.

6.10 MODELING OF STEERING SYSTEM

Figure 6-29 shows a typical pitman arm steering system.

This typical system links the steering wheel through the steering column to the rack and pinion or steering box, which moves various linkages that rotate the knuckles or hubs of the vehicle. However, while steering systems for passenger and cargo vehicles are often similar, there can be different variations in robotic systems, like direct electrical actuation of each steered wheel.

Modeling such a system should be done at a fidelity level appropriate for the application. In increasing order of complexity, a model could include the following details:

- Kinematic position imposed on wheels;
- Linkage geometry;
- Rack and pinion / steering box;
- Steering wheel and column;
- Mass and inertia of components;
- Bushing compliance;
- Flexibility of linkages; and
- Power assist.

Figure 6-29: Pitman Arm Steering System.

Whether these details are required would depend on the following several factors:

1) **Suspension model fidelity:** If the suspension system geometry of the vehicle is not modeled, there is nothing gained by modeling the steering system in detail.

2) **Wheel/ground model fidelity:** If the wheel/ground model does not account for contact angle of the wheel with the ground (toe or camber), there might be nothing gained by using a sophisticated steering system model.

3) **Force feedback for driver-in-the-loop:** If a user is interacting with a simulated vehicle, it should consider such factors as steering ratio and power assist, in order to accurately predict the movement and feedback forces.

4) **Fidelity vs. performance:** If real-time simulation is required, some compromises might need to be made in the fidelity of the steering system model.

Modeling of steering systems could be an important consideration for autonomous vehicles. Manual or power-assisted steering systems could be completely replaced by electrical or hydraulic actuators for fully autonomous systems. Models might need to include additional sensors to detect user input. Rather than a standard steering wheel, additional control inputs (joysticks, etc.) might need to be considered. Real-time simulation would also be a requirement for human-in-the-loop simulation.

6.11 MODELING OF BRAKES AND ASSOCIATED TC, ABS, SCP

The “service braking” system must enable the speed control of a vehicle and to stop it safely, rapidly and effectively, whatever its speed and load, on any up or down gradient. It must be possible to actuate brakes gradually [69]. There are two main issues in brake system design, the first one is to stop the vehicle in an acceptable distance, and the second is to maintain the stability and steerability of vehicle during braking preventing the lock-up of wheels. For a conventional vehicle, the driver must be able to achieve this braking action from his/her driving seat without removing his/her hands from the steering control. On an autonomous vehicle, on the other hand, the driver is partially or completely replaced by the vehicle control system and the service brakes must be controlled considering the stopping distance and stability of the vehicle. The “secondary braking” system is designed to stop the vehicle within a reasonable distance in the event of a failure. Gradual actuation of secondary brakes is also required. For an autonomous vehicle, actuation of secondary brakes must also be handled by the vehicle control system. It is assumed that not more than one failure of the service braking system can occur simultaneously. The parking braking system must make it possible to hold the vehicle stationary on an up or down gradient even in the absence of the driver, the working parts must be kept in the locked position by a purely mechanical device [69]. For an autonomous vehicle, the vehicle control system must be able to activate the parking brake system as well.

The energy transmission to wheels may be mechanical, hydraulic, pneumatic, electric or mixed. Control transmission is the transmission which controls the operation of the brakes, including the control function and the necessary reserve(s) of energy. Service brakes can be actuated by a pure external power. For a conventional vehicle, the driver controls a foot valve to actuate the brake system. Pneumatic (or air) brakes widely used in heavy vehicles is an example for this method. In hydraulic brakes, the hydraulic pressure generated in the master cylinder is amplified by a servo brake booster operating using vacuum, hydraulic accumulator or external air pressure. “Automatic braking” is braking of the trailer in the event of accidental separation. “Inertia (or overrun) braking” means braking by utilizing the forces generated by the trailer’s moving up on the towing vehicle. These systems are actuated without the drivers’ control. Therefore, there is no significant change is expected for autonomous vehicles in terms of modeling.

“Endurance braking system” is an additional braking system having the capability of providing braking effect over a long period without a significant reduction in performance, particularly on a steep decline. The retardation effect can be maintained by means of engine compression, hydrodynamic or electromechanical systems. These systems are usually actuated by the driver in a conventional vehicle. For an autonomous vehicle, endurance brakes must be actuated by the vehicle control system. Regenerative braking in electric motor driven conventional vehicles are typically actuated either by releasing actuator pedal or by applying the driver brake pedal. However, torque transmitted to the wheels are adjusted according to battery state of charge, selected gear and torque demand according to a predetermined algorithm. The amount of regenerative braking power is limited by the battery and electric motor capacity, and temperature. For electric vehicles equipped with an anti-lock and stability control devices, regenerative braking is also controlled by the anti-lock and stability control systems. The regenerative brake system must be disabled, or its action must be reduced in the cases of stability limits such as high-speed maneuvers.

6.11.1 Hydraulic Brake Models

A typical hydraulic brake system consists of a master cylinder providing hydraulic pressure to two independent circuits. Manual brakes use only the driver’s pedal effort to actuate the friction brakes and no additional energy source is used. Therefore, manual brakes are only used on lightweight vehicles. Brake boost systems used in conventional vehicles allow the driver to decelerate heavy vehicles with pedal force levels and pedal travels within the acceptable range of the average driver. The brake booster must be sensitive enough so that the operator can modulate braking effectiveness when low pedal forces are involved, particularly on low friction surfaces, and at the same time, lock-up of brakes during panic braking must be eliminated. Therefore, human factors play a significant role in the brake system design. In an autonomous system, on the other hand, human factor issues may have less of an importance since the braking action is maintained by the control system. There is no significant difference between conventional hydraulic brake systems and autonomous brake systems in terms of modeling. However, the simulation tools should have proper interfaces for the control signal and hydraulic circuits. Hydraulic circuits can be conveniently simulated by using one dimensional model. Typically, these models have cylinders, actuators, valves, pumps, reservoirs, etc. that can be modeled in one-dimensional form. An example for a hydraulic brake system model is shown in Figure 6-30.

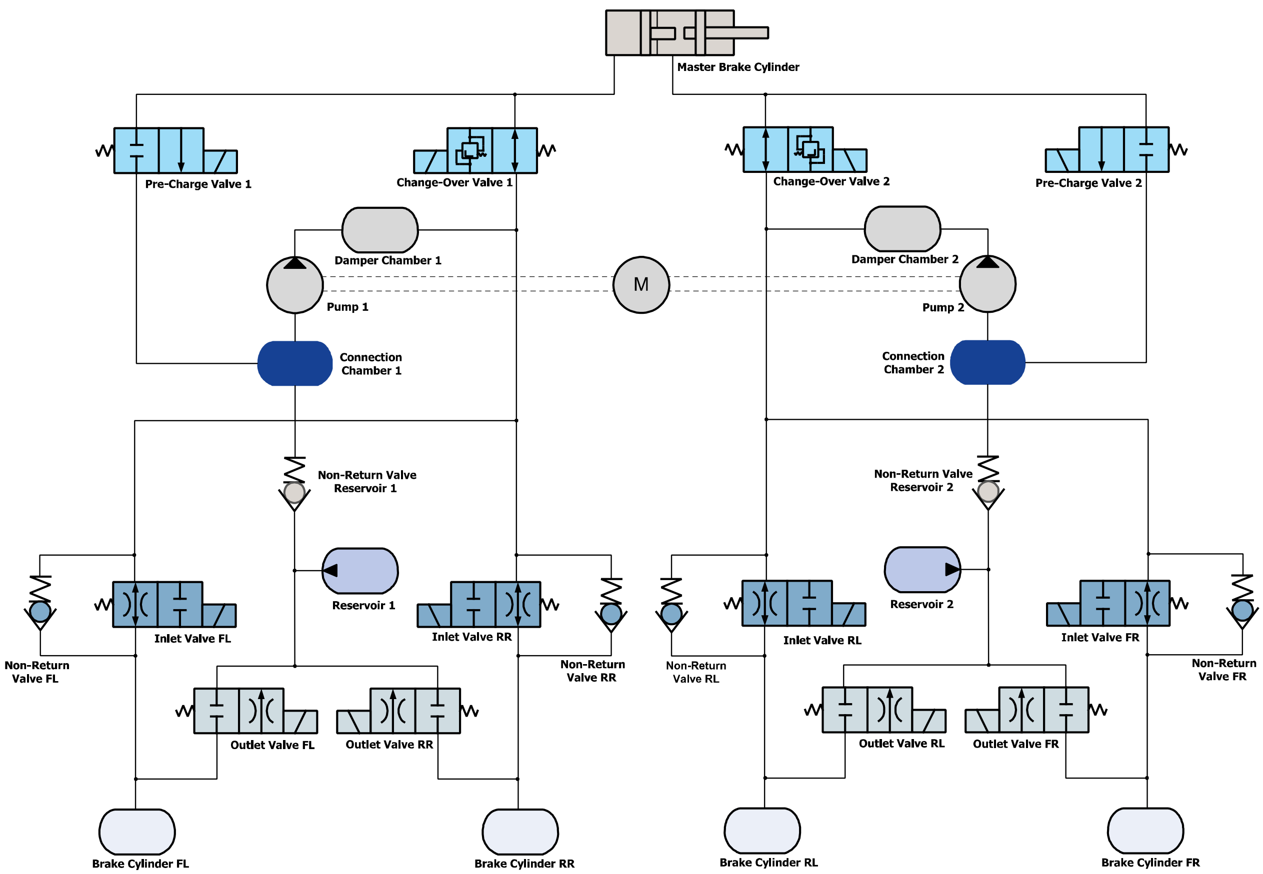


Figure 6-30: Schematic of the Brake Hydraulics [70].

6.11.2 Air Brake Models

Air brakes are external power systems using compressed air as the energy source and the brake pedal effort of the driver is used only to modulate the air pressure applied to the brake chambers. Similar to hydraulic brakes, air brake systems must have a dual circuit to actuate the brakes in the event of a failure. Although the energy source is compressed air, the transmission of the energy from the brake chambers to the friction surfaces involves pushrods, lever arms, slack adjusters, springs, cams, and rollers, or wedges [71]. In the case of air-over-hydraulic brakes, the air pressure is converted into hydraulic pressure, which is used to actuate the friction brakes. Air brakes have a relatively long response time and high pressure losses when compared with hydraulic brake systems. According to FMVSS 121, for trucks and buses a brake line pressure of 41 N/cm^2 (60 psi) be reached at the farthest brake chamber within 0.45 s or less [72]. The response time of air brakes may have significant influence on the stopping distance of a vehicle. Therefore, mobility prediction tools that will be used for the simulation of autonomous vehicles having air brakes should have brake system models capable of predicting the response time and the built-up time.

Typically, an air compressor charges a wet supply reservoir from which dry reservoirs are fed. The dual air brake system is modulated by the driver using the dual brake application valve. When the brake application valve is released, all brake chambers exhaust through release valves [71]. With known brake factor values for the friction brakes and brake chamber pressures, the applied brake torque can be calculated. In an autonomous vehicle case, the driver's pedal effort should be replaced by the control system input of the dual brake application valve. When a certain temperature in the friction brakes are exceeded, braking effectiveness will be reduced significantly due to brake fading. Air brake systems have high pressure losses due to thermal effects, compressibility, gas exchange and exhaust mechanism. These effects should also be considered in an air brake system model. These effects can be effectively modeled in one-dimensional models and usually multi-dimensional modeling is not crucial for air brake system models. A typical air plumbing model of a truck having air suspension and air brakes is shown in Figure 6-31.

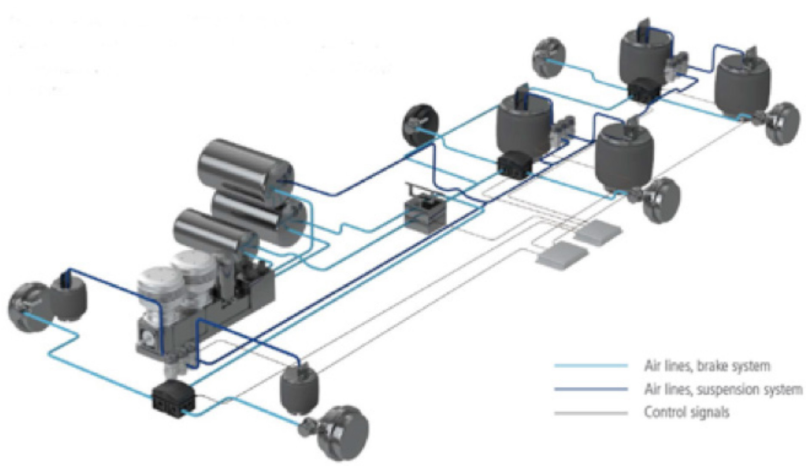


Figure 6-31: Air Suspension and Air Brake System of a Truck [70].

Brake-by-wire transmission is the ability to control brakes through electrical means. This technology replaces traditional components such as the pumps, hoses, fluids, belts and vacuum servos and master cylinders with electronic sensors and actuators. Brake-by-wire systems are widely used in hybrid and battery electric vehicles where regenerative braking is used.

6.11.3 Braking Redundancy

In an autonomous vehicle, when the driver is removed from the control, the requirements for reliability increase significantly. The "redundant brake system" is an example for fail-operational back-up system. Electromechanical boosters are commonly used to increase brake pressure in case of a panic braking. Electromechanical booster brakes and Electronic Stability control Program (ESP) brake system can be used independently. In case one of two systems fail, the other system can take over the braking functions without the driver having to intervene. In a brake system designed for autonomous drive, electromechanical booster and ESP can modulate brake pressure independently so that no lock-up occurs, and vehicle can be steered while braking. Similarly, the brake system could be used as a back-up to the steering system by braking individual wheels to control the direction of the car, which is called differential braking.

6.11.4 Anti-Lock and Brake Assist Systems

ABS brakes are standard equipment on nearly all ground vehicles today. ABS systems are used to modulate driver's pedal effort to prevent lockups, particularly on slippery surfaces, so that stability and steerability of the vehicle is maintained during braking. ABS systems for air brakes and hydraulic brakes are very similar. Major components of an ABS are wheel speed sensors, an electronic control unit, and pressure modulation valves regulating brake pressure using electrical solenoids. In an autonomous system, the driver's pedal input is replaced by the vehicle control system and there is no significant difference between conventional systems and autonomous systems in term of modeling. In an autonomous system all ABS control algorithms can be integrated into the autonomous control system. Typically, ABS control algorithms have large set of look-up tables for different scenarios. Therefore, mobility assessment tools used to simulate autonomous vehicles should have proper interfaces for the ABS system models.

Various driver assistance algorithms have been developed based on classical anti-lock brake system hardware with the addition of various types of sensors and actuators. These systems mostly activated without the driver's control. In brake assist system, if the driver's effort is not sufficient in an emergency braking system, the brake line pressure is automatically increased to reduce the stopping distance. In traction control systems, wheel torques are modulated so that maximum tractive effort can be maintained particularly on slippery surfaces. Stability control systems are used to control the directional trajectory of the vehicle by increasing the brake pressure of the outer front or inner rear wheels when the under-steer or over-steer events are determined. Also, electronic differential locks are used to improve traction on μ-split conditions by applying brake pressure to the slipping wheel. These driver assistance systems are generally activated without the drivers input and modeling of these systems in autonomous vehicles does not have significant differences. Assessment tools used to simulate autonomous vehicles should have proper standardized interfaces for the driver assist systems.

6.12 MODELING OF VEHICLE SYSTEM SENSORS

Sensoring is one of the crucial areas of today's manned and unmanned vehicle research and engineering. As a part of control of maintenance of vehicle systems and systems of vehicles, sensors play a vital role in "vehicle being". From autonomous mobility view, sensors that are in use on autonomous vehicles can be split in two main groups:

1) Sensors of autonomous vehicle systems that are in use for controlling vehicle systems and, thus, vehicle movements.
2) Sensors that sustain autonomous features of the vehicle-environment interaction (i.e., navigation and localization, obstacle recognition, terrain and environment identification, etc.).

In the first group, which is the subject of this analysis, commonly used sensors include, but not limited to:

- A torque sensor and steering angle in the steering system.
- A suspension travel sensor, rollover sensor, yaw sensor, lateral acceleration sensor – all related to stability control.

- A sensor for controlling the tire inflation pressure and temperature, and tire radius sensors (mounted inside of tires).
- A wheel rotation velocity sensor (a part of the traction control, ABS, ESP).
- Sensors of drive axles and locking differentials (for controlling the oil level and temperature in energy efficiency controls, sensors to lock a differential, and timers for keeping a differential locked, etc.).
- Transmission sensors (for switching gears, controlling the oil characteristics, etc.).
- Engine sensors in various engine sub-systems.

During the past two decades, the concept of intelligent or smart tire has been transformed in a sustainable research direction. Consequently, additionally to the above-listed sensors of the tire inflation pressure, temperature, and tire radius, two new types of sensors emerged, including load-sensing wheel hubs and wheel force transducers. Conceptually, the load-sensing wheel hubs are based on either measuring wheel bearing deflections by employing strain gages or using eddy-current sensors. The load-sensing wheel hubs have been researched to estimate the tire-road grip properties and the tire side force. Measurement data gained on the tire-surface grip can be utilized to estimate autonomous mobility margins (see Section 1.2.2.1), and data on the tire side forces is important for autonomous estimation of the side-skid risk of autonomous vehicles. However, technical problems associated with an in-situ vehicle calibration of the load-sensing wheel hubs and negative impacts of elastic deformations of other axle components on the bearing deflections in the hubs demands to continue research studies in these directions.

The wheel force transducers can provide data on three forces and three moments at the axis of the wheel rotation. However, some main technical problems the transducers include an increased unsprung mass of the wheel, potential impacts on the brake mechanism packaging, and associated difficulties with air circulation in the brakes. The cost of the wheel force transducers is another factor that stops them from implementation on vehicles.

When employed on autonomous vehicles, designs of the above-presented vehicle sensors should provide the similar characteristics that sensors of conventional vehicles demonstrate. Requirements to sensor design typically embrace:

- Accuracy and errors;
- Precision and bias errors;
- Resolution and discrimination (how much input you need to get an output);
- Sensitivity;
- Linearity;
- Drift;
- Range;
- Repeatability and Robustness; and
- Dynamic characteristics of transient response.

Mathematical and computer models of the sensors for modeling vehicle mobility may be developed for modeling all or part of the above-listed characteristics. The level of the model complexity depends on the purpose of a vehicle model, a scenario for modeling a particular maneuver or a move of a vehicle, statistical analysis of vehicle movements on a march or when fulfilling a task/mission, AI-based learning process, etc. With that, there are new characteristics that sensors of autonomous vehicles should demonstrate and, hence, the models of the sensors should be capable to simulate.

Requirements to the modeling of autonomous vehicle sensors are formulated below based on the analysis of Table 6-1, in which five distinctive features of the autonomous vehicle models were presented. Indeed, the modeling of autonomous vehicle sensors should be adequate to severe unprepared terrain conditions, in which manned systems cannot operate. The sensor models should be capable to run in real time and to comply with different levels of autonomy. The vehicle systems sensors should enable AI-decision-making process of the vehicle mission planning and its implementation at the level of AI-based vehicle system controls. The vehicle sensor should not cause additional power losses due to autonomous operation of the vehicle; instead, the number of the sensors and the measurement data provided by the sensor models should be optimized to support a required vehicle mobility performance. The sensor models should match the modeling of agile maneuvering and mobility of vehicles on battlefields and in tactical and operational conditions.

To satisfy the above-listed requirements to the sensors, the following new characteristics of the autonomous vehicle sensors and their models are defined here as follows:

- Sensor Agility;
- Sensor Redundancy;
- Sensor Fusion; and
- Active Protection of Sensors from Environmental and Adversary Impacts.

A sensor should provide agile (i.e., a very fast and precise) real-time data flow (no time delays in signal data). The ensuring of adequate redundancy/duplication of sensors will increase reliability of autonomous vehicle controls. However, an increased redundancy should not be achieved by implementing extra sensors; instead, the same signal should be recovered from data obtained by other sensors. For this purpose, sensor fusion is considered as a core feature of autonomous vehicle sensors. A nonconformity of the signal of a sensor to its calibrated characteristic caused by an environmental or adversary effects may cause significant impact on movements of autonomous vehicles. For this reason, sensors should be actively protected from any potential damage to their operation process. If the destroyed signal cannot be recovered, it should be substituted with any other data available between the vehicle systems. The above-introduced four characteristics of sensors of autonomous vehicles are proposed for incoming investigations and studies within the AVT-341. Additionally, the redundancy and fusion characteristics can be considerably improved by developing observation techniques and observers that can estimate vehicle system parameters using data from vehicle sensors, quantify variables that cannot be directly measured by the sensors, and reduce the number of sensors while increasing the redundancy in signals.

6.13 OBSERVATION TECHNIQUES AND OBSERVERS

To provide a fast and precise control and improve performance of vehicle systems, it may require tire-terrain characteristics and other data, which cannot be directly measured due some technical and cost-effective reasons, e.g., absence of an appropriate sensor, inappropriate operational conditions that limit the usability of sensors, external electromagnetic fields that generate extra noise to distort and spoof sensor signals, high cost of some sensors, etc. In order to quantify variables that cannot be measured by sensors, different estimation and observation techniques and estimators/observers have been recently in use. It can be suggested that these techniques will receive further enhancements and developments as autonomous vehicles continue to mature. Thus, mathematical modeling and simulation of observation techniques and observers requires a special consideration.

An estimator is referred to as a system, in which state variables represent estimates of some other physical systems. The estimator implementation can be in an open-loop or closed-loop form; the closed-loop estimator term is used to refer to observers. An observer is represented by a mathematical algorithm that operates with known parameters and characteristics of a system and also sensor-based measurements to compute unknown variables in real time. Typically, an observer is a component of a control system that can be positioned in the feedback loop to provide the necessary information to the controller.

The basic idea of the observer can be described by Figure 6-32 [73]. Here, a plant with a controller and the sensors are in blue color. The sensors determine some states; however, the plant has internal states that cannot be measured directly. So, in order to determine these quantities, an observer can be used, which is in orange color. The observer consists of a mathematical model of the plant and using it can find measured and unmeasured values. That can be enough. However, the mathematical model usually is not accurate and only approximates the physical process in the plant. In order to eliminate this approximation error, the correction step is used where the predicted states from the model are corrected based on the error between predicted and available measurements. After the correction step, the estimated values are obtained that are some combinations between measurement and prediction.

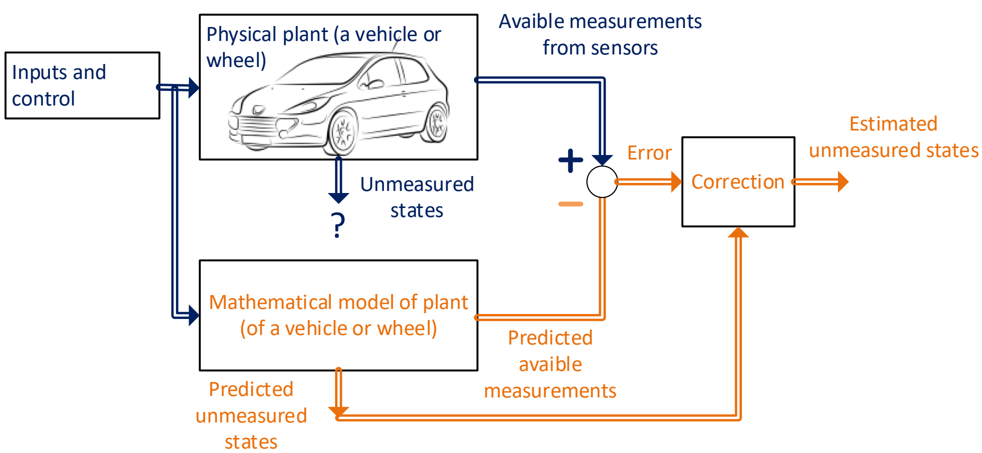


Figure 6-32: Observer Concept (Closed-Loop Form).

Usually, estimation approaches are divided into four groups, including kinematics model-based, dynamics model-based, combined kinematics-dynamics model-based and non-model-based (Figure 6-33).

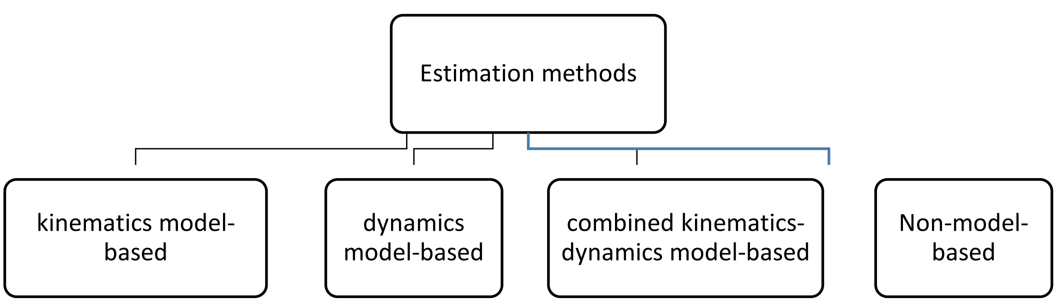


Figure 6-33: Groups of the Estimation Methods.

As an example of advantages that the observation-based approach can offer, Ref. [74] presents a method for a real-time estimation of the wheel dynamic normal reaction modeled in road and deformable terrain conditions with stochastic characteristics of the surface profile, the peak friction coefficient, the rolling resistance, and the tire-surface stiffness and damping. The novelty of the estimation method was founded on the reconstructing of the unknown disturbance input in the wheel equations. The input was introduced as the difference between the wheel normal reaction on a stochastic terrain and the wheel normal reaction on an even surface. Additionally, to the wheel dynamic normal reaction, the outputs of the observer included estimates of the relative displacement and velocities of the sprung and unsprung masses of the model.

The estimation method was implemented in an observer design that functions with use of only one sensor for measuring the relative displacement of the sprung and unsprung masses. Such a sensor was simulated as a magnetostrictive displacement sensor, which mathematical model contains a built-in measurement time delay and measurement noise. The virtual measurements of the sensor were validated against relative displacements computed from the differential equations of the locomotion module dynamics. The proposed observer was designed as a sliding mode observer. The accuracy of the wheel dynamic normal reaction estimation was validated on different terrains including dry asphalt, meadow, a snow road, and a soil field. A design method of the observer gains was derived from a condition of observer stability. As a numerical application of the method, the gains were determined for the observer designed for the open-link locomotion module. It is important to emphasize that the developed estimation method and the observer are terrain-free, i.e., they are applicable to any terrain and do not require any additional tuning of the gains when terrain conditions change. The terrain-free performance was achieved by excluding the stiffness and damping characteristics of the tire-terrain coupling from the observer's mathematical model. In addition, the estimation method is reasonable for its hardware implementation since its operation requires only one displacement sensor to measure the relative displacement of the sprung and unsprung masses.

It is proposed for the incoming AVT-341 to conduct studies on estimation techniques and observers for their contributions to the sensor signals in autonomous vehicles. In particular, an estimation of the following parameters and characteristics can facilitate autonomous vehicle path planning and mobility improvements [75]:

- 3D-tire forces (normal, longitudinal, and lateral tire reactions that can be used for 3D-vehicle dynamics estimation).
- Wheel torque and rotational velocities.
- Tire slippage.
- Pick friction coefficient.

6.14 FUTURE RTG WORK AREAS

Future RTG work areas in autonomous vehicle and system modeling and simulation is suggested to include, but not being limited to:

1) *Studying the formulated (5) distinctive features of autonomous vehicle models and vehicle system models related to*:
   - Environmental and terrain conditions that are much severe than dirt roads and unprepared terrain conditions where manned systems cannot operate.
   - Run time to enable AI- and model-based decision-making process with or without human inputs to comply different levels of autonomy.

- Simulating autonomous model-based vehicle system controls and interfacing with the AI-based mission planning and implementation.
- Adequately simulating power losses in the autonomous vehicle systems and the vehicle-terrain interaction and, hence, to assessing and autonomously controlling vehicle energy efficiency.
- Simulating and assessing autonomous agile maneuvering and mobility on battlefields in hyperactive conditions and in tactical and operational conditions.

2) *Assessing the autonomous vehicle capability to move through terrain in principle and estimating the vehicle ability to perform a task/mission*. In this regard, the mobility assessment methods should be functional for:

- Predicting *terrain mobility margins* of an autonomous vehicle during its motion, i.e., assessing the mobility state of a vehicle with regard to its immobilization state, and
- Estimating *terrain mobility performance* while the autonomous vehicle maintains certain mobility margins and performs its task/mission.

3) *Assessing Vehicle – AI – Operator interface models* with:

- Human driver models for mobility validation purposes.
- Simulation requirements for hand-over strategy (in shared control).
- Delays in taking-over in shared control.
- Faster than and slower than real-time simulation (e.g., needed for driver-in-the-loop tests).

4) *Selecting between the formulation of rigid MBD vehicle dynamics simulations and flexible body formulations in multi-body applications* for describing the state of the vehicle that depends on a particular autonomous mobility task. The choice of including body flexibility in multi-body simulations is primarily dictated by the balance between the necessary/desired accuracy for a given type of analysis and the ensuing (potentially significant) increased computational effort. The real-time simulation is a significant component of real-time mobility control technologies and can be included when needed while demonstrating characteristics of synchronization, timing, predictability, robustness and fault tolerance of a simulation. The above-listed reasoning is formulated with understanding that the vehicle modeling is a well-established field. There are many capable tools available and expertise. The flexibility of the available tools is important in modeling fidelity.

5) *Studying main requirements to the modeling of driveline systems of autonomous vehicles* that should be based on a mathematical method(s) that is capable to effectively model characteristics of various power-dividing units and, thus, to autonomously manage the power distribution between the driving wheels according to the autonomous navigation of the vehicle. The end goal of the autonomous management of the wheel power distribution should be to support required characteristics of mobility, maneuverability, and energy efficiency in coordination with the autonomously maintained trajectory path of the vehicle. Based on the technical complexity, drivetrain models were classified in three groups (see Section 6.6). It should be emphasized that requirements for the computation power vary to simulate different drivetrain models. The required computational power is the biggest for group 1. The less computational power is needed to simulate drivetrains from group 3. Mathematical models of autonomous vehicle mobility can integrate elements of types 2 and 3 models. This approach would allow for real-time simulations that might be needed for using the models in on-board real-time models for mobility assessment and controls.

6) *Modeling electric and hybrid-electric drivelines* with the purpose to make an extremely fast, exact and pre-emptive time response of the drivelines and, thus, to improve autonomous mobility by preventing an extensive tire slippage in severe dynamic changes of terrain. *Studying the flexibility and agility of delivering power individually to each wheel* that allows for significant mobility improvements, agile maneuvers, maintaining stability, and increased energy efficiency. *Introducing virtual driveline systems* to allow for emulating mechanical driveline generalized characteristics and, thus, to virtually connect the e-motor driveshafts and provide coordinated wheel power management to maximize mobility, maneuverability and energy efficiency of autonomous vehicles. *Modeling hybrid-electric drivelines* to improve autonomous vehicle mobility, maneuverability and energy efficiency by decoupling dynamic interferences of the driveline system with the steering system, suspension, and brakes.

7) *Modeling tires* in autonomous vehicles that should adapt to various operating conditions such as load, inflation pressure, temperature, coefficient of road adhesion, etc. and on-board generation of tire model parameters provide valuable information. *Sensing tire-terrain conditions* that are of great interest for autonomous vehicles from the mobility, vehicle dynamics and safety, and vehicle performance perspectives. Tire model parameters should be predicted for autonomous drive.

8) *Studying the complexity vs. simplifying assumptions in the modeling of the track locomotion system* to predict accurately tension variations along the track, transverse vibrations of track, and suspension system/surface wheel motion.

9) *Modeling ride quality* that can be important if the fulfilment of an autonomous vehicle mission/task requires a certain smoothness of ride. It is also essential to maintain a considerable tire patch for assuring high mobility and traction of autonomous vehicles. *Keeping the balance between the complexity and fidelity of suspension system models* is critical since autonomous vehicles plan their path in real time. *Modeling image and position information of the vehicle body* that is acquired in an autonomous vehicle to actively control vehicle body motions on an active suspension system. *Designing mobility assessment tools* to have proper interfaces with suspension models and co-simulation possibilities. *Requiring different control strategies* that need suspension intermediate variables' responses, such as the shock absorber temperature (which may affect the damping) response as well as different ways and frequency bandwidth to sense the wheel motions relative to chassis of autonomous vehicles.

10) *Modeling of steering systems* that could be an important consideration for autonomous vehicles. Manual or power-assisted steering systems could be completely replaced by electrical or hydraulic actuators for fully autonomous systems. Models might need to include additional sensors to detect user input. Rather than a standard steering wheel, additional control inputs (joysticks, etc.) might need to be considered. Real-time simulation would also be a requirement for human-in-the-loop simulation.

11) *Modeling of traction/mobility controls and ABS* of autonomous vehicles with partially or completely replaced drivers that should be controlled considering the stopping distance and stability of the vehicles. *Simulating autonomous vehicles* that should have proper interfaces with the driver assist systems. *Redundancy of brake systems in autonomous vehicle models* that is a reliability requirement.

12) *The modeling of autonomous vehicle sensors* that should be adequate to severe unprepared terrain conditions, in which manned systems cannot operate. The sensor models should be capable to run in real time and to comply with different levels of autonomy. The vehicle systems sensors should enable AI-decision-making process of the vehicle mission planning and its implementation at the level of AI-based vehicle system controls. The vehicle sensor should not cause additional power losses due to autonomous operation of the vehicle; instead, the number of the sensors and the measurement data

provided by the sensor models should be optimized to support a required vehicle mobility performance. The sensor models should match the modeling of agile maneuvering and mobility of vehicles on battlefields and in tactical and operational conditions. To satisfy the above-listed requirements to the sensors, the following new characteristics of the autonomous vehicle sensors and their models are defined here as follows:

- Sensor Agility;
- Sensor Redundancy;
- Sensor Fusion; and
- Active Protection of Sensors from Environmental and Adversary Impacts.

The modeling and simulating of vehicle sensors conducted together with the path planning that can have different requirements for fidelity of the vehicle system and sensor models. Different use cases might require different numbers of test runs, which would place limitations on computational cost.

13) *The modeling of estimation and observation techniques and estimators/observers* that can provide require tire-terrain characteristics and other data, which cannot be directly measured due some technical and cost-effective reasons. The reasons may include the absence of an appropriate sensor, inappropriate operational conditions that limit the usability of sensors, external electromagnetic fields that generate extra noise to distort and spoof sensor signals, high cost of some sensors, etc. *The estimating of the following parameters and characteristics can facilitate autonomous vehicle path planning and mobility improvements*:

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- Pick friction coefficient.

6.15 REFERENCES

[1] US Army Robotic and Autonomous Systems Strategy, 2017. Available at: https://www.tradoc.army.mil/portals/14/documents/ras_strategy.pdf. Accessed November 2019.

[2] Joint Combined Arms Maneuver in the 21st Century, 2017. Available at: https://www.tradoc.army.mil/Portals/14/Documents/MDB_Evolutionfor21st.pdf. Accessed January 2021.

[3] Bekker, M.G., and Butterworth, A.V., 1965. Terrain-Vehicle System Evaluation. J. Terramech. 2 (2), 47-67. Available at: http://dx.doi.org/10.1016/0022-4898(65)90072-8.

[4] Parry, S.H., 1975. Studies of Mobility, Agility, and Survivability in the Land Combat Environment. Naval Postgraduate School, Technical Report ADA020052, September 1975.

[5] Martin, L.E., and Niemeyer, W.A., 1977. A Mobility Analysis of Vehicles Participating in S-Tank Agility-Survivability (STAGS) Testing. Army Materiel Systems Analysis Activity, Technical Report ADA053731, September 1977.

[6] Rohani, B., and Baladi, G.Y., 1982. Steerability Analysis of Tracked Vehicles on Soft Soil: Theoretical Predictions versus Field Measurements. US Army Engineer Waterways Experiment Station, Technical Report ADA117834, June 1982.

[7] Defense Advanced Research Projects Agency Tactical Technology Office, 2014. Broad Agency Announcement, Ground X-Vehicle Technologies Program Technology Development. DARPA-BAA-14-50, October 7, 2014.

[8] Vantsevich, V.V., 2014. Agile Dynamics Fundamentals for Tire Slippage Modeling and Control. ASME DETC2014-34464, August 17 – 20, Buffalo, NY. Available at: http://dx.doi.org/10.1115/DETC2014-34464.

[9] Gray, J.P., Vantsevich, V.V., and Overholt, J.L., 2013. Indices and Computational Strategy for Unmanned Ground Wheeled Vehicle Mobility Estimation and Enhancement. ASME DETC2013-12158, August 4 – 7, Portland, OR. Available at: http://dx.doi.org/10.1115/DETC2013-12158.

[10] Gray, J.P., Vantsevich, V.V., Opeiko, A.F., and Hudas, G.R., 2013. A Method for Unmanned Ground Wheeled Vehicle Mobility Estimation in Stochastic Terrain Conditions. In: 7th Americas Regional Conference of the ISTVS, November 4 – 7, Tampa, FL. Available at: http://dx.doi.org/10.13140/2.1.2106.5922.

[11] Andreev, A.F., Kabanau, V.I., and Vantsevich, V.V., 2010. Driveline Systems of Ground Vehicles: Theory and Design. In: Vantsevich, V.V., Scientific and Engineering Editor (Ed.). Taylor and Francis Group/CRC Press, 758, (ISBN 978-1-4398-1727-8).

[12] Zhao, L., and Vantsevich, V.V., 2019. A Robust Estimation of Dynamic Normal Reaction for Open-Link Locomotion Module, International Journal of Vehicle System Dynamics.

[13] Platonov, V.F., 1989. All-Wheel Drive Automobiles, 2nd edition. Mashinostroenie, Moscow, 1989.

[14] Sadigh, D., Driggs-Campbell, K., Bajcsy, R., S., Sastry, S., and Seshia S., 2014. User Interface Design and Verification for Semi-Autonomous Driving. In Proceedings of the 3rd International Conference on High Confidence Networked Systems (HiCoNS '14). ACM, New York, NY, USA, 63-64. Available at: http://dx.doi.org/10.1145/2566468.2576851.

[15] Sokolsky, O., and Pappas, G., 2004. Platform-Independent Autonomy Modeling. Departmental Papers (CIS).

[16] Yurtsever, E., Lambert, J., Carballo, A. and Takeda, K., 2019. A Survey of Autonomous Driving: Common Practices and Emerging Technologies. arXiv preprint arXiv:1906.05113.

[17] Carsten, O., and Martens, M.H., 2019. How Can Humans Understand their Automated Cars? HMI Principles, Problems and Solutions. Cognition, Technology & Work., 1435-5566.

[18] Gold C., and Bengler K., 2014. Taking Over Control from Highly Automated Vehicles. Advances in Human Aspects of Transportation: Part II 8 (2014), 64.

[19] Martens, M.H., and van den Beukel, A.P., 2013. The Road to Automated Driving: Dual Mode and Human Factors Considerations. In Intelligent Transportation Systems – (ITSC), 2013 16th International IEEE Conference on. 2262-2267.

[20] Damböck, D., Bengler, K., Farid, M., and Tönert, L., 2012. Übernahmezeiten beim hochautomatisierten Fahren. Tagung Fahrerassistenz. München 15 (2012), 16.

[21] Gold, C., Damböck, D., Lorenz, L., and Benglerk, K. 2013. "Take Over!" How Long Does it Take to Get the Driver Back into the Loop? Proceedings of the Human Factors and Ergonomics Society Annual Meeting 57, 1 (2013), 1938 – 1942.

[22] Walch, M., Lange, K., Baumann, M. and Weber, M., 2015. Autonomous Driving: Investigating the Feasibility of Car-Driver Handover Assistance. Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, ACM, September 2015, 11 – 18.

[23] Shabana, A.A., 2005. Dynamics of Multibody Systems, 3rd ed. Cambridge University Press, 2005.

[24] Craig, R.R., 1981. Structural Dynamics: An Introduction to Computer Methods. John Wiley & Sons, 1981.

[25] Simo, J.C., 1985. A Finite Strain Beam Formulation. The Three-Dimensional Dynamic Problem. Part I. Computer Methods in Applied Mechanics and Engineering, 49, 1 (1985), 55-70.

[26] Shabana, A.A., 1997. Flexible Multibody Dynamics: Review of Past and Recent Developments. Multibody System Dynamics 1, 2 (1997), 189-222.

[27] Sopanen, J.T., and Mikkola, A.M., 2003. Description of Elastic Forces in Absolute Nodal Coordinate Formulation. Nonlinear Dynamics, 34, 1 (2003), 53-74.

[28] Nachbagauer, K., 2014. State of the Art of ANCF Elements Regarding Geometric Description, Interpolation Strategies, Definition of Elastic Forces, Validation and the Locking Phenomenon in Comparison with Proposed Beam Finite Elements. Archives of Computational Methods in Engineering 21, 3 (2014), 293-319.

[29] Andreev, A.F., Kabanau, V.I., and Vantsevich, V.V., Driveline of Ground Vehicles: Theory and Design. In: Vantsevich, V.V., Scientific and Engineering Editor (Ed.). Taylor and Francis Group/CRC Press, ISBN 978-1-4398-1727-8.

[30] Republic of South Africa (RSA) Military Standards Steering Committee (RMSS), 2006. Handbook for Wheeled Vehicle Mobility, Design and Evaluation Of, RSA-MIL-HDBK-62 Issue 2, January 2006, Publisher Armscor South Africa.

[31] Vantsevich, V.V., 2014. Agile Dynamics Fundamentals for Tire Slippage Modeling and Control, DETC2014-34464, ASME 16th International Conference on Advanced Vehicle Technologies, Buffalo, NY, August, 2014.

[32] Gray, J.P., Vantsevich, V.V., and Paldan, J., 2016. Agile Tire Slippage Dynamics for Radical Enhancement of Vehicle Mobility, Journal of Terramechanics, 65, 2016, 14-37, DOI: 10.1016/j.jterra.2016.01.002.

[33] Zhang, S., Salama, M.A., and Vantsevich, V.V., 2019. Response Time Analysis of the Electric Driveline of an Open-Link Locomotion Module, ISTVS 15th European-African Regional Conference, Prague, Czech Republic, September 9 – 11.

[34] Vantsevich, V.V., Gorsich, D., Paldan, J., and Letherwood, M., 2020. Virtual Driveline Concept to Maximize Mobility Performance of Autonomous Electric Vehicles, SAE Congress, 2020 (accepted).

[35] Vantsevich, V.V., 2014. Vehicle System Dynamics. Coupled and Interactive Dynamics Analysis, International Journal of Vehicle System Dynamics, Volume 51, Issue 11, 2014, 1489-1516. doi: 10.1080/00423114.2014.944869.

[36] Vantsevich, V.V., and Paldan, J.R., 2014. 4x4 SUV Energy Efficiency: Hybrid-Electric Transfer Case vs. Mechanical Driveline Systems, DETC2014-34245, ASME 16th International Conference on Advanced Vehicle Technologies, Buffalo, NY, August.

[37] Vantsevich, V.V., Paldan, J.R., and Farley, B.K., 2016. Mobility Optimization and Control of a 4x4 HE-Vehicle in Curvilinear Motion on Stochastic Terrain, ASME 17th International Conference on Advanced Vehicle Technologies, Charlotte, NC, August, 2016.

[38] Farley, B. K., Paldan, J.R., and Vantsevich, V.V., 2016. Mobility vs. Energy Efficiency of a 4x4 Hybrid-Electric Vehicle with An Active Driveline System, 2016 ISTVS Conference, Detroit, September 12-14.

[39] Vantsevich, V.V., and Dersjö, J., 2016. 6x6 Terrain Articulated Truck: Driveline – Suspension Coupled Dynamics and Energy Efficiency Evaluation. 2016 ISTVS Conference, Detroit, September 12 – 14.

[40] Vantsevich, V.V., Gorsich, D., Lozynskyy, A., Demkiv, L., and Klos, S., 2019. A Reinforcement Learning Enhanced Fuzzy Control for Real-Time off-Road Traction System, IAVSD 2017 International Symposium on Vehicle Dynamics, Paper #154, Gothenburg, Sweden, August 12 – 16.

[41] SAE Standards, J670, SAE International, 2008.

[42] Pacejka, H.B., and Besselink, I., 2012. Tire and Vehicle Dynamics, (Third Ed.), Elsevier.

[43] Bakker, E., Nyborg, L., and Pacejka, H.B., 1987. Tyre Modelling for Use in Vehicle Dynamics Studies. SAE Technical Paper 1987, 870421.

[44] Heydinger, G.J., Garrott, W.R., and Chrstos, J.P., 1991. The Importance of Tire Lag on Simulated Transient Vehicle Response. SAE Technical Paper 1991, 910235.

[45] Besselink, I.J.M, Schmeitz, A.J., and Pacejka H.B., 2010. An Improved Magic Formula/Swift Tyre Model That Can Handle Inflation Pressure Changes. Vehicle Syst Dyn 2010, 48(S1), 337-352.

[46] Schuring, D., Pelz, W., and Pottinger, M., 1993. The BNPS Model – An Automated Implementation of the "Magic Formula" Concept, SAE Technical Paper 931909, 1993, DOI: 10.4271/931909.

[47] Kuiper, E., Van and Oosten, M., (2007) The PAC2002 Advanced Handling Tire Model, Vehicle System Dynamics, 45:sup1, 153-167, DOI: 10.1080/00423110701773893

[48] López, A, Olazagoitia, J.L., Marzal, F., and Rubio, M.R., 2018. Optimal Parameter Estimation in Semi-Empirical Tire Models. Proc IMechE Part D: J Automobile Engineering, 2018, 1-15.

[49] Wong, J.Y., 2008. Theory of Ground Vehicles, (Third Ed.), John Wiley & Sons.

[50] Fiala, E. (1954). 'Seitenkräfte am rollenden Luftreifen'. VDI-Zeitschrift 96, p. 973. (In German).

[51] Pearson, M., Blanco-Hague, O., and Pawlowski, R., 2016. TameTire: Introduction to the Model, Tire Science and Technology, TSTCA, 44(2), April – June 2016, 102-119.

[52] Gipser, M., 2005. F. Tire: A Physically Based Application-Oriented Tyre Model for Use With Detailed MBS and Finite-Element Suspension Models. Vehicle System Dynamics, 43(sup1), 76-91, DOI: 10.1080/00423110500139940.

[53] Gallrein, A., and Bäcker, M. (2007) CDTire: A Tire Model for Comfort and Durability Applications, Vehicle System Dynamics, 45:S1, 69-77, DOI: 10.1080/00423110801931771

[54] Ortel, C., and Fandre A., 1999. Ride Comfort Simulations and Steps Towards Lifetime Calculations: RMOD-K and ADAMS, International ADAMS Users' Conference, Berlin.

[55] Ammon, D., 2005. Vehicle Dynamics Analysis Tasks and Related Tyre Simulation Challenges. Vehicle Syst. Dyn. 43 (1) (2005), 30-47.

[56] Ma, Z.D., and Perkins, N.C., 2002. A Track-Wheel-Terrain Interaction Model for Dynamic Simulation of Tracked Vehicles, Vehicle System Dynamics, 37(6), 401-421.

[57] Ma, Z.D., and Perkins, N.C., 2006. A Super-Element of Track-Wheel-Terrain Interaction for Dynamic Simulation of Tracked Vehicles, Multibody System Dynamics, May 2006, 15(4), 347-368.

[58] Sandu, C., and Freeman, J.S., 2005. Military Tracked Vehicle Model. Part I: Multibody Dynamic Formulation, International Journal of Vehicle Systems Modelling and Testing, 1(1/2/3), 48-67.

[59] Rubinstein, D., and Hitron, R., 2004. A Detailed Multi-Body Model for Dynamic Simulation of Off-Road Tracked Vehicles, Journal of Terramechanics, 41(2-3), 163-173.

[60] Ryu, H., Choi, J., and Bae, D., 2006. Dynamic Modeling and Experiment of Military Tracked Vehicle, SAE Technical Paper 2006-01-0929, SAE 2006 World Congress & Exhibition.

[61] Wasfy, T.M., and O'Kins, J., 2009. Finite Element Modeling of the Dynamic Response of Tracked Vehicles, ASME Paper No. DETC 2009-86563, ASME International Design Engineering Technical Conferences, 7th International Conference on Multibody Systems, Nonlinear Dynamics, and Control, San Diego, CA.

[62] Madsen, J., Heyn, T., Negrut, D., and Lamb, D., 2010. GPU-based High Performance Parallel Simulation of Tracked Vehicle Operating on Granular Terrain, SAE 2010 World Congress and Exhibition Detroit, MI.

[63] ADAMS, MSC Software. Available at: https://www.mscsoftware.com/product/adams. Accessed Nov. 2019.

[64] Recurdyn, Function Bay. Available at: https://www.functionbay.org/flexible-multibody-dynamics-software.html. Accessed November 2019.

[65] Simcenter 3D, Siemens. Available at: https://www.plm.automation.siemens.com/global/en/products/simcenter/simcenter-3d.html, Accessed Nov. 2019.

[66] Chrono. Available at: https://projectchrono.org/, Accessed Nov. 2019.

[67] DIS, Advanced Science and Automation Corp. Available at: http://www.ascience.com/, Accessed Nov. 2019.

[68] Wasfy, T.M., Yildiz, C., Wasfy, H.M., and Peters, J.M., 2016. Effect of Flat Belt Thickness on Steady-State Belt Stresses and Slip, ASME Journal of Computational and Nonlinear Dynamics, 11(5).

[69] United Nations Economic Commission for Europe, 2016. Regulation No. 13 of the Economic Commission for Europe of the United Nations (UN/ECE) – Uniform Provisions Concerning the Approval of Vehicles of Categories M, N and O with Regard to Braking.

[70] Automotive Simulation Models (ASM), D-space, e-book. Available at: http://www.dspace.com. Accessed November 2019.

[71] Limpert, R., 2011. Brake Design & Safety, SAE International; 3rd Edition.

[72] National Highway Traffic Safety Administration, 2009. Federal Motor Vehicle Safety Standards No. 121, 2009. Air Brake Systems.

[73] Vantsevich, V.V., Gorsich, D., Lozynskyy, A., Demkiv, L., and Borovets, T., 2019. State Observers for Terrain Mobility Controls: A Technical Analysis, 2019 IFToMM Congress, Krakow, Poland.

[74] Zhao, L., and Vantsevich, V.V., 2019. A Robust Estimation of Dynamic Normal Reaction for Open-Link Locomotion Module, International Journal of Vehicle System Dynamics, DOI: doi.org/10.1080/00423114.2019.1627468.

[75] Vantsevich, V.V., Gorsich, D., Lozynskyy, A., Demkiv, L., and Borovets, T., 2018. State Observers: An Overview and Application to Agile Tire Slippage Dynamics, 2018 Asia-Pacific ISTVS Conference, July 11 – 13.

Chapter 7 – SOFTWARE, HARDWARE, DATA, AND COMMUNICATION

7.1 GOALS AND TEAM MEMBERS

Thrust Area 4 (TA4), Simulation Software Requirements, seeks to describe the requirements for software tools used in the simulation of autonomous ground vehicles. Simulation can have a variety of purposes, from autonomy software development to fielded system maintenance. Even within a given purpose the simulation needs can vary depending on the focus. Developing a user interface for an autonomous system has significantly different simulation requirements compared with environment perception, for instance. Given the wide range of uses, no software is likely to meet every need. This chapter discusses what characteristics make for a good ground autonomy simulation software.

The team members are shown below:

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7.2 INTRODUCTION

Technologies to enable passenger [1] and military [2], [3] autonomous ground vehicle operation are currently being developed. Significant progress in the development of these technologies has been possible using real-world data. However, many groups have recognized the need for increased simulation to reach the desired level of system capability, reliability, and safety [4]. The area of autonomous ground vehicles is large with many opportunities for simulation. This chapter focuses on software that simulates real-world inputs and outputs such as sensors (e.g., Lidar) and vehicles. These software tools, either by themselves or working with other software tools, should allow an autonomy software to function similarly to the way it will on the physical vehicles.

7.3 VEHICLE AUTONOMY SOFTWARE

Before discussing the characteristics of the simulation software, it is necessary to first discuss the autonomy software itself. It is essential for the vehicle autonomy software to be designed such that it can run in many simulation configurations, rather than only on an operating vehicle. Simulation software provides no value if the autonomy software is incompatible. Creating a simulation-compatible autonomy software requires planning, and may impose costs on the autonomy developer, such as additional software development. The benefits of simulation compatibility, however, are significant. For example, the capability to perform automated regression testing of the autonomy software for numerous scenarios is faster and cheaper than similar physical tests. Without simulation it may be impossible to have sufficient confidence in the performance of a given autonomy software.

7.3.1 Desired Characteristics

- Autonomy provider-supported operation of software in simulation.
- Able to operate at varied clock speeds (slower or faster than real-time).
- Internal software states should be available for inspection (e.g., control signals, sensor fusion, etc.).
- Able to operate on varied hardware types, including virtual machines (e.g., x86/64 architecture, embedded processor, etc.).
- Capable of operating in multiple configurations (e.g., software/hardware, vehicle in-the-loop, etc.).
- Available interface control document for communication with outside sensors/controllers/etc.

7.3.2 Benefits of Simulation Compatibility

Having an autonomy provider consider the needs of simulation, and support operation in simulation, can provide significant benefits to many communities. Many groups, from the autonomy provider itself, to the autonomy system maintainer, need to extensively evaluate the autonomy software. Depending on the type of evaluation, live testing may be infeasible due to the number of test cases, level of danger involved, or the availability of the desired environmental conditions. Simulation also increases the ability to inspect the autonomy live operation software performance.

Compatibility with real-time simulation software can address these limitations. In addition to compatibility with real-time simulation software, the autonomy software should also be compatible with faster and slower than real-time simulation. Faster than real-time facilitates large numbers of simulation runs, while slower than real-time improves compatibility with high fidelity simulations unable to operate at real-time. For the autonomy software to be capable of performing large numbers of runs, it will need to be compatible with varied hardware types, such as cluster computers with x64 architectures. If the autonomy software can only be run on embedded hardware, for instance, then it may not be able to scale to the number of simultaneous simulation runs necessary.

Depending on the purpose of a given test, the autonomy software may need to be run in software-in-the-loop, hardware-in-the-loop, or vehicle-in-the-loop configurations. Allowing for an entirely software-based simulation provides significant opportunities, such as evaluating pre-production sensors, but requires the most consideration by the autonomy provider. Many physical systems that will not be present in such a test, such as the vehicle's drive-by-wire kit, will either need to be emulated or accounted for in the autonomy software. The autonomy software must also be compatible with simulated vehicle components, such as sensors. The autonomy software should have configuration settings, available to the simulation group, required to facilitate these varied operating modes. Since the groups performing the simulation may not be the same as the autonomy provider, detailed user and development documentation of the autonomy software must be available.

7.3.3 Benefits of Testing Using Simulation

Having the autonomy software be compatible with simulation has many benefits which vary depending on the setting. While the autonomy software is still in early development, software programmers have simulation needs that are different from those for fielded vehicle maintenance. The following provides some examples of the benefits of enabling simulated testing by the autonomy software.

7.3.3.1 Autonomy Software Development

Software developers are responsible for creating autonomy software that can greatly benefit from simulation. Simulation provides opportunities to shorten the development cycle of coding, testing, and evaluating the autonomous vehicle compared to relying entirely on physical tests. Increasing the speed of code evaluation can lead to improvements in the robustness and reliability of the autonomy software, while reducing development costs. Whenever a change is made to the autonomy code, regression tests can be performed in simulation to provide assurance no new errors or issues have been introduced. Simulation also allows for evaluation of scenarios which are difficult to perform in real-life; a test may be too hazardous to humans or may be difficult to recreate.

7.3.3.2 Safety Testing

Safety organizations are responsible for determining the safety risks associated with a given autonomy software. Autonomous driving contains too many variables and states to be able to evaluate all possible outcomes analytically, as may be possible with simpler software technologies. Instead, organizations are likely to require large amounts of test data to evaluate safety. Given the time and costs associated with real-world testing, simulation may be necessary to evaluate safety with sufficient confidence. Simulation provides an opportunity to greatly increase the number of scenarios, distance, and amount of time for which a given autonomy software is evaluated. Organizations can also intentionally search for edge cases or anomalies which may produce unsafe operation in a reasonable amount of time without risk to human life. If poor system performance is observed in real-life operation, simulation may be used to recreate or replay real data as a means for inspecting the internal operation of the autonomy software.

7.3.3.3 System Integration

System integrators are responsible for building an autonomous vehicle or integrating new components onto an existing vehicle. Integrators may be responsible for integrating an autonomy software onto an existing platform. Integrators need to be able to evaluate the compatibility of vehicle system components with the autonomy software. Much of this evaluation can be performed in simulation first, then with hardware in the loop, and finally on the vehicle. Evaluation in simulation can save time but may also be necessary if the physical item is not yet available. System integration may be necessary whenever new features are desired which require new components. This task requires the autonomy software provider has a complete interface control document available for the integration group.

7.3.3.4 Procurement

Procurement organizations are responsible for selecting which product will be purchased. These organizations frequently need to evaluate proposals before a physical article has been produced. Simulation provides an opportunity to evaluate products, including autonomy software, before a complete vehicle has been produced. Using identical simulation environments may provide a fair means for evaluating autonomy software from multiple providers. Simulation may assist in evaluating future technologies, such as determining whether a sensor with more range would provide significant performance gains for an existing autonomy software.

7.3.3.5 System Maintenance

System maintainers ensure a vehicle continues to perform up to its specifications. If a vehicle is operating poorly, a maintainer must find the source of the problem and perform a suitable fix. By recreating or replaying data from an observed incident in simulation, a maintainer may better be able to diagnose an issue. Simulation can also be used to evaluate individual components, such as determining whether a sensor is malfunctioning. Once the problem is identified and corrected, simulation can be used to evaluate whether the fix has adequately corrected the problem. Testing first in simulation can improve repair times, increase human safety, and reduce costs.

7.4 MODULARITY AND EXTENSIBILITY

Modularity refers to the principle of building a system from independent, linkable components. A modular architecture allows for large simulation goals to be accomplished through the interactions of many small software programs each performing a specialized function. Software programs that perform the same general function can be interchanged based on the needs of the simulation if the software interfaces are common. Extensibility refers to the ability to expand the capabilities and functionality of a given simulation software. A software cannot be designed to meet all future needs initially. When a new need is identified that a software cannot perform, an extensible design will allow for new functionality to be implemented without changing the core of the software.

7.4.1 Desired Characteristics

- Be composed of a component and/or plugin system to allow for expanding/detracting/upgrading features.
- Be user-extensible to add additional software capabilities (e.g., vehicles/sensors/controller/etc.).
- Define a minimum set of components required for an autonomy sub-system simulation (e.g., simulate only sensor models for evaluation of a perception sub-system).
- Define and minimize dependencies between components.

7.4.2 Impacts of Simulation Complexity

No single autonomy simulation software is likely to contain every feature and capability that is desired of a given user. The desired features and capabilities are also likely to change over time. As the complexity of a simulation increases, the number of features required of the software also increase. Modularity and extensibility are means to ensuring the desired simulation can be performed through a combination of software modules and extensions.

7.4.2.1 External Vehicle Communication

A software may be capable of simulating a single ground vehicle operating autonomously without any modifications. The same software may later be expected to simulate a fleet of autonomous vehicles communicating among one another. A modular software would allow for the addition of external communication, for example between the simulation software and another program. An extensible software would enable use of a proprietary communication protocol required by the autonomy software. Autonomous vehicles can require external communication with many systems, such as infrastructure (V2I, Vehicle to Infrastructure), vehicles (V2V, Vehicle to Vehicle), and controllers. Each communication method may require a new module to enable the particular communication method, which will need to be extensible to handle their particular communication protocols.

7.4.2.2 Data Input/Output

A software may provide a graphical interface for creating simulation assets (e.g., vehicles), which can be advantageous for some users. In some situations, a user may want to import assets that were created by another program. A modular software would allow for the addition of importing assets. An extensible software would enable use of a specific file format required by an outside program. This applies to importing assets, exporting assets, exporting simulation results for analysis, and many other data file input/output scenarios. Other data input/output scenarios are also applicable, such as supporting input/output of simulation sensor model data. One common scenario is the desire to input data from real sensor hardware into a simulated environment.

7.4.2.3 Auxiliary Functions

A software may be capable of simulating the core functions required for an autonomous ground vehicle, however new auxiliary functions may later become necessary. A modular software would allow for the addition of non-mobility features, such as simulation of weapons ballistics or unmanned aerial vehicles. An extensible software would enable use of a specific weapon or aerial vehicle in the simulation. Additional auxiliary functionality can include additional entities or actors, whether friendly or hostile, ground vehicle interaction with fluids, and many more.

7.4.2.4 Fidelity

A software must balance simulation fidelity with computation limitations based on the overall simulation goals. Higher fidelity simulations generally require more computation resources and reduce computation speed. A modular software provides the option of choosing low or high fidelity components based on the simulation goals. When evaluating interactions between a human operated controller and an autonomous vehicle, real-time operation is critical. In this situation a lower-fidelity sensor simulation module may be used. The core of the simulation software should not need to change, just the sensor module. An extensible software would help ensure the sensor module is compatible with the larger simulation software.

7.4.3 Impacts of Simulation Application

A modular and extensible software architecture can allow a software to support simulation for many use cases, even though the software requirements may vary among use case. The following are examples of likely use cases for autonomy simulation software, which benefit from a modular and extensible architecture.

7.4.3.1 Autonomy Software Development

One may want to evaluate a variety of perception, planning, and control algorithms when developing an autonomous vehicle. A modular architecture can allow for the algorithms to be interchanged without modifying other portions of the software, such as the virtual environment. As new sensors are developed a simulation software may not be able to support the sensor input requirements of a given algorithm. Extensibility can allow one to adapt and update the simulation software to meet the needs of any given algorithm.

7.4.3.2 Safety Testing

Before autonomy software can be used in a production vehicle, or given to soldiers in the field, it must first be evaluated for safety. To have confidence in the safety of the software, the system must be evaluated for many miles, hours, and varying scenarios. Given the limitations on time and cost, full vehicle hardware testing is likely insufficient. A common approach is to test the autonomy software in a range of software-in-the-loop, hardware-in-the-loop, and vehicle-in-the-loop System Integration Labs (SILs). A modular simulation architecture can allow the simulation software to support all of these evaluation methods, allowing for simulated components to be replaced with hardware and vice versa. This capability is particularly beneficial as new versions of the autonomy software are released. An extensible software can make it easy for a tester to create new scenarios to fully evaluate the autonomous system. Modularity and extensibility are necessary for a simulation software to sufficiently test autonomous systems with the necessary miles, time, and edge cases.

7.4.3.3 System Integration

During autonomous vehicle development and sustainment new components may need to be integrated into the system, such as new perception sensors. A modular simulation architecture can allow the autonomy software to be developed, integrated, tested, and maintained using software and hardware-in-the-loop SILs where vehicle components can be interchanged and replaced with simulated or real hardware as needed. An extensible software will make it possible to model new components or integrate new hardware as they are developed.

7.4.3.4 Procurement

The program management office for a Program of Record may need to evaluate autonomy solutions from multiple vendors. A modular simulation architecture may be able to replace components in the overall simulation, including the autonomy algorithms, without requiring entirely unique simulations for each vendor. This is also important to enable consistency between vendors for evaluation. An extensible architecture will enable necessary vendor-specific modifications required to support each autonomy software.

7.4.3.5 System Maintenance

A Program of Record may modify the vehicle or software after the initial procurement. A modular simulation architecture allows for evaluation of new algorithms (software) or hardware before purchase, while also helping with integration. A repair may also be evaluated in simulation before performing physical testing.

7.5 SCALABILITY

Scalability is the ability to simulate large systems, and to do so without proportionally requiring more computing resources, such as faster processor speeds or increased computer memory. Scalability can be organized into two groups: horizontal and vertical. Horizontal scalability relates to the size of the system: the number of vehicles, size of the terrain, number of dynamic obstacles, etc. Vertical scalability relates to the fidelity of the system: simple or complex ray-casting camera sensor, simple or complex vehicle dynamics, etc. In order to achieve the desired scale of a given simulation, the software may need to provide trade-offs to the user through capability settings (Figure 7-1). A software's modularity and extensibility can also assist with scalability by providing the option to swap low and high fidelity components as needed.

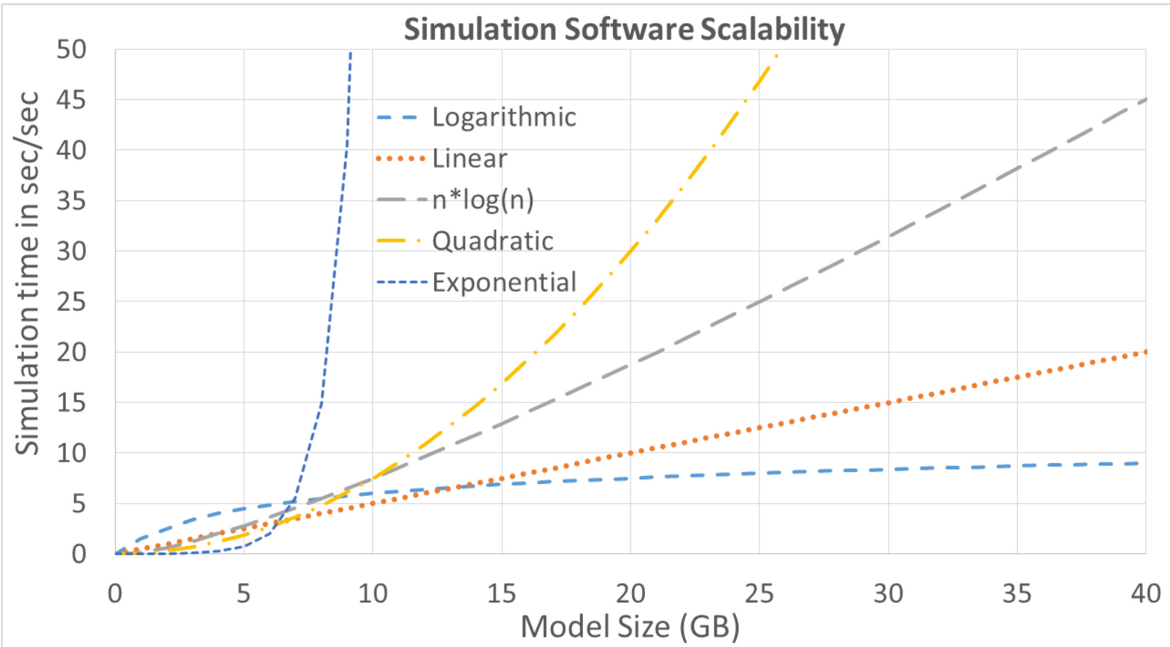

Figure 7-1: Simulation Software Scalability.

7.5.1 Desired Characteristics

- Scale with scenario complexity (e.g., number of vehicles, environment size, actor complexity, etc.).
- Provide options for trading between simulation fidelity and simulation speed (e.g., simulation step size, rendering, sensor, vehicle dynamics, etc.).
- Support forced real-time execution.
- Scalability, measured as a ratio of the total simulation size versus the simulation time, better than linear (e.g., logarithmic).

7.5.2 Common Techniques to Improve Scalability

The following are some common techniques for improving software scalability:

- Level-of-detail: Generate objects at different levels of detail. The closer an object is to the viewer, the higher the level-of-detail.
- Progressive loading: Only simulate objects which are close enough to affect the result of the simulation.

- Offload far objects: Unload, freeze, or do not process far away objects.
- Offload hidden objects: Do not visualize objects which are hidden from view.
- Offload objects outside the field of view: Do not visualize objects outside the field of view.
- Caching frequently used objects: Frequently used objects can be stored in memory rather than loaded from the disk.
- Distributed-memory parallel processing: Distribute the elements of a simulation among multiple computers, which communicate with one another, such that each computer has a reduced computational load.
- Shared-memory parallel processing: Share computation of the simulation with multiple processor cores.

7.5.3 Impacts of Simulation Application

Software scalability improves the likelihood that the same simulation software can be used for many purposes. If a software is horizontally scalable then it can be used to simulate both large and small systems. Autonomy developers can use the software tool for regular evaluation of code updates, while safety testers can use the same software for large scale vehicle formation evaluations. If a software is vertically scalable then it can be used to simulate both complex and simple models. Autonomy developers can use the software tool to evaluate perception algorithms with detailed sensor models, while safety testers can use the same software with simpler sensor models to evaluate an autonomy command and control software.

Some users may require high fidelity models, such as autonomy developers, while other may require fast performance to perform high numbers of simulation runs, such as safety testers. Both types of users could have difficulty finding computation hardware resources available to meet their needs if the simulation software is notscalable.

7.6 PORTABILITY

Portability relates to the ability for a software to be used on a range of computer systems, and the ease to which a user is able to operate the software. The simulation software should not dictate a user's computation environment and should not impose substantial burdens on new users. Outside forces, such as autonomy software requirements and available computation resources may impose constraints on the simulation software. The software should be a tool that is useful to a wide range of users and should not require the operator to be a simulations expert.

7.6.1 Desired Characteristics

- Compatible with variations in computation hardware:
    - Number of CPUs, graphics cards, memory, etc.;
    - With or without graphics (headless); and
    - Distribution of resources (networking, blade, cluster, etc.).
- Compatible with server computers:
    - Command line interface available; and
    - Compatible with virtual machines and containers.

- Operational on a portable computer.
- Support multiple operating systems.
- Operational without internet network access.
- Easily installable and operable by a user through a documented process.
- Test cases provided to test functionality.
- Benchmark performance expectations provided for multiple computation hardware and simulation setups.

7.6.2 Impacts of Simulation Complexity

In order for a software to be horizontally scalable, that is to be able to run larger simulations, the software must also be portable. As the simulation size (number of vehicles, size of the environment, etc.) increases, the software may require more computer resources (processors, memory, etc.). Depending on the computer resource requirements, the simulation size may dictate a change in computer architecture. While a software may have been able to simulate a small scene using a standard desktop computer, a large simulation may necessitate compatibility with server computers. A software should have compatibility with laptops, desktops, networked desktops, local servers, and cloud-based servers to be fully portable. Varying computer architecture may also necessitate changes in the computer operating system.

In order for a software to be vertically scalable, able to perform low and high fidelity simulations, the software must also be portable. Where horizontal scalability tends to strain the quantity of computation resources, vertical scalability can strain the quality of those resources. For example, increasing the fidelity of a Lidar sensor may require significantly more ray casts to be performed in the same amount of time. This requires a faster computer processor, or perhaps the need for a high performance graphics processing unit. Increased processor speed may also be necessary due to data transfer speeds, which would prevent parallelizing tasks across resources.

To allow dissemination and use of the software by users, it is desirable that the software be easily installable by a user through a documented process. This requirement falls into two categories. Where the source code for all or some of the software is available, the users need to have the ability to compile and build the software on their platforms. Once the binaries are available, users need to have instructions on installing any third party dependencies, as well as the tool itself so that it can be used. Smoke test cases should be provided to allow users to verify that they have a working tool.

As the configuration of the computation hardware, and the simulations themselves, become more complex, there is a need for the simulation software to provide test cases for the user to test that the software is operating correctly. When moving from a desktop simulation to a cloud-based server, for instance, a test case can help determine if data transfer delays are creating errors in the simulation. Before performing an autonomous multi-vehicle formation simulation, the user should evaluate a test case first to make sure the simulation software is operating properly. Because the behavior of the multi-vehicle formation may not be intuitive, it could be difficult to determine the simulation is properly configured without first performing a baseline test.

7.6.3 Impacts of Simulation Application

Portability has an impact on how, where, and when the tool can be used. As such, it is desirable to maximize the tool portability so that it can be used throughout the life-cycle including on development laptops and workstations, on High Performance Computing (HPC) / cloud platforms for large scale simulations, as well as in the field for test or operational use.

Large scale simulation runs, such as for Monte Carlo and parametric analysis, may require that the software tool run on HPC platforms and the cloud-based servers. Since HPC platforms can often be restrictive in the resources they provide (e.g., old operating systems, limited third party tools, no GPU), it is important to know if the tool has been used on HPC platforms and cloud-based servers, and the minimum requirements to deploy the tool to these platforms. Using servers may also require that the software run inside a virtual machine or container (e.g., Docker). Software components requirements, such as the availability of a GPU, must be well defined since resources can vary between computer configurations. Many servers require programs run through a Command Line Interface (CLI). In addition to requiring a CLI, having a CLI based on a common scripting language (e.g., Python) can provide the user more flexibility in how to use the software. The software's license must also be considered when using servers, since the server often does not have network access.

7.7 SOFTWARE INTERFACES

A software tool's supported software interfaces are critical for inter and intra communication among software modules and programs, and usability. While modularity and extensibility are critical and enable, among other things, the ability to adapt the software to changing needs, the user should not need to add or modify the software to enable standard software interfaces. The software should implement well-established open interfaces such as ROS (Robot Operating System)-like meta-operating systems and network protocols, such as Transmission Control Protocol/Internet Protocol (TCP/IP) and User Datagram Protocol (UDP). Newer standards, such as OpenSCENARIO [5], OpenDRIVE [6], and Open Simulation Interface [7] (all from project PEGASUS [8]) are emerging to handle the needs inherent with autonomous ground vehicles and should be support if possible. The Open Simulation Interfaces, for example, is a standard way to define data structures for weather, sensor inputs, etc. so that various simulated artifacts (e.g., simulated sensor, sensor fusion, planner, etc.) produced by different companies can be connected together in a simulation.

7.7.1 Desired Characteristics

- Support multiple connection interfaces (e.g., network interfaces, dynamic linked library, application program interface, etc.).
- Support co-simulation with other software using open standards.
- Allow for a non-restrictive interface to software functionality.
- Include a feature-rich scripting interface.

7.7.2 Impacts of Simulation Complexity

As a simulation becomes larger and more complex, there is a greater likelihood that multiple software components will need to be linked together. This may need to be accomplished in a variety of ways, such as networking (for information to flow between two systems) and through dynamically linked libraries (so that a given software has additional functionality at runtime). This interfacing may facilitate a simulation capability, such as providing a new sensor type, or it may be required for autonomous functionality, such as communication with a control station.

As an example, an autonomous vehicle may need to communicate with an outside system, such as another autonomous vehicle, a control system, etc. The simulation software must be capable of facilitating that communication by supporting common software interfaces which make open and proprietary communication methods possible. In addition to supporting the communication needed by the autonomous vehicle, the software must also support the communication needed by other software programs needed for the simulation. If a given simulation requires the base software tool to communicate with a satellite simulation software using TCP, for instance, it may also require the base software tool compile with the satellite software's dynamic linked library.

7.7.3 Impacts of Simulation Application

The user interface requirements can change significantly depending on the use case of the autonomy simulation software. While some users may be able to use the base, built-in software interface (e.g., graphical user interface), other more powerful interfaces are often required. Fully-featured, non-restrictive application program interfaces and scripting interfaces are frequently required to meet advanced user needs. Such interfaces give a user greater control over the software functions and increase its usefulness.

As an example, an autonomy software development user may need to create a new plugin to interface the simulation software with the autonomy software. A scripting interface can help the user develop this new module before running the finalized plugin. As another example, a user responsible for safety testing may need an application program interface to help setup a large number of automated simulations evaluating the effect of changes in simulation environment on autonomy performance. This type of test is commonly run by an outside program, which may need to interface with the simulation software.

7.8 HARDWARE INTERFACES

An important aspect for testing an autonomous system using simulation is the ability to interface with real hardware in support of human-in-the-loop, hardware-in-the-loop, and vehicle-in-the-loop testing. This ability allows developers to evaluate potential solutions and trade-offs in a system integration lab using real hardware before moving to real-world testing. Example systems which can be evaluated include sensors, drive by-wire systems, and vehicle user interfaces.

7.8.1 Desired Characteristics

- Support runtime two-way communication with external hardware (e.g., joystick, motion platforms, drive by-wire systems, etc.).
- Run real-time when the external hardware is operated by a human.
- Support communication with hardware through network protocols (e.g., CAN, FlexRay, etc.).

7.8.2 Impacts of Simulation Complexity

The software needs the ability to interface with hardware like sensors (e.g., Localization systems, LIDAR, RADAR, Cameras, FLIR), user devices (e.g., joysticks, tablets) and drive by-wire systems (e.g., steering wheel, wheel sensor, etc.) via different interfaces such as CAN BUS (SAE J1939) – Low Speed/High Speed/FD, Ethernet, EtherCat, FlexRay, USB, WIFI, MIL-STD-1553, IEEE 1394, Media Oriented Systems Transport (MOST), and Radios (Dedicated short range communications (DSRC) – V2V and V2I).

Hardware interfaces provide the ability to use the simulation software to evaluate the autonomous system software via human interaction using the actual devices the autonomous system will interface with on the vehicle, and have the autonomy software system run on the actual vehicle computation hardware.

7.8.3 Impacts of Simulation Application

The hardware interface has an impact on how, where, and when the simulation software can be used with human-in-the-loop, hardware-in-the-loop and vehicle-in-the-loop testing. As such, it is desirable to maximize the simulation software so that it can be used throughout the life-cycle. By being able to do testing in a hardware-in-the-loop SIL this allows both developers and testers to evaluate situations that could be very difficult or time consuming in the real-world.

7.9 COMMUNICATIONS

In the context of this document communications refers to the wireless communication between an autonomous or semi-autonomous system and any other system. Communication systems relevant to this effort include both long-range (i.e., cellular, land-mobile radio) and short range systems (i.e., Bluetooth, V2X (Vehicle to everything)). These systems may be based on open standards or be proprietary. Systems may be broadcast, packet-switched, or some combination of both. Communications refers both to technologies used to provide input to the autonomous/semi-autonomous system and for providing information to other autonomous systems and/or system operators.

7.9.1 Desired Characteristics

- Simulation software including modeling of communication systems effects should realistically model the limitations/characteristics of the system including, but not limited to system bandwidth, latency, congestion, and fading.
- It should be possible to integrate a communication system with the simulation software via a well-documented API.
- Simulation software should allow for both event-driven / broadcast communication and packet-switched / routed communications with acknowledgement and re-transmission.
- Simulate the effects of communication system degradation across a distributed, asynchronous simulation environment (i.e., more than likely a communications simulation module would need to model real-time effects in a non-real-time environment).
- Allow realistic simulation of security features (i.e., certificate verification, packet validation, intrusion detection, etc.).

7.9.2 Impacts of Simulation Complexity

Communications can provide both input to autonomous vehicle software while simultaneously communicating vehicle state or sensor information to other actors in a scenario. Actors may be human operators, autonomous, or semi-autonomous systems. As the number of actors in a scenario increases it is important to model the communication effects of limited channel bandwidth, collisions, and channel effects. In addition, it may be valuable to simulate degradation or denial of communications from EMI, jamming, and spoofing/intrusion/capture.

7.9.3 Impacts of Simulation Application

Simulation for current autonomous and semi-autonomous systems still require significant operator monitoring and intervention. Often this intervention is performed via wired or wireless communication; for example, a remote E-stop or operator pendant may be used to intervene if a system is malfunctioning. Semi-autonomous systems may also rely on sensor data provided by remote sensors for operation. Simulation software used in the development of autonomous system software should include the ability to model the effects communication systems have on autonomous system operation.

7.9.3.1 Channel, Protocol and Multi-User Effects

As described in this document communication system effects are limited to those described by layers 1 – 5 of the International Organization for Standardization Open Systems Interconnection model [9]. These include the physical layer, data link, network, transport, and session layer where the communication system would interface with the presentation and/or application layers by way of the simulation model API. At the physical layer the channel limits to the total bandwidth available to all users on a shared channel. If the channel is shared some mechanism for sharing the channel via a MAC scheme must be included. Implementation specific design decisions will necessarily limit the available bandwidth. Additional users may also contribute to latency depending on the MAC scheme. Packet collisions, congestion windowing, and packet drops would also be included here. For the purposes of simulating these effects it may be sufficient to model these effects stochastically.

7.9.3.2 Interference Effects Including Jamming

Communications systems are all susceptible to interference both from intentional jamming and from other Electro-Magnetic Interference (EMI) produced intentionally or unintentionally. Safe testing of communication systems would require the system be connected to a simulated autonomous system operating in a simulated environment. In many cases, it is possible to model these effects as channel degradation.

7.9.3.3 Cybersecurity Considerations

External communications systems are a preferred attack vector for an attacker attempting to either take control of an autonomous system or gain privileged knowledge about vehicle state or other privileged information. For this reason, attackers are likely to use the communication system as a means for attacking the vehicle. Also, many techniques for preventing attack rely on encryption schemes that either rely on specialized hardware or can significantly increase computational complexity of the simulation. It is important that the simulation software have the ability to both simulate an attack via a communication system and expose the autonomy software to such an attack via a realistic API.

7.9.3.4 System Integration

Communication systems developers are unlikely to have access to the full autonomous system. Also, the integrator of the autonomous system is unlikely to have access to a complete communication system until late in the development cycle. Simulation software that accurately models the autonomy software API and exposes the autonomy software to realistic communication systems effects will reduce development time and request for hardware surrogates.

7.9.3.5 Procurement and Maintenance

Communications systems are rapidly evolving and may be replaced or augmented throughout the life-cycle of a Program of Record. Simulation software with the ability to model communication system effects will allow procurement offices to specify and evaluate new communication systems.

7.9.3.6 OTA System Updates

Over The Air (OTA) software updates may be used to resolve issues with autonomous systems operating in the field. It is also an attack vector that may be used to gain control over a vehicle system. To the extent that a system is capable of receiving OTA updates, the simulation software should duplicate communication system effects that may impact these updates. These include but are not limited to dropped connections, denial of service, or other congestion-based attacks. Here, detecting Man-In-The-Middle (MITM) attacks or other injection attacks may be a valuable feature of simulation software.

7.10 LICENSING

A software license is a license given by the software copyright owner (licenser) to a user that gives this user license owner (licensee) certain rights regarding a software tool regarding running, copying, modifying, and/or distributing (sublicensing) the software, which are subject to terms such as price, usage purpose, and other conditions. Software licenses can be classified according to the categories listed below. A software license typically includes clauses which specify for each one of those categories the specific allowances and the conditions/terms of those allowances that the licenser has given to the licensee. The categories are:

Price:

- **Free.**
- **Free trial:** This means the software is free for a specific period of time after which the user typically has to switch to a paid license in order to continue using the software.
- **Paid per seat:** This typically means that only one user can use the software at any one time.
- **Paid per site per company/division:** This typically means that any number of users can use the software at any one time but only at a specific site, company, or division of a company.
- **Royalty:** This means the user can distribute the software as part of an integrated software system only after paying a royalty fee which can be a flat fee, or a fee based on the number of the integrated software system licenses sold.

Copyright: refers to what rights the software owner has given to users of the software specifically to use, copy, distribute, and modify the software. Note that if a license allows modifying the software then it has to allow access to the source code. Also, note that copyright restrictions and terms can be very complicated since they can involve many conditions and sub-conditions.

- **Public domain** means that no body owns the software and that anybody can freely use, copy, distribute, and modify the software.
- **Permissive** means that the owner of the software has given the rights to use, copy, modify and/or distribute the software to other users without royalty, provided the copyright notice and a notice that the file is offered as-is, without any warranty are preserved.” Typical, permissive licenses include the MIT, BSD-2, BSD-3, BSD-4, and LGPL.

- **GPL** (GNU General Public License) is a free open-source software license that guarantees end users the freedom to run, copy, and modify the software. The main difference between GPL and permissive licenses is that GPL is a copy left type license which means that any derivative work must have the same GPL license terms.
- **Proprietary** means that the software has an owner which has restricted what other users can do with the software. A proprietary software owner may allow other users to use, copy, and/or distribute the software but only if a license to do so is granted by the software owner through a license agreement. The copyright of most commercial software falls under the proprietary category.
- **Trade Secret** means the software can only be used by its owner and a small set of users who the owner allows to use the software and cannot be used by other users. A trade secret is typically used to restrict potential competitors from getting access to the software.

Source Availability:

- **Open-source:** the source code of the software is freely available.
- **Paid-source:** the source code of the software can be provided for a certain fee.
- **Closed-source:** the source code of the software is not provided (i.e., the software is only provided in executable binary form).

License Term Restriction:

- **Perpetual:** the software has no term restrictions (i.e., the license does not expire).
- **Limited term:** the term when the license can be used is specified. The most common term for simulation software licenses is one year.
- **Limited number of uses**.

Node restriction:

- **No node restriction** means the license can be used on any computer.
- **Floating network license** means the license can be used on only one computer at a time. The license has to be checked out from a license server. If the license is checked out, then it cannot be used concurrently at another computer until the current user releases the license by exiting the software.
- **Node-locked license** means that the license is limited to one physical computer. This is typically done using a hardware dongle, the computer IP address, the computer name, and/or a registry key on the computer.
- **Site license** means that the software can be used at a specific site. The license can be a floating network license, or it can be tied to an IP address range at that specific site.

Usage Restrictions:

- **Commercial:** User is using the software to generate commercial revenue. This includes for-profit companies or individuals who use the software for generating.
- **Individual:** user is using the software for a personal purpose that does not involve generating a revenue.
- **Educational:** user is using the software for learning purposes. This will typically include schools, colleges, universities, and students.

- **Government:** user is using the software for a government purpose. Government usage can include federal, state or foreign governments. It can include military as well as non-military usages.

User Restriction: The owner of the software or its government can have certain types of user restrictions. This can include for example users in a certain country, industry, or company.

Function Restrictions. Certain functions of the software can be restricted by the software owner. Examples of function restrictions include:

- Development versus runtime license.
- Model size may be restricted to certain value.
- Network communication speed maybe restricted to certain value.
- Ability to co-simulate: The license may either allow or not allow co-simulation with other software tools. It may also have other restrictions regarding co-simulation such communication speed.
- Shared-memory parallel cores: The maximum number of cores the software can run simultaneously on one simulation problem can be limited to a certain number.
- Distributed-memory parallelization nodes: The maximum number of computer nodes that can run the software simultaneously on one simulation problem can be limited to a certain number.

Software Maintenance and Updates:

- Not included.
- Free.
- Paid: perpetually included or included for a term.

Technical Support:

- Not included.
- Free.
- Paid: perpetually included; included for a term; paid per hour.

Training:

- Not included.
- Free.
- Paid.

7.10.1 Impact of the License Restrictions on the Simulation Software

A public domain software, if available, and if it satisfies the simulation requirements may be the best option since it has no restrictions. This is followed by permissive licenses which just have a notice restriction. However, public domain and permissive software usually do not include training or technical support which could be important considerations for simulation software. For GPL and proprietary software, the user has to consider the various license restrictions options. Each restriction can be assigned a cost. The best software from a licensing point of view will be the software which has the lowest cost. Some restrictions can be a no-go.

For example, if the source code is not available, this can be a no-go if the source code is required to integrate the software into a software system. Cost could also be a no-go. For example, if a separate license is required for each computer that runs the software code for performing a single multi-node distributed-memory simulation run, then the cost of the software may be prohibitive. Also, if the simulation software is used on an HPC with thousands of nodes, then it has to provide a license option where the license is not node-locked, otherwise this restriction can be a no-go restriction. Since simulation software can be very complicated, technical support and training must typically be included at an affordable cost.

7.11 DOCUMENTATION

Documentation of the tool is very important as users refer to it to learn the tool, use it correctly, and for trouble-shooting.

The documentation should include installation and setup instructions including those for any supporting software needed to run the program.

After installation, the user's guide should introduce the features provided by the simulation tool. It must describe the model structure and give an overview of how to use it including example input/output. It also has to list and reference all related available documents. The document should have a "quick start" section as well as more detailed information regarding each component of the software. The latter should include module/plugin interfaces, mathematical theory, solvers, and intended module usage where applicable.

In general, the documentation should be easily accessible by the user both on the user's own computer and as a link to on online version which is regularly updated. It should include links/information for training and support if available.

7.11.1 Desired Characteristics

- Provide user-level software documentation (e.g., setup guide, user guide, quick start).
- Provide developer level software documentation (e.g., API, plugin).
- Make software training available or have a known vendor support training.

7.11.2 Developer Level Documentation

- List of software packages used.
- Dependencies.
- Inputs/Outputs – minimum and complete list.
- GIT repositories for open-source material and documentation.

7.12 MATURITY

While a software product may provide multiple features and capabilities, their maturity is an important factor on the usability of the software product and the component features. Software maturity covers a diverse set of attributes including level of validation, deployment history, robustness, usability, and ability to handling real-life usage needs. While software features can be directly evaluated, maturity is often inferred from the level of usage and user experience with the software.

7.12.1 Desired Characteristics

Maturity level can be assigned to the overall simulation software, as well as to its component features. Some of the key maturity dimensions are:

- **Architectural:** Simulation tools are meant to be used to support different vehicles and scenarios. A measure of the architecture quality and maturity is the ability to accommodate scenarios and modeling needs that go beyond the nominal and perhaps beyond what the tool was designed for. Architectural maturity would be measured by the different types of autonomous mobility scenarios that the tool has been used for.
- **Deployment:** An important measure of a tool is its deployment history, usage history, and user community type and size. These are important measures of the viability of the tool. Questions to ask can include: Can the tool be used by user outside of the development team? Is there version tracking of the tool? Are the external users/experts in the field or newcomers? Has the tool been used in field-tests, for vehicle evaluation, or vehicle planning and operation?
- **Validation:** Model validation is essential for a given software to be used as an engineering tool. Questions to ask can include: What kind of validation has been carried out at the component models level, as well as at the scenario levels? Has the software been cross-validated against other tools or against test data?
- **Models:** It is important that the component models have sufficient fidelity to meet the needs for engineering applications. While scenarios do not always require the highest level of fidelity across all the models, there will be scenarios which stress different modeling areas. It is normal for a tool to have a variable level of maturity over the different models in the tools. Thus, the maturity of component areas such as vehicle models, terramechanics, sensors, terrain topography, etc. need to be assessed.
- **Terrain Environment:** Real-world mobility scenarios require the use of terrain environment data from external sources and can be especially demanding on simulation tools. Terrain data sets can be large, high-resolution, and imperfect (e.g., missing data). They also come in a variety of formats and may consist of multiple layers (i.e., soil type, textures, topography, moisture, etc.). A key aspect of a mobility simulation tool is its ability to work with such terrain data. A listing of its usage history with different terrain data sets is an important measure of the tool’s maturity in this area.
- **Usability:** Tools are often built with a certain usage in mind and will provide an API to support such use. Users come to a tool with their own applications in mind. A big contributor of the maturation of a tool’s API is the feedback from users on the awkwardness or incompleteness of the API in meeting user needs. It is important to know the usage history (i.e., duration, types of scenarios, desktop or out in the field, etc.) of a tool to assess the usability maturity of a tool.

- **Extensibility:** Mobility simulation tools are often used in conjunction with other tools. This requires the ability to interface and integrate the tool into larger simulation environments and interfacing with external tools. Experience and history with integrating with other tools or standard interfacing software is a measure of the maturity of the tool in this area.
- **Support:** What level of user support is available for the use of the tool.
- **Training:** Are there training options available for users on the use of the tool.
- **Software Quality:** The general measures of software quality based on test coverage, continual test, and development practices are used to assess software maturity. These also apply to mobility simulation software tools.

7.12.2 Impacts of Simulation Complexity

It is important to define the size of the "simulation box" a tool is suitable for. The dimensions of the box can include fidelity, speed, scalability, etc. While features may be advertised, their maturity is what determines whether the feature is actually usable and hence the size of the box actually available to users. Some example questions which can help determine tool maturity as it relates to simulation complexity include:

- Can the tool be used reliably?
- Can it scale up to handle real-world scenarios with complex vehicles, sensors, terrain environments?
- How hard is to create a simulation for different vehicles and scenarios?
- Does the tool have sufficient fidelity at the component and system level to meet user needs?
- Does the tool have sufficient performance speed to be usable for autonomous mobility applications?

7.13 SUMMARY

This chapter focused on the desired qualities of simulation software used to allow an autonomy software to function similarly to the way it will on physical vehicles. Since the autonomous vehicle field is still developing and evolving, features such as modularity and extensibility are stressed over usability and maturity. The chapter also details some of the measured requirements of the autonomy software itself to enable simulation. These recommendations should be considered during software development and software selection.

7.14 REFERENCES

[1] Hu, W., 2019. Driverless Cars Arrive in New York City, The New York Times, 6 August 2019. Available at: https://www.nytimes.com/2019/08/06/nyregion/driverless-cars-new-york-city.html.

[2] Thibodeau, I., 2018. Driverless Vehicles May Reshape Future of Warfare, The Detroit News, 14 May 2018. Available at: https://www.detroitnews.com/story/business/autos/2018/05/14/army-transforming-warfare-self-driving-vehicles-tanks-tardec/34880891.

[3] Halleaux, D., 2017. U.S. Army Brings Autonomous Technology Across Blue Water Bridge, U.S. Army, 6 October 2017. Available at: https://www.army.mil/article/195049/us_army_brings_autonomous_technology_across_blue_water_bridge.

[4] Etherington, D., 2019. Waymo has now Driven 10 billion Autonomous Miles in Simulation, 10 July 2019. Available at: https://techcrunch.com/2019/07/10/waymo-has-now-driven-10-billion-autonomous-miles-in-simulation/.

[5] OpenSCENARIO, VIRES Simulationstechnologie GmbH, Germany, Available at : http://www.openscenario.org/.

[6] OpenDRIVE, VIRES Simulationstechnologie GmbH, Germany. Available at: http://www.opendrive.org/.

[7] Driesten, C.V., Open Simulation Interface. Available at: https://opensimulationinterface.github.io/osi-documentation/#. Accessed on 17 October 2017.

[8] Winner, H., Lemmer, K., Form, T., Mazzega, J., Meyer, G., and Beiker, S., 2019. PEGASUS – First Steps for the Safe Introduction of Automated Driving, Road Vehicle Automation 5, 2019.

[9] Zimmermann, H., 1980. OSI Reference Model – The ISO Model of Architecture for Open Systems Interconnection, IEEE Transactions on Communications, 28(4), 425-432.

Chapter 8 – AUTONOMOUS MOBILITY ASSESSMENT, VERIFICATION, AND VALIDATION

8.1 TEAM MEMBERS

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8.2 SUMMARY

With respect to Validation and Verification (V&V) of Autonomous Vehicle Mobility, the key difference from standard Mobility V&V is that the driver is replaced by an autonomous system. As such the autonomous system now perceives the state of the vehicle and its surroundings, appraises this state against the intended mission, decides upon and generates a desired action, then sends controller signals to navigate the vehicle. Autonomous system Modeling and Simulation (M&S) tools will attempt to replicate the environment and replacement of the driver's actions. The Mobility V&V goal is to validate the model(s) created and verify their performance. Established mobility assessment procedures will still be applicable and be employed but they will be augmented to challenge the new driver action models.

Driver action models that are expected to be created are listed below and graphically depicted in Figure 8-1:

- Sensing;
- Perception;
- Planning;
- Intelligence;
- Decision;
- Control (of Sub-Systems and of the Vehicle); and
- Uncertainty (of Each Model).

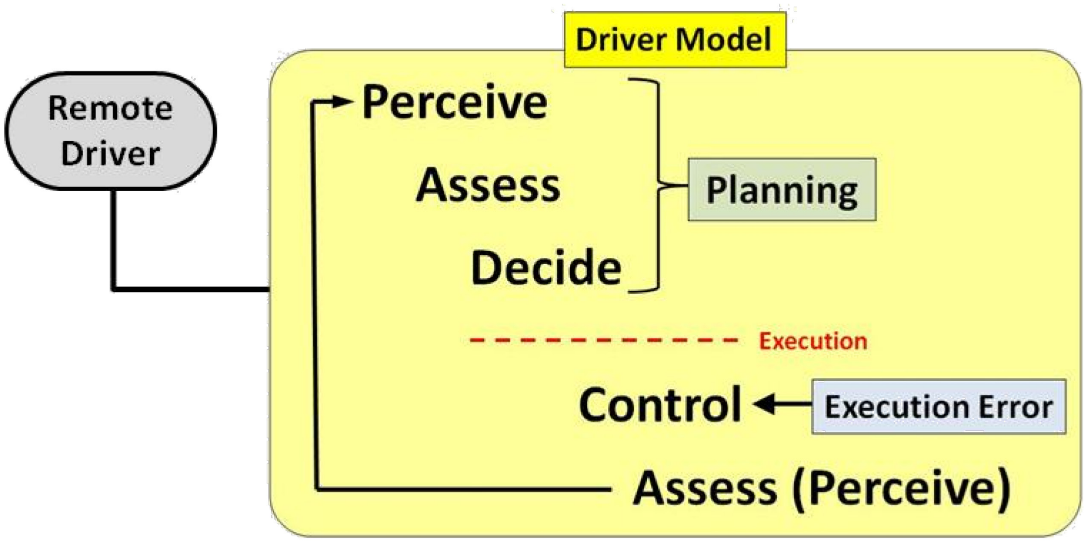


Figure 8-1: General Driver Model.

These models will require new methods and metrics for assessing autonomous mobility but will be grounded by legacy mobility assessment procedures. Moreover, autonomous systems will require a comprehensive understanding of the world including its infinite variability. Simulation of the natural environment will be dependent upon the sensors used to perceive the conditions surrounding the vehicle platform. The elements of mobility to be evaluated, scoring schemes, gross metrics (e.g., autonomy and mobility maps, mission performance potential MPP), stochastic vs. deterministic evaluations, and statistical tests to be utilized to understand the operating environment are expected to be an enhancement to the existing set of mobility assessment standards. Autonomous mobility verification and validation will be a new standard set of challenges and associated metrics that evaluate the new driver and its perception of the world and will be based upon missions and use cases that are not yet defined.

Standard validation and verification of mobility assessment tools is considered "Old Hat". Yet, in most mobility assessment procedures, great effort is spent to remove the driver's impact on the outcome of the event. Now with the insertion of "autonomy" the impact of the driver is the primary focus of the mobility assessment V&V. Instead of tailoring procedures to make the driver's input consistent and repeatable, the focus will need to highlight challenges to the driver's ability to assess the situation and produce a positive result. Therefore, the most significant adjustment expected for autonomous mobility is the validation of the system's assessment of the world as it relates to immediate surroundings and ultimate goals of the mission. This awareness will impact how the autonomous system will handle the environment.

With the infinite variability of lighting, weather conditions, surface textures, and material density, the validation of models that attempt to represent natural conditions will be difficult to replicate on a case to case basis. Empirical sensor data sets can be easily collected and then used to calibrate and verify the ability of modeling and simulation tools to embody the natural surroundings but re-creation of the natural conditions for validation of a select environment setting will be difficult at best. Environmental conditions will be what they are for a particular time and location, but it will be hard to specifically create and impossible to reproduce for follow on testing. Therefore, validation of the environment models will follow physical measurements and most likely be unable to predict environmental conditions. Environmental testing must inherently include:

1) Methods to measure a variety of environmental conditions and intensity; and/or
2) Use environmental cells to create specific conditions to challenge the autonomous system's ability to assess and operate in a wide range of environments.

A combination of both methods will likely be needed to fully assess and quantify the capabilities of modeling and simulation tools used to develop future autonomous vehicles. Initially static, validation methodology can be enhanced to be dynamic through the use of test rigs that still do not encompass vehicle motions produced by operating conditions and interaction with uneven ground. Final autonomous mobility validation of a combined vehicle and situational awareness model should be started by defining simple, singular mobility events with simple situational awareness tasks such as object recognition, scaling, and decision making. Although useful in evaluating a system's worth, the use of composite mobility traverses to validate modeling and simulation models is viewed as being extremely complex and must be carefully designed and measured to adequately assess system performance.

The current thoughts of the team are that validation efforts should focus on what data is needed for a required maneuver and why. This will largely depend upon what the data is used for (i.e., Localization, Object Recognition, Material Assessment, or Proximity) but also upon the state of the vehicle (i.e., Speed, Heading, Pose, Jounce, and Vibration) and environmental conditions that affect the data collection. Furthermore, validation of the modeling and simulation tools used to challenge the system's environmental assessment will need to focus on the key features of multiple sensor types and how these types are used by multiple vendors. A 3D Matrix of environment simulations is imagined (Sensor Type / Vendor Use / Data Collection Challenges). At this time, simulation of the natural world and all of its permutations is believed to be far too complex to efficiently validate. Validation should start with simple, un-obscured objects in controllable conditions and then have complexity added. Current efforts should move towards a "Good Enough" mentality and use validation to establish a "Confidence Level" that the simulation is "Good Enough" for the intended purpose.

The process for validation should be aligned to scenarios to develop a combined vehicle mobility and environmental assessment validation prototype for a set of specific scenarios. A broad-based guideline to define scenarios should be developed with separate assessment and validation categories conducted within a graduated application framework.

Therefore, a three (3) part, Assessment, Validation and Verification Methodology, can be imagined:

1) Standard Mobility Assessment:
   - Standard Mobility Events Similar to the NATO NG-NRMM CDT Data Set.

2) Environmental or "Situational" Awareness Assessment:
   - Within the Sensor Data Stream (Considered Technology Development);
   - Static System Model (Test Cell and Natural Environment); and
   - Simple Dynamic Movement Through the Environment (Test Rig).
3) Combined or Full Autonomous Mobility:
   - On Vehicle (Simple Events and Composite Traverses).

One additional important aspect of the assessment and validation process will be the measurements of actual environmental conditions such that the virtual simulation can be properly compared. Furthermore, graduation of conditions from light to heavy will need to be defined. It is imagined that the definition of the physical conditions may be as big of a challenge as the measurement. As an example, and in simple terms, how much dust is blowing in what direction, at what speed, and is this a light dust or heavy dust? It is surmised that past efforts to overcome degraded visual environments may have some beneficial input on how to characterize these conditions.

8.3 INTRODUCTION

Under the auspice of a NATO Advanced Vehicle Technology (AVT) effort, an Exploratory Team (ET) was formed to examine mobility assessment methods and tools for autonomous military ground systems. Identified as AVT-ET-194, the main objective was to explore the methods and approaches to access the performance and reliability of autonomous ground systems. The initial efforts of the team were divided into 13 categories that were later coalesced into six thrust areas. This section discusses Thrust Area 5 – Mobility Verification and Validation. The Thrust Area combines two of the initial exploratory categories, Task 6: Mobility Assessment with Task 12: Simulation, Validation, and Verification.

The original task purpose and goals were as follows:

1) **Task 6 – Mobility Assessment:** "Determine the methods and metrics for assessing mobility: the dimensions to be evaluated, scoring schemes, gross metrics (e.g., autonomy and mobility maps, mission performance potential MPP), stochastic vs. deterministic evaluations, statistical tests to be utilized; determine the state of the art; identify the gaps."
2) **Task 12 – Verification and Validation Task:** "Determine how the simulation results will be verified and validated: procedures for component level V&V, system level V&V, resources needed, potential demonstrations."

Per feedback from the initial task team, efforts presented at the 43rd Panel Business Meetings held in Slovakia, a combined Mobility Assessment, Verification, and Validation Thrust Area direction was defined as the following:

- Compile use cases (hereafter called scenarios vs user needs) and determine requirements;
- Determine how use cases (scenarios) will be validated;
- Identify vehicle dynamics modeling needed for autonomy and validation;
- Identify mobility requirements needed for the use cases (scenarios);
- Determine how the sensor models will be validated;
- Address how to quantify environmental conditions – how much rain, sun, etc. … affects the sensors; and
- Focus on outward looking sensors required for situational awareness.

Autonomous vehicle modeling and simulation use cases that were subsequently established are outlined below:

- Vehicle and Software Design and Development:
  - Platform Mobility; and
  - Autonomy, Navigation, Obstacle, Avoidance, and Safety Systems.
- Platform and Sub-System Evaluation;
- Procurement/Acquisition;
- Planning;
- Training;
- Operational Analysis; and
- UGV Protection and Counter UGV.

Since the modeling and simulation use cases are primarily mission dependent, scenarios were chosen to help unify, focus, and guide the efforts of the committee. A list of three (3) scenarios was established in Slovakia and entrusted to Thrust Area 1 to further develop and define. The scenarios are briefly outlined below, graphically depicted in Figure 8-2, and discussed more fully in Chapter 1. These scenarios will be used to establish the mobility assessment framework and explored later when discussing mobility assessment methods:

Leader/Follower: Involve a single vehicle (ego) in operation with similar conditions to use case one. The added complexity lies in its association in a collaborative or un-collaborative manner with one or more vehicles.

Movement from Point A to Point B: Involve a single vehicle (ego) in operation whose goal is to reach one or several specific locations. Routes can be free or include fixed obstacles that must be avoided to successfully reach the geo-localized target location.

Dynamic Environmental Changes: Involve a single vehicle (ego) in operation with similar conditions to use case two. The added complexity lies in the dynamic nature of the environmental change in the surrounding of ego requiring a higher level of adaptation to achieve mobility.

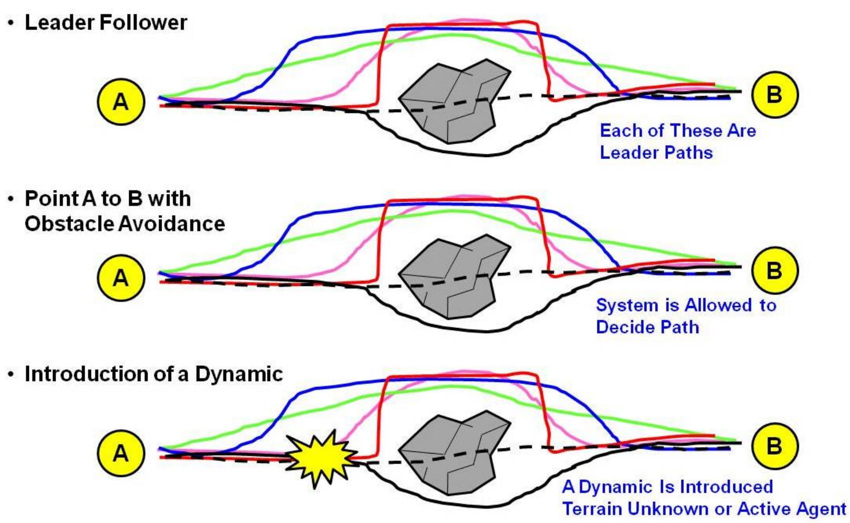


Figure 8-2: General Scenario Depiction.

Refinement and definition of the scenarios by Thrust Area 1 loosely followed a commercial, over the road vehicle effort commonly known as the Pegasus Project. With this method, definition of each scenario was moved through three levels of scenario description as defined below:

- Functional (Conception Phase):
  - Scenario must be expressed in a natural language on a high level abstraction.
- Logical (Development Phase):
  - Scenario must describe a parameter range in the physical state space.
- Concrete (Test and Validation):
  - Scenario depicts a concrete representative of a logical scenario in common data formats.

Definition is accomplished through the use of a layered approach by first separating scenario parameters into objectives possessing parameters with commonality. Five (5) objectives were identified as sufficient to describe the mobility of an autonomous military ground system. Each objective can be further subdivided into sub-layers affecting mobility as listed and illustrated below:

1) Operation:
   - Task;
   - Range;
   - Route Options;
   - Signature;
   - Threat Level; and
   - Contingency.
2) Environment:
   - Weather;
   - Terrain;
   - Time of Day; and
   - Airborne Particles.
3) Ground Vehicle and Configuration.
4) Embedded Sensors:
   - Vision;
   - Ranging;
   - Localization; and
   - Navigation.
5) Autonomy Context and Level of Autonomy.

Operation objectives are meant to set the purpose of the mobility event and should be used to establish mission performance parameters. The environmental objective aims are to fully incorporate the potential factors affecting the mobility environment, and in many ways are reflected in the geospatial input parameters defined in AVT-248. Similarly, the ground vehicle and embedded sensors establish the mobility asset that is being assessed. Lastly, autonomy context is in some ways an outcome of the assessment effort.

8.4 AUTONOMOUS MOBILITY ASSESSMENT – CONTEXT

For the purpose of this effort, autonomous mobility is defined as the ability of an autonomous ground vehicle to accurately sense and interpret the environment such that the ground vehicle can move freely and rapidly through the environment of interest [1]. Simply put, autonomous mobility is intimately intertwined with the vehicle's capacity to move and its ability to be aware and understand the surrounding terrain and environment. To assess autonomous mobility, the limits of the autonomous system's capacity to understand the situation and successfully employ the mobility of the vehicle need to be established. Depending upon the application, autonomy can be introduced at various levels of complexity. Referred to as autonomy levels, they look to define the human intervention needed to achieve the objectives of using a particular autonomous ground vehicle technology. Currently most systems still require some level of human intervention but, as technology progresses, modeling and simulation tools will be needed to challenge vehicle mobility and situational assessment at each level of autonomy.

With the stated objective to examine mobility assessment methods and tools for autonomous military ground vehicles, the team was specifically tasked with considering modeling and simulation tools used to assess mobility and not the mobility of the system technology itself. It was a struggle to find a clear cut demarcation line to guide efforts. Suffice it to say that to develop a good autonomous ground vehicle, M&S tools should be able to accurately challenge the system. For this effort, challenges to the mobility of the vehicle platform and the ability of the autonomous system to understand the situation that the vehicle is in were considered paramount. Moving to assessing the decision making process was considered moving out of scope. Hence, discussion here is limited to the ability of modeling and simulation tools to adequately conduct mobility assessment and subsequently verify and validate that ability.

With respect to verification and validation, this effort adopted the same software maturity levels as AVT-248 recognized. The important aspect of these maturity levels shown in Figure 8-3 is that modeling and simulation software validation is only achieved by a blind correlation to real test data.

1	**DEMONSTRATION:** *Demonstration of a correct implementation of a theoretically and conceptually consistent model.*
2	**PARAMETER SENSITIVITY DEMONSTRATION:** *Verification that performance change with a change in system parameter such as GVW or terrain deformability is consistent with theory and physics principles.*
3	**INDEPENDENT USER VERIFICATION:** *Independent user demonstration and correlation to vendor results*
4	**CROSS CODE VERIFICATION:** *Cross verification with another accepted mobility simulation code*
5	**CALIBRATION:** *Calibration to a real vehicle test data set*
6	**VALIDATION:** *Blind correlation to a real vehicle test data set*
7	**PARAMETER VARIATION VALIDATION:** *Blind correlation to a real vehicle test data set with a change in system parameter(s).*

Figure 8-3: Modeling and Simulation Capability Maturity Levels [2].

8.5 PROCESS/METHODOLOGY

The process identified by this task area examines mobility assessment methods and tools for autonomous military ground systems segregated into two distinct efforts. It would look to identify the capability of the modeling and simulation tool to adequately model the ground vehicle's mobility separate from the model's capability to sense the environment. While both are considered essential for assessing autonomous mobility, today's modeling and simulation tools currently consider the efforts separately. It is believed that once these separate capabilities are understood, a particular tool's ability to assess (or plug in the algorithms to assess) the modeled environment and successfully control the vehicle model through a complex mobility scenario can be evaluated. This methodology is contrary to the initial "scenario based validation" method envisioned by the team lead. In a scenario based validation as laid out below, each of the three (3) "Scenarios" (as eventually developed by Task Area 1, Scope, Definitions, Scenarios, Perception, Planning, Control) would be developed to assess aspects of autonomous mobility and the results would be directly compared to a physical replication of each scenario as follows:

1) Develop into functional, logical and concrete scenarios:
   - Utilize the "Pegasus Style" layered definition.
2) List which aspects of mobility that are exercised by the scenarios:
   - Initially adapt scenarios to include the AVT-308 CDT mobility test set.
   - Identify additions to the AVT-308 CDT mobility test set to embrace autonomy.
   - Focus upon driver perception and decision making events.
3) Assign metrics for mobility assessment:
   - Initially adapt metrics used in the CDT mobility test set.
   - Identify new standards that are required to embrace autonomous systems.

Figure 8-4 shows a potential scenario event including vehicle and environmental considerations that could be used to assess the autonomous mobility of a military ground vehicle. However, discussions regarding scenario based validation became concerned with consistency of data. The AVT-308 Cooperative Demonstration of Technology (CDT) events, including the traverses, where conducted with specific driver direction on how to conduct the event. Without this control, it is difficult to imagine the generation of a data set that could have been validated. With the autonomous system, vehicle control is relinquished; otherwise assessment is no different to a human driven platform.

Figure 8-5 represents two similar mobility assessment events. Both have the vehicle moving from a position "A" to a position "B". The lower part of Figure 8-5 depicts a very structured mobility assessment event know as a "Double Lane Change". The purpose is to identify high speed vehicle stability. The event uses a well-defined path and process to confidently establish the ability to control the vehicle at high speeds on various surfaces. To conduct a "Double Lane Change" the driver is often removed through the use of steering and throttle robots. This is done to eliminate inconsistencies introduced by the driver that cloud the assessment of the speed results. The upper part of Figure 8-5 depicts a comparable "A to B" scenario attempting to force a mobility event similar to a Double Lane Change maneuver. To produce a distinct difference for the autonomous system assessment the exact path is not provided, and an obstacle is introduced to induce something more than a simple straight line movement. However, since the exact path of the vehicle is not given to the autonomous system, there are an infinite number of paths that could avoid the obstacle including negotiating the vehicle over or through the obstacle. An assessment metric such as "time to complete" could be used but the assessment would not be associated to dynamic stability of the system. Instead, the metric would be dependent upon several system capabilities dependent upon how the movement was conducted. Regardless, the test would be difficult to validate and the worth of such a test would be limited other than as a Pass/Fail outcome.

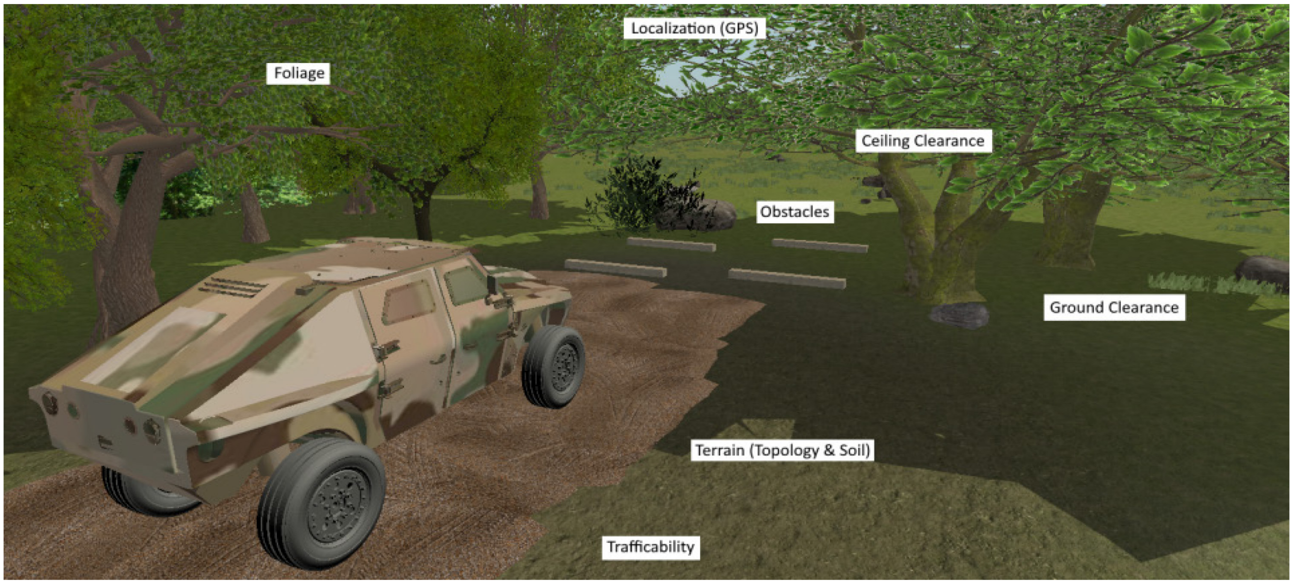


Figure 8-4: Graphic Depicting Possible Scenario Validation Event.

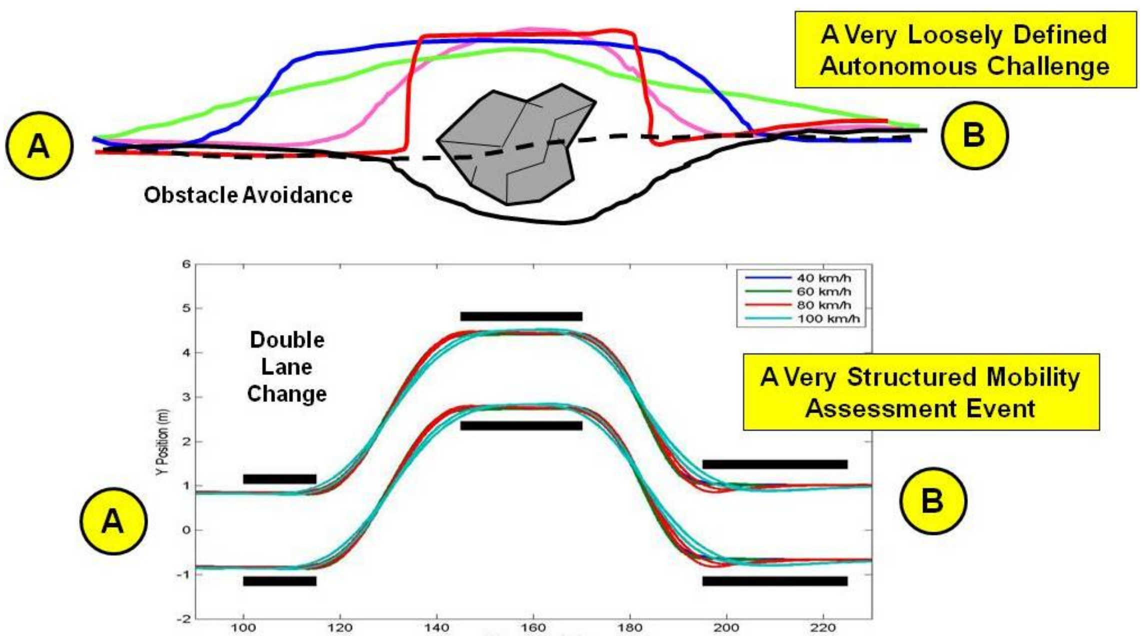


Figure 8-5: Graphic Depicting Concern WRT Consistency and Control of Validation Process.

It was realized early on that control of the autonomous vehicle inherently needed to be assessed. However, system control was considered technology and, therefore, outside the scope of examining modeling and simulation tools. The autonomous mobility assessment methodology then shifted to simply separating the well-trodden path of modeling mobility from the new effort to model situational awareness. The modeling of situational awareness was further segregated into "internal" sensing of the vehicle's state and "external" sensing of the environment and localization. It should be noted that assessment of the "internal" vehicle state sensing models was assigned to Task Area 3, Vehicle System Models, and is discussed in Chapter 6. Assessment of the "external" environment sensing models was assigned to Task Area 2, Virtual Environments, Sensors, Uncertainty Quantification, and is discussed in Chapter 5.

The segregation of the autonomous mobility assessment essentially categorizes the process as depicted in Figure 8-6.

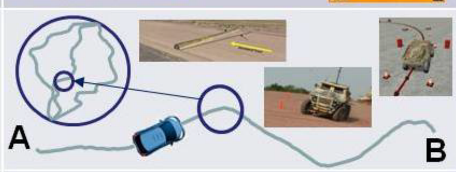
Assessment Category	Description	Illustration and relevance
Category 1: Vehicle Mobility – Component Level	**Single Component Contribution Assessment:** Can be in-situ or lab tests - single tire or track link, CTIS functionality - active suspension performance - adaptive braking or slip differential response	
Category 2: Vehicle Mobility – Vehicle System	**Vehicle System & Internal Subsystem Assessment:** Can be included in a specific scenario/traverse - such as traction and stability control - suspension adaption to environment etc.	
Category 3: Situational Awareness – Environment & State Sensors	**Autonomous Sensor Specific Assessment:** Can be conducted in unison with other assessments - sensor sensitivity - environmental impacts - weather degradation - sensor degradation	
Category 4: Autonomous Mobility – Specific Singular Events	**Low Level Autonomy Assessment:** - specific mobility events - trafficability decisions "whether to go into soft soil" - how to deal with decisions made - obstacle recognition, avoidance or negotiation - decision outcome challenges (cross slope)	
Category 5: Autonomous Mobility – Full Scale	**Full Scale Autonomous Mobility Assessment:** large traverse A to B type scenarios with multiple environmental and objective challenges: - obstacles, terrain conditions, seasons, formation, threats, search and recovery, etc.	

Figure 8-6: Autonomous Mobility Assessment Categories.

In each category, specific contributions to the overall assessment of autonomous mobility are expected to be evaluated. Category 1 and 2 can be viewed as the standard mobility assessments that have been done for years. These categories focus the assessment on using sub-system and vehicle models. Category 3 assessment methods are evaluating "machine vision" and the ability to understand the situation. In Category 3, concentration is placed upon the external sensor and environment models. Category 4 is for full system autonomous mobility assessment but is meant to be focused upon specific events or a specific attribute of autonomy. Category 5 is also a full system autonomous mobility assessment but, at a grander scale.

Due to the current maturity of autonomy in military ground vehicles, specific deployment of technology has not been established. Subsequently, other than the grand notions of relieving human burden, danger, or dread the evaluation of worth has been ill-defined. At first, it is expected that metrics will be developed on a case by case basis, slightly tuned for whatever desire the technology evaluator imagines. As technology is developed, test and evaluation metrics will solidify.

It is clear that for Category 1 and 2 mobility, assessment metrics will follow standard mobility methods that have been employed for years. Category 3 assessments are primarily based upon sensor data, so they will need to focus upon what the data is being used for relevant to mobility and how that fits into the general military application. As an example, ground speed can be derived using several types of sensing devices. Actual speed can be used as the metric to assess worth to the technology, but each method can also be assessed with respect to sensitivity to vehicle integration, physical inputs, ground interaction, light conditions, weather, and communication. A very accurate speed sensor may be useless after the sun goes down or may need substantial satellite communications. The important metric will be how much precision can be lost and still be able to conduct the required task? It is imagined that a key focus for sensors will be the ability of the algorithms to use the data provided. How bad can the data be and still have the algorithms using said data still perform their intended task.

There is no hard division between Category 4 and 5 assessments, but the metrics used to assess worth will shift from task completion to mission success. Category 4 will be more aimed at assessing the ability to complete common mission relevant “Tasks”. This assessment will tend to be more of a Pass/Fail event with some speed or time based metrics but the measurement of control latency during execution of the task will also be essential. Synchronization of controls will be key to conducting off road operations. As an example, maximizing traction and momentum in soft soil conditions weighed against vehicle control. Knowing that vehicle mobility is in trouble and being able to do something about it is two completely different issues.

However, Category 4 assessments will also be used to examine the ability to follow instructions. These instructions will be linked to the intended purpose or objective. For a Leader/Follower example, does the leader’s exact path need to be followed or is maintaining a general linear distance sufficient. This will depend upon the route conditions encountered and the capacity of the follower vehicle technology to understand the intent of the leader. A simplistic follower technology will need to be continually given a specific data from the leader and will need to closely follow “the path” otherwise risk hitting obstacles or getting lost. A more sophisticated technology suite may be able to operate on a general knowledge of the leader’s intent so the worth of assessing exact path following will be negligible. Risk in this case would be the capacity to assess and deal with situations that thwart the follower’s ability to follow “the path” and how fast the system regains “the path” after an event. To conclude, instruction following metrics will need to be centric to mission risk.

Category 5 will expand to a full mission relevant assessment and metrics will be much more macroscopic. Parameters such as Speed to Complete, Energy Consumed, Damage to Vehicle and Stealth will become the metrics to assign worth. Use of these high level assessments will probably mean that the technology being evaluated is very sophisticated and capable. At this level worth may be evaluated based upon the need for human intervention to complete the full mission. Intervention to improve performance could also be used. Interventions will need to be documented as remote user or intimate, “close-by” operator.

The verification and validation of the models utilized in each of these assessment categories is expected to be similarly segregated. A possible verification and validation methodology is characterized below. It should be noted that Category 5 scenario based efforts are included but as a culminating effort once the separate mobility and awareness models are verified and validated.

1.0 Mobility

- Validated at Two (2) Levels Similar to AVT308 CDT.
  - As Specific, Singular Events.
  - Within Composite Traverse (Scenarios).
- Add in Specific Decision and Control Challenges.
- Add Random Encounters into the Challenges.

2.0 Perception

2.1 Internal Vehicle State Awareness (Vehicle Motion and Sub-System Sensors)

- Validate Similar to Mobility.
- Add in Efforts to Validate Simulation of Degraded Sensors and Sub-System Capabilities.

2.2 External Situational Awareness (Environment Sensors)

- Validated at Five (5) Levels.
  - In Sensor Data Stream (Difficult as a 3rd party, must rely upon sensor developer).
  - At sensor output through the use of over the air sensor input.
  - In Environmental Test Cells.
  - On Simple Motion Rigs with Environmental Conditions Included.
  - On Vehicle with Environmental Conditions Laid Over Mobility Validation Events.
- Add in Efforts to Validate Simulation of Degraded Sensors and Vehicle Control.

3.0 Full Autonomous Mobility Assessment

- Validated at Three Levels.
  - Simple Mobility Events.
  - Expanded Mobility Events.
  - Full Large Scale Scenarios.

Simple mobility event validation is considered possible but performed as a two part effort. Simple automotive actions combined with un-obscured object recognition in various environmental conditions. Next, expanded mobility events (simple traverses) combined with obscurants and environmental conditions would be added. Both parts can be augmented with consistently repeatable inputs to the vehicle to induce specific vehicle states. Any scenario based validation will be complex. Driver options will need to be controlled which contradicts purpose. Infinite variability of objects, surfaces, and environmental conditions will make it difficult to produce consistent and repeatable results. Multiple scenarios will be needed to demonstrate the validity of a simulation further challenging consistency.

8.6 APPLICABLE MOBILITY ASSESSMENT AND AUTONOMY STANDARDS

Basic Automotive Performance (Acceleration, Braking, Cornering):

TOP 2-2-602, Acceleration.

TOP 2-2-608, Braking, Wheeled Vehicles.

SAE J299, Stopping Distance Test Procedure.

SAE J2181, Steady State Circular Test Procedures for Trucks and Buses.

SAE J266, Steady State Directional Control Test Procedures for Passenger Cars and Light Trucks.

TOP 2-2-609 Steering.

Dynamic Stability (Double and Single Lane Changes):

NATO Allied Vehicle Testing Publication (AVTP) 03-160W, Dynamic Stability.

Ride Quality and Vehicle Inputs (RMS and Half Round):

TOP 1-1-014, Ride Dynamics.

Gradeability and Side Slope:

TOP 2-2-610, Gradeability and Side Slope Performance.

Trafficability (Draw Bar and Rolling Resistance):

TOP 2-2-604, 4.3 Drawbar Pull in Soft Soil.

TOP 2-2-619, Soft Soil Vehicle Mobility.

Obstacles (V-Step, V-Ditch, Gap Crossing):

TOP 2-2-611, Standard Obstacles.

Traverses:

TOP 2-2-506, Endurance Testing of Tracked and Wheeled Vehicles.

Vehicle Sub-systems:

TOP 2-2-718, Electronic Stability Control.

Environmental Conditions:

TOP 2-4-001, Desert Environmental Testing of Wheeled and Tracked Vehicles.

TOP 2-4-002, Arctic Environmental Test of Tracked and Wheeled Vehicles.

Military Operations:

U.S. Army FM 30-10, Military Geographic Intelligence (Terrain).

U.S. Army FM 34-130, Intelligence Preparation of the Battlefield.

TRADOC Pamphlet 525-41, Topographic Support for Terrain Visualization.

TRADOC Pamphlet 525-70, Battlefield Visualization Concept.

General Autonomy Guidance:

TOP 2-2-004, Telemetry.

TOP 2-2-540, Testing of Unmanned Ground Vehicle (UGV) Systems.

TOP 2-2-541, Safe Operation of Mobile Unmanned Ground Vehicle (UGV).

TOP 02-2-542, Safe Operation of Weaponized Unmanned Ground Vehicle (UGV) Systems.

TOP 2-2-543, Line-of-Sight and Non-Line-of-Sight Testing of Unmanned Ground Vehicles.

TOP 6-2-598, Position Location and Navigation Systems (Plans).

TOP 03-2-812, Field of Vision.

ASTM E2854-12 Standard Test Method for Evaluating Emergency Response Robot Capabilities: Radio Communication: Line-of-Sight Range.

ASTM E2855-12 Standard Test Method for Evaluating Emergency Response Robot Capabilities: Radio Communication: Non-Line-of-Sight Range.

ASTM F2541-06 Standard Guide for Unmanned Undersea Vehicles (UUV) Autonomy and Control (Withdrawn 2015).

SAE J2958_201111 Report on Unmanned Ground Vehicle Reliability.

SAE J3016, Taxonomy of Automation Levels and Definitions of Terms.

SAE J3131, Provide Terms and Definitions of Automated Driving Software Architecture.

SAE J3164, Provide Definitions, Taxonomies and Preliminary Best Practices.

SAE J3018, Safety-Relevant Guidance for On-Road Testing of Prototype Automated Driving Systems (ADS) Systems.

SAE J3077_201512 Definitions and Data Sources for the Driver Vehicle Interface.

SAE J3092, Dynamic Test Procedures for V&V of ADS – Proposed.

ISO 26262, Road Vehicles – Functional Safety.

ISO 21448, Road Vehicles – Safety Of the Intended Functionality (SOTIF).

DTC Policy Bulletin No. 1-09, Software Safety Verification Policy and Guidelines.

Unmanned Systems Safety Guide for DOD Acquisition.

NIST Special Publication 1011-I-2.0 Autonomy Levels for Unmanned Systems (ALFUS) Framework Volume I: Terminology Version 2.0.

Autonomous Mobility:

ASTM E2801-11 Standard Test Method for Evaluating Emergency Response Robot Capabilities: Mobility: Confined Area Obstacles: Gaps.

ASTM E2802-11 Standard Test Method for Evaluating Emergency Response Robot Capabilities: Mobility: Confined Area Obstacles: Hurdles.

ASTM E2803-11 Standard Test Method for Evaluating Emergency Response Robot Capabilities: Mobility: Confined Area Obstacles: Inclined Planes.

ASTM E2804-11 Standard Test Method for Evaluating Emergency Response Robot Capabilities: Mobility: Confined Area Obstacles: Stairs/Landings.

ASTM E2826-11 Standard Test Method for Evaluating Emergency Response Robot Capabilities: Mobility: Confined Area Terrains: Continuous Pitch/Roll Ramps.

ASTM E2827-11 Standard Test Method for Evaluating Emergency Response Robot Capabilities: Mobility: Confined Area Terrains: Crossing Pitch/Roll Ramps.

ASTM E2828-11 Standard Test Method for Evaluating Emergency Response Robot Capabilities: Mobility: Confined Area Terrains: Symmetric Step fields.

ASTM E2829-11 Standard Test Method for Evaluating Emergency Response Robot Capabilities: Mobility: Maneuvering Tasks: Sustained Speed.

ASTM E2991/E2991M-17 Standard Test Method for Evaluating Response Robot Mobility: Traverse Gravel Terrain.

ASTM E2992/E2992M-17 Standard Test Method for Evaluating Response Robot Mobility: Traverse Sand Terrain.

ASTM F3244-17 Standard Test Method for Navigation: Defined Area.

ASTM WK27852 Test Method for Evaluating Ground Response Robot Maneuvering: Hallway Labyrinths with Complex Terrain (In Development).

ASTM WK54291 Evaluating Ground Response Robot Maneuvering: Traverse Angled Curbs (In Development).

ASTM WK53649 Evaluating Ground Response Robot Maneuvering: Align Edges (In Development).

ASTM WK33260 Evaluating Ground Response Robot Maneuvering: Traverse Hallway Labyrinths with Complex Terrain (In Development).

ASTM WK54402 Evaluating Ground Response Robot Mobility: Traverse Pitch/Roll Rail Obstacles (In Development).

ASTM WK54403 Evaluating Ground Response Robot Mobility: Traverse Mud (In Development).

ASTM WK55025 Evaluating Ground Response Robot Endurance (In Development).

ASTM WK58931 Evaluating Aerial Response Robot Maneuvering: Maintain Position and Orientation (In Development).

ASTM WK58932 Evaluating Aerial Response Robot Maneuvering: Orbit a Point.

ASTM WK58933 Evaluating Aerial Response Robot Maneuvering: Avoid Static Obstacles (In Development).

ASTM WK58934 Evaluating Aerial Response Robot Maneuvering: Pass Through Openings (In Development)

ASTM WK58935 Evaluating Aerial Response Robot Maneuvering: Land Accurately (Vertical) (In Development).

Sensor Specific:

ASTM E2566-17a Standard Test Method for Evaluating Response Robot Sensing: Visual Acuity (In Development).

ASTM WK33261 Evaluating Ground Response Robot Sensing: Point and Zoom Cameras (In Development).

ASTM WK42364 Evaluating Ground Response Robot Sensing: Visual Dynamic Range (In Development).

ASTM WK49478 Evaluating Ground Response Robot Sensing: Video Latency (In Development).

ASTM WK57967 Thermal Image Acuity (In Development).

ASTM WK54755 Evaluating Ground Response Robot Sensing: Match Colors (In Development).

ASTM WK58677 Evaluating Aerial Response Robot Sensing: Visual Image Acuity (In Development).

ASTM WK58925 Evaluating Aerial Response Robot Sensing: Visual Color Acuity (In Development).

ASTM WK58926 Evaluating Aerial Response Robot Sensing: Visual Dynamic Range (In Development).

ASTM WK58927 Evaluating Aerial Response Robot Sensing: Audio Speech Acuity (In Development).

ASTM WK58928 Evaluating Aerial Response Robot Sensing: Thermal Image Acuity (In Development).

ASTM WK58929 Evaluating Aerial Response Robot Sensing: Thermal Dynamic Range (In Development).

ASTM WK58930 Evaluating Aerial Response Robot Sensing: Latency of Video, Audio, and Control (In Development).

Situational Awareness:

ASTM WK58936 Evaluating Aerial Response Robot Situational Awareness: Identify Objects (Point and Zoom Cameras) (In Development).

ASTM WK58937 Evaluating Aerial Response Robot Situational Awareness: Inspect Static Objects (In Development).

ASTM F3265-17 Standard Test Method for Grid-Video Obstacle Measurement.

ASTM WK60390 Describing Stationary Obstacles Utilized within A-UGV Test Methods (In Development).

STANAG 4545 Ed.2 May 2013, NATO Secondary Imagery Format (NSIF).

STANAG 4575 Ed.2 Mar 2005, NATO Advanced Data Storage Interface (NADSI).

STANAG 4607 Ed.3 Sep 2010, NATO Ground Moving Target Indicator (GMTI) Format.

STANAG 4609 Ed.3 May 2009, NATO Digital Motion Imagery Standard.

STANAG 7023 Ed.4 Oct 2009, Air Reconnaissance Imagery Data Standard.

Communications:

ASTM WK60731 Evaluating Response Robot Radio Communications: Wireless Attenuation.

ASTM F1764-97(2018) Standard Guide for Selection of Hardline Communication Systems for Confined-Space Rescue.

SAE J2945/2_201810 Dedicated Short Range Communications (DSRC) Performance Requirements for V2V Safety Awareness.

STANAG 4609 JAIS (Edition 3)-NATO Digital Motion Imagery.

STANAG 4586 – Standard Interfaces of UAV Control System (UCS) for NATO UAV Interoperability.

STANAG 7085 Ed.3 Oct 2011, NATO Interoperable Data Links for ISR Systems.

Modeling and Simulation:

ITOP 1-1-002, General Procedure for Modeling and Simulation Verification and Validation Information Exchange.

8.7 PROTOTYPE DEMONSTRATION

To demonstrate the usefulness of a particular method or tool to access the mobility of an autonomous system, a prototype process should be defined and exercised. It is recommended by the Task Area 5, Mobility Assessment, Verification, and Validation team, that this process should first segregate the evaluation. The ability of the method or tool to represent basic vehicle mobility should be evaluated separate from the ability to represent the various aspects of situational awareness. Each aspect is essential to the understanding of autonomous mobility but depending upon the use case the worth of either should be considered on a graduated scale. Once the capacity of these assessment capabilities is understood, verified and validated, then a combined assessment of the tool's ability to assess autonomous mobility worth for a particular use case can be attempted. What metrics should be used to assign worth to the mobility assessment method or tool can be progressively defined for each category as listed below:

- Vehicle Mobility Assessment Methods and Verification and Validation (Category 1 and 2).
- Situational Awareness Assessment Methods and Verification and Validation (Category 3).
- Autonomous Mobility Assessment Methods and Verification and Validation (Category 4 and 5).

Regardless, the culminating process prototype should be challenging or "of interest" to either the state of the simulation software, or relevant to current autonomous system issues. Broad-based mobility of military relevant vehicles in an unstructured world should be paramount in the development of the prototype. The process should also understand that many of the autonomous systems will use artificial intelligence to learn. With this understanding, artificial intelligence will tune in on the statistics of the simulation and not the statistics of the real world. The ability to assess all aspects of situational awareness should be wary of the execution of a "Crazy Ivan" every time a certain simulated pattern is recognized. Ultimately, methods and tools are used to solve problems. How much fidelity is required to solve an autonomous mobility issue without overlooking key characteristics of the problem should be considered to keep it simple as needed.

Therefore, the purpose of the Prototype Assessment Process is to:

- Be relevant to military applications.
- Stress the simulation.
- Highlight an autonomous mobility issue.
- Identify required fidelity and validate methods to confirm.
- Establish state of the art.

8.7.1 Mobility Assessment Methods

Modeling and simulation tools used to evaluate the mobility of autonomous military ground systems will need to be able to conduct basic mobility assessments. The mobility of a military ground vehicle regardless of the level of autonomy employed will need to be assessed using well established methods and procedures. The basic purpose of mobility assessment is to excite the individual operations and motions of the vehicle and the sub-systems that are responsible for control of the vehicle's dynamic state. Identified by this report as a Category 1 and 2 mobility assessment, the outcome should define mobility limits for safe operation of the vehicle. Depending upon mission expectations mobility assessments are conducted at various speeds and surface conditions.

This means to:

- Excite the Vehicle's Basic Degrees Of Freedom (DOF):
  - Gross Pitch, Roll, and Yaw.
  - Associated Track and Wheel Motions and Forces.
- Excite the Basic Operations of the Vehicle:
  - Rolling Resistance.
  - Power Train, Braking, Steering.
- Define Limits of Vehicle and Sub-System Stability:
  - Traction, Lateral Slip.
  - Wheel Hop and Lock.
  - Roll, Trip.
- Define Obstacle Negotiation Limits:
  - Approach/Departure, Ground Clearance, Belly Drag.
  - Gradeability, Step Climb.
- Define Limits for Ride Quality and Vehicle Damage:
  - RMS, Body Collision, Impact.

8.7.2 Mobility Simulation V&V

Modeling and Simulation (M&S) of ground vehicle mobility has been done for many years. Through relentless use and to various degrees, the capability of several M&S software packages to replicate vehicle mobility has been verified and validated. Their worth is well known. The procedures and metrics used to verify and validate analytical models are firmly established. Changes in the process are introduced for specialty situations but have been rare. This section provides a quick review of the standard procedures and associated metrics that are used to conduct ground vehicle mobility assessments and subsequently verify and validate an M&S tool's capacity to conduct mobility assessments.

Most procedures are specific singular mobility events conducted with well-defined methods. A NATO Advanced Vehicle Technology (AVT) committee investigating next generation mobility models expanded the standard mobility assessment procedures to include a cross country traverse. The process utilized by the AVT-308 effort was used to validate the ability of a modeling and simulation tool to predict the speed made good prediction for a vehicle executing a particular cross country traverse.

For most procedures, and even the expanded mobility event used by AVT-308, the vehicle driver is given specific instructions on how to control the vehicle during the event. It is envisioned that autonomous mobility assessments will first conduct these same mobility events and build upon the lessons learned from the AVT-308 traverse to create additional expanded mobility events. Furthermore, additional environment aspects beyond simple surface conditions will be introduced and maybe some additional metrics.

These are primarily full system tests. Sub-System evaluations would be similar:

1) Specific Singular Mobility Assessment Events:
   - Acceleration;
   - Braking;
   - Constant Corner;
   - J-Turn;
   - Double Lane Change (DLC);
   - Draw Bar;
   - Rolling Resistance;
   - Gradeability;
   - Side Slope;
   - RMS;
   - Half Round;
   - V-Ditch;
   - Vertical Step; and
   - Gap Crossing.
2) Expanded Mobility Assessment Events (Traverses or Scenarios):
   - CDT Traverse.

8.7.3 Situational Awareness Assessment Methods

To assess autonomous mobility, modeling and simulation tools need to adequately replicate the data stream going to the planning, perception and control algorithms used to direct vehicle operations. This means that factors affecting the data also need to be adequately replicated. As shown in Figure 8-7, much work has been conducted simulating and stimulating the data stream. Whether it is termed Hardware-In-The-Loop (HIL) or Software-In-The-Loop (SIL) these efforts are primarily considering internal influences on the data. With these methods there is an assumption that the surrounding situation is constant or at least consistent and predictable. For military ground vehicle applications this is far from the truth. Two primary external influences on the data stream are the natural environment and the reaction of the vehicle as a system within that environment.

As such, autonomous mobility assessment requires an understanding of the natural surroundings and conditions being encountered as well as how the system handles that situation. It is simply being continuously aware of and coping with situations. Referred to as a Category 3 mobility assessment, situational awareness depends upon the data available and what that data will be used for. The fidelity or certainty of the data will be dependent upon the source (locally generated or communicated), the quality of the data collection device (sophisticated or simple and in good or degraded operation), and the algorithms that manipulate the raw data. An in depth discussion of the sensors generating this data is provided in chapters written by Task Area 2, Virtual Environments, Sensors, Uncertainty Quantification, (External Sensors) and Task Area 3, Vehicle System Models, (Internal Sensors). A general list for both "external" environmental surroundings and "internal" vehicle state situational awareness data is provided below.

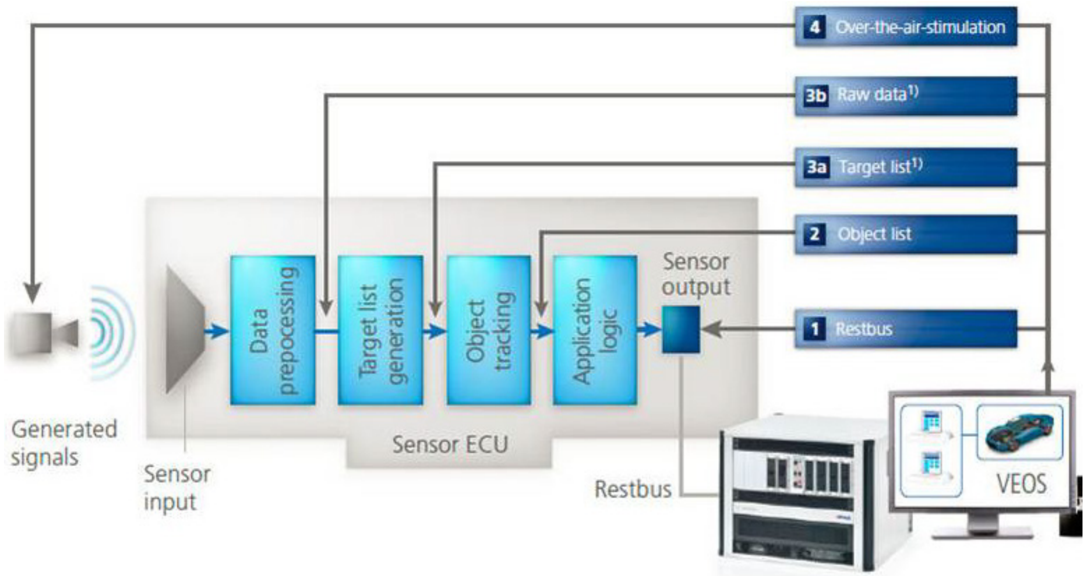


Figure 8-7: Overview of the Various Options for Stimulating/Simulating an Environmental Sensor (Graphic Courtesy of dBase) [3].

"External" Data – Environmental Surroundings:

- Vision Sensors (Multiple Inputs with Varying Quality);
- Obstacle Recognition (Uncertainty);
- Proximity Sensors (Ultrasonic);
- Roll Over Prediction (IMU);
- Ground Clearance;
- Slope and Grade Estimate;
- Soil and Surface Assessment;
- Navigation (GPS Quality and Loss);
- Planning Algorithms (Global and Local);
- Local Decision (Stop, Go, Slow, Route Change);
- Global Oversight (Energy, Stealth, Objectives);
- Communication (V2V, Remote);

- Multiple Sensor Types and Quantity (Uncertainty);
- Sensor Placement and Mounting; and
- Rigid and Dynamic Motion Effects on Sensor Data.

"Internal" Data – Vehicle State and Control:

- Command and Response Latency;
- Course Adjustment Fidelity and Latency;
- Braking Capacity;
- Vehicle Speed;
- Wheel and Track Speed Sensors;
- Terrain Loads to Components and Vehicle;
- Soil Sinkage Measurement;
- Traction Control Algorithms;
- Ride Height (Ground Clearance);
- Tire Pressure;
- Track Tension;
- Suspension Stiffness and Damping;
- Drivetrain;
- Power Transfer; and
- Vehicle Posture Sensors (IMU).

To be useful, modeling and simulation tools need to recreate the infinite variability of the natural environment and the subsequent vehicle response to a degree that is useful to assess situational awareness. The need to replicate each pixel or minute aspect of the surrounding is, however, highly suspect. In general terms, assessment tools need to understand objects and terrain. Simulation of an exact physical object is not considered efficient. It is considered more important to obtain general recognition of the object as well as the character and lay of the land. An in depth discussion of the environmental conditions is provided in Chapter 5 written by Task Area 2, Virtual Environments, Sensors, Uncertainty Quantification. Suffice it to say that beyond the addition of environmental effects on the sensor data stream, environmental conditions should be considered a blanket over the existing vehicle mobility tests previously mentioned (i.e., similar tests in different conditions).

Similar to environmental surroundings, situational awareness data depends upon the state of the vehicle (i.e., Speed, Heading, and Pose). Physical inputs to the sensors can also potentially affect the use of the data. Gross vehicle motions (Pitch, Roll, Yaw), harsh impacts, and vibratory inputs to the sensors can affect the data collection method especially if the mounting methods rely upon a compliant structure.

Lastly, assessment and subsequent validation of situational awareness also needs to focus on the key features of using multiple sensors and sensor types. Similar to single data sources, the data resulting from the fusion of multiple sensor inputs will also be considered as data and this effort will focus upon what the data is used for not necessarily the method to create or analyze the data. How the sensor data is manipulated to satisfy a need is not the focus of this process. This process will focus upon the assessment method's ability to create situations and assess how those situations are handled. Known challenges for sensors such as lighting, aerial obscurants, and surface conditions that need to be considered are listed below.

Environmental Factors to Consider:

- Vehicle Terrain Interactions with Various Surfaces/Soils.
- Gross Vehicle Motions, Vibratory and Impact Inputs.
- Operations on Slopes and Grades.
- Occluded Vision – Positive and Negative Terrain.
- Degraded Vision – Rain/Fog/Dust/Snow.
- Degraded Operation – Sensor Failure or Obstruction / Vehicle Sub-System.
- Date and Time Effects on Lighting Level – Sun, Stars, Moon Position and Phase.
- Surface Perception Issues – Glossy, Wet, Reflectance.
- Material Recognition – Soft, Firm, Low Traction.
- Object Recognition.
- Communications.
- Random Occurrences.
- Weather:
    - Temperature;
    - Relative Humidity;
    - Cloud Cover;
    - Fog;
    - Precipitation Amount and Rate;
    - Precipitation Type (Rain, Hail, Sleet, Snow); and
    - Lightning.

Summarizing, the focus of situational awareness assessment is not on the technology that generates the data but more upon what affects the data, what the data is used for (e.g., Localization, Vehicle Safety, and Mission Performance) and the subsequent evaluation of the outcome. With respect to assessing mobility of a military ground vehicle, the primary metrics for vehicle operation are outlined below:

- Localization.
- Vehicle Safety.
- Stability:
    - Roll Over or Tipping.
    - Loss of Lateral Control or Flat Spin.

- Obstacle Identification:
  - Positive Obstacle, Vertical Step and Ground Clearance.
  - Impact and Vibration.
  - Negative Obstacle or Gap.
  - Collision Avoidance.
- Mission Performance:
  - Task and Contingency.
  - Proficiency, Range and Consumption.
  - Gradeability, Trafficability and Route Options.
  - Threat Level and Signature.

8.7.4 Situational Awareness Verification and Validation

Verification and validation of methods and tools used to assess situational awareness will be affected by the type of sensor, the challenges of using that type of sensor data, and how a particular vendor uses the data from that particular sensor type to satisfy a need. Each combination of these three things will produce a Category 3 mobility assessment method that will need to be validated. Therefore, a three-dimensional matrix of situational awareness simulation is imagined (Sensor Type / Sensor Challenges / Vendor Use). With the number of sensor types possible for use on an autonomous system shown below, the number of validations could be quite large (Table 8-1).

Table 8-1: List of Probable Sensors to be Employed by Autonomous Ground Vehicles.

Spatial Sensors	Ambient Sensors
Camera	Barometer
Automotive Radar (NB, UWB, LRR, SRR)	Humidity
LIDAR	Temperature
IR (SWIR, MWIR, LWIR)	Light Meter
Ultrasonic	
GPS	
Compass/Magnetometer	
Hyperspectral	
Ground-Penetrating Radar	
Laser (Covered)	
Laser (Open)	

The replication of standard sensor validation procedures would be a good initial effort to verify and validate sensor models, but sensor standards are limited. ASTM E2566 provides procedures to validate the acuity of on board cameras. Figure 8-8 provides examples of camera acuity charts and figures that are often used. These examples are expected to be used as “signs” and it is imagined that they could be inserted into scenario simulations and physical tests and complicated with the use of obscurants. Various surface conditions and textures could also be introduced but these conditions will still not replicate a natural surface.

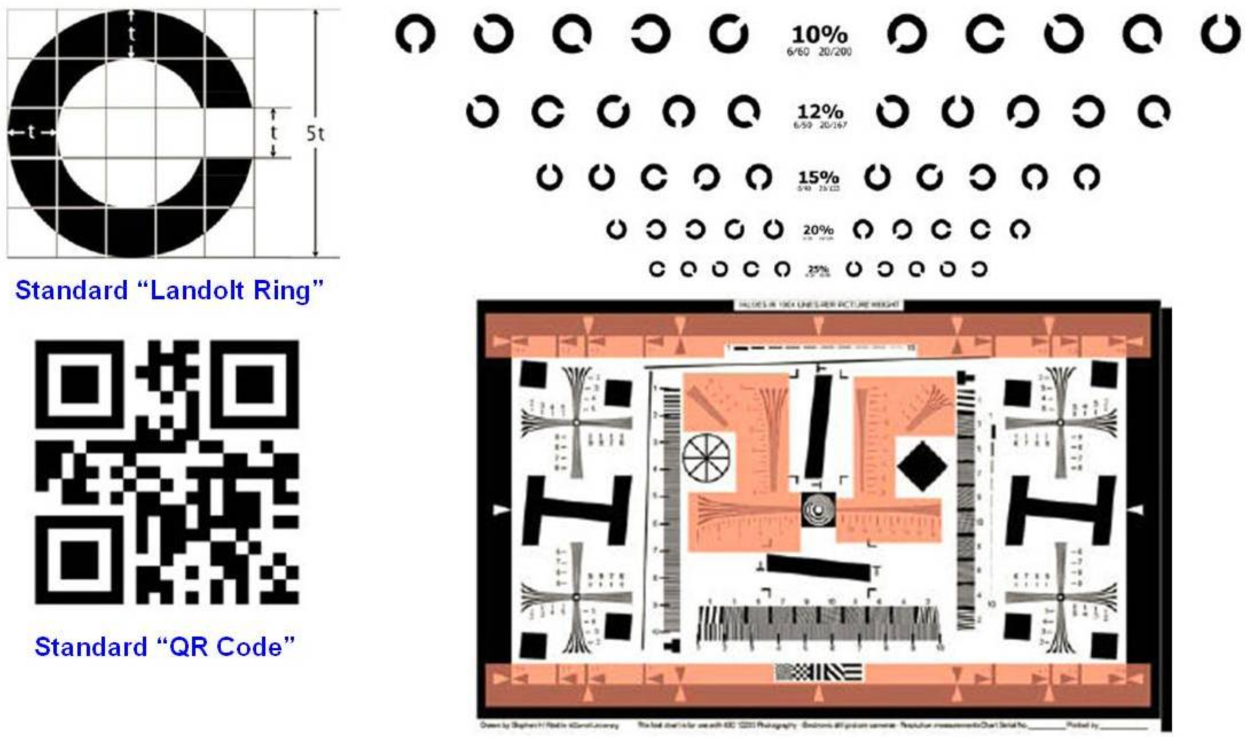


Figure 8-8: Sensor Validation (ASTM E2566 Visual Acuity of Onboard Cameras).

Stepping back from the direct sensor validation effort, it is currently thought that the world is too complex to model in great detail. Simulation tools modeling these sensors should, therefore, use a staged approach by starting with recognizing simple objects then adding complexity. Create tools that are “Good Enough” to solve problems at hand and use validation to establish a “Confidence Levels” that the simulation is useful. Then build upon success.

So, the validation of the ability for a method or tool to assess situational awareness should be accomplished with a similar staged approach. For example, validate the sensor data stream on known data, then on a test stand within a controlled environment test cell. Dynamics would then be added first, with the use of a test rig and then on “a” vehicle conducting simple mobility events that are expanded to more complex movements, maneuvers, traverses and ultimately scenarios.

This section will highlight the staged approach of going from simple sensor based validation up to include vehicle motions.

- Validated at Five (5) Levels:
  - In Sensor Data Stream (Difficult as a 3rd party, must rely upon sensor developer).
  - At Sensor output through the use of over the air sensor input.
  - In Environmental Test Cells.
  - On Simple Motion Rigs with Environmental Conditions Included.
  - On Vehicle with Environmental Conditions Laid Over Mobility Validation Events.
- Add in Efforts to Validate Simulation of Degraded Sensors and Vehicle Control.

As stated during the situational awareness assessment discussion, exact replication of each pixel or minute aspect of the surrounding environment is not expected. Similarly, one to one signal validation is considered an inefficient method due to the number of permutations that exist in the natural environment. Hence, it is more appropriate to validate a simulation to gain a general recognition of an object type (Big tree, little bush, grass, boulder, large rock, log, low branch, etc.) or terrain feature (ditch, gap, cliff, etc.) through various obscurants, degraded visual, surface and environmental conditions. With this thought it is believed that a part of a Category 3 mobility assessment would be the creation of a library of specific “things”, which would be created as data from various sensor types showing those items in specific “conditions”.

In essence, an empirical data base of natural objects in natural conditions as viewed by sensors that are relevant to military ground vehicle operations. As described below, this data base would also be enhanced to not only include “things” in “conditions” but also in “dynamic states”:

- Empirical Data Collected with Various Environmental and Surface Conditions:
  - As a Stationary Set Up – Test Frame.
  - During Simple “Pass By” Event(s) without Obscurants – Test Rig or Vehicle.
  - Incorporated into Specific Traverse(s) with Obscurants – Test Vehicle.

There would be some issues with relating the sensor data collected to how a particular vendor is using that sensor data, but the empirical data library of objects would be a starting point in validating a particular assessment method or tool. Care would need to be taken to also capture relevant meta data related to the conditions in which the data was collected. Furthermore, combined data sets like 3D Lidar points clouds colorized with camera images as shown in Figure 8-9 could be an empirical data set that provides multiple positive effects. Unique natural patterns are presented with realistic spatial position to offer realistic images as the AGV navigates inside the point cloud. Points could also be slightly enlarged and represented in the simulation as hit objects to assist Lidar sensor simulation.

Some meta data and the scanner accuracy details for Figure 8-9 are provided below are:

Leica P50 Scanner:

- Accuracy:
  - Range.
  - 1.2 mm + 10 ppm over the full range for 120 m and 270 m maximum range mode.

- 3.0 mm + 10 ppm over the full range for 570 m and 1 km maximum range mode.
- Angle.
- (Horizontal/Vertical) 8”/8” (40 µrad/40 µrad).

Camera:

- Type: Color sensor, auto-adjusting, parallax-free integration.
- Full Dome = 274 images stitched and blended together.
- 1 image = 1920 x 1920 pixels (4 megapixel).

Figure 8-9: Combined 3D Lidar Point Cloud Augmented with Camera Imagery.

The resolution and range for the data is .13”@30’ for max range 120m because of the close proximity to vegetation and trees. Typical resolution for a more open environment would be set the resolution .06”@30’. Too high of a resolution near vegetation creates a lot of noise and unnecessary points that require more cleaning. Range and resolution get adjusted based on how close the scanner is to certain objects.

It is envisioned that this type of empirical data set could be utilized as data inserted into various points within a sensor data stream (if possible per sensor vendor granted access), as playback within a specialized test cell, or as a comparison to the same event recreated in a virtual environment. Furthermore, verification and validation of the assessment method would focus upon what the data is and what it is used for. Simple valuation metrics as listed below could be used to allocate worth:

General Sensor Validation Metrics:

- Spatial Position Accuracy
- Return Intensity
- Number of Returns

Primary Objectives

- Recognize Objects
- Recognize Terrain
- Overcome Obscurants
- Overcome Environmental Effects

Sensitivity to Primary Collection Issues:

- Environmental Conditions, Participants and Obstacles, and Communication

Beyond the creation of empirical data sets, a Category 3 mobility validation would be conducted at several levels. Figure 8-10 represents validation of a sensor output through the use of "over the air" sensor input. For this level, an empirical data set would be displayed to a particular sensor. The sensor would then be treated as a "black box" and the output would be compared to the output of a simulation sensor model attempting to recreate the same data set. Figure 8-10 depicts this method for a camera image and Lidar image but essentially each type of sensor could be fed a representative "view" of the world and the output could be compared. Using an "over the air" validation method would require care to not create images that are pleasing to the human eye and not how a particular sensor actually "views" the world. Use of copy/pasting patterns to ease world representation should not be allowed. Moving up in validation complexity, environmental test cells could be used to recreate weather conditions that cannot be otherwise controlled or reproduced. Chassis dynamometer rigs could allow use of vehicle controls and "over the air" inputs could be used to feed sensors data as weather conditions are dialed in. Figure 8-11 shows examples of how this type of validation effort might look.

The major issue with the environmental chamber is the static nature of the mobility assessment. Simple motion rigs within large environmental chambers or controlled movement of objects around the vehicle can add a sense of a true mobility event but are still lacking the vehicle response to control and terrain inputs.

It is believed that representative on-vehicle behavior is only obtainable with a vehicle. How a vehicle responds to control and terrain inputs is difficult to simulate but even harder to replicate in real life without actually performing the test itself. Furthermore, with the stated variability of natural objects it is thought that a lower level validation effort would be the use of common objects in an open environment, void of natural elements similar to what is shown in Figure 8-12. Objects would be arranged in a pattern that would allow vehicle movement without concern of collision. Vehicle motions would include speed variations, acceleration, braking, steering inputs, and with surface roughness or the insertion of calibrated mobility enhancements like shown in Figure 8-13. This validation method could be conducted outside under various environmental conditions or within large environmental chambers like the one shown in Figure 8-14 that would allow better control of conditions.

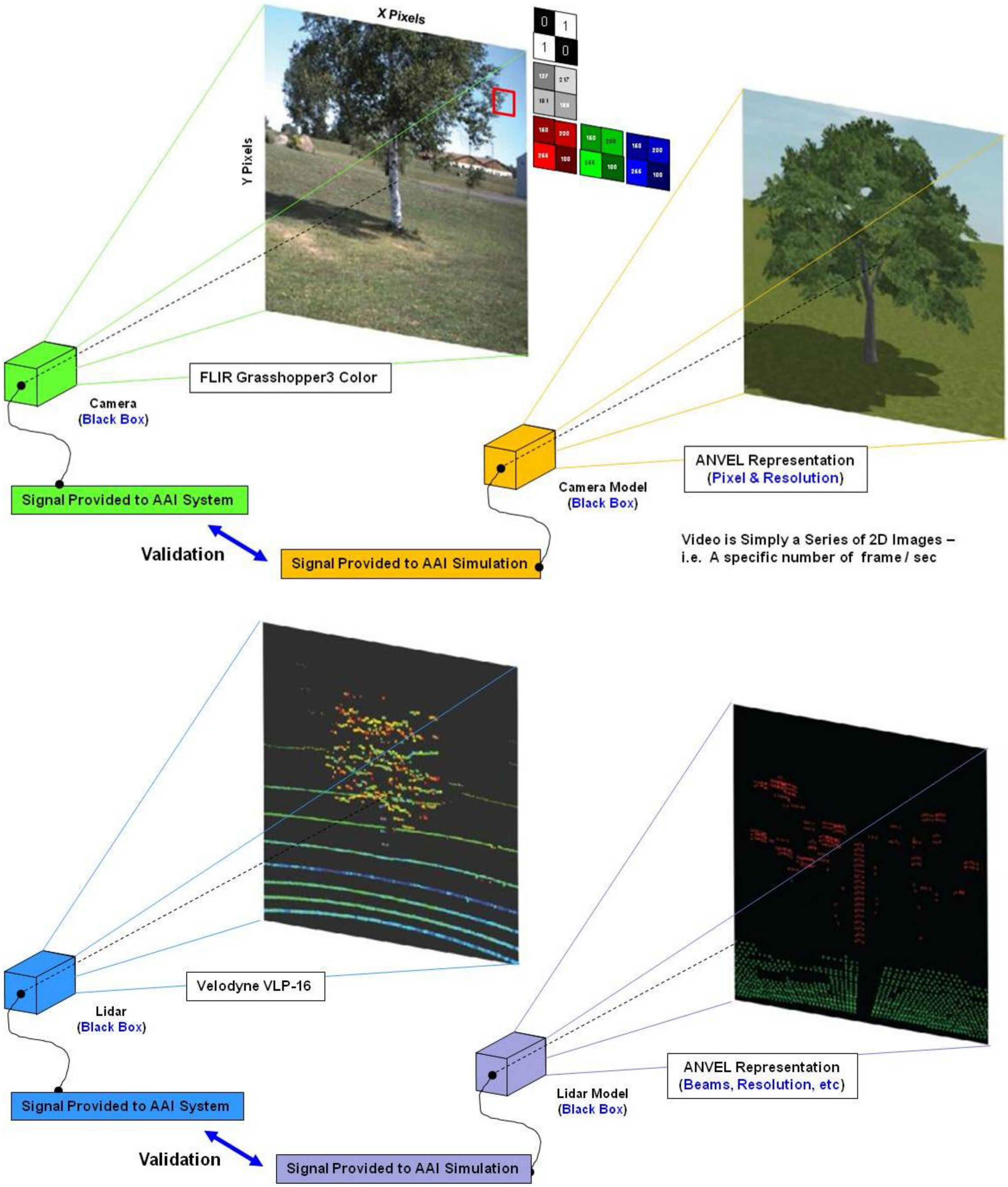


Figure 8-10: Direct Sensor Model Validation Using Empirical Data Set [4].

Figure 8-11: Sensor Validation Using Test Rig in Environmental Chamber [4].

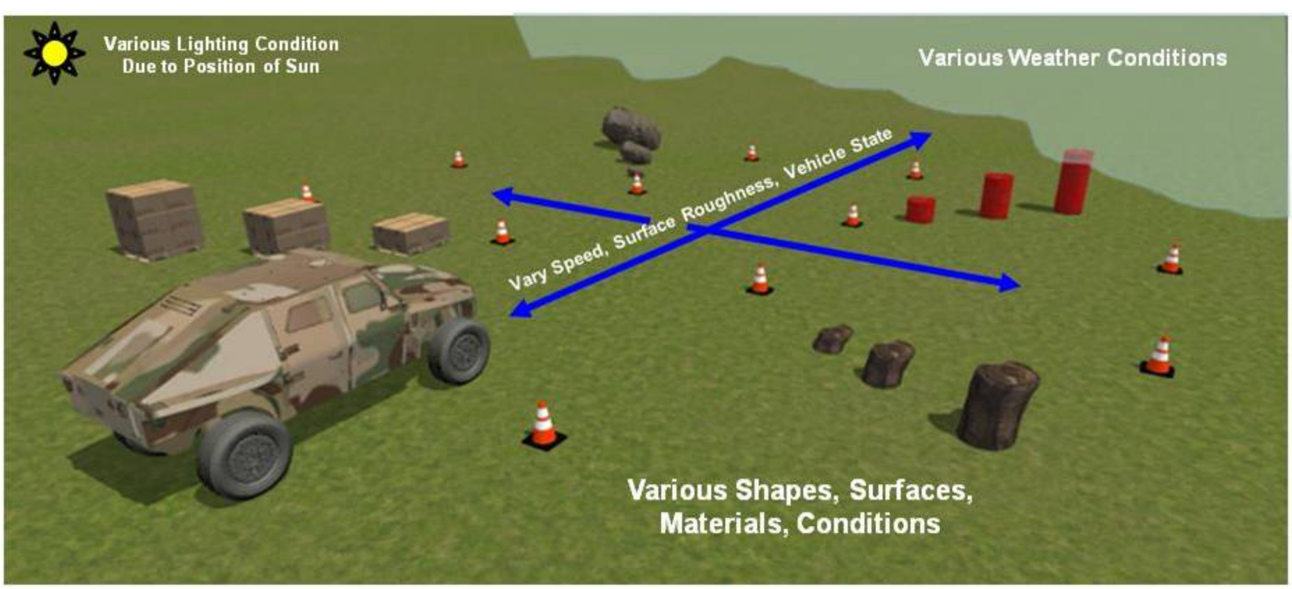


Figure 8-12: Simple On-Vehicle Mobility Sensor Validation.

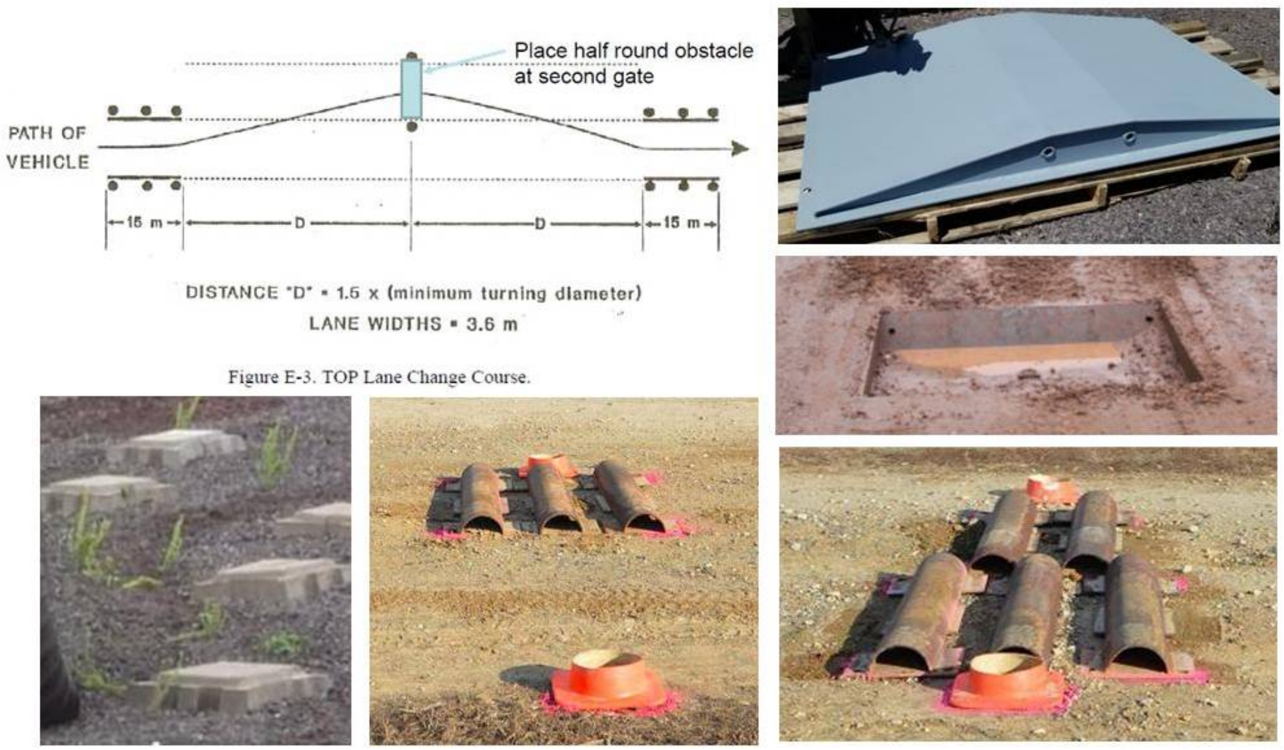


Figure 8-13: Sample Library of Mobility Enhancements to Simple Mobility Events.

Figure 8-14: View of the Largest Indoor Weather Testing Facility in the World McKinley Climatic Lab in Florida, 76.8 x 61.2 x 21m^3 [5].

It is envisioned that a Category 3 mobility assessment could be validated with each of the Category 1 and 2 mobility events. As an example, Figure 8-15 shows a cornering test with object recognition. The use of simple objects in an un-obscured field could be elevated by operating the vehicle along a tree line. Each of the Category 3 mobility assessments and subsequent validations would be conducted with minimal autonomous control of the vehicle. It is envisioned that in a Category 3 mobility assessment, the path of the vehicle would be predetermined and executed.

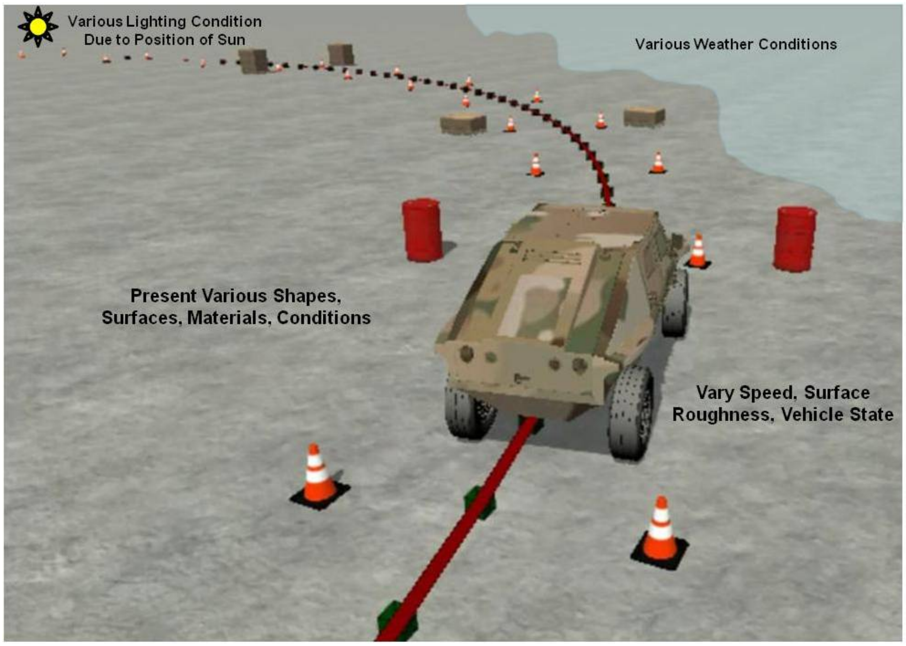


Figure 8-15: Single Mobility Event – Cornering with Object Recognition.

8.7.5 Full System Autonomous Mobility Assessment Methods

To culminate the methods and approaches to assess the performance and reliability of autonomous ground systems, Category 4 and 5 mobility assessments are meant to examine full vehicle systems. The primary difference between the two levels is the scale of the assessment. Category 4 and 5 mobility assessments are meant to combine all aspects together into a complete Autonomous Mobility Assessment method that highlights the thought of "expanded mobility events". Simple singular events already performed can be combined or enhanced to further challenge the mobility and situational awareness modeling but also start to include the effects of the decision making process. Category 4 and 5 assessments combine vehicle mobility and situational awareness but will also focus upon the assessment method's ability to create situations and assess how those situations are handled by the autonomous technology.

It is understood that assessing the autonomous decision making process is moving dangerously towards the assessment of technology. However, full system methods need to examine this process to ultimately create tools that will be of worth in the future. Examples of theses expanded mobility events are as follows:

- Soft Soil Object Negotiation (Figure 8-16).
- Unpaved Side Slope Object Avoidance (Figure 8-17).
- Simple Forested Traverse (Figure 8-18).

Assessment, verification, and validation of full autonomous mobility should be first conducted using simple events that are a composite of the basic mobility procedures and situational awareness methods previously mentioned. Referred to as a Category 4 Autonomous Mobility Assessment, these methods would fully combine the vehicle and environmental models and create situations in which the autonomous system will need to interpret and make decisions. Figure 8-16 and Figure 8-17 are samples of such assessments. In Figure 8-16, a vehicle is presented with an obstacle within a soft soil terrain. Low traction represents a trafficability situation that needs to be assessed and dealt with and the obstacle is the challenge to overcome. The event can be expanded even further by the introduction of the choice to accept a “go around” path that would be longer. Figure 8-17 is an obstacle avoidance exercise that adds an understanding that the side slope will affect vehicle operation. This event could be expanded by starting on level ground and where avoidance of the obstacle forces the vehicle onto the side slope. Category 4 assessments would also include simple military movements such as “Leader/Follower”.

Full scenario based assessments are considered Category 5 Autonomous Mobility Assessments. Even with Category 5 assessments, it is recommended that efforts should move from simple to complex in order to establish trust in the method. With these methods, simple traverses as shown in Figure 8-18 can introduce known obstacles, terrain conditions, and obscurants in a controlled course. This course can be established and then conducted during four seasons of environmental conditions. Additional traverses can be generated to match urban conditions or open field operations. Military maneuvers can also start to be assessed such as “Move to Contact”, “Bounding Over-watch”, “Conduct a Hasty Search”, as well as assorted movement formations, and the use of tactical pauses. Ultimately multiple scenarios will be needed to demonstrate the validity of a simulation. It is recommended that a broad-based scenario generation guideline be developed to help define and standardize scenario creation.

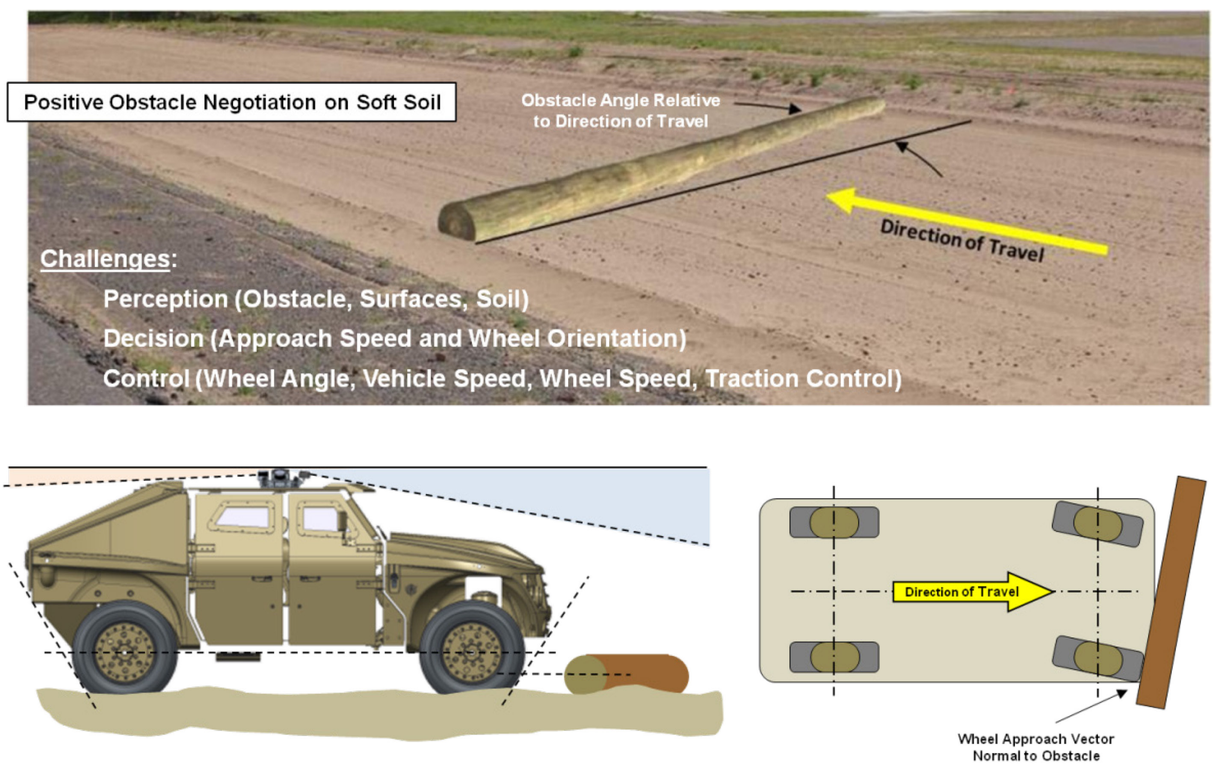


Figure 8-16: Expanded Mobility Event (Soft Soil Object Negotiation).

Figure 8-17: Expanded Mobility Event (Unpaved Side Slope Object Avoidance).

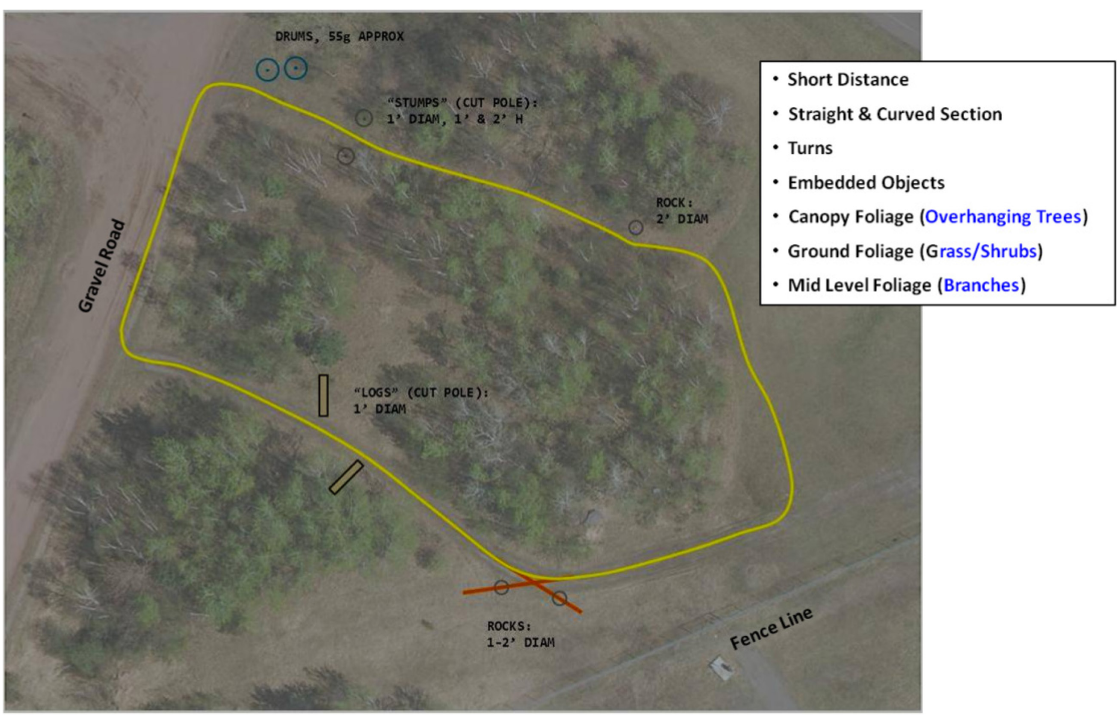


Figure 8-18: Expanded Mobility Event (Simple Forested Traverse).

8.8 GAPS AND PATH FORWARD

There have been decades of effort developing ground vehicles used for military operations. As a result, methods and tools to assess the performance of these vehicles have been thoroughly scrutinized by vehicle development experts creating a set of well-rehearsed mobility assessment procedures. The basic goals for conducting any system assessment are to establish:

- What is the system's purpose?
- How well does it perform that purpose?
- What makes it fail?

There is nothing magical about the methods and tools used to conduct autonomous mobility assessments but there is still a need to be able to answer these three questions. With autonomous ground vehicle mobility, the novelty of not having a human to see and understand the world is the largest gap. The method of how a machine views and subsequently interprets the world has not yet been understood in even the simplest of situations. The effort to recreate, verify, and then validate the "machine vision" world for a military ground vehicle currently taxes not only our computational capacity but also our ability to represent it as seen by the machine.

Furthermore, the effort to stimulate machine awareness of the environment far outweighs the need to properly depict vehicle behavior and terrain interaction. The result is currently a hyper focus on simulating the "machine vision" phenomenon and a neglect of understanding the vehicle's mobility. Current autonomous system development efforts are completely ignorant of off road mobility and systems created can only operate in highly structured, firm ground, perfectly sunny day environments. This unbalance is also evident in the fact that most autonomy software packages employ only very basic mobility models. So much of the computation horsepower is spent upon the creation of the environment that computing vehicle dynamics beyond a rudimentary 16 Degrees Of Freedom (DOF) is not possible. To some, the thought of introducing even simple Vehicle Terrain Interaction (VTI) soft soil models is taken as heresy. To pile on, the infinite variability of nature also makes verifying the validity of the "machine vision" assessment methods and tools daunting. As autonomy is introduced, the need for more and more artificial intelligence will only be increased, further taxing the modeling and simulation burden.

It is obvious that assessment needs are large and are continuously being expanded by the user community. Similarly, assessment methods and tools are being conjured by technology developers. The gap is both the validity and, therefore, worth of the assessment. Combined with the ignorance of off road mobility, the autonomous mobility assessment methods and tools need to focus on the established knowledge base. The suggested path forward is, therefore, to start simple, establish a base to move from, minimize options at first, and then expand as confidence in the methods and tools grows. Always be reevaluating the process. With that stated, the path forward suggested is to establish basic capabilities within the framework of set objectives guided by scenarios as listed below:

- Basic Capabilities;
- Obstacle and Agent Recognition and Avoidance;
- Ability to Follow;
- Trail;
- Tracks;

- Agent; and
- Ability to Stop.
  - Basic Objectives:
    - Military Operation;
    - Environment;
    - Ground Vehicle and Configuration;
    - Embedded Sensor Suite; and
    - Autonomy Context and Level of Autonomy.
  - Basic Scenarios:
    - Collaborative;
    - Point A to B; and
    - Dynamic.

Specific tactical steps forward are:

- Establish Procedures for Combined Autonomous Mobility Assessment:
  - Define a Broad-Based Guideline to Develop Scenarios.
  - Separate Assessment and Validation into Categories and Examine as Needed.
  - Conduct Assessment and Validation with a Graduated Approach Adding in Complexity as Trust is Developed.
  - Document Procedures Conducted, Identify Shortcomings, Suggest Improvements, Socialize and Gather Input, Refine.
- Establish Adequate Simulations:
  - Simplify Simulation of the Environment (Objects, Terrain, and Participants/Agents).
  - Identify How Much Modeling Fidelity (Mobility and Environment) is “Good Enough”.
  - Gain Trust from the Test Community.
  - Gain Trust from the Autonomous System Development Community.
- Establish Adequate V&V of Simulations:
  - Categorize the V&V of an Infinitely Variable World.
  - Increase the Availability of Empirical Data Sets for Autonomous Relevant Sensors.
  - Match Empirical Data Sets to How an Autonomous Vendor Uses the Sensor Data.
  - Identify How to Validate Whether the Modeling Fidelity is “Good Enough”.
  - Provide the Mechanisms to Validate Future Sensors and Sensor Uses.

8.9 REFERENCES

[1] Durst, P., J. 2019, The Reference Autonomous Mobility Model: A Framework for Predicting Autonomous Unmanned Ground Vehicle Performance. PhD Dissertation Mississippi State University. http://sun.library.msstate.edu/ETD-db/theses/available/etd-03192019-130959/.

[2] Balling, O., McCullough, M., Hodges, H., Pulley, R. and Jayakumar, P., 2018. Tracked and Wheeled Vehicle Benchmark – A Demonstration of Simulation Maturity for Next-Generation NATO Reference Mobility Model, NDIA Ground Vehicle Systems Engineering and Technology Symposium, Novi, MI, USA, August 2018.

[3] dSPACE Jan 2019. Objective Capture – Validating Functions for Autonomous Driving by Means of Realistic Sensor Simulation, dSPACE Magazine, 39-44.

[4] Bosch, 2017. Double récompense pour Bosch au Prix del'Equipement de l'année 2018. Available at: https://www.bosch.fr/actualites/aa-equipement-annee-2018/.

[5] March, R., Jan 24, 2017. McKinley Climatic Laboratory, AEDC/PA7.

Chapter 9 – BENCHMARKS

9.1 GOALS AND TEAM MEMBERS

The goal of the benchmarks team was to review a large set of modeling and simulation tools to determine whether the tools meet requirements defined by the ET. The team set out to determine what benchmarks were required, to define the benchmarks, and to establish a procedure for evaluating available tools. The objective was to understand the capabilities of current modeling and simulation frameworks for the assessment of the mobility of an autonomous military ground vehicle across a range of operational environments and conditions. Based on an understanding of the capabilities, the team was to determine the state of the art and to identify gaps in current capabilities. The results of the survey of current tools could identify tools or a combination of tools that would meet the requirements for the Next-Generation NATO Reference Mobility Model (NG-NRMM) and provide extended capabilities for modeling and simulation of autonomous vehicle technologies including sensors and advanced control systems.

The team members included:

Country	Name
Turkey	Ozgen Akalin
United States	**Daniel Carruth, Leader**
United States	Abhinandan Jain
Germany	Torsten Kluge
United States	Michael McCullough
South Africa	David Reinecke

9.2 INTRODUCTION

Advanced Driver Assistance Systems (ADAS) and Autonomous Vehicle (AV) technologies are rapidly advancing, particularly in consumer on-road self-driving vehicles. Modeling and simulation tools that support ADAS and AV system development and testing are also rapidly advancing. Modeling and simulation tools allow developers to implement and test autonomous systems without the cost of expensive physical hardware, with reduced risk, and in many varied environments and conditions. However, most of the development in this area has been focused on modeling and simulation for on-road consumer vehicles.

The modeling and simulation of off-road autonomous mobility for military ground vehicles has entirely different requirements: the vehicle physics, vehicle-terrain interactions, unstructured and complex environments, vegetation, etc. While NATO and its partners may be able to leverage modeling and simulation tools for on-road autonomous vehicles, it is important to consider and assess whether the tools meet the modeling and simulation requirements for off-road autonomous mobility.

In this chapter, we review the use cases for modeling and simulation tools for off-road autonomous mobility, discuss requirements for those tools, and describe an evaluation of 17 current modeling and simulation tools based on those requirements. The current state of the art in modeling and simulation tools is described and recommendations for future work are presented.

9.2.1 Use Cases

As part of the development of requirements for autonomous mobility modeling and simulation tools, the benchmarks team identified a set of use cases that describe how the tools may be used. These use cases emphasize different requirements on the M&S tools.

9.2.1.1 Vehicle and Software Development

Our first case is the use of modeling and simulation tools to develop and test autonomous vehicle systems and sub-systems. These tests are likely to use detailed physics-based models and require more flexibility and higher fidelity from the M&S tools when defining vehicles, vehicle components, environments, and scenarios. Developers will require capture of internal system data for sub-system evaluation and debugging. In this use case, users will expect the M&S tools to map to and support system and software development life cycles. For autonomous vehicle systems, a related use case is the generation of data for training neural network and deep learning models.

9.2.1.2 Acquisition

In acquisition, modeling and simulation will be used to evaluate the performance of proposed or existing vehicle designs against a specific set of requirements. Standard test procedures will be used to evaluate the vehicle's performance and may include testing of individual components up to multiple vehicles in large scale simulations. M&S will need to be able to accommodate the specific test scenarios required for the performance evaluations. M&S tools may also be used to test failure modes for the systems.

9.2.1.3 Field Operations

The M&S tools can also be used by soldiers in the field. Soldiers can use M&S tools to evaluate the best use of AV assets for specific operations. The soldier would be expected to have access to a set of assets and will need to predict performance on proposed missions in a specific region. Typically, this user will need answers quickly. Simulations will use real-world but limited data. Expected results will be map-based go/no-go, speed-made-good, and mission performance prediction. In this case, the soldier will expect to be able to model a very specific mission. In this usage, the M&S tools will need to be able to ingest field environment data (possibly large), with multiple data attribute layers. While the fidelity requirements will be moderate, there will be a larger emphasis on speed and turnaround time.

9.2.1.4 Vehicle Evaluation

The M&S tools may also be used to identify deficiencies or opportunities to improve performance in current assets. In this case, the user will want to model an existing vehicle and then evaluate its performance with modified software modules, sensors, etc. against benchmark standards, historical mission profiles, etc. The M&S tools may also be used to perform root cause analysis. As such M&S and tools will have high-fidelity vehicle model requirements to generate engineering quality data for performance analysis.

9.2.1.5 Training

Modeling and simulation tools can also be used to train personnel on the operation and use of autonomous vehicles. The objective is for personnel to understand the operation of the AV and its strengths and weaknesses in operations. These M&S tools must be real-time and must capture the essence of the behavior of the real system including quirks, failures, and known system weaknesses.

9.3 REQUIREMENTS

The requirements for autonomous vehicle modeling and simulation tools were developed by members of the entire AVT-ET-194. Initial requirements were developed based on previous work completed by AVT-ET-194, Next-Generation NRMM Development, and on the input of members of AVT-ET-194. The requirements were discussed with members of AVT-ET-194 at the 43rd AVT Panel Business Meeting Week 20 – 24 May 2019 in Liptovský Mikuláš, Slovakia. Additional requirements were collected from team members through summer 2019. Some final adjustments were made to the requirements following discussion of initial results at the 44th AVT Panel Business Meeting Week 7 – 11 October 2019 in Trondheim, Norway. The final set of requirements were itemized into a list of 173 requirements organized into 15 major topic areas: communication, datasets, environment, interfaces, licensing, metrics, modularity, operator, performance, portability, scalability, sensors, support, validation, and vehicle model.

9.3.1 Communication

The communication requirements address level of support in modeling and simulation frameworks for simulating Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I/V2X) communication in connected and automated vehicles. This includes support for simulating latency in communications not only between vehicles and infrastructure, but also between systems on-board the vehicle platform. This would include latency from an event in the environment to sensor detection to processing for recognition and decision making to action. The communication section also addresses level of support for modeling of sun and satellite data for GPS and satellite communication. This section also includes requirements for models of radio communication. Additional information on the digital information layer is covered in Chapter 5, Task Area 2, Virtual Environments, Sensors, and Uncertainty Quantification.

9.3.2 Datasets

With regard to datasets and data formats for environments, we focused primarily on datasets of interest to legacy and Next-Generation NRMM: the NRMM MapTable format, GeoTIFF raster data formats, and file geodatabase datasets. While these datasets are commonly associated with military applications and civilian GIS applications, we did not expect to find broad support for them in AV/ADAS modeling and simulation frameworks.

9.3.3 Environment

Task Area 2, Virtual Environments, Sensors, and Uncertainty Quantification provided requirements related to representation of the environment for the modeling and simulation of autonomous mobility of military ground vehicles. Many of the environment requirements related to mobility carried over from the efforts of AVT-ET-194. The Task Area 2 team provided additional requirements that extended the capability described in NG-NRMM and provided features required to support sensor models.

The environment topic area is the second largest topic area with 40 requirements. Over half of the requirements address capabilities related to representations of the 3D terrain. A quarter of the requirements are related to representations of objects in the environment including definitions of meshes, materials, and animations. The remaining requirements address representation of environmental conditions, support for scripting and editing environments, building interiors, and dynamic events (e.g., explosions, sinkholes, etc.).

9.3.4 Interfaces

Interfaces describes the connections between the modeling and simulation framework being evaluated and other tools. This covers requirements to support human-in-the-loop, hardware-in-the-loop, and software-in-the-loop testing. The interface requirements also cover APIs, shared libraries, and network interfaces that provide users with additional options for integrating the tools and for co-simulation with multiple tools. Interfaces also addresses standard data formats for scenarios, roadways, and surfaces. This section also assessed connections to common software development (Matlab, Python) and machine learning tools.

9.3.5 Licensing

The licensing section examined license restrictions and costs associated with the modeling and simulation tool. The only scored licensing item evaluated the level of support for open-source development and distribution of the tool. Reviewers were also asked whether the tool required a licensing fee or if it was free for all uses, free for non-commercial uses, free for academic uses, or free for government uses. Reviewers also identified whether licenses were provided by processor, by seat, or by site and provided rough order of magnitude cost information for the license fee.

9.3.6 Metrics

A modeling and simulation tool must provide methods for measuring and recording data. In some cases, the frameworks provide advanced data analysis packages that help design experiments, capture data, perform system analyses, and generate reports. A powerful and flexible data capture and analysis system can be helpful to users. However, it is also important that the tool expose internal data to the user so that the user can monitor any simulation variable of interest. The review specifically evaluated capabilities related to legacy NRMM and NG-NRMM operational metrics: calculation of Go/No-Go trafficability, speed for speed-made-good maps, and energy efficiency.

9.3.7 Modularity

Three modularity requirements focused on the ability of users to extend the capabilities of the platform. We assessed whether users could replace or extend major systems of the tool including the vehicle and sensor models, underlying physics models, and controllers for agents in the simulation (other vehicles, pedestrians, and animals).

9.3.8 Operator

The five operator requirements examined the availability of models of human operators within the modeling and simulation framework. In addition to addressing whether the framework provides models of human operators, this section addressed specific capabilities including support for models to operate the primary controls (steering, throttle, brake, clutch, and shifting). A basic human operator model capability is the ability to define a sequence of waypoints that the operator can follow. Path planning capabilities are more advanced but allow a human operator model to perform higher-level operations and exhibit basic decision making. The most advanced capability requested was the ability to model how a human operator would supervise and interact with an autonomous system.

9.3.9 Performance

Our performance requirements evaluated the user's ability to manipulate performance to achieve different objectives with the modeling and simulation framework. For example, one requirement was the ability for faster-than-real-time functions to be slowed and to operate in real-time to support human-, hardware-, or software-in-the-loop operations. Other requirements addressed the ability to leverage reduced fidelity approaches or to high-performance computing resources to reduce total run time for simulations. The performance section included an estimation of typical runtimes (faster than real-time, real-time, hours slower than real-time, days slower than real-time or weeks slower than real-time).

9.3.10 Portability

The portability requirements focused on where the user can access the modeling and simulation tools. The specific requirements were used to determine support for operating systems (Windows vs. Linux), portable hardware, and operation on remote systems. An additional requirement assessed whether the system required network access to run simulations.

9.3.11 Scalability

The scalability requirements related to performance but specifically addressed the ability of the modeling and simulation framework to scale beyond a single vehicle or a single computing platform. Five of the eight requirements addressed scalability related to computing performance. These requirements included capabilities related to parallel processing, numbers of computing cores, and types of processors supported (CPU, GPU, etc.). The requirements also addressed the ability to run headless simulations and to distribute the simulation across available computing resources. Two of the requirements related to the ability to define and run tests using an automated system. The final requirement related to support for simulations of multiple vehicles.

9.3.12 Sensors

For autonomous mobility, a vehicle must be able to perceive the environment in which it is operating. The sensors used to perceive the environment are the most significant additional capability required for autonomy. Additional details on the requirements for and the complexity of sensor models can be found in Chapter 5 from Task Area 2, Virtual Environments, Sensors, and Uncertainty Quantification and Chapter 3 and from Task Area 6, Vehicle System Models.

We could easily define hundreds of requirements for modeling the sensors used for autonomy. For this evaluation, we focused on the basic level of support for a selection of 18 sensors used on autonomous vehicles. Our requirements assessed which models were provided by each framework. The requirements did not evaluate the details of how the sensors were modeled or the accuracy of the models. In addition to requirements for the 18 sensors, this section included requirements related to the availability of bypass sensor models (models that provide internal data without simulating actual sensor performance) and ideal sensor models (perfect sensing of world data, usually provided for comparison to realistic models). General level of support for modeling vehicle state effects (e.g., vibration or shock) on sensor performance was also evaluated. Two requirements assessed the level of support for matching modeled sensors to real-world sensor performance.

The 18 sensors assessed in our survey included:

- LiDAR;
- Automotive Radar;
- Ground penetrating radar;
- Camera;
- Thermal/IR;
- Hyperspectral;
- GPS;
- IMU;
- Laser rangefinder;
- Ultrasonic;
- Contact;
- Accelerometer;
- Suspension travel;
- Wheel encoder;
- Tachometer;
- Speedometer;
- Tire Pressure; and
- Fuel Gauge.

9.3.13 Support

The effectiveness of a modeling and simulation framework is as much about usability and support for its users as it is its technical capabilities. In our evaluation, we assessed the level of support for 15 requirements related to user support. Four of the requirements related to specific functions that would allow users to create and edit environments and scenarios within the frameworks. Nine requirements related to availability of examples, documentation, training materials, and community support for the framework. The last two requirements related to usability of user interfaces provided by the framework.

9.3.14 Validation

In the validation section, two requirements assessed the availability of validation data and/or records of validation for the models incorporated into the modeling and simulation framework.

9.3.15 Vehicle Model

The requirements related to vehicle models were largely based on the survey developed by AVT-ET-194 and then expanded upon by members of Task Area 3, Vehicle System Models. The 25 requirements included in this section address a wide range of capabilities related to vehicles and vehicle-terrain interaction. The requirements address simple (Bekker-Wong type) and complex (FEA/DEM) terramechanics models for on-road tire models, off-road tire models, and tracks. This section also includes requirements for models of the powertrain and components including engine, transmission, drivelines, suspensions, etc. We also assess level of support for models of the vehicle hull and the interaction of vehicle components other than tires and tracks with the environment. This section also addresses support for other vehicles: air vehicles, legged vehicles, and amphibious vehicles. See Chapter 6 from Task Area 3, Vehicle System Models for more details on the requirements for vehicle models.

9.4 FRAMEWORKS

9.4.1 Autonomous Vehicle and ADAS Modeling and Simulation Frameworks

The benchmarks team identified 42 potential modeling and simulation frameworks for further investigation (listed below). The list is not an exhaustive list of AV/ADAS or of ground vehicle mobility modeling and simulation frameworks. The tools are a mix of open-source, commercial, and research tools for autonomous vehicle and ADAS or ground vehicle development and testing. The development teams range in size from a single non-commercial developer to small start-up development teams to large open-source communities to large companies. Multiple products changed names and at least one product ended development over the course of one year:

- AAI ReplicaR [1];
- AIMotive aiSim [2];
- ANSYS VREXPERIENCE [3];
- Applied Intuition AV Simulator [4];
- ASAC Dynamic Interactions Simulator [5];
- AVSimulation SCANer [6];
- Baidu Apollo Game Engine Based Simulator [7];
- CARLA [8];
- CESIUM [9];
- CM Labs Vortex Studio [10];
- Cognata [11];
- Coppelia Robotics CoppeliaSim [12];
- CVEDIA SynCity [13];
- Dash [14];
- Voyage DeepDrive [15];
- dSPACE ASM [16];
- FAAC SimCreator [17];
- IPG Automotive CarMaker/TruckMaker [18];

- LGSVL [19];
- MADRaS [20];
- Mathworks Matlab Automated Driving Toolbox [21];
- Mechanical Simulation VehicleSim [22];
- MetaMoto [23];
- Microsoft AirSim [24];
- Mississippi State University Autonomous Vehicle Simulator (MAVS) [25];
- MonoDrive Autonomous Vehicle Simulator [26];
- MSC Virtual Test Drive [27];
- NASA JPL ROAMS [28];
- Nervtech VirtualTraining [29];
- NVIDIA DRIVE Sim [30];
- OPAL-RT RT-LAB ORCHESTRA [31];
- OpenDS [32];
- OSRF Gazebo [33];
- OTSL COSMOsim [34];
- Quantum Signal ANVEL [35];
- Renault SCANeR II [36];
- rFpro Virtual Test [37];
- RightHook [38];
- Tass international PreScan [39];
- Udacity Self-Driving Car Simulator [40];
- VT MAK VR-Vantage IG [41]; and
- ZMP IZAC [42].

9.4.2 Leveraging Gaming Technology

As AV and ADAS modeling and simulation environments have developed, a number of tools have leveraged state of the art gaming technologies as the backbone of not only the rendering pipeline for simulating camera sensors but also for physics, environment modeling, scenario scripting, and more. Two real-time simulation frameworks have been of interest to the AV and ADAS modeling and simulation community: Epic Games Unreal Engine [43] and Unity Technologies Unity Engine [44]. Both Unreal and Unity provide far more than real-time graphics. However, the core frameworks provided by Unreal and Unity are the skeleton of a modeling and simulation environment. They provide technologies and tools that can be used to provide a comprehensive modeling and simulation framework.

9.4.2.1 Unreal

Epic Games' Unreal is a 'suite of integrated tools' with applications not only to games but also to simulations, film, and visualizations [43]. Epic provides access to the complete source code for the Unreal Engine, a platform that has been used to develop hundreds of games. In addition to C++ development, the Unreal Engine provides a visual-programming system, Blueprints, that allows developers to rapidly prototype extensions without requiring expertise in complex system programming. Aside from the photorealistic rendering capabilities, the Unreal Engine toolset also provides networking, animation, artificial intelligence, cinematics, and terrain models. The Unreal Engine toolset also provides an editor for creating and scripting complex 3D environments. There is a very large community of professional and hobbyist developers and artists that provide a wide range of assets and tutorials. Epic Games offers free licenses for non-commercial games and for non-gaming activities (e.g., modeling and simulation frameworks). For commercial activities, license fees are based on revenues. The Unreal Engine is a popular platform for AV and ADAS modeling and simulation frameworks including CARLA, Deep Drive, AirSim, monoDrive, and COSMOSim.

9.4.2.2 Unity

Unity is a platform of tools for high quality real-time graphics for gaming, film, design and manufacturing, and other simulations [44]. Unity development is centered around the Unity editor that provides tools for creating and managing the art and codes that make up a project. Unity provides multiple rendering pipelines and physics systems to support different levels of fidelity. The Unity Engine is supported by numerous partners that provide extensions and plugins for the core product. For example, the PiXYZ plugin supports direct import of CAD models into Unity environments. Unity provides a version that is free to use for non-commercial purposes while commercial development licenses are available for an annual fee. The Unity Engine is currently being used by AV and ADAS modeling and simulation frameworks including Apollo, LGVSL, MetaMoto, and Udacity.

9.4.2.3 Graphics Engines

There is a distinction between real-time simulation frameworks like Unreal and Unity and graphics engines like the open-source Object-Oriented Graphics Rendering Engine (OGRE) or Godot. While Unreal and Unity provide development platforms, asset stores, physics systems, etc., graphics engines typically focus on the core technologies to support real-time visualization. The tools that use a graphics engine provide their own framework for vehicle dynamics, terramechanics, sensor simulation, and other modules required for ADAS and AV M&S. Graphics engines still provide significant advantages by allowing developers to focus on other aspects of their M&S frameworks. Versions of OGRE have been used by ANVEL, Gazebo and ROAMS M&S frameworks.

There are advantages to development of proprietary visualizations, especially for commercial developers. There are no licensing fees required if you have complete ownership of the M&S framework. Proprietary systems can also provide focused solutions designed specifically for environment visualization and sensor simulation for ADAS and AV systems that may provide enhanced validity compared to a general solution.

9.4.2.4 Advantages

There are many reasons that modeling, and simulation frameworks are increasingly leveraging gaming technologies. The clearest reason is the ability to quickly generate high quality, high definition, real-time visualizations. Driven by fierce competition in gaming, real-time graphics engines can deliver near photo-realistic imagery at 60 to 120 frames per second. Building a new image generation framework capable of achieving the same performance and quality is an enormous technical undertaking that is necessary but not sufficient for developing a modeling and simulation framework for autonomous mobility. It is far easier and more cost effective to leverage existing gaming technology. A new framework can rapidly advance to a usable product using a game engine to provide the fundamental technology.

In addition to the general high quality of visualizations, gaming engines offer built-in physics, networking, and support for complex 3D objects including advanced materials and animations. Gaming frameworks also provide support for complex agent behavior systems. As gaming engines have become standalone tools marketed to other gaming companies and to developers outside of gaming, both the tools built within the framework and support for the frameworks in external toolsets have seen significant improvements. Many 3D tools for creating and editing environments, objects, materials, etc. have built-in support for the most popular gaming engines. There are even 2nd tier tool developers that build tools exclusively for one of the gaming engines.

Many of the gaming engines are at least in part free to use for students and non-commercial purposes. This accessibility has led to the development of large communities of developers that support the game engines with plugin development, art assets, and an enormous library of online tutorials. This also ensures a large community of developers available for recruitment to work on systems that leverage one of the major gaming engines.

9.4.2.5 Disadvantages

The objective of a gaming engine is to generate images and physics that are compelling and exciting for players as fast as possible. The priority for a commercial game engine is not the scientific accuracy of either the visual fidelity or the physical fidelity of the simulation. Many of the methods used to achieve photorealistic rendering of images are unrelated to the physical reality of the environment being modeled.

It is also important to recognize that, while gaming technology provides many of the fundamental capabilities required for a modeling and simulation framework, that is all that it provides. Gaming engines provide excellent support for rendering high quality images, for loading and manipulating assets, and more. However, the engines provide very little support for controlling how vehicles, humans, and objects move through and react to the environment. These capabilities are left as an exercise for each game developer and must be defined by each simulation developer. This includes support for custom data (e.g., GIS terrain datafiles or OpenScenario scenario descriptions) that are commonly used for autonomous mobility modeling and simulation but are not typical for gaming.

Finally, gaming technology commonly provides support for a wide range of consumer devices. However, gaming technology typically provides limited support for high-performance computing environments.

9.5 MATERIALS

9.5.1 Request for Information

The benchmarks team developed a request for information document to solicit information on modeling and simulation tools directly from vendors. The request for information document introduced the objectives of the benchmarks task, described the purpose of the evaluation, provided some conceptual mission scenarios, and requested specific information related to the requirements identified by the team. In the request for information, the requirements were stated as open-ended questions to try to elicit as much detail as possible on the level of support provided by the framework with respect to each requirement.

9.5.2 Review Form

A review form was created based on the requirements provided by the members of AVT-ET-194. The final review form included 173 requirements defined as positive statements describing a desired capability of a modeling and simulation framework (e.g., 'Supports geo-referencing of terrain datasets.'). For 169 of the requirements, reviewers were asked to determine the level of support for each requirement. Reviewers were instructed to select one of seven possible responses (Table 9-1): no support; limited support; supported; mature support; above expectation; unknown level of support; and via co-simulation.

Table 9-1: Definitions of Levels of Support.

Support Level	Definition
No Support	M&S tool has zero support for this topic in any sense.
Limited Support	M&S tool provides partial or limited support that does not meet the intent of the requirement.
Supported	M&S tool supports the capability. This level of support may be incomplete, error-prone, not validated, difficult to use, etc.
Mature	M&S tool fully supports the capability described by the requirement. At this level of support, the function should not be incomplete, error-prone, lacking validation, difficult to use, etc.
Above Expectation	M&S tool fully supports and exceeds the capability as described by the requirement.
Unknown	Reviewer does not know what level of support is provided by the M&S tool.
Via Co-simulation	M&S tool does not inherently provide support for this requirement, but support can be accomplished by combining the platform with another tool. This capability should be a demonstrated capability and not simply a theoretical ability to co-simulate.

For the other 4 requirements, 3 were given custom response options specific to the requirement. Under licensing, reviewers were asked to specify whether the framework was open-source, free for all use, free for non-commercial use, free for government use, free for commercial use, required a licensing fee, or licensing was unknown. A second licensing question asked reviewers to indicate whether the framework was licensed by seat, by CPU, or by site at four cost levels ($100, $1000, $10,000 or $100,000). Under performance, reviewers were asked to indicate whether simulations typically run faster than real-time, real-time, slower than real-time (hours), or much slower than real-time (days), or performance was unknown. Finally, the fourth item was an open-ended question asking the reviewer to indicate the runtime of an average simulation on the platform.

The requirements were organized into 15 topic areas with as few as 2 and as many as 40 requirements in the topic area. Table 9-2 lists the major areas and the number of requirements associated with the area.

Table 9-2: Number of Requirements per Topic Area.

Topic Area	Number of Requirements
Communication	3
Datasets	3
Environment	40
Interfaces	18
Licensing	3
Metrics	12
Modularity	3
Operator	5
Performance	8
Portability	5
Scalability	8
Sensors	23
Support	15
Validation	2
Vehicle Model	25

9.6 PROCEDURE

Data was collected on the capabilities of the modeling and simulation tools in one of three ways:

1) Expert user review;
2) Specific vendor provided information; and
3) Generally available information.

While our preference was for a review of the system by an expert user with practical experience applying the tool, the benchmarking team did not have access to expert users for the full range of tools of interest. Our second level of review was to request information from the vendors and their technical staff. If we were unable to acquire information from the vendor, we reviewed capabilities based on publicly available information on the simulation platform. Vendor information was translated into the review form by a member of the benchmarking team. Expert reviewers were recruited from the members of AVT-ET-194. Expert users self-reported a level of expertise with the modeling and simulation framework of interest. Each expert reviewer was provided with a review form prepared for the software tool with initial spreadsheet values set to ‘Unknown’ or blank. Reviewers completed the form based on their personal knowledge of the capabilities of the framework.

9.7 ASSESSMENT

9.7.1 Evaluated Frameworks

A total of 17 of the identified tools were reviewed either by expert users, by vendors, or by reviewing publicly available materials describing the capabilities of the modeling and simulation frameworks as follows:

- ANSYS VREXPERIENCE;
- ASAC Dynamic Interactions Simulator;
- AVSimulation SCANer;
- CARLA;
- CM Labs Vortex Studio;
- dSPACE ASM;
- FAAC SimCreator;
- IPG Automotive CarMaker/TruckMaker;
- LGSVL;
- MathWorks Automated Driving Toolbox;
- Mechanical Simulation Corporation VehicleSim (BikeSim/CarSim/TruckSim);
- Mississippi State University Autonomous Vehicle Simulator;
- MSC Virtual Test Drive;
- NASA JPL ROAMS;
- NVIDIA DRIVE Sim;
- OSRF Gazebo; and
- Quantum Signal ANVEL.

Two major real-time simulation and visualization frameworks were also evaluated:

- Unity; and
- Unreal.

9.7.2 Results

9.7.2.1 Scoring Support Levels

All scoring was based on the contents of the review forms created for each framework. For 169 of the 173 requirements, a point value was assigned to the support level. For the five levels of support, points were assigned starting at 0 points for ‘No Support’ and incrementing by 1 for each level up to 4 points for ‘Above Expectation’.

9.7.2.1.1 Two Dimensions

When considering how to score the level of support provided by the frameworks, we identified two separate questions of interest: First, what is the breadth of support for the requirements? Second, what is the depth or maturity of support for the requirements? We separate the scored level of support into two dimensions: level of support and maturity of support. To address level of support, we reduce level of support to a binary response: ‘No Support’ is kept at 0 and other levels of support are recoded to ‘Supported’ and given a value of 1. To address maturity of support, we give no value to ‘No Support’ and retain values from 1 to 4.

9.7.2.1.2 Unknown Levels of Support

Many of the frameworks are complex collections of multiple systems with varying levels of documentation. Regular users of a product may specialize in one system or sub-system in the product and never use other systems included in the product. Users sometimes do not have full knowledge of the details of all the systems that comprise a product. In some cases, expert reviewers were unable to fully determine the capabilities of the system. In these cases, the level of support and maturity of support was recorded as unknown and given no numeric value.

For the purposes of scoring levels of support, an unknown level of support was not included in the calculations. For example, it was unclear to a reviewer whether Product E met any of the requirements related to validation of models. Therefore, all validation items were marked as unknown and Product E has no score for validation. In Product H’s case, the reviewer was unable to determine details of the vehicle model support for several individual requirements. Product H received a score of 63% indicating that, for those items that could be determined, the product included support for about two-thirds of them. If it were determined that Product H’s vehicle models in fact did not support lug and treads in simplified terramechanics models, Product H’s score would be reduced. If it did support them, its score would increase. If a product receives a 0% support for a topic area, that indicates that for at least one requirement in that area the reviewer was certain that the product provided no support for that capability. This scoring method allows us to report levels of support for known capabilities and avoids penalizing products when the reviewer is unaware of a product’s true capabilities.

9.7.2.1.3 Support via Co-Simulation

Almost all the reviewed frameworks supported co-simulation with other tools to provide capabilities that they did not internally support. Many of the frameworks theoretically provided some level of support for most requirements through co-simulation or a combination of tools. However, in our scoring, frameworks were only given credit for meeting a requirement by co-simulation if there was an example demonstrating the co-simulation. The different tools used provide different levels of support and maturity and not all tools used for co-simulation were evaluated. For the purposes of assessing the level of support, co-simulation was recoded to ‘Supported’ and given a value of 1, equivalent to support in the core product. However, for the purposes of assessing the maturity of support, any requirement supported only via co-simulation was considered to have ‘Unknown’ maturity and therefore given no value in the calculation of maturity of support.

9.7.2.2 Level of Support

The level of support for each topic area was calculated as the percentage of the requirements in the topic area that were supported by the framework under evaluation (see Table 9-3). In addition, an overall percentage of requirements supported is calculated for each framework. In order to assess the breadth of support by topic area, we also report average level of support for each topic area across all the evaluated frameworks.

We find very good support (90% or higher) for 3 topic areas: portability, modularity, and user support. We find broad support (75 % to 90 %) for interfaces, scalability, performance, operator models, and virtual environment requirements. We find marginal support (40 % to 70 %) for vehicle models, sensor models, metrics, open-source licensing, and communication models. We find very limited support (40% or less) for datasets and validation. In fact, only 5 of the 17 frameworks provide any validation information for their models. Of note, every requirement was supported by at least two frameworks.

Table 9-3: Level of Support by Product and Topic Area.

Topic Area	A	B	C	D	E	F	G	H	I
Communication	100%	0%	33%	33%	100%	100%	0%	0%	100%
Datasets	50%	33%	0%	0%	50%	100%	0%	0%	100%
Environment	97%	88%	70%	92%	54%	98%	55%	73%	84%
Interfaces	100%	83%	78%	72%	83%	61%	67%	80%	94%
Licensing	100%	0%	100%	0%	0%	0%	100%	100%	100%
Metrics	100%	75%	42%	40%	50%	100%	25%	33%	75%
Modularity	100%	67%	67%	100%	100%	100%	100%	100%	67%
Operator	100%	33%	17%	100%	100%	83%	17%	83%	83%
Performance	100%	67%	67%	50%	80%	83%	50%	60%	100%
Portability	100%	100%	100%	80%	100%	100%	100%	67%	100%
Scalability	100%	88%	88%	63%	100%	88%	75%	38%	100%
Sensors	100%	62%	55%	41%	83%	91%	52%	17%	91%
Support	100%	93%	67%	67%	100%	93%	93%	93%	100%
Validation	100%	50%	0%	0%	-	0%	0%	0%	100%
Vehicle Model	96%	92%	48%	58%	42%	88%	20%	63%	60%
Overall Support	98%	78%	61%	65%	68%	88%	51%	57%	86%

Topic Area	J	K	L	M	N	O	P	Q	Topic Area Support
Communication	67%	0%	0%	67%	0%	0%	67%	67%	42%
Datasets	33%	-	-	0%	0%	-	67%	0%	30%
Environment	90%	46%	92%	85%	64%	93%	79%	73%	77%
Interfaces	94%	94%	100%	100%	78%	100%	100%	89%	86%
Licensing	0%	0%	0%	0%	100%	0%	100%	100%	47%
Metrics	100%	80%	100%	100%	33%	33%	70%	58%	66%
Modularity	100%	100%	100%	100%	100%	100%	100%	100%	94%
Operator	100%	100%	100%	100%	100%	100%	83%	50%	79%
Performance	100%	83%	100%	100%	50%	100%	83%	67%	79%
Portability	80%	100%	100%	100%	100%	60%	100%	100%	94%
Scalability	100%	-	100%	100%	50%	100%	100%	100%	86%
Sensors	91%	43%	95%	95%	55%	57%	82%	57%	68%
Support	100%	79%	100%	93%	93%	100%	93%	92%	90%
Validation	-	-	100%	100%	0%	-	-	0%	35%
Vehicle Model	92%	48%	82%	71%	44%	52%	83%	75%	65%
Overall Support	92%	63%	93%	88%	60%	74%	85%	72%	75%

- Indicates unknown level of support by the product for all elements of a topic area.

9.7.2.3 Maturity of Support

Mean maturity scores were calculated for each category of requirements (see Table 9-4). An overall maturity was calculated for each framework. We also calculated a topic area maturity that reflects the average maturity of support across those frameworks that provided some level of support. As noted, when a product had a demonstrated capability to meet a requirement through co-simulation, the product was given credit for providing support for that requirement. However, to reflect the uncertainty in levels of maturity provided by the co-simulation system, the maturity level for any requirement met solely through co-simulation was marked with a maturity level equivalent to unknown. Therefore, when we examine Table 9-4, additional cells are marked as unknown or no level of support.

Table 9-4: Maturity of Support by Product and Topic Area.

Topic Area	A	B	C	D	E	F	G	H	I
Communication	2.7	-	2.0	2.0	2.0	-	-	-	2.3
Datasets	4.0	1.0	-	-	2.0	1.3	-	-	1.7
Environment	3.3	2.6	1.9	1.7	1.8	1.7	1.8	2.1	2.1
Interfaces	3.1	2.9	2.1	1.6	1.9	1.3	1.4	1.6	2.5
Licensing	2.0	-	3.0	-	-	-	2.0	1.0	1.0
Metrics	3.5	1.6	2.0	1.5	1.3	1.8	1.0	2.0	1.4
Modularity	3.3	3.0	4.0	2.7	-	1.5	1.3	2.7	2.5
Operator	3.0	2.5	1.0	1.8	1.8	1.6	1.0	2.2	1.8
Performance	3.8	2.5	2.0	2.0	1.8	1.8	2.0	2.3	2.7
Portability	3.0	2.8	2.0	2.8	1.5	2.0	2.0	1.5	2.0
Scalability	3.6	2.0	1.9	1.0	2.0	1.7	1.2	1.7	2.0
Sensors	2.9	2.4	1.7	1.8	1.6	1.8	1.5	1.8	1.9
Support	2.6	2.4	1.4	2.3	1.6	1.4	1.2	1.9	1.6
Validation	1.5	2.0	-	-	-	-	-	-	1.0
Vehicle Model	2.5	2.3	1.0	1.5	1.9	1.9	1.4	2.8	1.9
Overall Maturity	3.0	2.4	1.9	1.8	1.7	1.7	1.5	2.0	2.0

Topic Area	J	K	L	M	N	O	P	Q	Topic Area Maturity
Communication	1.0	-	-	1.0	-	-	-	1.0	1.8
Datasets	1.0	-	-	-	-	-	1.0	-	1.5
Environment	2.1	3.1	2.3	2.2	2.5	2.4	2.1	2.0	2.1
Interfaces	2.8	2.8	2.4	2.3	2.3	2.6	2.4	2.0	2.3
Licensing	0.0	0.0	0.0	0.0	3.0	0.0	2.0	3.0	2.1
Metrics	1.8	2.5	2.3	2.3	2.3	1.7	2.0	1.4	2.0
Modularity	2.0	1.0	3.0	3.0	2.3	2.0	2.7	3.0	2.5
Operator	2.2	2.3	3.0	3.0	1.8	2.0	1.4	1.0	2.1
Performance	2.0	3.0	2.7	2.7	1.7	1.8	1.6	1.5	2.3
Portability	3.0	2.8	2.6	2.6	2.0	1.7	1.5	1.8	2.2
Scalability	2.1	-	2.3	2.3	1.5	1.9	1.1	1.7	1.9
Sensors	2.0	1.8	3.1	2.7	1.5	1.7	1.5	1.8	2.0
Support	2.4	2.6	2.7	2.8	1.7	1.6	1.5	1.6	1.9
Validation	-	-	3.0	1.5	-	-	-	-	1.7
Vehicle Model	-	3.1	2.1	1.9	1.6	1.2	1.7	1.3	1.9
Overall Maturity	2.2	2.7	2.5	2.4	2.0	1.9	1.8	1.7	2.0

- Indicates unknown or no level of support for topic area.

Overall, we find that frameworks provide support for the basic capabilities described by the requirement, but, in most cases, support is not mature and rarely exceeds expectations. Every framework reported providing limited capabilities in some topic area.

9.7.2.4 Support and Maturity

In Figure 9-1, we graph the overall level of support for a product and the average maturity score of the product's level of support. By examining the chart, we can see that every reviewed tool provided at least some level of support for at least half of the 169 scored requirements. However, the maturity level of that support generally falls between limited support and supported with a small selection of tools achieving an average maturity of supported and only one tool achieving an overall mature level of support. One tool (K) had a high level of maturity (approaching mature) but for a limited number of requirements.

Neither of these findings is particularly surprising when we consider that 14% of the requirements are related to a relatively new capability (sensor modeling) that supports the also relatively new objective of autonomous mobility for military ground vehicles. The minimum level of support for the requirements described for modeling and simulation of autonomous mobility is encouraging.

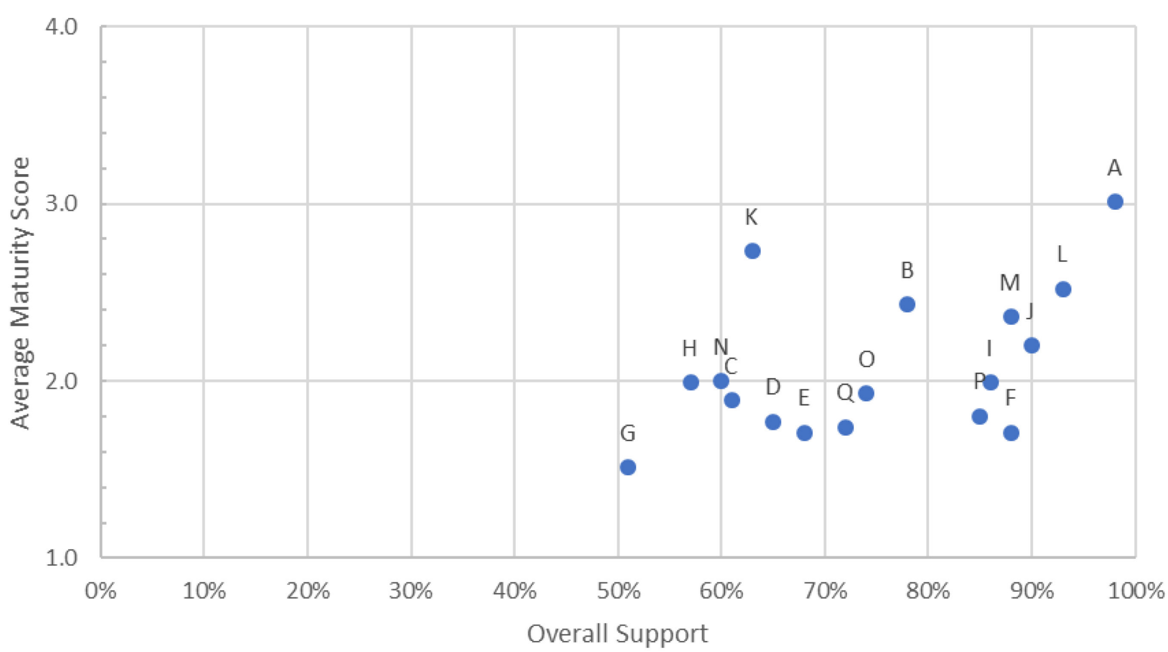


Figure 9-1: Plot of Overall Support for Requirements by Average Maturity Score of the Product.

9.7.2.5 Game Technology Support and Maturity

As noted in the preceding sections, modeling and simulation tool developers leverage game technology to rapidly develop the foundations of an autonomous vehicle modeling and simulation framework. We undertook an effort to score two population game technology frameworks: Unity and the Unreal Engine (see Table 9-5). Scoring the frameworks was challenging. While both Unity and the Unreal Engine provide an impressive collection of technical capabilities, they are primarily a collection of capabilities that must be leveraged by one or more developers to create an effective tool. For our purposes, the game technology frameworks were assessed primarily according to what capabilities are provided by the base system and not the many extensions, plugins, and co-simulations. Based on that assessment, the game technologies provide support for 53 – 62 % of the M&S tool requirements.

Table 9-5: Game Technology Level and Maturity of Support.

Topic Area	Unity	Unreal		Unity	Unreal
Communication	0%	67%		-	-
Datasets	33%	33%		-	-
Environment	75%	74%		1.8	2.1
Interfaces	67%	78%		2.4	2.4
Licensing	100%	100%		1.0	2.0
Metrics	17%	17%		3.0	3.0
Modularity	100%	100%		2.7	3.0
Operator	83%	83%		3.0	3.0
Performance	67%	67%		2.3	2.3
Portability	80%	100%		2.0	2.0
Scalability	13%	25%		2.0	2.0
Sensors	17%	17%		1.3	1.3
Support	73%	87%		2.0	2.0
Validation	0%	0%		-	-
Vehicle Model	48%	79%		1.1	1.0
Overall Support	53%	62%		1.9	2.0

Despite the similarity in scores, there are significant differences between Unity and Unreal Engine technology. There are differences in the details of technical systems, file format support, rendering pipelines, networking systems, integrations with machine learning tools, and more. A key difference is in licensing. Unity is free for non-commercial use but, for any commercial use, developers must pay a per-seat license fee to use Unity. At this time, the Unreal Engine is free for all non-game uses. There are examples where the game technology provides basic level of support for a feature (e.g., raster-based terrain data) but that feature is not available in a tool built on the technology. As M&S tool developers build on the foundations of the game technology, they may choose to modify or disable features according to their specific objectives. As an example, a custom road network tool built on top of the underlying framework may not be compatible with built-in height map data support.

Despite the limitations in applying our scoring method to Unity and the Unreal Engine, our analysis does demonstrate that a significant portion of the M&S tool requirements can be quickly met by starting with one of the frameworks. There are significant questions about the fidelity of M&S tools that build on gaming technologies. As with the more complete tools, future benchmarking of the tools should use quantitative assessments of both model fidelity and computational performance.

9.8 CONCLUSION

The research and development of autonomous vehicles is fast moving with rapid developments in capabilities, particularly in on-road consumer advanced driver assistance systems and self-driving systems. Real-world development has out-paced modeling and simulation tool development. However, testing and certification of autonomous vehicle systems cannot be completed using physical testing alone. Modeling and simulation of sensor systems are rapidly advancing but many modeling and simulation tools have limited vehicle models that are not sufficient for modeling and simulation of off-road autonomous systems. To determine the state of the art in modeling and simulation for autonomous mobility of military ground vehicles, we undertook a review of current modeling and simulation tools.

With the support of the entire NATO AVT-ET-194 team, we identified over 170 requirements in 15 major topic areas. We collected data from expert users and vendors for 17 M&S tools including open-source and commercial tools focused on autonomy, mobility, or both. The high level of support demonstrated by some tools is encouraging. The minimum level of support (over 50%) is high for a relatively new area of modeling and simulation. The low level of maturity in support is concerning. Most tools provided limited or minimum required levels of support. Few tools provided mature levels of support. The key areas lacking in maturity included support for GIS and related datasets of value to the military, vehicle-terrain interaction, sensor modeling, and, importantly, validation of models.

There is very limited support for the dataset formats prescribed for NG-NRMM modeling and simulation. Only two of the M&S tools support the legacy NRMM Code 11/Map 11 (MAPTBL) terrain data format, only a quarter of the tools support File Geodatabase datasets, and half of the reviewed tools supported GeoTIFF terrain data files. Even in those tools that provided support, the support was, on average, limited.

There is better support for general GIS datasets and terrain databases. Over 70% of the reviewed M&S tools supported import of some GIS formatted datasets and raster terrain data files. The nature of the support varies across the reviewed tools. Some tools provide support for Digital Elevation Map (DEM) files and some work with commercially available terrain databases. There is no single terrain data file format that is broadly supported across all the tools. Most of the terrain data formats that were supported do not provide the soil data required by for NG-NRMM modeling and simulation.

In the absence of broad support for a terrain database that supports advanced mobility modeling, it will be difficult to develop standard, interoperable terrain environments for quantitative benchmarking of M&S tools. Future NATO research teams should encourage broad adoption of terrain data formats that will support modeling and simulation of autonomous mobility.

Most of the M&S tools support over 75% of the environment requirements. Just under half of the tools provide very high levels of support (90% of higher). While only one product averaged mature level of support for the environment requirements, only a few requirements had limited or no support. First, as noted above, the reviewed tools had very limited support for legacy and NG-NRMM environment requirements. Less than a third of the tools could represent the minimum soil data required by NG-NRMM. Other environment requirements with limited support included deformable and movable terrain, hydrodynamic forces, soils with embedded rocks and other objects, layers of snow, multi-resolution layered maps, and localized dynamic visual and physical effects (e.g., blasts).

While there was broad support for modeling of atmospheric conditions (e.g., fog, dust, and haze) and precipitation effects, the maturity of support was limited. In most cases, the available models are simple approximations of the effects. Most precipitation models have limited realism and few M&S tools incorporated precipitation effects on sensors (e.g., raindrops on a camera lens) or surfaces (e.g., reduced friction and increased reflectivity). Accurate evaluation of autonomous mobility will require testing in adverse atmospheric conditions with precipitation. Future work should evaluate the relative importance of accurate models of atmospheric conditions and precipitation and encourage modeling and simulation tool developers to continue to develop existing models.

In the M&S tools that were reviewed, we found broad support for the sensors of primary interest for autonomous mobility: LIDAR, automotive radar, camera, GPS, and IMU. In addition, we found generally good support for contact sensors, laser rangefinders, ultrasonic sensors, wheel encoders, and speed sensors. Fewer than half of the reviewed tools provided models of thermal/infrared sensors, hyperspectral sensors, ground penetrating radar, tire pressure, or fuel gauges. In addition, we found limited support for providing vendor-specific sensor models or for allowing users to calibrate sensor models based on real sensor data. There is significant variation between vendors and within classes of sensors that users should be able to represent in the M&S tools.

Our analysis of the sensor support is very limited. We did not assess the fidelity or the computational performance of each sensor model. Future work should develop quantitative benchmarks for evaluating the fidelity of sensor models that would provide a more detailed assessment of the M&S tools.

There is a pronounced lack of support for modeling communication systems both for V2X communications and communications between systems on-board the vehicle. Over half of the frameworks offered limited or no support for communication system modeling. In our analysis, the communication requirements are very limited in scope. Future work should further refine the communication requirements.

In the set of M&S tools that were reviewed, the average support for sensor and vehicle model requirements is not particularly good (less than 70%). In most cases, sensor and vehicle model support levels are similar. In five of the tools (B, E, G, H, and I), there are significant differences in the level of support for either sensors or vehicle models. For B and H, the focus was on vehicle model support. For E, G, and I, the tools focus on sensor model support. Co-simulation may allow tools like B, E, and I to address their weak areas.

There were four primary areas of weakness for vehicle model support in the reviewed tools: mobility models, tracked vehicles, soil adhesion effects, and other forms of mobility (legged, water, and air vehicles). Overall, the level of support for detailed vehicle models was spotty and limited. Few M&S tools provided the full range of desired mobility modeling capabilities. Many of the M&S tools provide low fidelity models adequate for nominal on-road vehicle operation. Few provide off-road models, tracked vehicle models, or high-fidelity models of any type. As with the sensor assessment, our analysis of vehicle model support is high level and qualitative. Future evaluations should move towards quantitative evaluations of model performance for benchmarking M&S tools.

A challenge for benchmarking M&S tools for evaluation of military ground vehicles will be the limited support for metrics of value to the military. The reviewed M&S tools provided limited support for calculation of go/no-go and speed-made-good maps or assessment of vehicle efficiency. Only about 40% of the tools provided any support for calculation of costs associated with traversing terrain. However, every tool provided some level of support for users to define and record their own metrics within the M&S tools. Also, while most tools did not provide tools for design of experiments, many tools did support stochastic models and provided users with the ability to vary inputs to assess repeatability of performance.

For sensor models, vehicle models, and metrics, there are questions related to the fidelity of the models and simulations supported by the M&S tools that require validation of the component and system-level models. Only five of the reviewed tools provided any validation of their models and in only one product was the validation rated as mature. There is a need for a collection of test scenarios for quantitative benchmarking of modeling and simulation tools for autonomous mobility.

9.8.1 Limitations

This project evaluated the current state of the art in modeling and simulation by checking off boxes of required features. The actual execution of the tools was not tested. Moving forward, the community must develop benchmarking methods that assess the performance of these tools in terms of accuracy, computational efficiency, etc.

Our evaluation is limited by the relatively high level nature of our requirements used in our scoring method. Our sensor assessment is largely limited to whether the framework provides any model of the sensor and does not evaluate the fidelity or computational performance of the sensor model. In at least one of the products evaluated, the LIDAR model is essentially a depth map image treated as an array of distances with no actual modeling of the rays. In another product, the LIDAR model includes a detailed geometric model of the moving parts and can capture the sweep of the beam from one frame to the next. While this difference is captured in a difference in sensor model maturity, we were not able to evaluate the fidelity of the model or the effect of differences in fidelity on system-level modeling and simulation. Future work should define benchmark tests to quantitatively assess model fidelity at the component and system levels.

9.8.2 Recommendations for Future Work

The objective of the current effort was to determine the state of the art in modeling and simulation tools for autonomous mobility of military ground vehicles. A qualitative review of 17 modeling and simulation tools has identified limited support for required capabilities in several areas: datasets, communication, environment models, sensor models, vehicle models, metrics, and validation.

The current evaluation assessed whether a modeling and simulation tool provided some level of support from no support to exceeding expectations for a set of requirements. The evaluation was not quantitative. The evaluation was subjective and depended on the assessment of expert users. While the results of the evaluation have provided insight into the level of support provided by current modeling and simulation tools, further evaluations should use quantitative benchmarks that can provide detailed insight into the fidelity and performance of current and future modeling and simulation tools for autonomous mobility in military ground vehicles.

To that end, we recommend the development of a collection of benchmark scenarios designed for quantitative evaluation of the modeling and simulation tools. The benchmarks should provide scenario definitions (see Chapter 4, Scope, Definitions, Scenarios, Perception, Planning, Control) in portable data formats. The benchmarks should require support for legacy and NG-NRMM data and encourage use of the data formats specified by NG-NRMM. The benchmarks should include tasks that encourage development in areas of interest to NATO and its partners. Based on the requirements identified here, this would include very large environments, snow-filled environments, weather and precipitation effects, scenarios requiring deformable and movable terrain. The benchmarks should include component validation scenarios that evaluate the performance of specific sensor and vehicle models. The benchmarks should also include system-level scenarios that require military-relevant outputs such as go/no-go maps, speed-made-good maps, and efficiency metrics.

The benchmark scenarios should be implemented in multiple modeling and simulation tools and used to quantitatively evaluate the fidelity and performance of current tools. Products A, L, J, M, I, F, and P would all be good candidates for system-level evaluations.

9.9 REFERENCES

[1] ReplicaR, 2019. AutomotiveAI. Available at: http://www.automotive-ai.com/.

[2] aiSim, 2019. AIMotive. Available at: https://aimotive.com/aisim/.

[3] VREXPERIENCE, 2019. ANSYS. Available at: https://www.ansys.com/products/systems/ansys-vrxperience.

[4] AV Simulator, 2019. Applied Intuition. Available at: https://appliedintuition.com.

[5] Dynamic Interactions Simulator, 2019. ASAC. Available at: http://www.ascience.com/DIS.htm.

[6] SCANer, 2019. AVSimulation. Available at: https://www.avsimulation.fr/solutions/.

[7] Apollo Game Engine Based Simulator, 2019. Baidu Apollo. Available at: http://apollo.auto/gamesim.html.

[8] CARLA, 2019. Available at: http://carla.org/.

[9] CESIUM, 2019. CESIUM. Available at: https://cesium.com/industries/autonomous-cars/.

[10] Vortex Studio, 2019. CM Labs. Available at: https://www.cm-labs.com/vortex-studio/.

[11] Cognata, 2019. Cognata. Available at: https://www.cognata.com/.

[12] CoppeliaSim, 2019. Coppelia Robotics. Available at: http://coppeliarobotics.com/.

[13] SynCity, 2019. CVEDIA. Available at: https://www.cvedia.com/solution/syncity/.

[14] Dash, 2019. Matt Bradley. Available at: https://mattbradley.github.io/dash/.

[15] DeepDrive, 2019. Voyage. Available at: https://deepdrive.io/.

[16] Automotive Simulation Models, 2019. dSPACE. Available at: https://www.dspace.com/en/inc/home/products/sw/automotive_simulation_models.cfm.

[17] SimCreator/SimDriver, 2019. FAAC. Available at: https://www.faac.com/realtime-technologies/solutions/research-simulation-adas-autonomous-vehicles/.

[18] CarMaker/TruckMaker, 2019. IPG Automotive. Available at: https://ipg-automotive.com/products-services/simulation-software/carmaker/.

[19] LGSVL, 2019. LG. Available at: https://www.lgsvlsimulator.com/.

[20] Multi-Agent DRiving Simulator, 2019. MADRaS. Available at: https://github.com/madras-simulator/MADRaS.

[21] Matlab Automated Driving Toolbox, 2019. Mathworks. Available at: https://www.mathworks.com/products/automated-driving.html.

[22] VehicleSim, 2019. Mechanical Simulation Corporation. Available at: https://www.carsim.com/products/carsim/index.php.

[23] MetaMoto, 2019. MetaMoto. Available at: https://www.metamoto.com/.

[24] AirSim, 2019. Microsoft. Available at: https://microsoft.github.io/AirSim/.

[25] Mississippi State University Autonomous Vehicle Simulator, 2019. Mississippi State University. Available at: https://gitlab.com/cgoodin/msu-autonomous-vehicle-simulator.

[26] monoDrive Autonomous Vehicle Simulator, 2019. monoDrive. Available at: https://www.monodrive.io/.

[27] Virtual Test Drive, 2019. MSC Software. Available at: https://www.mscsoftware.com/product/virtual-test-drive.

[28] ROAMS, 2019. NASA. Available at: https://dartslab.jpl.nasa.gov/ROAMS/index.php.

[29] Virtual Training, 2019. NervTech. Available at: https://www.nervtech.com/services.

[30] DRIVE Sim, 2019. NVIDIA. Available at: https://www.nvidia.com/en-us/self-driving-cars/drive-constellation/.

[31] RT-LAB ORCHESTRA, 2019. OPAL-RT. Available at: https://www.opal-rt.com/orchestra/.

[32] OpenDS, 2019. DFKI. Available at: https://opends.dfki.de/.

[33] Gazebo, 2019. Open Source Robotics Foundation. Available at: http://gazebosim.org/.

[34] COSMOsim, 2019. OTSL. Available at: https://otsl-biz.jp/en/product/cosmosim/.

[35] Durst, P.J., Goodin, C., Cummins, C., Gates, B., Mckinley, B., George, T., Rohde, M.M., Toschlog, M.A., and Crawford, J., 2012. A Real-Time, Interactive Simulation Environment for Unmanned Ground Vehicles: The Autonomous Navigation Virtual Environment Laboratory (ANVEL). 2012 Fifth International Conference on Information and Computing Science, Liverpool, 2012, pp. 7-10. Available at: https://doi.org/10.1109/ICIC.2012.5.

[36] SCANeR II, 2019. Renault. Available at: http://www.experts.renault.com/kemeny/projects/scaner2/.

[37] Virtual Test, 2019. rFpro. Available at: http://www.rfpro.com/virtual-test/adas-and-autonomous/.

[38] RightHook, 2019. RightHook. Available at: https://righthook.io/.

[39] PreScan, 2019. Tass International. Available at: https://tass.plm.automation.siemens.com/prescan.

[40] Self-Driving Car Simulator, 2019. Udacity. Available at: https://github.com/udacity/self-driving-car-sim.

[41] VR-Vantage IG, 2019. VT MAK. Available at: https://www.mak.com/products/visualize/vr-vantage-ig.

[42] IZAC, 2019. ZMP. Available at: https://www.zmp.co.jp/en/products/izac/about.

[43] Epic Games, 2019. What is Unreal Engine 4, Available at: https://www.unrealengine.com/en-US/. [Accessed 8 December 2019].

[44] Unity Technologies, 2019. Unity 2019: Performance by default, high-fidelity real-time graphics, and artist tools. Available at: https://unity3d.com/unity. [Accessed 8 December 2019].

Chapter 10 – FOLLOW-ON RTG RECOMMENDATIONS

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Even as full autonomy remains the eventual goal, essential to the reliable operation of autonomous vehicles in the field to successfully carry out a mission is the ability to predict its mobility performance and risk over a specified region. Such predictive capability is needed to effectively monitor and guide autonomous vehicles to keep the vehicle safe while meeting mission constraints (e.g., no-go areas) and maximizing performance metrics (e.g., time, speed, fuel consumption). The viable use of autonomous vehicles depends on the development of predictive models and data products that can guide the vehicle safely and effectively in the field. The future of analytical soft soil mobility analysis clearly rests with NG-NRMM as it holds the promise of allowing manufacturers, planners, and users the ability to model virtually any platform, over any soil and terrain type. It is vital to the Army's mission as it will add new capabilities in the design, modelling, and simulation of a broad class of vehicles, with the potential to reduce costs and improve performance. Future intelligent autonomous mobility may involve many different classes and sizes of vehicles such as wheeled and tracked vehicles, small robots, legged robots, humanoid robots, and other emerging technologies traversing a variety of environments that may include on-road, urban, off-road, and building interiors.

The NATO Exploratory Team ET-194 was approved in the fall of 2019, assembled, and was comprised of subject matter experts from eleven (11) NATO nations who were brought together to explore methods and approaches to assess the performance and reliability of autonomous ground systems and, more importantly, cultivate a strategy to develop an overarching framework to develop, integrate, and sustain advanced manned and autonomy-enabled ground system capabilities for the current and future force. This activity leveraged results from AVT-ET-148, AVT-248 and AVT-CDT-308 on the NG-NRMM and, together, they demonstrated that autonomous vehicles have specialized modelling and simulation requirements with regard to mobility. The activity also leveraged current activities ET-184 (Physics of Failure for Military Platforms), AVT-ET-185 (Goal-driven, Multi-Fidelity Approaches for Military Vehicle System-Level Design), AVT-327 (STANREC for a NG-NRMM), and AVT-ET-196 (Technology Trends in Manned and Unmanned Armored Ground Vehicles). Based on the results of the exploration of tool choices, a benchmarking exercise was also conducted to understand the capabilities of the physics-based tools available from software developers.

Subsequently, task areas were developed and teams assembled to work on challenges and special requirements for M&S of autonomous military systems, definitions related to autonomous military systems, current software available for assessing the mobility of autonomous systems, approaches to assessing the interdependence of mobility with communications and data, and building on NG-NRMM AVT-248 results to determine approaches for assessing off-road mobility of autonomous systems. To enable that evaluation, six (6) work groups were stood up in the areas of:

1) **Task 1:** Scope, Definitions, Scenarios, Perception, Planning, Control.
2) **Task 2:** Virtual Environments, Sensors, Uncertainty Quantification.
3) **Task 3:** Vehicle System Models.
4) **Task 4:** Software, Hardware, Data, Communication.

5) **Task 5:** Mobility Assessment, Verification, and Validation.
6) **Task 6:** Benchmarks.

A short summary of the conclusions and follow-on RTG recommendations for each theme area are presented below.

10.1 TASK 1: SCOPE, DEFINITIONS, SCENARIOS, PERCEPTION, PLANNING, AND CONTROL

The goals of the Scope, Definitions, Scenarios, Perception, Planning, Control task group were to explore methods for evaluating algorithms and determine the M&S requirements for supporting those evaluations. Primary objectives were to define autonomous mobility, reliability, levels of autonomy, as well as operational environments and scenarios. In addition, efforts were expended to determine the scope of the effort, the minimum set of scenarios that needs to be supported, and the requirements for supporting external perception, planning, and control algorithms. A framework was proposed in order to provide tools and methods to assess the mobility of autonomous ground vehicle platforms. If mobility is a mature field, the autonomy part on the other hand, in the sense of an autonomous system is a wide field where there is no strict consensus, and which is constantly evolving. With this in mind, a framework was designed that aims to integrate both fields while providing a scenario generation and validation process. This process is inspired by the PEGASUS Project approach in which layers and level abstraction features were extended from the on-road only context to handle off-road as well as a wider range of situations. The framework also proposes to extend the NG-NRMM model by integrating autonomy into it. Similarly, Autonomy Levels for Unmanned Systems' (ALFUS) level of autonomy situational approach, although limited, was found to be a strong foundation to propose an extended version. Taken together, this framework will enable the necessary generalization and adaptability to address continuous change in situational and technological aspects. The competition as well as the two (2) planned CDTs will test and mature this novel framework through simulation and field tests in order to validate and benchmark solutions for autonomous ground vehicle mobility in a military context.

The proposed follow-on RTG should be able to address convergent research challenges due to the fact that the simulation tools created will be uniquely comprehensive in terms of bringing the perception, planning, and control elements together in a directly army-relevant context, and, it will provide the required diverse multi-disciplinary expertise to support dialog amongst these disciplines. Therefore, the RTG can address some of the most challenging research questions facing autonomous mobility, such as:

- The impact of the performance of the perception algorithms on the performance of the planning algorithms, and the performance of the planning algorithms on the performance of the control algorithms.
- The impact of external factors such as the environment and the other agents in the environment.
- The impact of different sets of algorithms and autonomy capabilities on the performance of other team members, be it other vehicles or humans.
- Capturing these impacts in models and recreating them in simulation.
- Developing the tools and methodologies that can identify the most suitable set of perception, planning and control algorithms for a given use case.
- Developing methods to efficiently assess the reliability of an autonomous vehicle in simulation for a given use case and set of algorithms.

10.2 TASK 2: VIRTUAL ENVIRONMENTS, SENSORS, AND UNCERTAINTY QUANTIFICATION

The Virtual Environments, Sensors, Uncertainty Quantification task group was tasked with evaluating the requirements for representing the operational environment within an M&S framework, evaluating autonomous mobility of military ground vehicles and, for M&S of the sensors used by autonomous systems to perceive the environment. Specifically, its objectives were to establish the requirements for representing the virtual environment and determining the state of the art, as well as the gaps, for open source and existing data sets. In addition, the group focused on determining the sources of uncertainty that need to be considered and the state of the art for measuring and modelling these uncertainties as well as the associated gaps.

The group identified a considerable number of gaps such as the need for development of shared libraries of scenarios and for extensions to the open data format standards to support the requirements of off-road scenarios. Libraries of object and agent models that support complex vehicle-object and vehicle-agent interactions are needed that support representations of the effects of environmental conditions as well as libraries of surface material property distributions required to accurately model the camera, LIDAR, radar, thermal, and other sensors. Other identified gap areas were the need for improved nano-behavior models for human and animal agents that can generate the enormous range of intelligent, complex, and interpretable behaviors of humans and animals necessary to model micro-behaviors for vehicles, pedestrians, and animals.

The ability to predict a vehicle's mobility performance and risk over a specified region is paramount to autonomous navigation and gaps persist in being able to model sensor perception of the environment such that the appearance of the soil to sensors matches the soil properties used for vehicle-terrain interaction. Realistic models of precipitation that include effects on the surfaces of sensors and effects on the environment are needed. Other gap areas include reduced order models that can provide sensor data and meta-data that may be used by intelligent algorithms and reduced order radar models that can achieve real-time performance but still provide a more accurate representation of real-world performance. Improvements in modelling of on-board, V2V, and V2I communications with multiple sources of noise, potential system latencies. Potential points of failure are necessary and there is a need for evaluations of the sensitivity of sensors, algorithms, and system performance to variations in environment parameter values.

Recommendations for the follow-on RTG work groups are to create a series of quantitative benchmarks that not only will provide metrics for the assessment and validation of the models incorporated into the simulation tools, but also will exercise the data formats used to define the environments and the sensors leading to better representations of scenarios. Future work should also consider how to define, validate, and use sensor models of varying levels of fidelity. M&S tool users would benefit from prescription of best practices for testing systems.

10.3 TASK 3: VEHICLE SYSTEM MODELS

This Vehicle System Models group was task with identifying distinctive features of M&S of autonomous navigation and mobility as well as formulating requirements for autonomous vehicle models. The group's objectives were to determine the requirements of transitioning from conventional to autonomous vehicles and formulating requirements for functional features and operational properties that autonomous vehicles and autonomous systems should demonstrate during on and off-road combat and tactical operations. This included defining the modelling requirements for vehicle systems and analyzing mobility assessment methods for their compliance with the functional features and operational properties of autonomous vehicles.

The task group developed requirements for autonomous vehicle models needed for virtual assessment of vehicle mobility and included a discussion of capabilities needed for simulating the autonomous vehicle models. They also identified requirements pertaining to the modelling of vehicle dynamics, vehicle systems, vehicle sensors, and vehicle-operator and vehicle-terrain interaction while the vehicle models interface with other components of the virtual mobility assessment framework, as well as virtual environments, autonomous mobility sensor models, planning and control subsystems. Specifically, this section focused on the M&S of autonomous vehicle system components including vehicle-AI-operator interface modelling, shared control, AI-driver/operator handover, internal combustion engines drivetrains, torque converter and transmission, driveline, electric and hybrid-electric drives, other locomotion systems, tire and track models, suspension/steering/brake systems, and system sensors.

Potential follow-on RTG work areas were identified regarding M&S autonomous vehicles and related systems. The group recommends studying distinctive features of autonomous vehicle models and vehicle system models such as environmental and terrain conditions, run times to enable artificial intelligence and model-based decision-making processes, simulating autonomous model-based vehicle system controls and interfacing with the artificial intelligence based mission planning and implementation. They also suggested assessing the capability to move through terrain in principle and estimating the vehicle ability to perform a task/mission. The mobility assessment methods should be functional for predicting terrain mobility margins during motion, assessing the mobility state of a vehicle with regard to its immobilization state, and estimating terrain mobility performance while maintaining certain mobility margins and performing its' task and mission.

10.4 TASK 4: SOFTWARE, HARDWARE, DATA, AND COMMUNICATION

This Software, Hardware, Data, Communication group was responsible for determining the requirements for software and hardware tools used in the simulation of autonomous ground vehicles as well as data and communication characteristics necessary to determine the needs for communication and connectivity that the simulation needs to support. This included the requirements for the input and output data and the software/hardware requirements.

Their analysis focused on software that simulates real-world inputs and outputs such as sensors (e.g., Lidar) and vehicles. These software tools, either by themselves or working with other software tools, must allow an autonomy software to function similarly to the way it will on the physical vehicles. The group provides and extensive discussion on a set of generalized requirements for an autonomy simulation software that can be run in many simulation configurations, rather than only on an operating vehicle. It describes software level requirements such as modularity, open source, real-time needs, support for X-in-the-loop simulation(s), standard APIs, scalability, etc., and presents the state of the art as well as discusses the gaps in autonomy software. Requirements for the input and output data such as data types and formats for defining the models, scenarios, inputs, outputs, information exchange between modules, visualization, machine learning, open source, etc. are discussed. Communication and connectivity that the simulation needs to support that includes human-vehicle, intervehicle, and vehicle-infrastructure communication(s), trust, quality of communication (e.g., latency, noise, drop outs, bandwidth) are discussed. A through discussion of the necessary hardware requirements to support hardware-, human, and software-in-the-loop simulations, as well as emulation of hardware limitations such as computational power or memory were presented.

This chapter detailed desired qualities of vehicle autonomy simulation software that can be used to allow an autonomy software to function similarly to the way it will on physical vehicles. The group outlined a set of desired autonomy characteristics for consideration:

- Autonomy provider-supported operation of software in simulation.
- Able to operate at varied clock speeds (slower or faster than real-time).
- Internal software states available for inspection (e.g., control signals, sensor fusion, etc.).
- Able to operate on varied hardware types, including virtual machines (e.g., x86/64 architecture, embedded processor, etc.).
- Capable of operating in multiple configurations (e.g., software/hardware, vehicle in-the-loop, etc.).
- Available interface control document for communication with outside sensors/controllers/etc.

Since the autonomous vehicle field is still developing and evolving, features such as modularity and extensibility are stressed over usability and maturity. The chapter also details some of the measured quantities required by the autonomy software itself to enable simulation. The group recommends that these recommendations be considered during software development and selection by the follow-on RTG.

10.5 TASK 5: MOBILITY ASSESSMENT, VERIFICATION, AND VALIDATION

The Mobility Assessment, Verification, and Validation team was responsible for developing the requirements for assessing mobility as well as verifying and validating simulation results. Their efforts focused on determining the methods and metrics for assessing mobility such as the dimensions to be evaluated, scoring schemes, gross metrics (e.g., autonomy and mobility maps, mission performance potential MPP), stochastic vs. deterministic evaluations, and statistical tests to be utilized. They were also task with determining how simulation results will be verified and validated which included procedures for component level Verification and Validation (V&V), system-level V&V, resources needed, potential demonstrations, and standards development. Other primary tasks were to compile use cases or scenarios and their mobility requirements and look at quantifying environmental conditions and their effects on the sensors

The team's goal for the RTG would be to validate the model(s) created and verify their performance. Established mobility assessment procedures will still be applicable and employed but they will be augmented to challenge the new driver action models. These models will require new methods and metrics for assessing autonomous mobility but will be grounded by legacy mobility assessment procedures and, moreover, will require a comprehensive understanding of the world including its infinite variability. Simulation of the natural environment will be dependent upon the sensors used to perceive the conditions surrounding the vehicle platform. Some of the elements of mobility to be evaluated will be the scoring schemes, gross metrics, stochastic vs. deterministic evaluations, and statistical tests to be utilized to understand the operating environment. Autonomous mobility V&V will be a new standard set of challenges and associated metrics that evaluate the new driver and its perception of the world and will be based upon missions and use cases that are not yet defined.

The RTG focus will need to highlight challenges to the driver's ability to assess the situation and produce a positive result. Therefore, the most significant adjustment expected for autonomous mobility is the validation of the system's assessment of the world as it relates to immediate surroundings and ultimate goals of the mission. Validation of the environment models will follow physical measurements and most likely be unable to predict environmental conditions. Environmental testing must inherently include: 1) Methods to measure a variety of environmental conditions and intensity; and/or 2) Use environmental cells to create specific conditions to challenge the autonomous system's ability to assess and operate in a wide range of environments. A combination of both methods will likely be needed to fully assess and quantify the capabilities of modelling and simulation tools used to develop future autonomous vehicles. Initially a static, validation methodology can be enhanced to be dynamic through the use of test rigs that still do not encompass vehicle motions produced by operating conditions and interaction with uneven ground. Final autonomous mobility validation of a combined vehicle and situational awareness models should be started by defining simple, singular mobility events with simple situational awareness tasks such as object recognition, scaling, and decision making.

Further recommendations for follow-on RTG validation efforts are to focus on what data is needed for a required maneuver, and why, that will largely depend upon what the data is used for (i.e., Localization, Object Recognition, Material Assessment, or Proximity) but also upon the state of the vehicle (i.e., Speed, Heading, Pose, Jounce, and Vibration) and environmental conditions that affect the data collection. Furthermore, validation of the M&S tools used to challenge the system's environmental assessment will need to focus on the key features of multiple sensor types and how these types are used by multiple vendors. A 3D Matrix of environment simulations is imagined (Sensor Type / Vendor Use / Data Collection Challenges). Simulation of the natural world and all of its permutations is believed to be far too complex to efficiently validate, consequently, validation efforts should start with simple, un-obscured objects in controllable conditions and then have complexity added. Current efforts should move towards a "Good Enough" mentality and use validation to establish a "Confidence Level" that the simulation is "Good Enough" for the intended purpose. The process for validation should be aligned to scenarios to develop a combined vehicle mobility and environmental assessment validation prototype for a set of specific scenarios. A broad-based guideline to define scenarios could be developed with separate assessment and validation categories conducted within a graduated application framework.

It is obvious that assessment needs are large and are continuously being expanded by the user community. The suggested path forward is to start simple, establish a base to move from, minimize options at first and expand as confidence in the methods and tools grows, and constantly re-evaluate the process. The suggested path forward is to establish basic capabilities within the framework's set objectives, guided by defined scenarios. Specific tactical steps forward are described in the chapter that boil down to establishing procedures for combined autonomous mobility assessment as well as adequate simulations and V&V of simulations.

10.6 TASK 6: BENCHMARKS

The goal of the benchmarks team was to review a large set of modelling and simulation tools to determine whether the tools meet requirements defined by the ET. The team set out to determine what benchmarks were required, to define the benchmarks, and to establish a procedure for evaluating available tools. The objective was to understand the capabilities of current modelling and simulation frameworks for the assessment of the mobility of an autonomous military ground vehicle across a range of operational environments and conditions. Based on an understanding of the capabilities, the team was to determine the state of the art and to identify gaps in current capabilities. The results of the survey of current tools could identify tools or a combination of tools that would meet the requirements for the Next-Generation NATO Reference Mobility Model (NG-NRMM) and provide extended capabilities for M&S of autonomous vehicle technologies including sensors and advanced control systems. To determine the state of the art in M&S for autonomous mobility of military ground vehicles, the committee undertook an extensive review of current M&S tools. The team identified over 170 requirements in 15 major topic area and collected data from expert users and vendors for 17 M&S tools including open source and commercial tools focused on autonomy, mobility, or both.

This project evaluated the current state of the art in M&S by checking off boxes of required features. The actual execution of the tools was not tested and, moving forward, the community must develop benchmarking methods that assess the performance of these tools in terms of accuracy, computational efficiency, etc. The evaluation is limited by the relatively high-level nature of our requirements used in the scoring method. The sensor assessment is largely limited to whether the framework provides any model of the sensor and does not evaluate the fidelity or computational performance of the sensor model. Future RTG work should define benchmark tests to quantitatively assess model fidelity at the component and system levels.

The current evaluation assessed whether a modelling and simulation tool provided some level of support from no support to exceeding expectations for a set of requirements. The evaluation was not quantitative, subjective, and depended on the assessment of expert users. While the results of the evaluation have provided insight into the level of support provided by current modelling and simulation tools, further evaluations should use quantitative benchmarks that can provide detailed insight into the fidelity and performance of current and future modelling and simulation tools for autonomous mobility in military ground vehicles. To that end, the team recommends the development of a collection of benchmark scenarios designed for quantitative evaluation of the modelling and simulation tools. The benchmarks should provide scenario definitions (see Chapter 4: Scenarios) in portable data formats. The benchmarks should require support for legacy and NG-NRMM data and encourage use of the data formats specified by NG-NRMM. The benchmarks should include tasks that encourage development in areas of interest to NATO and its partners. Based on the requirements identified here, this would include very large environments, snow-filled environments, weather and precipitation effects, scenarios requiring deformable and movable terrain. The benchmarks should include component validation scenarios that evaluate the performance of specific sensor and vehicle models. The benchmarks should also include system-level scenarios that require military-relevant outputs such as go/no-go maps, speed-made-good maps, and efficiency metrics. The benchmark scenarios should be implemented in multiple modelling and simulation tools and used to quantitatively evaluate the fidelity and performance of current tools. Products A, L, J, M, I, F, and P would all be good candidates for system-level evaluations.

Annex A – ET-194 TECHNICAL ACTIVITY PROPOSAL (TAP)

ACTIVITY REFERENCE NUMBER	AVT-ET-194	ACTIVITY TITLE ***Assessment Methods and Tools for Mobility of Autonomous Military Ground Systems***	APPROVAL 14DEC2018
TYPE AND SERIAL NUMBER	**Exploratory Team**		START 01/2019
LOCATION(S) AND DATES		In conjunction with AVT PBWs	END 12/2019
COORDINATION WITH OTHER BODIES		None	
NATO CLASSIFICATION OF ACTIVITY		NU	Non-NATO Invited Yes
PUBLICATION DATA		TM, Misc.	NU
KEYWORDS	autonomous systems; data analytics; mobility; performance and reliability; physics based methods		

A.1 BACKGROUND AND JUSTIFICATION (RELEVANCE TO NATO)

Autonomous ground systems are a key part of the future military strategy for many NATO Nations, and commercial companies are racing to develop autonomous systems to be first to market. In this race to field these systems, there is still a lack of understanding of the capabilities and reliability of these systems. One key performance measure of autonomous ground systems is their mobility on-road and off-road. How fast can the system move and how reliably can it reach its destination under a wide range of conditions? How well can these systems maneuver with soldiers under a variety of operations? How are these measures defined? These are important topics that need to be addressed in order to fully field and operationalize these new technologies. This proposed activity will leverage the results from AVT-ET-148, AVT-248 and AVT-CDT-308 on the Next Generation NATO Reference Mobility Model (NG-NRMM). Together, they demonstrated that autonomous vehicles have specialized modeling and simulation requirements with regard to mobility. The activity will also leverage current activities ET-184 (Physics of Failure for Military Platforms), AVT-ET-185 (Goal-driven, Multi-Fidelity Approaches for Military Vehicle System-Level Design), AVT-327 (STANREC for a NG-NRMM), and AVT-ET-196 (Technology Trends in Manned and Unmanned Armored Ground Vehicles).

Modernization efforts of NATO Nations' militaries involve the integration of communications and control technologies, which we call autonomous technologies, to provide greater operational capability. The proposed exploration has the potential to significantly reduce costs and improve understanding of current and future autonomous system performance. The proposed exploration is vital to NATO's mission. It promises to enable new capabilities in the design, modeling, and simulation of a broad class of vehicles. These modeling capabilities are of high importance to current and future NATO missions because they have the potential to significantly reduce costs and improve performance. The new tool will be applicable to various running gear morphologies, including conventional wheels and tracks, and more novel bio-inspired limb designs.

A.2 OBJECTIVE(S)

This proposed activity is to explore the methods and approaches to assess the mobility performance and reliability of autonomous ground systems. The primary objectives of the proposed panel are to: 1) Identify the challenges and special requirements associated with modeling and simulation of autonomous military systems; and 2) Determine the current state-of-the-art software for assessing the performance (mobility) of autonomous military systems. The panel will leverage the results from other existing and related NATO STO and TTCP activities with collaboration from multiple nations and tri-services interested in this topic area.

The proposed activity will include assessment approaches of current ground platforms in NATO, both from an acquisition perspective, but also operational perspectives. The U.S. Manned-Unmanned Teaming (MUM-T) will have a large future impact on NATO operations as both the U.S. and other Member Nations move towards these approaches to increase combat effectiveness. The proposed panel will benefit from several other existing AVT activities. For example, AVT-248 completed its tasks during the AVT panel business meeting week in Athens Greece. Many of the AVT-248 members are interested in addressing the problem of off-road mobility assessment for autonomous ground systems, and this ET will be a natural activity for them to transition to.

A.3 TOPICS TO BE COVERED

The proposed panel will attempt to cover the following scientific topics:

- Challenges and special requirements for modeling and simulation of autonomous military systems.
- Definitions related to autonomous military systems.
- Current software available for assessing the mobility of autonomous systems.
- Approaches to assessing the interdependence of mobility with communications and data.
- Build on the work of AVT-248 NG-NRMM to determine an approach for assessing off-road mobility of autonomous.

A.4 DELIVERABLE AND/OR END PRODUCT

The Exploratory Team will prepare a report of findings and recommendations on the benefits and value of the "Assessment Methods and Tools for Mobility of Autonomous Military Ground Systems" activity. The report will also detail the various resources required and committed by the various Member Nations to support this committee. This summary report will detail the current state-of-the-art and provide recommendations for the development and implementation of an autonomous navigation framework.

Document providing a concise summary of existing capabilities and planned future activities on the subject.

Strategic direction for the follow-on RTG.

It is expected that the findings of this ET will lead to a RTO Task Group (RTG) which will work on this cooperative research project in the 2020 – 2023 timeframe. The future RTG will bring together experts in the field from all NATO and supporting Nations to first develop the technical research required to develop the next-generation NRMM model, and secondly develop computer algorithms to rapidly compute and automate NRMM output generation. It is also possible that one or more RTO Workshops (RWS) may be necessary in conjunction with the bi-annual AVT Meetings to focus on specific aspects of the challenges facing the RTG. A final Technical Report is expected to be delivered in or around October 2018.

A.5 TECHNICAL TEAM LEADER AND LEAD NATION

Co-Chair: Dr. Lounis Chermak (Cranfield University), UK.

Co-Chair: Dr. Ekaterina Fedina (Swedish Defence Research Agency – FOI), SWE.

Co-Chair: Dr. Paramsothy Jayakumar (U.S. Army Ground Vehicles System Center), USA.

Lead Nation: USA.

AVT Panel Mentor: Dr. David Gorsich (U.S. Army Ground Vehicles System Center), USA.

A.6 NATIONS WILLING/INVITED TO PARTICIPATE

Canada, Czech Republic, Denmark, Estonia, Germany, Poland, South Africa, Sweden, Turkey, United Kingdom and United States.

A.7 NATIONAL AND/OR NATO RESOURCES NEEDED

The Exploratory Team will need meeting space during AVT Panel Business Weeks.

Standard support for a Workshop (RWS) and/or Specialists' (RSM) Meeting and Exploratory Team. This will include:

- National support for the Exploratory Team activity.
- Technical Evaluator for the Workshop/Specialists' Meeting.
- Distribution of Workshop/Specialists' announcements.
- Publication of the proceedings of the Workshop/Specialists' Meeting on the RTO Website.
- Publication of the Exploratory Team report.

A.8 RTA RESOURCES NEEDED

Standard support for a Workshop (RWS) and/or Specialists' (RSM) Meeting and Exploratory Team.

This will include:

- Technical Evaluator for the Workshop/Specialists' Meeting.
- Distribution of Workshop/Specialists' announcements.
- Publication of the proceedings of the Workshop/Specialists' Meeting on the RTO Website.
- Publication of the Exploratory Team report.

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14. Abstract

Autonomous Ground Systems (AGS) are a key part of the future military strategy for many NATO Nations. This activity explored the methods and approaches to assess the mobility performance and reliability of AGS and included assessment approaches of current ground platforms in NATO, both from an acquisition and operational perspectives. The result was to identify the challenges and special requirements associated with modeling and simulation of AGS and determine the current state-of-the-art software for assessing the performance (mobility) of AGS.

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