NATO OTAN

AC/323(AVT-047)TP/61

www.rta.nato.int

RTO TECHNICAL REPORT   **TR-AVT-047**

All Electric Combat Vehicles (AECV) for Future Applications

(Les véhicules de combat tout électrique (AECV) pour de futures applications)

Report of the RTO Applied Vehicle Technology Panel (AVT)

Task Group AVT-047 (WG-015).

Published July 2004

AC/323(AVT-047)TP/61

www.rta.nato.int

RTO TECHNICAL REPORT

TR-AVT-047

All Electric Combat Vehicles (AECV)
for Future Applications

(Les véhicules de combat tout électrique (AECV)
pour de futures applications)

Report of the RTO Applied Vehicle Technology Panel (AVT)

Task Group AVT-047 (WG-015).

The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

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

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

All Electric Combat Vehicles (AECV) for Future Applications

(RTO-TR-AVT-047)

Executive Summary

During the last ten years, several studies and demonstrator projects dealing with electric and hybrid electric vehicles were carried out in the United States and Europe, both in the military and the commercial sectors. Three of these studies were conducted under the NATO Long Term Scientific Studies; namely LTSS43, LTSS47 and LTSS50. The current effort was performed by Task Group AVT-047. It analysed new electric technologies, technology requirements, systems for mobility, survivability and lethality. These included the pulse power requirement and the energy storage needed to meet all vehicle power requirements and identified enabling technologies that require further development and/or breakthroughs. The previous studies served as a basis for investigating the potential payoffs versus the technical issues and challenges. The study was complemented by a vehicle demonstration AVT-098 held in Spring 2003 in Brasschaat, Belgium where several hybrid and mechanical drive vehicles were demonstrated on a test track running side by side to highlight the advantages of the electric powered vehicles.

The main conclusions that resulted from the study are summarized below:

- Hybrid electric drive systems are needed to support military missions and commercial applications.
- Automotive performance of hybrid electric vehicles in terms of speed, acceleration, gradeability and stealthy operations is superior to the performance of mechanically driven vehicles.
- Hybrid electric drive systems provide better fuel economy than their mechanical counterparts due to the use of optimum engine performance and energy recovery during braking.
- The fuel economy gain has not yet been quantified and will require extensive field testing before any prediction is substantiated. Current predictions range from 20% to 30% improvement based on various mission scenarios.
- Energy storage onboard hybrid electric vehicles can support silent watch operations and also electric weapons such as Electro-thermal Chemical (ETC) Gun and Directed Energy Weapons (DEW).
- Emerging technologies such as Silicon Carbide (SiC) and Lithium Ion Batteries will greatly enhance the packaging and integration of the hybrid electric drive systems for both continuous and pulsed power in a combat vehicle.
- Life Cycle Cost (LCC) studies are based on models with existing systems as baselines and cannot be totally substantiated without extensive field testing. However, the results available today show that development costs for hybrid electric drives are currently excessive. However, most of these costs are likely to be offset in the long run by the fuel and maintenance savings.
- Pulsed power technology particularly for ETC gun applications is achievable and can be integrated in combat vehicles depending on the its size and repetition rate requirements.

The study result and conclusions are detailed in the report. The task group responsible for the study is convinced of the viability of electric drive for military and civilian applications. A study on the criteria such vehicles have to meet has been initiated as AVT-106 on Hybrid Vehicle Rating Criteria drawing on the expertise of the experts already having been involved in the development and maturation of hybrid electric systems.

Les véhicules de combat tout électrique (AECV) pour de futures applications
(RTO-TR-AVT-047)

Synthèse

Au cours de la dernière décennie, un certain nombre d'études et de projets de démonstration de véhicules électriques et hybrides ont été réalisés aux Etats-Unis et en Europe, tant dans le secteur civil que militaire. Trois de ces études furent conduites dans le cadre des Etudes scientifiques à long terme de l'OTAN ; à savoir LTSS43, LTSS47 et LTSS50. Le projet qui fait l'objet de la présente synthèse a été réalisé par le groupe de travail AVT-047. Le groupe a fait le point des nouvelles technologies électriques, des besoins technologiques, ainsi que des systèmes assurant la mobilité, la surviabilité et la létalité. Entre autres, il a examiné les besoins en courant pulsé, ainsi que les capacités de stockage d'énergie nécessaires pour répondre à l'ensemble des besoins d'énergie des véhicules. En plus, le groupe a identifié les technologies clés devant être développées davantage et/où pour lesquelles des progrès décisifs seraient souhaitables. Les études antérieures ont servi de base pour l'examen des gains possibles par rapport aux différents défis et questions techniques. L'étude a été complétée par une démonstration de véhicules AVT-098 organisée au printemps 2003 à Brasschaat, en Belgique, qui a rassemblé différents véhicules à transmission mécanique et hybrides, roulant côte à côte sur une piste d'essais, afin de démontrer les avantages des véhicules électriques.

Les principales conclusions de l'étude sont résumées ci-après :

- Des systèmes de propulsion électriques hybrides sont demandés pour le soutien des missions militaires, ainsi que pour des applications commerciales.
- Les performances automotives des véhicules électriques hybrides en termes de vitesse, d'accélération, de capacité de gravissement de pente et d'opérations furtives sont supérieures à celles des véhicules à propulsion mécanique.
- Les systèmes de propulsion électriques hybrides offrent une meilleure consommation de carburant que leurs équivalents mécaniques, grâce à leurs performances motrices optimales ainsi qu'à la récupération d'énergie constatée lors du freinage.
- Les économies de carburant n'ont pas encore été quantifiées. Les prévisions actuelles devront être validées par des essais en vraie grandeur complets. Ces prévisions vont de 20% à 30% de réduction, sur la base de différents scénarios opérationnels.
- Le stockage d'énergie à bord de véhicules électriques hybrides peut servir au soutien du canon électrothermochimique (ETC), des armes à énergie dirigée (DEW), et des opérations de veille silencieuse.
- Des technologies émergentes, telles que celles des piles à carbure de silicium (SiC) et aux ions de lithium, amélioreront de façon significative le conditionnement et l'intégration des systèmes de propulsion électriques hybrides dans les véhicules de combat, qu'il s'agisse de courant pulsé ou de courant continu.
- Les études des coûts globaux de possession (LCC) sont basées sur des modèles créés à partir de systèmes existants et ne peuvent pas être validées à cent pour cent sans disposer des résultats d'essais sur le terrain. Cependant, les résultats disponibles aujourd'hui démontrent qu'actuellement les coûts de développement de systèmes de propulsion électriques hybrides sont excessifs. Néanmoins, à terme, la plupart de ces coûts pourrait être contrebalancée par des économies de carburant et de maintenance.
- La propulsion à courant pulsé est réalisable, en particulier pour le canon ETC, et peut être intégrée dans les véhicules de combat en fonction de leurs dimensions et de la période de répétition nécessaire.

Les résultats et conclusions de l'étude sont inclus dans le rapport. Le groupe de travail est convaincu de la viabilité de la propulsion électrique pour des applications civiles et militaires. Une étude sur les critères auxquels de tels véhicules doivent répondre à été lancée sous l'appellation AVT-106 sur « Les critères d'appréciation de véhicules hybrides ». Elle s'appuie sur les connaissances de spécialistes ayant déjà été impliqués dans le développement et la maturation de systèmes électriques hybrides.

Table of Contents

Publications of the RTO
Applied Vehicle Technology Panel

MEETING PROCEEDINGS (MP)

Novel Vehicle Concepts and Emerging Vehicle Technologies
MP-104, April 2004

Fire Safety and Survivability
MP-103, October 2003

Advances in Rocket Performance Life and Disposal
MP-091, October 2003

Combat Survivability of Air, Sea and Land Vehicles
MP-090, September 2003

Reduction of Military Vehicle Acquisition Time and Cost through Advanced Modelling and Virtual Simulation
MP-089, March 2003

Advanced Flow Management: Symposium Part A – Vortex Flows and High Angle of Attack for Military Vehicles / Part B – Heat Transfer and Cooling in Propulsion and Power Systems
MP-069(I), February 2003

Low Cost Composite Structures / Cost Effective Application of Titanium Alloys in Military Platforms
MP-069(II), February 2003

Ageing Mechanisms and Control: Symposium Part A – Developments in Computational Aero- and Hydro-Acoustics / Part B – Monitoring and Management of Gas Turbine Fleets for Extended Life and Reduced Costs
MP-079(I), February 2003

Ageing Mechanisms and Control: Specialists' Meeting on Life Management Techniques for Ageing Air Vehicles
MP-079(II), February 2003

Unmanned Vehicles (UV) for Aerial, Ground and Naval Military Operations
MP-052, January 2002

Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles
MP-051, June 2001

Design for Low Cost Operation and Support
MP-37, September 2000

Gas Turbine Operation and Technology for Land, Sea and Air Propulsion and Power Systems (Unclassified)
MP-34, September 2000

Aerodynamic Design and Optimization of Flight Vehicles in a Concurrent Multi-Disciplinary Environment
MP-35, June 2000

Structural Aspects of Flexible Aircraft Control
MP-36, May 2000

New Metallic Materials for the Structure of Aging Aircraft
MP-25, April 2000

Small Rocket Motors and Gas Generators for Land, Sea and Air Launched Weapons Systems
MP-23, April 2000

Application of Damage Tolerance Principles for Improved Airworthiness of Rotorcraft
MP-24, January 2000

Gas Turbine Engine Combustion, Emissions and Alternative Fuels
MP-14, June 1999

Fatigue in the Presence of Corrosion
MP-18, March 1999

EDUCATIONAL NOTES (EN)

MEMS Aerospace Applications
EN-AVT-105, February 2004

Internal Aerodynamics in Solid Rocket Propulsion
EN-023, January 2004

Intelligent Systems for Aeronautics
EN-022, June 2003

Active Control of Engine Dynamics
EN-020, November 2002

Supercavitating Flows
EN-010, January 2002

Aging Aircraft Fleets: Structural and Other Subsystem Aspects
EN-015, March 2001

Aging Engines, Avionics, Subsystems and Helicopters
EN-14, October 2000

Measurement Techniques for High Enthalpy and Plasma Flows
EN-8, April 2000

Development and Operation of UAVs for Military and Civil Applications
EN-9, April 2000

Planar Optical Measurements Methods for Gas Turbine Engine Life
EN-6, September 1999

High Order Methods for Computational Physics, Published jointly with Springer-Verlag, Germany
EN-5, March 1999

Fluid Dynamics Research on Supersonic Aircraft
EN-4, November 1998

TECHNICAL REPORTS (TR)

Future Technological and Operational Challenges Associated with the Single Fuel Concept
TR-066, September 2003

Performance Prediction and Simulation of Gas Turbine Engine Operation
TR-044, April 2002

Evaluation of Methods for Solid Propellant Burning Rate Measurements
TR-043, February 2002

Design Loads for Future Aircraft
TR-045, February 2002

Ice Accretion Simulation Evaluation Test
TR-038, November 2001

NATO East-West Workshop on Magnetic Materials for Power Applications
TR-031, August 2001

Verification and Validation Data for Computational Unsteady Aerodynamics
TR-26, October 2000

Recommended Practices for Monitoring Gas Turbine Engine Life Consumption
TR-28, April 2000

A Feasibility Study of Collaborative Multi-facility Windtunnel Testing for CFD Validation
TR-27, December 1999

RTO Technical Team AVT-047

CHAIRMAN

Mr. Ghassen KHALIL
US Army Tank-Automotive & Armaments
AMSTRA-TR-R/MS 121
Warren, Michigan 48397-5000
UNITED STATES
email: khalilg@tacom.army.mil

BELGIUM
Prof. Y. BAUDOIN
Royal Military Academy (RMA)
Department of Applied Mechanics
Hobbemastreet, 8
B-1000 Brussels
email: yves.baudoin@rma.ac.be

Kapt. Ir. K. MATHOT
Royal Military Academy
Hobbema 8,
B-1000 Bruxelles
email: guy.mathot@mapp.rma.ac.be

GERMANY
Bdir Wolfgang BRAND
BWB-Koblenz KG 16
Ferdinand Sauerbruch Str. 1
D-56073 Koblenz
email: wolfgangbrand@bwb.org

Mr. Uli HOEHLER
Industrieanlagen-Betriebsgesellschaft mbH
Postfach 12 12
Einsteinstr. 20
D-85521 Ottobrun
email: hoehler@iabg.de

Dr. Emil SPAHN
French-German Research Institute
of Saint Louis (ISL)
5, rue du General Cassagnou, BP 34
68301 Saint Louis
email: spahn@isl.tm.fr
email: wpotkan@ilot.edu.pl

THE NETHERLANDS
LtCol. J.J.F. FRITZ
MODNL/RNLA
LAS/BO-WO
P.O. Box 90822
2509 LV The Hague
email: laswo@army.dnet.mindef.nl

Mr. E.J. LANS
MODNL/RNLA
DM/MANMAT
Frederikkazerne, van der Burchlaan 31
P.O. Box 90822
2509 LV The Hague
email: manmat2@dm.army.dnet.mindef.nl

Ir. Peter VAN GELDER
National Aerospace Laboratory NLR
P.O. Box 153
NL 8300 Ad Emmeloord
email: gelder@nlr.nl

Mr. P. VAN KAN
MODNL/RNLA
DM/MANMAT
Frederikkazerne, van der Burchlaan 31
P.O. Box 90822
2509 LV The Hague
email: manmat1@dm.army.dnet.mindef.nl

UNITED KINGDOM
Mrs. P. ENDERSBUY
DSTL, Fort Halstead
Sevenoaks, TN14 7BP
email: pcendersby@dstl.gov.uk

Mr. Steven GOLDSACK
QinetiQ
Cody Technology Park, Ively Road
Farnborough, Hants, GU14 8SN
email: s.w.goldsack@qinetiq.com

Mr. D. HAUGH
DSTL, Fort Halstead
Sevenoaks, TN14 7BP
email: dchaugh@dstl.gov.uk

Mr. R. RAWLINS
Room 308, Bldg A20/Spur 2
DSTL, Fort Halstead
Sevenoaks, Kent TN14 7BP
email: rmrawlins@dstl.gov.uk

UNITED STATES
Mrs. K.A. WHITEHEAD
US Army TACOM
Cost and Systems Analysis
(AMSTA-CM- BV), 6501 E 11 Mile Road,
Warren, MI48397-5000
email: whitehek@tacom.army.mil

Chapter 1 – TASK GROUP 47
ALL ELECTRIC VEHICLE STUDY

1.0   INTRODUCTION

The LTSS/43 which was concluded in 1996 focused on the advantages of the diesel electric vehicles applied to military applications. Although, the advantages described in the study report were reasonable, their validity relied on predictions based on limited experience with some earlier demonstrators in Germany (8x8 test-bed and the Marder) and the US (M113, and the EVTB) and also on the relative success of the electric cars developed mainly to reduce the dependence on fossil fuels and cut down the emission of toxic gases. The findings of the LTSS/43 report clearly identified the need to explore further the benefits of electric drives for military vehicles and to address new issues that were revealed during the LTSS/43 such as Life Cycle Cost (LCC), Safety, Standardization, testing, Electro-magnetic interference (EMI), durability and reliability.

A first attempt at estimating the LCC was conducted under LTSS/50 and was concluded in late 1999. The study identified cost savings in the long term Operations & Support (O&S) area that can offset the high development costs. The study was based on data obtained from conventional vehicle development and maintenance and on predictions of electric systems performance as applied to All Electric Vehicles (AEV). The LCC calculations were made using the French Model "Cesar". The conclusions of the study had to be verified with test data which the current study will provide from actual field testing of the hybrid electric US HMMWV and some data also from tracked vehicles extracted from the US/GE Project Agreement PA 97.

The current effort conducted by Task Group AVT-047 looks at the technologies required to support an AEV and covers all the capabilities of a military vehicle: mobility, lethality and survivability. It builds on the previous two studies to include state-of-the-art component technologies and emerging technology trends and their state of development based on the existing programs of the participating nations. Furthermore, it includes an updated investigation into the pulsed power requirements for high auxiliary loads such as electric weapons, electro-magnetic (EM), armour and directed energy weapons (DEW). For reference purposes, the pulse power chapter is also an extension of the previous LTSS/47 study.

The highlight of the Task Group AVT-047 function was a major demonstration of electric drive vehicles (AVT-098), which took place in Belgium in the Spring of 2003. Five participating nations took part in the demonstration with electric, hybrid electric vehicles and standard wheeled and tracked vehicles currently used in the NATO fleets. The purpose of the demonstration was to get a back to back comparison of the electric/hybrid electric vehicles versus the mechanical vehicles and to provide an opportunity for NATO & PfP members to witness the performance of the electric drive technology.

1.1   AIM

The objective of this study is to update and expand the findings of the LTSS/43 on the Mobile Electric Weapon Platform (MEWP) and reassess the state of development of electric technology and its potential application in military vehicles. The study has been refocused on 20-ton wheeled and 40-ton tracked vehicles as dictated by future battlefield scenario and vehicle deployability requirements (C130 transportability). The study is also intended to investigate the Life Cycle Costs associated with the fielding of electric vehicles.

Specifically, the goals of the study cover the areas listed below:

a) Update the study conducted under the LTSS/43 assessing the state of the required enabling and emerging technologies for fielding an All Electric Vehicle (AEV);

b) Incorporate the findings of the Pulse Power study conducted under LTSS/47 as applied to Electro Thermal Chemical ETC gun and EM armour;

c) Use the LCC study under LTSS/50 as a baseline to investigate the cost impact of each auxiliary system (Mobility, Lethality, Survivability);

d) Publish a comprehensive report to include worldwide advancements of the electric drive technology describing its benefits and technical challenges;

e) Conduct a major vehicle demonstration of electric vehicles in Belgium in the Spring of 2003 to provide a clear understanding of the state of technology to the NATO nations and their partners.

1.2   EXPECTED BENEFITS

There are several potential benefits of electric and hybrid electric drives that are driving the technology advancement towards civil and military applications. While some of the payoffs are common to both civil and military markets, there are some that are unique to either application as shown in Table 1.1.

Table 1.1: Hybrid Electric Vehicle Benefits

Military	Civil
• Vehicle Packaging Flexibility • Improved Fuel Economy (25 – 30%) • Onboard Power Generation • Stealth Potential (Silent Movement) • Improved Accelerations • Reduced Maintenance • Increased Silent Watch Period	• Improved Fuel Economy (30 – 35%) • Reduced Emissions • Improved Driveability • Improved Accelerations • Reduced Maintenance Cost • Reduced Emissions
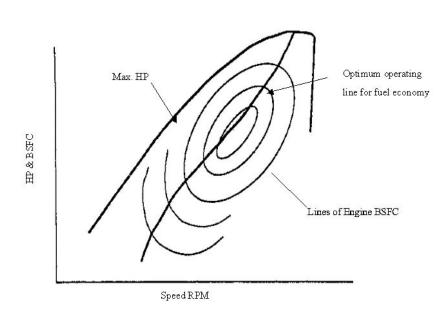
For military applications the most tangible benefits are:

1) Fuel economy,

2) Available power onboard,

3) Silent watch and silent mobility,

4) Flexibility of component packaging and integration,

5) Enhanced diagnostic and prognostics.

1.2.1 Fuel Economy

The fuel economy is a direct result of the engine being programmed to operate along or near the optimum fuel economy region in its fuel map as shown in Figure 1.1 This is possible because the engine speed is not dictated by the road speed of the vehicle. The engine drives an AC generator at almost constant speed and the electric power from the generator is delivered to the wheels or tracks through the power conditioning units (PCU) to match the requirements of the traction motors. In the case of hybrid electric drive where the engine power is supplemented by energy storage (batteries, flywheels, capacitors, etc.), there is another reason for the fuel economy; the engine power is mainly used during steady state driving where the least amount of fuel is consumed for mobility. The transient conditions are mainly powered from the energy store, which is topped up by regenerating the energy from braking as well as from the generator. This feature results in significant savings of fuel, and reduces exhaust emissions and thermal signature. The fuel economy improvement that has been demonstrated through preliminary testing on the US HMMWV programme is in the order of 25 to 30 %.

Optimum fuel economy operation

Figure 1.1: Fuel Consumption.

1.2.2 Available Power Onboard

The hybrid electric drive system consists of two sources of power, the engine generator and the energy storage system. The main power management and distribution system can be designed and sized to meet the demand of all electrical power users in the vehicle. This is extremely beneficial due to the increasing demand for electrical power for future military systems onboard a vehicle. The power management and distribution system can supply continuous power to meet such loads as propulsion, thermal management and other small power users and can also be used to supply the intermittent power to drive/charge a pulsed power system for electric weapons (ETC gun and DEW) or EM armour. Furthermore, the availability of these high levels of electrical power onboard may be used to reduce the logistical burden of the fleet by eliminating, in certain instances, the towed generators necessary to provide electric power in the field.

1.2.3   Silent Watch and Silent Mobility

The significant onboard energy storage system can be used to meet silent watch requirements for extended periods of time for various missions. Depending on the power requirements of the silent watch, a mission can be extended over a few hours; far exceeding the silent watch capability of the current fleets. Silent mobility over a limited distance is also achievable where the vehicle can move in or out of a hostile territory with a reduced chance of being detected.

1.2.4   Flexibility

An electric drives system consists of modular components connected by cables thus giving the vehicle designers more packaging freedom. This avoids the constraints of conventional mechanical drive systems, which require the engine to be connected to the wheels via gearboxes and rigid shafts. This means that the components can be arranged and integrated in the vehicle for the optimum utilization of the available space.

1.2.5   Enhanced Prognostics and Diagnostics

In an AEV every operation is controlled by microprocessors which lends itself to the provision of a Health and Usage Monitoring System (HUMS). This HUMS would be capable of identifying any impending failure before it happens and provide data on the fault so that reliability centered maintenance can be implemented. This should help reduce the operation and maintenance costs over the life of the vehicle and help offset the acquisition cost, to achieve an improved whole of life cost for the AEV. At the current level of maturity the acquisition cost is likely to exceed that of a mechanical system.

1.3   TECHNICAL CHALLENGES

Electric drive can be fielded now for certain missions, however, there are some technologies that are not ready for production yet and there are some technologies that, if they can be realised, will lead to a much more efficient vehicle. These important technical challenges are undergoing research but they are not expected to be resolved before five years from now.

The technical challenges are:

- High operating temperature power electronics,
- High energy density storage devices,
- High torque and power density traction motors.

1.3.1   Power Electronics

The currently available power semi-conductors have a relatively low operating temperature. The Silicon based IGBT switch for instance has a maximum operating temperature of 125 °C at the junction. To maintain that temperature, the coolant into the base plate of the switch must be maintained at 65 °C leaving a very small margin with the ambient temperature. Consequently, the cooling system and its power demand is too large to be integrated into the vehicle. Repackaged IGBT switches have improved the thermal limits by 50% raising the coolant temperature from 65 °C to 90 °C. This improvement however is still in its experimental stage and requires further development and testing. The ultimate solution for power electronics is the Silicon Carbide (SiC) device, where the operating junction temperature can be as high as 500 °C and therefore the coolant

temperature can be easily maintained at 200 to 250 °C. This type of device would allow the cooling system to be much smaller due to their high efficiency and operating temperature. SiC switches at present are limited to small current ratings due to the impurities of the material, a crystal defect known as "micropipes". Significant improvements have been achieved in the last three years in SiC and the technology is expected to reach the required level of power rating in a reasonable yield within the next five years.

1.3.2   Energy Storage

Energy Storage is an essential part of the hybrid electric drive application. Thus far three types of energy storage have been used: the battery, the flywheel and the Ultra Capacitors. Batteries have been used more extensively than the other two devices for their higher energy density and lower cost. However, the most commonly used battery (lead-acid) has low energy density, limited cycle life, cannot be stored in a discharged conditions as the cell voltage must not drop below 2.1 v, is environmentally unfriendly because it has a toxic electrolyte that must be disposed of safely. In addition, battery thermal management is required as the battery loses power at low temperature and requires preheating and will start deteriorating at elevated temperatures. Although the lead acid battery does not have a serious shelf discharge problem like the NiMH battery, its shelf life is limited.

Other advanced types of batteries are being considered for hybrid vehicle applications. The most important candidates at this time are:

- Lithium-ion (Li-Ion),
- Nickel Metal Hydride (NiMH),
- Sodium nickel chloride (ZEBRA^{TM}),
- Lithium-metal polymer (LMP).

All these batteries have higher energy densities than the lead acid batteries but they are all in the development stage and present some challenges that must be resolved before they can be considered suitable for military use. The NiMH hydride has a self-discharge problem that will drain the battery in a short time. It is used in a number of commercial hybrid electric vehicles. The Li-Ion is very sensitive and can be dangerous if it is not designed and manufactured with overcurrent and/or shock protection as well as a thermal management system. The ZEBRA^{TM} battery has a lower power density than the others, but research is underway to improve this. The cells are in limited production and the batteries come complete with battery and thermal management systems. LMP batteries are relatively new but seem to be ideal for military applications if their predicted performance can be realised. The cost of any of these batteries is currently high because they are in development still and under limited production.

1.3.3   Traction Motors

The traction motors have to meet the torque/speed curve dictated by the mobility requirements of a ground military vehicle – Figure 1.2.
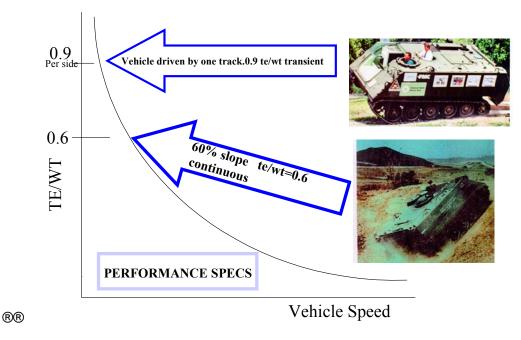
Figure 1.2: Torque/Speed Mobility Requirements.

The challenge is to meet the power requirement with a motor that is suitable for integration into either the chassis or the hub of a wheeled vehicle or behind the sprocket in the case of a tracked vehicle. There are generally three types of motor suitable for meeting these requirements:

- Permanent magnet (PM) brushless motors,

- Induction motors,

- Switched reluctance motors.

Of these the first two are currently receiving the most attention, however the traction motor cannot be considered in isolation and it is necessary to consider the way they are to be integrated into the vehicle platform. For a tracked vehicle the choice is between the 'two-line' approach where one traction motor is used to drive each track or the 'single-line' approach where one traction motor and one steer motor is used. The former approach would offer the maximum flexibility in design of the vehicle if the traction motors associated control systems can be reduced in size significantly. The problem is due to steering of a high-speed tracklayer, which requires the power to be transferred across the vehicle to maintain efficiency as the vehicle steers. If this is done electrically it is necessary to transfer in the order of 2.5 times the power of the main engine from one track to the other (the two-line approach). The utilisation of a mechanical cross shaft to transfer this power (the single-line approach) means that the electrical motors need only be rated at the main engine power, but clearly some packaging freedom is given up.

With wheeled vehicles the basic choice is between mounting the traction motors in the chassis, where there is the disadvantage that drive shafts are still needed to transfer the power to the wheels and hence the design freedom is lost or in the hubs. The in-hub approach offers the optimum solution, however, the challenge is to keep the unsprung mass as low as possible, ideally not greater than a conventional vehicle, in order not to compromise the mobility of the vehicle at high speeds, particularly cross-country. Two approaches are being offered: a single speed reduction gear or a two-speed gear arrangement where low range is only needed for

high torque/low speed operation. The latter approach enables the motor size to be reduced, thus reducing the unsprung mass.

Most of the current traction motors have some design limitations, which if overcome would enable better overall designs to be produced. Their size and weight limit their packaging. They require cooling and they are expensive

It should be noted that despite the challenges mentioned above, the state-of-the art traction motors have been successfully integrated and demonstrated into electric vehicles. The challenges described above are intended to point out that improvements to the traction motors are needed and this will enhance their packaging and integration in ground military vehicles.

1.4   DEVELOPMENT COST

Electric drive technology as applied to military vehicles is the most advanced system and is in its development and demonstration phase. Almost every component is designed for specific application in a very limited quantity. Currently, there are few, if any, situations where systems designed for the civil environment can be directly applied to the military. This is particularly true for the enabling technologies that are needed to advance the state of the art such as advanced batteries, traction motors and power electronics. It is to be hoped that the cost challenge will start to be met as electric drive components become more available commercially with the growing demand for electric cars and trucks.

Chapter 2 – ASSUMED REQUIREMENTS
NATO STUDY: REQUIREMENTS SECTION

2.0   INTRODUCTION

This section sets the context for technology discussions in the following chapters of this report. It does so by considering the future capability requirements of the military user, and the technology performance level required to achieve future military aspirations. Each NATO member has different capability requirements, and this section does not attempt to define a common NATO set of requirements. It does however; consider the principal needs of some of the participating nations' current equipment programs (e.g. UK – FRES, FR – EBRC, US – FCS, and GE – SPz3). From this, it draws out a general representative set of requirements for two notional study vehicles. These are then used to provide technical design requirements and envelopes for consideration of electric drive technologies, in the following Chapters.

2.1   OVERVIEW OF MILITARY NEEDS

This section analyses the above mentioned national equipment programs in order to form the representative design requirements of the notional study vehicles. The respective programs are discussed in the following sections and summarized in Table 2.1.

2.1.1   UK – Future Rapid Effect System (FRES)

FRES is a medium weight force that will provide the UK with the ability to conduct a variety of operations. The primary operational aim of FRES is to contribute to the warfighting capability of the UK armed forces. As such FRES will have the capability to fulfill a wide range of roles, of which the following are perhaps the most dominant:

- Armoured reconnaissance/surveillance/scout,

- Indirect fire,

- Direct fire,

- Mechanised infantry.

FRES will also have the capability to mount rapid intervention operations, which will require a rapid deployment and operational impact once deployed. FRES platforms will exhibit the following characteristics:

- High levels of tactical and strategic deployability,

- High levels of reliability,

- A high degree of commonality at sub-system and component level,

- Very wide utility,

- Good mobility,

- Good road range and fuel economy.

Although it is still open as to whether FRES will be wheeled or tracked, it is assumed here that the majority of vehicles will be tracked. An initial operating capability is required for utility variants in 2007, followed by the more complex variants two years later.

2.1.2   Engin Blindé à Roues de Contact (EBRC)

The latest French program is for the EBRC: a wheeled armored combat vehicle that is required to be fielded by 2015. It is intended that this vehicle will fulfill a number of roles covering both short and long-range action. It will require a Reconnaissance, Surveillance and Target Acquisition (RSTA) capability; a direct fire weapon to deal with close combat and a beyond line of sight (BLOS) capability for the longer ranges. It is envisaged that the EBRC family of vehicles may include a 'mother' vehicle plus 'daughter' vehicles that will provide an aerial and ground unmanned RSTA capability. Concepts have been prepared that include: 16-ton 6x6 wheeled and tracked vehicles and a 24-ton 8x8 wheeled vehicle for the BLOS capability with a 105 mm ETC gun.

Technologies of interest have been identified as:

- **Lethality:** 40 mm CTA remote operation cannon; LOS weapon: either fibre-optic guided missile or a 105 mm ETC gun;

- **Survivability:** Electro-optic counter measures (EOCM); collective NBC protection; active protection systems; a stealth kit and a titanium structure;

- **Mobility:** Electric transmission and band track;

- **Vetronics:** Man Machine Interface and video observation/acquisition capability.

2.1.3   US: Future Combat System (FCS)

The principal objectives of the FCS program are to:

- Project a lethal, survivable, and sustainable FCS equipped land combat force, capable of rapid deployment and immediate employment upon arrival, as a unit, and defeat any threat well into the 21st century.

- Reduce logistical and sustainment requirements and deployed support structure by reducing demands for consumables (fuel, ammunition, and repair parts) and maintainers while maximizing system, sub-system, and component commonality throughout the force.

The FCS equipped force will provide: a direct combat capability, delivering both line-of-sight (LOS) and beyond-line-of-sight (BLOS) munitions against a wide range of air and ground targets; performing reconnaissance; and transporting infantry, combat engineers and materiel. With minimum platform modification FCS units will be capable of: performing mobility and counter-mobility tasks; conducting maintenance, recovery and resupply operations; and providing command and control functions to the force while on the move. The FCS force will consist of a combination of manned and unmanned air and ground elements acting in a system of systems.

- **Lethality:** A primary objective is to markedly increase lethality (both LOS and BLOS fire) of the FCS equipped force compared to the current force. FCS forces must include a broad range of scaleable lethal (kinetic energy (KE), chemical energy (CE), high explosive (HE), and anti-personnel (AP)) and non-lethal (NL) options to accommodate operations across the spectrum and various battlefield missions and situations.

- **Survivability:** FCS equipped units must be capable of surviving first round engagements from future armoured platforms, shoulder fired AT missiles (either CE or KE munitions), and mines.

- **Mobility:** FCS should be capable of traversing all anticipated land environments, including urban, complex, and open and rolling terrain. It should possess unsurpassed battlefield agility in terms of manoeuvre, cross-country (dash and sustained) and hard surface speeds.

- **Deployability:** Individual FCS platforms must be smaller and lighter, compared to current platforms. FCS design will facilitate deployment in unit sets on C~130~like (volume and weight) platforms.

- **Supportability:** The overall objective is to drastically reduce operational sustainment requirements compared to the current force. Toward this end, FCS platforms will include quantum improvements in reliability, availability and maintainability characteristics. Individual FCS platforms must maintain increased mobility while requiring less external support, such as refuel, resupply, maintenance and engineer assistance. Optimum use will be made of embedded diagnostics (identifying faults to the component level in near real time), prognostics, and repair capabilities to reduce soldier tasks.

2.1.4   GE – Mechanized Infantry Fighting Vehicle (SPz3 IFV)

The current German requirement is for a mechanized infantry fighting vehicle that will be transportable in the Future Transport Aircraft (A400M), which gives it a maximum weight target of 32 ton. The program is currently in the planning and development phase. Fielding of the first 20 vehicles (step 1) is foreseen in 2005 and further 330 vehicles (step 2) is due between 2008 – 2012.

- **Lethality:** A rapid-fire cannon is envisaged that will enable a range of targets to be addressed.

- **Survivability:** It is recognised that the desired protection levels cannot be achieved within a weight limit of 32 ton and it is therefore proposed that the protection system should be modular:

    Level 1: within the weight limit of 32 ton, will provide a basic level of protection;

    Level 2: takes the vehicle weight up to 40 ton and provides enhanced levels of protection;

    Level 3: takes the vehicle weight up to 42 ton and provides further enhanced levels of protection.

- **Mobility:** It is required to have a high level of mobility that is defined as similar to Leopard 2A4.

2.2   SUMMARY

The following table summarizes the main features of each equipment program.

Table 2.1: Features of National Equipment Programmes

Nation	Equipment Program	Deployment Date	Airportability Requirement	Roles	Emphasis
UK	FRES	2007	A400M. C130 highly desirable for certain roles	Mechanized infantry Armored recce/ surveillance Command & control Direct fire	Rapid effect High survivability Good mobility Good range Good utility Subsystem commonality
FR	EBRC	2015	2 in A400M	RSTA; Direct fire Urban warfare BLOS	Mother platform with UGV and UAVs (daughters) Modularity Upgradability Adaptability
US	FCS	2008	C130	All roles	System of systems (manned & unmanned platforms) Rapid Deployability Good lethality Good survivability Good mobility Reduced logistical and sustainability requirements
GE	SPz3 IFV	2008	A400M	Mechanized infantry	Good mobility Modular survivability

It is evident that there is a common theme of medium weight vehicles that correspond to the principal strategic air transport aircraft – C130 and A400M. At a range of 2000 nautical miles, a sensible point on the range payload curve where capacity starts to drop sharply with range, the aircraft payload limits are 17 t and 35 t respectively.

The scope of this report thus considers two notional combat vehicles (herein referred to as NV1 and NV2):

- NV1: 17 ton,
- NV2: 35 ton.

Although these vehicles have been set as the focus of this report, it is stressed that electric technology has significant potential to improve performance in a range of other military vehicle types, such as wheeled combat support (tactical) vehicles (trucks). Many of the programs demand high levels of mobility, survivability and lethality, whilst reducing logistic footprint. The vehicles are required to be ready for introduction into service in approximately 2010. The technology discussions in this report should therefore consider technology readiness in the near term.

2.3   CONSIDERATION OF VEHICLE ROLE

To define the technology requirements for these notional vehicles, it is necessary to define a vehicle role or application. Naturally, each role gives different challenges to the implementation of electric technology. The following table includes a typical range of roles and indicates the main emphasis of each vehicle role in terms of mobility, lethality and survivability.

Table 2.2: General NATO Vehicle Roles Matched to Principal Requirements

	Mechanized Infantry	Scout	Direct fire	Command & Control	Indirect Fire (BLOS)
Mobility	Highest	Highest	Highest	Baseline	Baseline
Lethality	Medium	Medium	Highest	Baseline	Highest
Survivability	Highest	Highest	Highest	Baseline	Baseline

Key to requirement level	▓ (dark)	Highest
	▒ (medium)	Medium
	░ (light)	Baseline

From this table, it can be seen that the most demanding roles are the Direct Fire and Scout. To provide a range of challenging case studies for the different electric technologies considered in this report it has been decided to assign the Scout role to a wheeled platform and the Direct Fire role to a tracked platform.

- NV1: Scout – 17-ton wheeled platform,

- NV2: Direct fire – 35-ton tracked platform.

2.4 OVERVIEW OF PERFORMANCE REQUIREMENTS FOR THE VARIOUS ELECTRICAL SYSTEMS

2.4.1 Introduction

Given the definition of the Notional Vehicle 1 and 2 above, this section provides an overview of each of the notional vehicles. The overview describes a typical electrical installation and outline performance envelopes for each of the major components. This chapter considers NV1 and NV2 separately.

2.4.2 Notional Vehicle 1: 17-Ton Wheeled Vehicle – Scout Role

An overall impression of NV1 is shown in Figure 2.1. Outline system level requirements have been established for NV1, and they are detailed in Table 2.3.
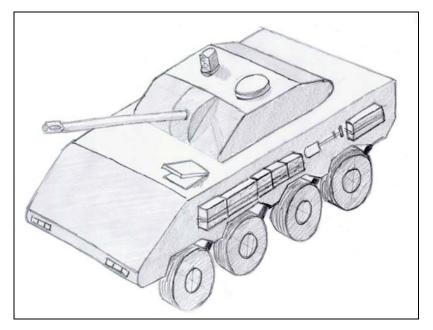
Figure 2.1: Overall Impression of NV1.

Table 2.3: System Level Requirements for NV1

Category	Indicative Requirement
General Vehicle Characteristics	
GVW (ton)	17 ton
Volume constraint	Rail gauge & C130J
Height target (m)	<= 2 – 2.5
Approx tyre sizes (m)	Diameter =1.35; Width=0.45
Mobility	
Power to weight (cont) (kW/ton)	>= 15
Power to weight (peak) (kW/ton)	>= 25
Maximum speed (road) (kph)	>= 110
Maximum speed (cross-country – sand(kph)	50
Range (road) (km)	>= 600 – 700
Range (road/track/cross-country) (km)	>= 500 – 600
Stealth range (cross-country) (km)	>= 20 km @ 30 kph
Maximum acceleration 0 – 60 km/h (s)	12
Braking (m/s^2)	=> > 5
Turning circle (m)	= < 18
Fording depth (m)	Prepared >= 1.5, Unprepared >= 0.76
Overturn angle (degrees)	40
Road legislation	Compliant
Lethality	
1) Defeat light/medium armour;	
2) Provide covering fire for tactical withdrawal;	
3) No capability against structures.	

Category	Indicative Requirement
Survivability	
Survive:	
4) Small calibre weapons (essential);	
5) Hand held shaped charge projectiles direct hit (desirable);	
6) Limited protection against mines (desirable).	
Others	
On-board power generation	600 Voltage, 400 Amps

There are numerous electrical systems, technologies and configurations that could be employed in NV1 and the precise arrangements would clearly need to be defined against a detailed analysis of the system requirements. Nonetheless, the study team has concluded that the following systems would typically be employed.

Table 2.4: Typical Electrical Systems in NV1 – 17-Ton Scout Vehicle

Serial	System Area	Description
1	Mobility	Hub mounted electric drives. Diesel based power generator and battery energy storage system. Power delivery controlled by a vehicle management unit with driver interfaces. Electrically driven ancillaries would include air compressor for CTIS, hydraulic pumps for the brakes and electric drives for the cooling fans. The concept assumes a 'dual steer' system where skid steer is combined with natural steering.
2	Survivability	Energy storage system for silent watch/mobility. Electric armour.
3	Lethality	Electrothermal Chemical (ETC) Gun

2.4.2.1   Mobility

Mobility covers a number of different aspects of the performance of a military vehicle. These include: fuel consumption (range), acceleration, speed over the different types of terrain, overturn angle, handling, turning circle, traction control, rolling resistance, limiting soil strength, ride, wheel travel and ground clearance. These aspects of performance are all determined by the powertrain installed on the vehicle, of which there are a number of options. The optimum configuration is considered to be a series hybrid electric, incorporating power generation and energy storage devices and electrical cable transmission, as shown in Figure 2.2.
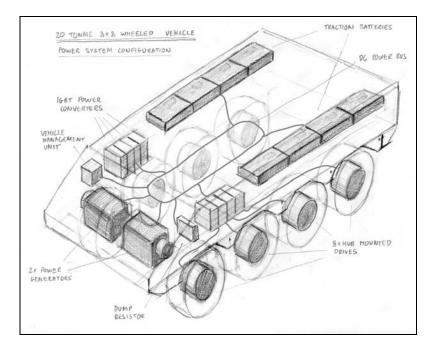
Figure 2.2: NV1 Power System Sketch.

Multiple power generators have been assumed, which could be diesel or gas turbine driven generators (fuel cells with diesel reformers are not considered feasible in the near/medium term future). It is assumed that the vehicle will have an energy storage device, which could be a chemical battery (and could be of a number of different chemistries), flywheel or ultra-capacitor. There are a number of drive options, but the optimum is considered to be hub mounted drive motors in each wheel. The drives and the diesel generator will have power converters to provide/draw power from a DC bus. Power flow will be managed by the vehicle management unit across a controller area network (CAN) bus. The vehicle can have an electric suspension system with electromechanically actuated struts. Steering would be achieved using conventional hydraulic power assist with the pumps being powered electrically. Longer-term actuation could be implemented electrically in a drive-by-wire type configuration.

Improvements in fuel consumption are realized through efficient power management and electrical regenerative braking. Pulse acceleration is achieved by using the power generators and energy storage in series. The packaging of electric drive components gives control of overturn angle; individual wheel control can provide improved traction, and skid/dual steering can improve turning circle.

The system architecture that has been assumed is depicted in Figure 2.3.
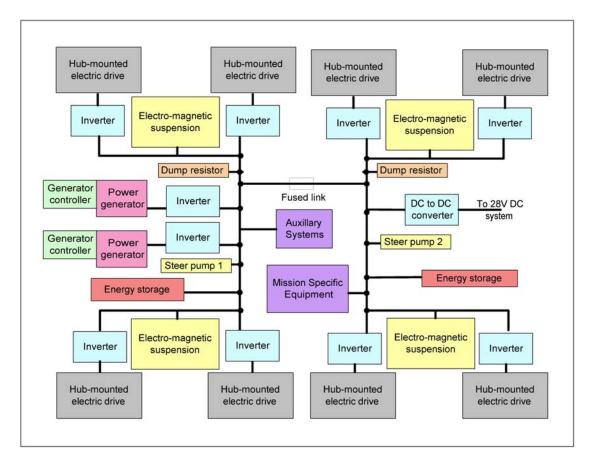
Figure 2.3: NV1 Power System Architecture Block Diagram.

The approximate design targets for the power system components of NV1 are detailed in Table 2.5.

Table 2.5: Power System Component Design Targets

Vehicle Components Affecting Mobility	Design Target
Power Generators (Total)	
Electrical power output (cont) (kW)	>= 200 – 250
Power density (kW/m^3)	**>= 9000 – 10000**
Specific power (kW/kg)	>= 1.0 – 1.5
Efficiency (peak) (%)	>= 95
Energy Storage (Total)	
Power output for 30 sec (kW)	100 – 150
Energy (C rate) (kWh)	>= 25
Energy (2 hour discharge) (kWh)	>= 30
Specific energy (Wh/kg)	>= 100
Energy density (Wh/litre)	>= 150
Specific power (W/kg)	>= 1000 Li-Ion
Power density (W/l)	>= 3000 Li-Ion
Full power ambient temperature operation (Celcius)	-40 to +55

Vehicle Components Affecting Mobility	Design Target
Hub Mounted Drives (per drive)	
Features	Gear change/reduction; mechanical brake; central tyre inflation; 4 quadrant operation including electrical regenerative braking;
Dimensions	Fit inside 25" wheel rim
Volume (litres)	< 160
Mechanical power output (cont) (kW)	>= 50
Power output (peak) (kW)	>= 100
Torque output (cont) (kNm)	>= 10
Torque output (peak) (kNm)	>= 20
Specific power (cont) (kW/kg)	> 0.75
Specific power (peak) (kW/kg)	> 1.25
Specific torque (cont) (Nm/kg)	> 30 – 32
Specific torque (peak) (Nm/kg)	> 64
Torque density (cont) (Nm/kg)	> 62 – 90
Overall efficiency (peak) (%)	> 90 (including gearing, inverters, motors etc.)
Power Converters	
Features	4 quadrant operation
Power density (kVA/litre)	>= 4.7 (35)
Overall efficiency (average) (%)	>= 98%
Dump Resistor	
Rated power (kW)	> 50
Power density (kW/kg)	> 10
Active Suspension	
Travel (mm)	>= 400
Peak power/pulse (kW)	> 100
Steering	
Dual steer	

2.4.2.2   Lethality

Scout type vehicles like the notional 17-ton wheeled vehicle are normally lightly armed and armored. Conventional weapons could be used with such vehicles, and for vehicles coming into service soon, would be the only consideration. It is likely that a small caliber weapon would be fitted, of 30 – 35 mm caliber, and a replacement weapon system would be similarly sized but have improved performance. Electromagnetic rail guns offer the potential of hyper-velocity projectile launch, providing increased terminal ballistic defeat over similarly sized conventional weapons. Electrothermal ignition promises more uniform propellant ignition, shorter ignition delay and reduced variance in gun barrel dynamic response, which raises hit probability.

Electrical requirements for ETI and EM gun options are detailed in the following table.

Table 2.6: Electrical Power Requirements for EM and ETI Guns

	Units	EM Railgun	ETI Gun
Gun Requirements			
Electrical energy stored/shot	MJ	3	0.05
Peak power /shot	MW	750	50
Pulse duration	ms	3 – 4	1
Electrical energy for a burst	MJ	9	0.15
Average power for one shot	MW	550	40
EPPS voltage	KV	2 – 5	10 – 20
Current	MA	1.5	0.1 – 0.3
Assuming a 3 round 3 Hz burst capability, 35 – 40 mm equivalent calibre			
Energy Storage Requirements			
Mass	Kg	500	500
Volume	m^3	0.125*	0.125*
Energy density	MJ/m^3	72	1.2
Specific energy	kJ/kg	18	0.3
Power density (avg)	MW/m^3	4400	320
Power density (peak)	MW/m^3	6000	400
Specific power (avg)	MW/kg	1100	0.1
Specific power (peak)	MW/kg	1500	0.125
*Assuming dimensions of 0.5 m × 0.5 m × 0.5 m			

These figures are speculative, based on the infancy of the technology.

Novel weapon systems (including laser and microwave beams) could have a secondary lethality capability (against personnel and equipment electronics). The technologies for electric weapons are immature and require some years of investment and development to make them ready for service. However, when designing new electric vehicles, certain basic factors relating to upgraded weapons can be considered, allowing the possibility of up-grades at a later date.

All the new electric weapon concepts are covered in more detail in Chapter 4. Some of the components already exist in an electric vehicle for other purposes, and may need re-sizing. It is not possible yet to describe in detail any notional weapon system, since none of them is close to fieldability. All these concepts are under continual improvement and development, and whilst most have been proven in principle and in the laboratory, have not commenced the weaponisation process. They do offer new possibilities for offensive and defensive actions beyond those possible with conventional weapons. Suitable operational analysis will be needed to identify which types provide the greatest benefits to military action.

2.4.2.3   Survivability

Survivability is a combination of many factors, including active and passive protection, mobility (covered in mobility section), signature, and operational use. For protection, the availability of greater electrical power on future combat vehicles will allow the use of new electric armors. The placement of these systems is a matter for specific vehicle design, and cannot be covered here. It is normal to have a high degree of protection on the front of a vehicle, medium protection on the top, bottom and sides of the vehicle, and light protection over

the remainder. The combination of currently available protection techniques with these new armor types has not yet been considered. Electric armor is covered in Chapter 5, and as with electric weapons, the basic technology is understood and has been demonstrated. Development to military standards has not been started, and will take some years.

The system requirements for electromagnetic active armor are outlined in the Table 2.7 below.

Table 2.7: Electric Armour Power Requirements

Description of Function	Launching of Protective Elements (250 m/s to 800 m/s and 4 kg to 30 kg)
Energy/pulse (MJ)	5
Peak power/pulse (GW)	10
Pulse duration (ms)	1 (damped sine wave)
Repetition rate (s)	30 (setup time)
Average charging power/burst	170 kW
Burst: No. of pulses	2 – 3 (average power/burst 170 kW)

Signature covers acoustic, thermal, electromagnetic, and visual emissions from the vehicle at all times. Electric systems have the potential to reduce the acoustic and thermal signatures significantly, may or may not increase the electromagnetic signature, and will have little/no effect on the visual signature. Hybrid electric drive has the ability to generally provide reduced thermal signature by having a more efficient powertrain, and by being able to optimize the power management of the system for reduced emissions. In addition, it offers the possibility of dramatically reduced temporary mode of operation, where the vehicle's main power generator(s) are turned off and the vehicle is powered by a pure electric power source (such as a chemical battery, a flywheel generator or an ultracapacitor or perhaps even a fuel cell).

Silent watch provides low power for extended periods to power on-board systems whilst stationary. Silent mobility offers a limited movement capability for stealth operations. Thus to obtain a silent watch/ mobility capability, an energy storage system is required on the vehicle providing sufficient power and energy to fulfill the military requirements. For silent watch, the power requirement is 1 – 3 kW for >= 15 hours (essential) or >= 24 hours (desirable). This means an energy storage >= 15 – 20 kWh. For silent mobility, the power requirement is >= 80 kW (peak), 40 kW (average) for 0.5 hours (implying 20 kWh). Thus the minimum requirements for an energy storage device are 80 kW, 20 kWh.

As long as the powertrain is properly shielded to the required EMC standards (MIL-STAN 841e Def-Stan 49-51), the EMC signature should be the same as a conventional vehicle. Electric weapons could introduce a stronger signature for the short period of firing the weapon.

2.4.3   Notional Vehicle 2: 35-Ton Tracked Vehicle – Direct Fire – Role

An overall impression of NV2 is shown in Figure 2.4.
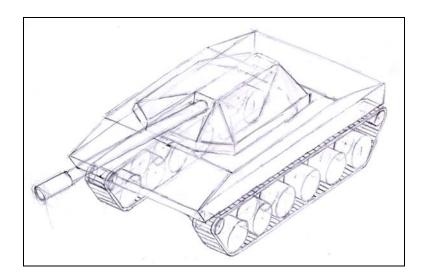
Figure 2.4: NV2 Overall Impression.

The 35-ton tracked vehicle is the same as the 17-ton wheeled vehicle in a number of respects such as having a power generator, and a means of transmitting power to the wheels. The requirement for an energy storage capability would similarly be used to improve vehicle acceleration, fuel economy and provide power for other mission systems. It is noted that the high rolling resistance associated with tracked vehicles is likely to reduce the amount of regenerated power. As a direct fire role has been assumed for this vehicle, there is scope for installing electric weapons and armour systems which will need to interface with the propulsion power bus. Indicative requirements for a 35-ton tracked vehicle are shown below.

Table 2.8: NV2 System Level Design Targets

Category	Indicative Requirement
General Vehicle Characteristics	
GVW (ton)	35 ton
Volume constraint	Rail gauge and A400M
Height target (m)	<= 2 – 2.5
Approx track dimensions (m)	Diameter = 1.35; Width = 0.45
Mobility	
Power to weight (cont) (kW/ton)	>= 20
Power to weight (peak) (kW/ton)	>= 30
Maximum speed (road) (kph)	>= 80 – 90
Maximum speed (cross-country) (kph)	30 – 40
Range (road) (km)	>= 600
Range (road/track/cross-country) (km)	>= 500
Stealth range (cross-country) (km)	>= 4 – 6 km @ ?kph
Maximum acceleration (0 – 60 km/h)	20
Braking (m/s^2)	< 5
Fording depth (m)	1.5
Overturn angle (degrees)	
Road legislation	Compliant

Category	Indicative Requirement
Lethality	
Defeat medium/heavy armour; Capability against troop formations and structures.	
Survivability	

Survive:
   1)   Frontal direct hit from large calibre weapons;
   2)   Medium calibre direct hit all round (desirable);
   3)   Small calibre all round (essential); frontal direct hit from hand held shaped charge projectiles (essential).
   4) Enhanced mine protection.	

Others	
On-board power generation	Voltage, Amps?

There are numerous electrical systems, technologies and configurations that could be employed in NV2 and the precise arrangements would clearly need to be defined against a detailed analysis of the systems requirement. Nonetheless, the study team has concluded that the following systems would typically be employed.

Table 2.9: Typical Electrical Systems in NV1 – 17-Ton Scout Vehicle

Serial	System Area	Description
1	Mobility	In board rear sprocket drives with a drive motor and cross-shaft arrangement. Diesel based power generator and battery energy storage system. Power delivery controlled by a vehicle management unit with driver interfaces. Electrically driven ancillaries would include hydraulic pumps for the brakes and electric drives for the cooling fans.
2	Survivability	Energy storage system for silent watch/mobility. Electric armour.
3	Lethality	Electromagnetic (EM) railgun or electrothermal ignition (ETI) gun.

2.4.3.1   Mobility

Notional Vehicle 2 is assumed to be a series hybrid (essential in removing the bulky conventional transmission), with multiple power generators, which would most likely be diesel powered generator. Gas turbines are an alternative power source. The requirement for an energy storage capability is limited to silent watch/mobility requirements, as not much energy would be generated through braking due to the large rolling resistance associated with tracked vehicles. Power density of the powertrain is of prime importance, as more volume under armor means that more armour is required for the same amount of protection, increasing vehicle mass.

Tracked drive systems can be either single line (retaining a mechanical cross-shaft) or two line systems. Two-line systems give the advantage of easier access to the rear of the vehicle. Single line systems offer superior steering performance, with drives of a lesser power rating for the same performance. A single line system is assumed for the notional vehicle.

It is assumed that the vehicle will have an energy storage device, which could be a chemical battery (and could be of a number of different chemistries), flywheel or ultra-capacitor. Power flow will again be managed by the vehicle management unit across a controller area network (CAN) bus. The vehicle can have an electric suspension system with electromechanically actuated struts.

The system architecture that has been assumed is depicted in Figure 2.5.

Figure 2.5: NV2 Power System Sketch.

Improvements in fuel consumption are realized through efficient power management, electrical regenerative braking (limited) and reduced mass (from reduced volume over armor as well as reduced powertrain mass) reducing rolling resistance. Pulse acceleration is achieved by using the power generators and energy storage in series.

The approximate design target for the 35-ton tracked vehicle is as follows.

Table 2.10: NV2 Power System Design Targets

Vehicle Components Affecting Mobility	Design Target
Power Generator	
Electrical power output (cont) (kW)	>= 1000
Power density (kW/m^3)	**10000**
Specific power (kW/kg)	1050
Energy Storage	
Power output for 30 s (kW)	200 – 300
Energy (C rate) (kWh)	>= 30
Energy (2 hour discharge) (kWh)	>= 50
Specific energy (Wh/kg)	>= 100
Energy density (Wh/litre)	>= 159
Specific power (W/kg)	>= 1000
Power density (W/l)	>= 3000
Full power ambient temperature operation (Celcius)	-40 to +55
Drives	
Features	Gear change/reduction; mechanical brake; electrical regenerative braking; mechanically regenerative steering
Dimensions	Fit inside 25" wheel rim
Volume (litres)	< 160
Mechanical power output (cont) (kW)	>= 50
Power output (peak) (kW)	>= 100
Torque output (cont) (kNm)	>= 10
Torque output (peak) (kNm)	>= 20
Specific power (cont) (kW/kg)	> 0.15
Specific power (peak) (kW/kg)	> 0.24
Specific torque (cont) (Nm/kg)	> 32
Specific torque (peak) (Nm/kg)	> 64
Overall efficiency (peak) (%)	> 80
Power Converters	
Power density (kVA/litre)	>= 35
Overall efficiency (average) (%)	> 95%
Dump Resistor	
Rated power (kW)	> 50
Power density (kW/kg)	> 10
Suspension	
Configuration	Electromagnetic struts
Capability	Net power generation
Steering	
Configuration	Mechanically regenerative
Motor power (peak) (kW)	200
Motor power (cont) (kW)	100

Figure 2.6: NV2 Powertrain Block Diagram.

2.4.3.2   Lethality

Direct fire vehicles like the notional 35-ton study example are equipped with a main armament focused on anti-armor operations. Conventional weapons could be used with such vehicles, and for vehicles coming into service soon, would be the only consideration. It is likely that a medium-large caliber weapon would be fitted, of >= 90 – 120 mm caliber, and a replacement weapon system would be similarly sized but have improved performance.

Electrical requirements for ETC and EM gun options are in the following table.

Table 2.11: EM and ETI Gun Electrical Requirements

Electric Gun Electrical Requirements			
	Units	EM railgun	ETI gun
Gun requirements			
Electrical energy stored/shot	MJ	24	0.1
Peak power/shot	MW	4800	0.1
Pulse duration	ms	4 – 5	1
Electrical energy for a burst	MJ	N/A	0.6
Average power for one shot	MW	3500	0.08
EPPS voltage	KV	2 – 5	10 – 20
Current	MA	3	0.2 – 0.3
Assuming a burst of 6 shots per minute, 60 – 70 mm equivalent calibre.			
Some recharging of energy will take place within burst cycle time.			

Energy Storage Requirements			
Mass	Kg	1500	1500
Volume	m^3	0.375*	0.375*
Energy density	MJ/m^3	384	1.6
Specific energy	kJ/kg	288	1.2
Power density (avg)	MW/m^3	9333	0.21
Power density (peak)	MW/m^3	12800	0.27
Specific power (avg)	kW/kg	7000	0.16
Specific power (peak)	kW/kg	9600	0.2
*Assuming dimensions of 0.72 m × 0.72 m × 0.72 m			

These figures are speculative, based on the infancy of the technology.

A direct vehicle will have a capability against troop formations and structures, which could be provided by the main armament or a secondary weapon system. If the main armament is optimized for defeating armor, then a secondary weapon would be required for this purpose. Otherwise the main weapon would need to be designed for a generic purpose.

2.4.3.3   Survivability

Survivability is a combination of many factors, including active and passive protection, mobility (covered in mobility section), signature, and operational use. The direct fire role requires an effective protection system against all types of battlefield attack. Electric armor would provide a valuable increase in armor performance, but would only be part of an overall system including conventional technologies. The placement of these systems is a matter for specific vehicle design, and cannot be covered here. For this vehicle, maximum protection is necessary on the front of a vehicle, high protection on the top, bottom and sides of the vehicle, and medium protection over the remainder. The overall level of armoring would be maximized within vehicle weight constraints. Electric armor is covered in Chapter 5, and as with electric weapons, the basic technology is understood and has been demonstrated. Development to military standards has not been started, and will take some years. The system requirements for electromagnetic active armor will be roughly the same as for NV1, detailed in Table 2.7.

Signature considerations are covered in the scout vehicle survivability paragraph above. The direct fire vehicle (like all other combat vehicles) would gain considerable benefit from silent watch/mobility requirements. For silent watch, The power requirement is 1 – 3 kW for >= 15 hours (essential) or >= 24 hours (desirable). This means an energy storage >= 15 – 20 kWh. For silent mobility, to achieve 30 km/h for 15 km, the power requirement is >= 160 kW (peak), >= 80 kW (average) for 0.5 hours (implying 40 kWh). Thus the minimum requirements for an energy storage device are >= 160 kW, 40 kWh. As long as the powertrain is properly shielded to the required EMC standards (MILSTAN 841e Def-Stan 49-51), the EMC signature should be the same as a conventional vehicle. Electric weapons could introduce a stronger signature for the short period of firing the weapon.

Chapter 3 – MOBILITY

3.1 GENERAL

LTSS/43 on All Electric Vehicle – Mobile Electric Weapon Platform (AC/243(LTSS)TR/43) describes the technology and benefits of the AECV. Based on the new technologies for diesel-electric drive systems revolutionary technical solutions for mobile land vehicles became feasible during the last decade and were proven by various demonstrator types (wheeled and tracked).

The main effort now focuses on further improvements of the key components, which are now an evolutionary process.

3.2 IMPROVEMENT IN COMPONENT DESIGN

3.2.1 Prime Mover

Up to now tanks are exclusively driven by diesel engines in combination with a mechanical transmission. The German company MTU, Friedrichshafen, offers with the 880 series the most compact diesel engine for all heavy MBTs and howitzers. For a diesel electric drive system even these compact engines are still the heaviest and most voluminous components. Therefore optimization of the diesel engine size and weight will have a big impact on system improvement. The need for more flexibility in arrangement of the propulsion system leads to new drive system configurations for armored vehicles (Figure 3.1).

Size Comparison 12V HPD – MT883 (Cross-section)

610 mm/2.0 ft
808 mm/2.6 ft
590 mm/1.9 ft
977 mm/3.2 ft

Figure 3.1

Progress in engine design using matched turbocharging, improved cooling systems and air filtration has allowed a new diesel engine concept called High Power density (HPD). This HPD engine is optimized to operate with a gearless transmission like electric drive. In comparison with the 880 engine family a reduction

in weight and volume of 50% together with lower fuel consumption and a smaller cooling system will be achieved.
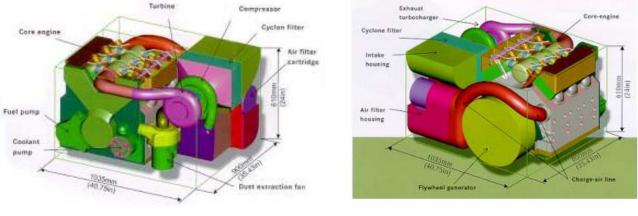
Figure 3.2.1 shows a 552 kW diesel electric power unit inside 0,57 m^3.

Figure 3.2: (1)   Figure 3.2: (2)

Figure 3.2.1: Cross Section of MTU 883 and HPD Engine.

- As MTU announces this HPD diesel engine will be developed in 2003.

- MTU plans a whole HPD family with the following features:

  - Highly compact, high speed 4-stroke diesel engine,

  - 1 liter swept volume per cylinder,

  - Integrated design of subsystems (e.g. pumps, filters and oil system),

  - State-of-the-art common rail injection system,

  - Fully digitized engine management,

  - High temperature cooling system.

The HPD engine family is planned for 6 V, 8 V, 10 V, 12 V and 16 V with the max. speed of 4250 rpm. The power ranges from 552 to 1472 kW. The power-to-volume ratio is 1200 to 1360 kW/m^3, the weight-to-power ratio is 0,94 to 0,81 kg/kW.
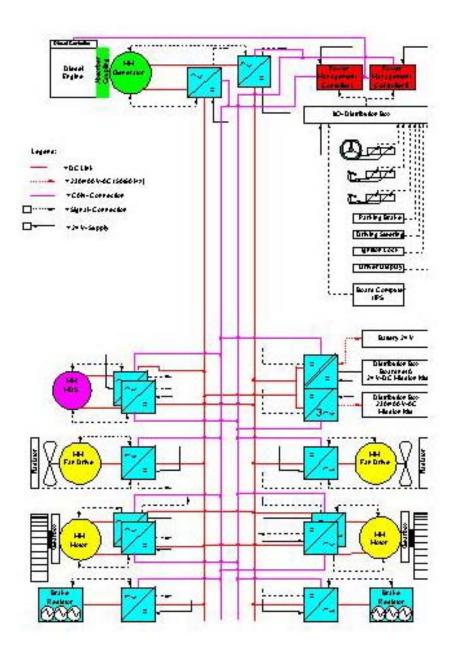
Figure 3.3: Structure of the AECV.

3.2.2   Electrical Machines

3.2.2.1   Magnetic Materials

From the beginning of the study on the new technologies involved it was very clear that drive systems for military combat vehicles based on conventional electric components cannot be integrated in an all-electric vehicle. They do not provide sufficient power and torque. Such systems would be far too bulky and heavy. Therefore the required electric machines must be able to provide many times more power and torque and at the same time are smaller and lighter than conventional types.

One solution is based on permanent magnet allowing new technologies for generators and motors. They are an essential key element for the AECV systems.

Up to now FeNdB and SmCo types are used. These materials can provide with new arrangement of the magnets; enhanced flux concentration to yield the required energy density and the power density needed for military applications.

Further improvement is mainly determined on the magnetic characteristics of the permanent magnets. Nevertheless additional effort is still necessary to improve the design and performance of Permanent Magnet Machines. Therefore, the following areas for further work on magnetic material are to be addressed:

Requirements	Consequences
High remanence B_r [T]	High torque M [Nm]
High intrinsic coercive force H_{CJ} [kA/m]	High stability against demagnetising fields
High specific energy product $(B \cdot H)$ [kJ/m^3]	High power capability or low construction volume
High thermal resistance	Demagnetisation only at high temperatures
High electrical resistivity	Low losses by eddy currents
High resistance against humidity	Long life and corrosion resistance and reagents
Low dependence on temperature of: • remanence B_r • intrinsic coercive Force H_{CJ}	Decrease of temperatures causes lower: • reversible reduction of the B-field • irreversible damages of magnets at higher temperatures
Beneficial mechanical features (e.g. sturdiness, flexural strength, ...)	Long life, simple mechanic construction

3.2.2.2   Generator/Motor

For AECV Germany still relies on permanent Magnet machines in Multiple Electronic-Permanent Magnet (MEP)-design for generators and motors, as those machine types assure a very high level of power density and specific torque for land mobile military vehicles. They also have proven their reliability and durability in Dual Use applications. The basic technology for this MEP machine is described in TR743, Chapter 3.4.2.3.1. It can be characterized as follows:

- Outer rotor design with permanent magnetic excitation by high energy permanent magnets (FeNdB and SmCo type).

- Inner stator with single coil structure. The copper windings of the coils and the stator iron are directly cooled by oil for an optimal heat transfer.

- Simple mechanical and electrical construction without parts subject to wear and tear, no brushes, no sliding contacts, large air gap, simple end windings without interconnections.

During the last 5 years further work on the machines reduced the specific weight and volume up to a factor of three which was mainly achieved with flux compression geometry to increase the exploitation of the magnet material. Altogether this leads to an optimally large bore diameter of the electric machine compared to the

outside diameter and, thus, to an optimal exploitation of the integration conditions. These machines have a hollow cylinder shape that opens simple integration possibilities. It is no more a separate element, it is rather possible to integrate other mechanical elements in the inside of the electric machine, e.g. parts of the bearings of the wheel or of a planetary gear.

For generators these efforts have given the following results:

- Volume specific power of 9,1 kW/dm^3,
- Weight specific power of 4,1 kW/kg.

For land mobile vehicles a generator with 1.1 MW rated power output has been built with the new technology.

For motors the following data have been realized:

- Volume specific torque of 90 Nm/dm^3,
- Weight specific torque of 30 Nm/kg.

In order to match the mobility requirement for a heavy tracked vehicle (MLC 60) the motors were built with the corner power of 6,04 MW, each.

3.2.3   Power Electronic (PE)

The power electronics is a key technology for AECV realization. In Germany the increase of power density for the year 2000 was about 50 kVA/dm^3 which was realized in the lab. This goal has been achieved based on common IGBT technology in combination with micro-coolers providing very large cooling surface and less insulation layers for more direct cooling. The advantages of the emerging SiC-technology will provide a further improvement.

From the experience of realized projects different kind of PE have been developed. Their common power interface is the DC intermediate net with a voltage in the range of 300 to 800 VDC, where the upper limit may increase depending on the progress of PE characteristics.

The main group within the PE is the propulsion power electronics to supply the MEP machines. The PE must be able to operate the machine in generator mode and in motor mode (four quadrant operation). Another important electronic device is the brake power electronics. Together with the brake resistor it ensures the electric brake ability of an electrically driven vehicle. It transfers the DC power and energy generated by the drive motors in generator mode into the resistors. If there is a storage system incorporated, the power management governs energy recovery and power dissipation. For this application the brake PE operates only as a chopper. For better system integration propulsion PE and brake PE can be combined into one box. Another kind of power electronics are the DC/DC and DC/AC power inverters. They adapt the intermediate DC voltage to the voltages (DC or AC) required for internal or external subsystems. Depending on the rated power of these inverters the AECV can operate as mobile power plant up to the installed power of the prime mover.

A separate type of DC/DC converter combines the 24 V DC conventional vehicle board network with the power system (main DC power bus). It works in bi-directional way, thus the battery can be charged from the main DC power bus (replacement of the alternator) and the diesel engine can be started directly by the MEP generator (generator in motor mode, replacing the conventional DC starter motor).

3.2.4   System Control Electronics and Power Management

The system control electronics is the common control, regulation and monitoring electronic device for all individual components of the energy system including the drive system. It links the drive components (motors, generators and their appropriate power electronics) together with the other elements of the system like brake power electronics, storage devices and auxiliaries with their DC/DC and DC/AC power inverters as well as the diesel engine control to a working system. A principal sketch of the connections of the system control to the individual elements is shown in Figure 3.4 (1) for a tracked vehicle. Its primary task is to evaluate and process the input parameters coming from the driver/operator and the internal system status parameters, to convert those data into reactions of the drive elements and to optimize coordinated operation between all components. The controlling of the diesel engine is also included into the optimization of the propulsion functions.

A main task of system control electronics as part of the power management is to evaluate the energy level of storage devices for their charging and discharging. According to the mission the software is designed to distinguish between several operational strategies (e.g. priority levels for different consumers and emergency supply).

Monitoring and diagnosing of all propulsion components within the system are other important tasks of the system control electronics.

The system control is equipped with microprocessor components. A special development hereby represents the communication of the system control to other internal system components and external interfaces via an optical data link by means of fiber-optic cables. They are very insensitive to electro-magnetic interference (EMC) ensuring a safe data communication.
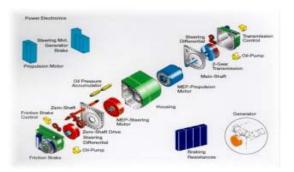
3.2.5   Electro Mechanical Transmission (EMT)
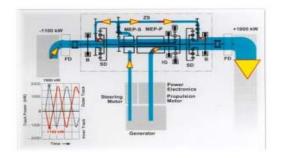
The drive system of a tracked vehicle has to fulfil tasks which far exceed those known from wheeled vehicles. Apart from forward and reverse driving, it also assumes the relevant safety functions of braking and steering, and thus considerably contributes to the mobility performance characteristics of a tracked vehicle.

Electromechanical drive systems have the following specific advantages with respect to mobility (Figure 3.4 (1)):

- Continuously adjustable driving and steering operation;
- Recovery of braking power;
- Crawling operation with the combustion engine turned off and the energy storage system installed;
- Conversion of the entire combustion engine output power into electrical energy;
- Flexibility for vehicle integration with multi-engine concepts;
- Integratable into an all-electric combat vehicle (AECV).

Main groups of the electro-mechanical drive system RENK 1100

Steering required to steer a 55 t vehicle in slalom motion

Figure 3.4: (1)   **Figure 3.4: (2)**

The combination of mechanical and electrical components result in synergy effects which currently still have advantages over a purely electric drive with respect to safety, weight, design volume and cost. Thus, electromechanical drives for future tracked vehicles are the subject of various studies.

As a consistent step in further development, the realization of an electromechanical drive system (joint development by the companies Renk, Augsburg and Magnet Motor, Starnberg) is planned. The electromechanical drive system combines the benefits of proven mechanical drive technology with those of the future oriented electrical drive technology.

The specific advantages of this concept are:

- The two-speed transmission provides for two operating modes. The first mode will only be required in extreme situations, such as difficult cross-country terrain. The second mode with direct transmission can be used in paved light terrain and on primary roads (highways).

- Maximum speed is continuously adjustable.

- The requirements for electrical components can be reduced.

- In both modes the MEP main engine can be operated at optimum efficiency.

- Independent drive, steering and braking systems provide for a high level of system safety.

- Stabilized straight-ahead movement.

- Maintenance of the regenerative mechanical steering principle with neutral shaft.

- Flexible concept design obtained by integrating all components in one block ("power pack") or independent arrangement by the separation of combustion engine(s) and drive block.

3.2.6   Storage

The use of a storage system is a precondition for the initial operation of the AECV and its optimization. It applies to the start/initial activation of the AECV, the mobility of the vehicle as well as the operation of the subsystems.

As an additional electric element for power supply it provides a lot of other benefits for the vehicle and its functions:

- Power reserve and power redundancy which leads to:
  - Decisive improvement of the maneuverability especially in heavy terrain,
  - Highly increased acceleration,
  - Quick position change ability, as jumping out of cover position, stealth mode, and underwater operation without Diesel engine running;
- Energy saving and regeneration e.g. during braking operation;
- Electric energy supply to all consumers during standstill of the vehicle, e.g. silent watch;
- Option for future internal and external supply of high power consumers.

According to the wide area of the different tasks greater energy and greater power have to be provided. In addition short duration and long duration of use have to be taken into account.

High level of energy is needed for long time application to meet the power requirement of the subsystems e.g. for system initiation/activation or silent watch. High level of power is needed for:

- The start of the prime mover,
- Mobility e.g. acceleration,
- Weapon power supply like ETC-gun,
- Active armor,
- Active suspension.

To manage all these aspects no unique type of storage is available. Different types have to be integrated. Therefore the following storage systems are identified.

3.2.7   MDS

The magneto-dynamic storage is a flywheel storage with an integrated electric machine that can be used either as a generator (discharge mode), or as a motor (recharge mode via re-accelerating the flywheel rotor) depending on the momentary needs.

The energy carrier of the MDS is a cylindrical rotor made of wound carbon fiber. The rotor's axle stands on a vertical plane. The motor/generator (M/G) unit is inside the cylindrical rotor, accepting or delivering electric power.

To reduce the friction in the bearings most of the rotor's weight is compensated for by magnetic forces. Air friction is reduced to a minimum as the complete rotor unit runs in a vacuum enclosure.

The most important advantages of the MDS compared to other energy storages, i.e. chemical batteries are first of all the high power ability with respect to weight and volume and the indefinite cycle number potential. This is due to the fact that the MDS is an electric machine and is not limited by electrochemical elements.

These characteristics open the benefits to use the MDS in military vehicles as an additional energy and power source. The results are the excellent features of the MDS and its related advantages.

Some current MDS types for mobile applications are summarized in Figure 3.6, with photographs and related data. Presently the MDSs reach specific values of energy/mass = 80 MJ/ton and power/mass = 2,5 MW/ton in the laboratory. In the next few years approximately 5 MW/ton will be achievable.

MDS Laboratory Types MDS L1 and MDS L2 with Series MDS K3

MDS - Type	MDS L1	MDS L2	MDS K3
Power	80 MJ	80 MJ	7,2 MJ
Energy	5,0 MW	2,5 MW	150 kW

Figure 3.6: Typical MDS Systems.

This MDS type has been safe proved by the German technical authorities and is authorized for use in public transport applications. With more than 200,000 operation hours and more than 2.5 million kilometers in vehicles this technology stands for an evident reference.

3.3   MOBILITY ASPECTS

3.3.1   Introduction

Future combat platforms are considered for the next generation as multi-role platforms with great payload and great volume available inside the hull to match different missions like armored personnel carriers, missile carriers or combat vehicles. Therefore, future military ground platforms should have a high level of mobility off road and on road, for close quarters in urban environment or for strategic mobility, a great survivability, a great ergonomic volume inside the hull for personnel or for high performance gun systems with a class not exceeding 18 tons for air transportable requirement. That is a great challenge that needs the best technology, like with electric drive, on an optimized architecture, like the dual steering.

3.3.2   Dual Steering

3.3.2.1   Definition

Dual steering is the combination of the natural steer angle of traditional vehicle with skid steering of tracked vehicle. This combination provides a high level of performance in terms of maneuverability and driveability but above all it provides greater volume inside the hull.

Indeed, natural steer angle is a very efficient steering system particularly for strategic road travel that needs low power for steering. However, swept volume required for steer angle lowers the volume of the front side of the vehicle and when it comes to all ground surfaces, maneuverability is not successful.

Contrary to natural steer angle, maneuverability on all ground surfaces for skid steering vehicle is almost perfect. And, as steer angle is not necessary, the volume in the front hull is almost the same as the rear hull. However, skid steering reduces considerably life cycle of pneumatics particularly on road. The driveability at high speeds is very bad and needs high control of the driver and moreover, maneuverability at low speeds needs far more power than traditional steering.

	Advantages	*Inconveniences*
Natural steer angle	Strategic road travel Low power	Off road maneuverability Swept volume
Skid steering	Off road maneuverability Swept volume	High power Driveability at high speeds Life cycle of pneumatics

MODIX a 8x8 25-ton vehicle and DEFIX a 4x4 2.5-ton vehicle, two demonstration vehicles using dual steering confirm the high level of drivability and maneuverability provided by dual steering.

3.3.2.1.1   Dual Steering Laws

Traditional steering is designed by steer angles of wheels. Considering a 4x4 vehicle with a fixed wheelbase and width, turn radius requirement at low speeds imposes maximal steer angles of wheels using Ackerman's steering. These maximal steer angles represented 100% of natural steer angle.

Skid steering is designed by the speed ratio between wheels of the same axle. Considering a 4x4 vehicle with a fixed wheelbase and width, the turn radius requirement at low speeds imposes the maximal speed ratio between outside wheels and inside wheels. For DEFIX, an optimal speed ratio of 2.5 was determined. This speed ratio is the best compromise between the necessary power to maneuver and maneuverability performances. This speed ratio represented 100% of skid steering.

As dual steering is a combination of both steering systems, dual steering laws will be a combination of a definite percentage of traditional steering and a definite percentage of skid steering.

When it comes to future combat platforms, dual steering is particularly interesting considering volume and propulsion architecture. Since different combinations of traditional steering and skid steering have the same results in terms of maneuverability and drivability, a compromise can be found depending on volume and necessary steering power.

Indeed, wheels steer angle will affect:

- Swept volume in the front side of the vehicle and volume inside the hull,
- Maneuverability and drivability.

Skid steering will affect:

- Steering power,
- Maneuverability and drivability.

Lowering the swept volume of wheels allows a greater volume in the front hull and more flexibility for organizing the propulsion architecture to make it as compact as possible. However, the low steer angle must be combined to more skid steering to reach maneuverability performance which implies more power at wheel for maneuverability and shorter life for pneumatics.

Figure 3.7 below are an example of dual steering application to a 6x6.

Epure de JEANTAUD
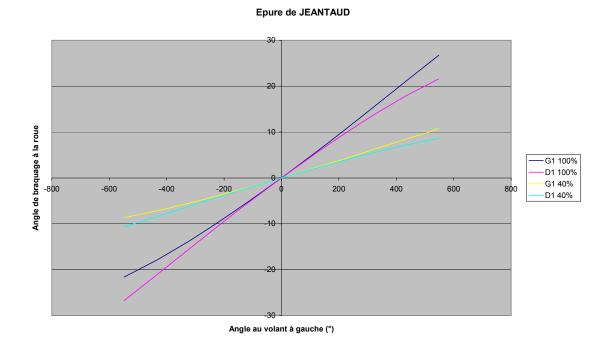
Figure 3.7: JEANTAUD.

The first law concerns Ackerman's steering. That is to say steer angle of wheels according to steering wheel angle.

Lines G1 100% and D1 100% above concern respectively the left wheel steer angle and the right wheel steer angle of a conventional 6x6 front axle. Lines G1 40% and D1 40% are similar laws but 60% lower.

With a 40% traditional steering law, maneuverability lowers and has to be combined to skid steering. For example, a 100% traditional steering law for the front of a 6x6 allows a 9 m turn radius at low speeds, whereas the same law 60% lower allows a 19.5 m turn radius at low speeds.

However, a 60% steer angle reduction allows a hull 300 mm wider on the front side of the hull, which is not insignificant.

To compensate for 60% lower steer angle, skid steering has to be combined, this is the skid steering law.

3.3.2.2   Skid Steering Law

Considering a conventional class 4x4 vehicle, optimal speed ratio has been evaluated at 2.5. Skid steering law is the speed ratio according to steering wheel angle. The 2.5 speed ratio is reached at the maximal steering wheel angle. The higher is the speed ratio, the higher is the vehicle maneuverability and the higher is the power necessary for maneuvers.
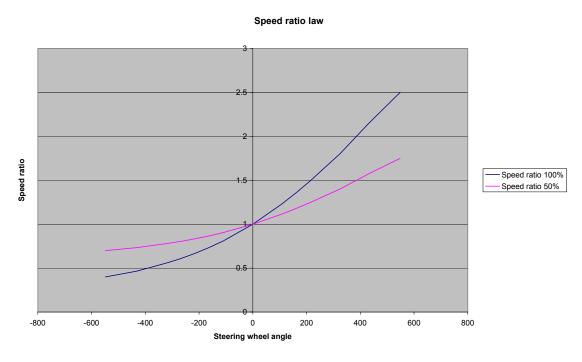
Figure 3.8: Speed Ratio Law.

The skid steering law above is applied to a 4x4 conventional vehicle. At maximal steering wheel angle, the speed ratio reaches 2,5 and when it comes to void steering wheel angle, the speed ratio is 1.

Since skid steering, a great consumer of power, needs precise control at high speeds and reduces pneumatics life, it is important to combine the just necessary skid steering to traditional steering.

A 2,5 speed ratio necessary for skid steering wheeled vehicle is not necessary in terms of performance and power for a vehicle with steering wheels. To optimize vehicle performances according to necessary power, a coefficient is applied to the skid steering law. The figure above is an example of 50% lower skid steering law.

By combining the 40% traditional steering law and the 50% skid steering law, the previous 6x6 reaches a 9 m turn radius with a hull 300 mm larger.

On all ground surfaces, dual steering laws are different and gives greater importance to skid steering for a better maneuverability. The modeling of all ground surfaces being difficult, DGA have ordered a demonstrator to evaluate dual steering laws for future combat platforms. The perfect vehicle should have three dual steering laws available directly on the dashboard and selectable by the driver: a road law for strategic road travel and maneuvers in urban environment, an off road law and a pivot law for example.
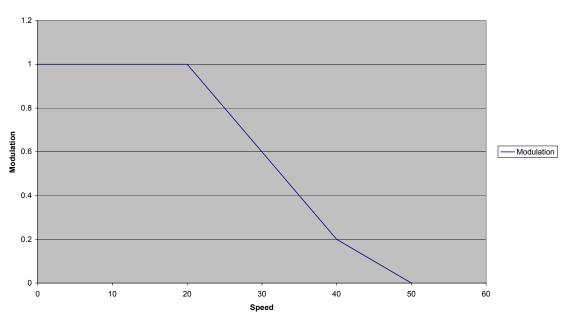
3.3.2.3 Speed Ratio Modulation

In a vehicle, a maximal lateral acceleration exists (which depends on vehicle mass and transversal roadholding) above which the vehicle skids. Dual steering use is therefore dependent on vehicle characteristics and speed. It is important to understand that, dual steering superposes skid steering to the natural wheel angle to allow tight turns at low speeds, but at these speeds the skidding of the vehicle is easy to control. At high speeds, skid steering is dangerous and difficult to control.

It is obvious therefore, that dual steering laws depend on a percentage of skid steering and a percentage of steer angle according to the steering wheel and depend on speed.

Up till 20 km/h, skid steering is necessary to perform tight turns. Between 20 km/h and 50 km/h skid steering has to be modulated to avoid instabilities of the vehicle. Above 50 km/h, the natural wheel angle is sufficient to steer and control the vehicle.

The law below is superposed to the dual steering law to modulate the speed ratio according to the speed.

Speed ratio modulation

Figure 3.9: Speed Ratio Modulation.

It is important to note that modulation only concerns the superposed skid steering to the traditional steering. Thus, above 50 km/h a void modulation implies that the vehicle behaves itself as a vehicle with a traditional steering and a traditional differential. So, during a low turn at 50 km/h, a speed ratio exists equivalent to the speed ratio provided by a traditional differential.

3.3.3 Optimization of Greater Volume in the Front Hull

In order to optimize the reduction of the swept volume, it is necessary to use a suited steering suspension. Indeed, for non steering wheels, the ideal suspension system is a trailing arm suspension. When wheels

become steering wheels, some systems allow a quite good optimization of the reduction of the swept volume. The first one is a steering trailing arm like those developed by PANHARD or HENSCHEL (Figures 3.10a and 3.10b below). Another one could be the use of a bogie like on the AHED.

Figure 3.10a: MODIX.

Figure 3.10b: MODIX.

MODIX is a 8x8 25/32-ton vehicle. This demonstrator had been ordered by DGA in 1992 to study strategies of dual steering according to all ground surfaces for future combat platforms.

Figure 3.11: MODIX.

MODIX has 8 independent hydrostatic transmissions, 8 independent steering systems (one for each wheel), and 8 independent suspensions. MODIX enables independent control of each wheel and therefore enables simulation of various differentials combined with various steering strategies.

Modification of a differential or of a steering strategy is done on a computer on board at the rear side of the vehicle. Speed ratio laws according to steering wheel angle are modifiable for each axle and steer angle according to steering wheel angle is modifiable for each wheel. That is to say that for each configuration, twelve laws have to be entered.

MODIX is able to simulate pure skid steering strategy, natural wheel angle strategy and, above all, strategies combining both steering. Up to date trials were done on road and off road.

3.4 ELECTRIC DEMONSTRATOR: DPE

DPE is an electric demonstrator ordered by the SPART in order to evaluate interests of electric drive for military applications and particularly for the future combat platform of BOA (Battlefield Optimized Armament): EBRC (Engin Blindé à Roues de Contact). EBRC is the first platform using the BOA concept.

This project was first based on a 8x8 25-ton platform but new air transportable requirements impose a 18-ton mass in combat mode. Considering this new class and considering integration, mass and payload problems, DPE project is now based on a 6x6 18-ton platform by adding one axle.

Requirements for the demonstrator are EBRC requirements (Engin Blindé à Roues de Contact):

- **Hull**
  - 18-ton mass in combat mode
  - 6,5 m^3 payload

- **Hybrid mode (diesel engine/generator + wheel motors)**
  - Maximal speed 90 at 115 km/h
  - 60% slope
  - 70 cm step forward
  - Dual steering
  - Pivot
  - 750 to 1000 km range at 60 km/h

- **Furtive mode on batteries**
  - 20 to 25 km range at 40 km/h

Dual steering will be directly applied on this concept thanks to four dual steering laws selectable on the dashboard by the driver. These laws will be given by ETAS according to the size of the concept: a road law, a trail law, an off road law and a pivot law. This concept will have a restricted steer angle for the front wheels on which skid steering will be superposed. To optimize the reduction of the swept volume, steering trailing arm suspension will be used on the front axle. Rear axles will be equipped with trailing arm suspension.

3.5 INCREASE OF UNSPRUNG MASS

Since the introduction of electric motor in wheel hub, the problem of increasing unsprung mass is set. According to vehicle class (4x4 4 tons, 4x4 12 tons, 6x6 18 tons, 8x8 25 tons) integration of electric motor in wheel hub implies 50 to 300 kg more in each wheel.

This wheel mass has theoretical consequences on vehicle behavior on road because of the great inertia of wheel motors and because of a greater mass going up in the suspension when the wheel gets off the ground. Consequences on transversal behavior and on off road behavior are also possible but these consequences are easier to verify by trials.

In order to define consequences of important mass in wheel on an all ground surfaces vehicle, a VBL (Véhicle blindé léger 4x4) was equipped with 60 kg heavier wheels. Trials were carried out on road, off road and on special tracks in comparison with a classical VBL. The two VBL were the same, wheel mass and center of gravity excepted.

3.6   MOBILITY EVALUATION

3.6.1   On-Road Evaluation

On-road evaluation consists of evaluating and quantifying vehicle on road behavior in order to lay emphasis on behavior failure and particularly those concerning security. Trials done on ETAS road ring and on Camp Fontevraud involved "tenue de cap", front/rear balance, steering, turns and comfort according to one dozen criteria. Increasing wheel mass has not worsened the vehicle on road behavior.

3.6.2   Off-Road Evaluation

Off road evaluation is a subjective overall evaluation of vehicle behavior according to longitudinal, transversal, clearing, drivability, and comfort criteria. Performances and off road behavior of the two VBL are similar. However, the comfort of the VBL with heavy wheels is worse because of greater impacts due to the heavier wheel going up the suspension when clearing obstacles.

3.6.3   Special Tracks Evaluation

On road and off road subjective evaluations have not laid emphasis on particular problems due to the increase of unsprung mass. Most of comfort problems were due to impacts related to the heavier wheel mass going up the suspension when the wheel got off the ground. In order to precisely define these few differences, trials on special tracks have been carried out (small potholes, wrinkled tracks, 6-in trapezium, 4-in bump, stepping down dynamic step).

- Stepping down dynamic step: same wheel travel and same level of acceleration at the center of gravity.

- 4-in bump at 5, 10, 20 and 30 km/h: wheel travels are slightly different. Indeed, the impact implies a displacement of heavier wheel which itself implies a higher displacement of the suspension.

- 6-in trapezium at 35 and 45 km/h: pitching values and wheel travels are higher for the VBL with increased unsprung mass which implies less comfort for the driver.

- Small potholes and wrinkled tracks trials studying are still in progress.

Increase of unsprung mass has no consequences on vehicle behavior on road (braking and acceleration excepted) but on dynamic obstacles clearing and off road vehicle comfort. The energy to disperse in suspension is higher during obstacles clearing which implies more vehicle pitching and more wheel travel.

The last part of the study concerns the quantification of the additional energy to disperse in suspension when using a 60 kg heavier unsprung mass during dynamic obstacles clearing and off road maneuvers.

Chapter 4 – LETHALITY AND SURVIVABILITY

4.1 OPERATIONAL AND TECHNICAL REQUIREMENTS

The introduction of all electric (or more electric) power trains in military vehicles will increase overall efficiency and performance when incorporated with electric pulse-powered weapons (electrothermal-chemical (ETC) gun, EM railgun, HPM, etc.).

For both prime electrical and pulsed power, the system improvements can be fundamentally determined by the operational characteristics of the electrical components which are common to each. Many component development technologies can have a dual purpose.

In this chapter some potential applications are reviewed and the required levels of pulsed electrical power, energy, durations and repetition rates are evaluated.

Electrical weapons open the way for viable improvements in performance, since in principle they exceed the technical limitations of classical weapons. They offer greater hit and kill probabilities because of a shorter flight time and a greater penetration (due to the higher initial velocity of the projectile from electric guns together with the use of novel projectiles).

Military applications will greatly benefit from these new possibilities. The challenge of target evolution – with improvements in armor, velocity, maneuverability, stealth, and short reaction time for defense systems – can be met.

Each military application – anti-tank, anti-air, etc. will require different values of performance to be reached for the system and its components, depending upon each particular target characteristics.

Studies of electric weapons must consider the sub-systems which constitute the complete integrated weapon system from detection to interception – sensors, pointing device, launching, projectile characteristics and interception are some of the parts to be studied.

A full system integration study must be undertaken for each application.

4.1.1 Electric Weapons

4.1.1.1 Electrothermal-Chemical (ETC) Guns

In ETC guns, a propellant charge is ignited by electrically generated plasma and the burning processes are improved by the interaction of plasma and propellant charge.

The energy in this concept is predominantly the chemical energy of the powder. The energy in the electrical arc is used to ignite the propellant charge (with high loading densities > 1 g/cm^3 possible) and to produce an improved pressure profile at the rear of the projectile. Furthermore, it is possible to use additives to improve the generation of propellant gases. A muzzle velocity up to 2100 m/s is possible for ETC accelerators.

For electro-thermal ignition (ETI), an electrical energy of about 0.1 MJ per shot will be necessary, supplied, for example, by a pulse forming network (PFN) consisting of a RLC circuit. In outline, a capacitor is discharged through the circuit containing the plasma generator (e.g. an exploding wire or a discharge channel). Such a circuit needs high-energy density discharge capacitors coupled with high performance

switching components. An alternative approach is to use normal air inductances (e.g. the X-RAM generator consisting of coils charged in series and discharged in parallel), or, in the future, superconducting coils.

The electrical characteristics of pulsed power systems supplying ETC and ETI guns are listed in Table 4.1.

Table 4.1: Example of Electrical Requirements for Electric Guns Applied to the Anti-Armor Mission for the Following Conditions: ETC Muzzle Kinetic Energy Ek > 14 MJ; Number of Shots/Burst equals 5; Charging Time is 6s.

	Electrical energy stored/shot MJ	Peak power/shot MW	Pulse duration ms	Energy per burst MJ	Average power per shot kW	Typical voltage kV	Current MA
EM railgun	20	4000	3 – 6	100	2800	5 – 10	2 – 4
ETC-ETI gun	0.1	60 – 200	1 – 5	1	50	10 – 20	0.1 – 0.3

4.1.1.2 Electromagnetic (EM) Railguns

Railguns use no chemical propellant at all, so must provide all the launch energy electrically. This makes them the most demanding of all electrical weapon systems, with up to 20 MJ in each launch projectile. Inefficiencies in the pulsed power chain raise this value in the prime power supply considerably. Multiple shots demand that several shots worth of energy are stored for immediate use, since it will not be possible to charge up the pulsed power supply at the same rate that energy can be extracted from it. Smaller calibre guns will need less energy per shot but at a greater rate, with the end power requirements probably being similar to larger calibre weapon systems. Table 4.1 gives some likely requirements for a large calibre weapon.

An energy storage requirement of over 100 MJ severely limits the options for supplying this on a mobile platform. Capacitor based systems are currently achieving around 3 – 4 MJ/t in large storage sized units, and forecasts for improvements in large scale energy density capacitors are very low. It is extremely unlikely that such a system will ever be realised for railguns in the near future. Flux generators can achieve the levels of energy density required, but have many problems in supplying multiple shots, and may re-introduce chemical propellants onto the platform. The large peak current demanded by railguns – of the order of several Meg-Amperes, rules out any system which needs an opening switch. Producing opening switches with a capacity of even tens of kilo Amps is a challenge today. Solid state improvements will help, but at the expense of mass and volume.

The most promising pulsed power system available today is the compulsator. This uses the well-known ability of rotating flywheels to store large amounts of energy compactly, coupled with an internal coil arrangement and power electronics to produce the required pulse shape. Iron cored types have been available for many years, but the highest energy densities result from the use of composite construction air-cored types. The early versions of these have achieved around 1 MJ/T – energy density related to energy delivered to the gun per shot. A value of 10 MJ/T is required to be considered for a mobile system.

4.1.1.3 Electromagnetic Coilguns

Coilguns, or linear induction launchers, were the first type of electric gun to be studied over 150 years ago. As the name suggests, a coilgun is composed of a linear series of coils, which, when energised, produce an accelerating force along their length. There are two main types of coilguns. One uses a fixed frequency power supply, with the coil pitch changing to produce ever-increasing velocities. The other uses a fixed design of

coil but needs a rising frequency electrical supply to produce increased velocities along the launcher length. Such a power supply is extremely difficult to produce, so the latter type of machine has rarely been considered.

The simplest form of coilgun uses an alternating current power supply of fixed frequency, usually hundreds of Hertz. The coils are designed to produce incremental increases in velocity, and the whole machine is powered at once. This obviously makes it very inefficient, with efficiencies of only a few per cent. However, it is electrically very simple to produce and operate, needing only one switch for the whole machine. Nowadays it is usual to power such machines using a series of capacitors, switched to power individual coils or groups of coils at any one time. This increases the efficiency at the expense of electrical complexity.

Coilguns have a number of advantages over railguns. They can be non-contact systems, needing no sliding armature to pass large currents. They are also usually self-centering, further reducing in-bore forces. They have been shown to accelerate projectiles to several hundreds of metres per second on many occasions by many researchers worldwide. There are a few reported cases where a velocity of 1000 ms^{-1} or more has been achieved under special conditions. However, they have failed to demonstrate any success at high velocities.

There are a number of reasons for this. As the velocity along the launcher rises, so does the voltage, which has to be applied to the coils in order to produce the required force in the requisite time frame. This can lead to voltages of 50 kV or more being required. Such voltages do not lend themselves to practical weapon systems because of insulation and safety problems. A more significant factor is the magnitude of the radial compressive force induced in the projectile. In common with all electric guns, force is produced wherever current flows, and is not restricted to the launcher structure alone. The induced forces can easily deform solid projectiles at moderate velocities, long before even 1000 ms^{-1} is reached. The coils also experience large bursting forces, and need to be very firmly constrained. Large temperature rises also accompany the force, both in the projectile armature and in the coils, due to the induced currents in the former and the applied currents in the latter.

For these reasons, most researchers have tried coilguns and then moved on to railguns as the preferred method of achieving high velocities. Since that is where the greatest military need is, it is a logical step. However, coilguns are quite a practical method of launching projectiles at low velocities sub-sonically, and could be used to launch mortars or decoys, replacing chemical propellants. Variants are also under development for future aircraft launch systems such as the US EMALS.

4.1.1.4   Laser Weapons

4.1.1.4.1   Low Energy Laser Weapons

Recent developments concerning low energy lasers for defense applications are strongly related both to dielectric solid state lasers as well as to semiconductor lasers. Adapted to specific applications, different architectures have been designed and continue to be improved. High power diode lasers and diode laser arrays (from single diode to multi-stack-bars) provide either:

- Directly usable efficient laser sources for lower beam-quality applications, currently up to powers in the kW-range,

or

- Novel pumping sources for dielectric rod, slab or fibre lasers (providing both lower thermal losses and higher efficiencies than flash-lamp pumped systems) for high brightness and high beam-quality requirements.

Special interest is afforded to tunable lasers in various spectral ranges. Conversion and tunability is provided by non-linear optics, such as by harmonic generation towards shorter wavelengths or by optic parametric oscillators (OPOs) which allow frequency conversion from the visible or near infrared towards the longer wavelength mid-infrared band II (3 – 5 µm) or band III (8 – 12 µm). For future needs, ultra-short (ps to fs) laser pulses will have to be taken into account as well.

Important military low energy laser applications presently refer to optronic countermeasures as well as to counter-countermeasures. Some further important fields are put together in the following list which is not comprehensive and could be extended:

- Communication;

- Battle field illumination, active imaging;

- Range finding, reconnaissance, obstacle warning;

- Pointing, tracking, beam riding, guidance;

- Jamming, dazzling, damaging of sensors.

In all cases, low energy lasers in electronic warfare provide interesting solutions, especially in case of "in-band" and "in the field of view" situations.

For single pulse systems, electrical energy requirements are low, typically in the range below several tens to hundreds of Joules. In the case of high repetition rate devices (> 10 kHz), average power levels do not usually exceed several tens of kW.

4.1.1.4.2   *Medium Energy Laser Weapons*

Similar to the low energy case, medium energy lasers are normally conceived as anti-sensor or anti-optronic weapon systems. The larger specific energy and/or power densities allow medium energy weapons to be useful for tactical applications, typically to a range of several km (mostly, however, below several tens of km). They have proved to be versatile tools, especially covering the (most important) so-called "out of band" applications in optronics.

Degradation or damage of operational characteristics is thereby achieved by remote transfer of radiation (directed energy), inducing thermal or thermo-mechanical surface or volume effects on any type of windows, optical lenses, protective filters at the entrance of sensors or imaging systems (including canopies). These mechanisms are highly efficient, even if the incident radiation is "out of the field of view". It would be advantageous that these extrinsic processes are largely unaffected by spectral constraints of the internal optically active devices (sensors and adapted electronic circuits behind). Due to the high "out of band" absorptivities of most dielectrics and semi-conductors, medium energy laser damage mechanisms are not critically dependent on spectral sensitivities. Particular interest is therefore related to the vulnerability of external components in a broad spectral band, covering the UV, visible and IR bands up to the high frequency range (including radar or other microwave devices), for example combined in multi-spectral sensor heads.

The medium laser energy requirements depend on:

- Operational scenarios,

- Target characteristics (the vulnerability of optronic components, as used in armed vehicles, tanks, aircrafts, helicopters, unmanned air vehicles, missiles, etc.),

- As well as on environmental specifications.

Pumping energies are required, up to the range of several tens to hundreds of kJ, depending on laser efficiencies, on transmission losses and upon energy coupling conditions during the target exposure.

Power supplies for electrically excited medium energy lasers are feasible. Mature systems have been developed and continue to be improved. The main advantage is that electric discharge pumping allows temporal exposure conditions to be varied and adapted to specific military requirements more easily than by any other pumping scheme. As experimentally confirmed, periodically pulsed radiation proves to be more efficient than continuous wave (cw) or quasi-cw radiation of same overall energy, both with respect to propagation through the atmosphere and subsequent energy transfer to targets (yielding ablation and degradation by thermal and thermo-mechanical processes). Some features and details are listed in Table 4.2.

Table 4.2: Electrical Pulse Power Requirements of Lasers Being Considered as Possible Candidates for Medium Energy Laser Weapon Applications

Type of Laser	Excitation Schemes	Typical Efficiencies	Typical Voltage Requirements	Typical Current Requirements

Gas Lasers:
   cw, quasi-cw
   single pulsed (ms,µs, ns)
   repetitively pulsed (µs)
	electr. discharges preionized, or non-selfsustained	up to 20%	tens of kV tens to hundreds of kV	< 10 A
				$I_{pre\text{-}ionization} < 1$ A
				$I_{sustainer} < 10$ A

Solid State Lasers:
   quasi-cw, long pulse (ms)
   rods, slabs, fibers
	flash lamp pumped diode pumped	> 5%
		< 10%
			~ several kV
			< several tens of V
				> kA
				< 100 A

High Power Diode Lasers:
   single diodes
   diode arrays, bars
		> 40%	< tens of V	< 10 A
				< 100 A

4.1.1.4.3   High Energy Laser Weapons

High energy laser weapons would be used in strategic scenarios, as well as for tactical defence against missiles, satellites, aircraft, and for many other military applications in the army and navy which require extremely high precision target irradiation across very large distances. Particular interest is in ballistic theatre scenarios, such as in the case of tactical ballistic missile (TBM) programs presently under discussion.

Optical laser energies for remote damaging of structures under particular far-field conditions are estimated to be of the order of several MJ and above. For quasi-cw exposure (with typical irradiation durations of several seconds), the corresponding optical power levels are in the multi-MW range. Electrically stored primary energy, comprising highly flexible pulse forming networks, including capacitive or inductive storage and commutation, fast switching or modulation are beyond the current state of the art. The realization of realistic concepts of reasonably sized (volume, weight) electrically pumped real high energy laser demonstrators is therefore not to be expected in short term.

Pumping energy requirements under these circumstances are well met by chemical means. This has been shown in the past, for example in US by the Alpha and Nautilus Lasers with HF or DF and is presently demonstrated by the realization and integration of the air-born Chemical Oxygen Iodine Laser (COIL). It should be pointed out, however, that high energy chemically pumped lasers so far are only operational as quasi-cw devices. Consequently, non-linear processes, as in the case of periodically pulsed radiation effects, with the peak power orders of magnitude greater than the average power level, cannot be favourably used so far.

Further candidates, such as Free Electron Lasers, still provide the most interesting scientific characteristics, both spectrally and temporally (lower frequency pulse burst mode, even with ps-pulsed micro-structures), but have not yet proved to be mature enough to provide an alternative short term solution for military high energy laser weapons.

4.1.1.5   High Power Microwave Weapons

4.1.1.5.1   Introduction

A high power microwave (HPM) weapon is a directed energy weapon (DEW). Directed energy weapons emit a high power electromagnetic (EM) wave to the target. In the case of an HPM weapon, this is a microwave in the range of 1 to 300 GHz. This is in the radio frequency (RF) band, therefore a HPM weapon is sometimes called a radio frequency weapon (RFW).

HPM waves cause electromagnetic induced overvoltages or overcurrents in target systems. The effects of these can be temporary malfunction (sensor blinding, shut down) or permanent damage (blowout, overheating). If the radiated energy couples into a receiving aperture of the target, the term 'front door' coupling is used. If there is no receiving aperture and the energy couples through whole body effects, cracks or interfaces, the term 'back door' coupling is used. Once the energy enters the major system, it must still couple into the subsystem and circuit board to eventually get to the vulnerable components.

To achieve permanent damage, a minimum field strength of about 10 kV/m is required. As the intensity of the electromagnetic field decreases with R^{-1}, (R is the distance between the weapon and the target), the requirement for the HPM weapon is hard to achieve. This "distance problem" can be solved by using an HPM missile, thus bringing the weapon close to the target (Figure 4.1).
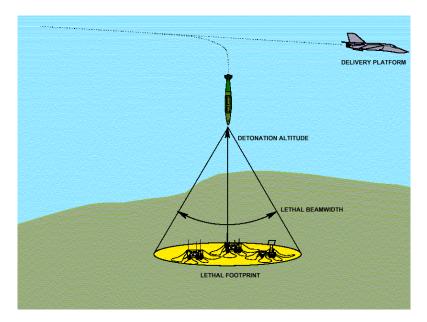
Figure 4.1: Delivery of a HPM Missile Close to the Target.

A target can also be temporarily eliminated by disrupting computerized systems. In this case a field strength of only 100 V/m may be sufficient to change, for example, bios data, to write wrong data to a disk or create a

malfunction of the operating system. The HPM pulse must be applied during the time that the computer processes are active. As there is no correlation between the time of the HPM pulse and the time in which the device is active, multiple pulses must be applied in order to be sure that the operation of the device is disrupted. HPM experiments confirm that the application of multiple HPM pulses is much more effective than the application of single pulses.

The power requirement for an HPM weapon is a strong argument for the introduction of hybrid vehicles, as traction and weapon power can be shared. On the other hand, the application of HPM weapons is a threat to the electronics applied in these vehicles. Therefore components and systems must be made less vulnerable by 'hardening', that is, making a system or component less sensitive to EMI by adequate (sub)component design, circuit-layout improvement or EM shielding/protection (e.g. a protecting box).

An HPM weapon emits a cone-shaped beam that strikes a very large target area. The advantage of a broad beam is the absence of the need to precisely aim at the target. A disadvantage is that every system within the wide beam area is affected (risk of fratricide) and the possibility of suicidal effects.

The majority of useful HPM missions appear to be below 10 GHz, because then the attenuation due to atmospheric absorption is negligible (range < 10 km). Above 10 GHz, air attenuation can be appreciable (but there is a propagation window at 35 GHz). Atmospheric effects due to dust particles, aerosols, etc. are negligible. Air breakdown will happen if the local power density in the air reaches a certain limit (in general about 1 MW/cm^2). This air breakdown limit is far above current HPM needs.

There are two types of HPM sources: the narrow-band microwave source and the ultrawide-band (UWB) source. The UWB source can be used as a weapon (nuclear EMP is a UWB radiation), but the main application is radar. UWB means that the waveform has an instantaneous fractional bandwidth greater than 25% (or 20%) of mean frequency. For comparison, conventional (narrowband) radio/radar have fractional bandwidths of less than 1% of mean frequency. UWB signals are short duration impulse signals or non-sinusoidal waveforms, i.e. square, triangular, chirped, etc.

Some examples of promising narrow-band HPM sources are:

- **Relativistic Klystron:** The klystron of TITAN Corp. is called Super-Reltron and is claimed to be the first candidate for directed energy, HPM or power beaming. Some data are: 3 GHz, output 400 MW peak, 80 J/pulse, t_{pulse} = 400 ns, η = 40%. A Reltron is similar to a klystron, but no separate (heavy) magnets are needed. At 600 MW: U = 1.1 MV, I = 1.4 kA, Z = 800 Ω, Pin = 1.5 GW, duty cycle = 10^{-5}. With PRF < 100 Hz, a Marx generator is the best PFN choice. For higher PRF a magnetic modulator is also an option. Figure 4.2 shows a Super_Reltron of 9 GHz.

- **Relativistic Magnetron:** At 600 MW: η = 10 – 20 %, U = 0.55 MV, I = 11 kA, Z = 50 Ω, Pin = 6 GW.

- **Multiwave Cerenkov Generator (MWCG):** relativistic diffraction generator (RDG): 15 GW, 500 J, 9.4 GHz and 2.8 GW, 520 J, 46 GHz. (High magnetic field coil needed).

Figure 4.2: 9 GHz Super Reltron.

4.1.1.5.2   Operational Considerations

HPM systems offer improved capabilities in countering artillery fire, ship defence against cruise missiles, aircraft self-protection, suppression of enemy integrated air defence systems and destruction of command and control assets. All of these requirements potentially can be addressed by HPM weapon systems that upset or damage the electronics within the target. HPM systems offer military commanders the options of:

- Speed-of-light, all weather attack of enemy electronic systems;

- Area coverage of multiple targets with minimal prior information on threats characteristics;

- Surgical strike (damage, disrupt, degrade) at selected levels of combat;

- Minimum collateral damage in politically sensitive environments;

- Simplified pointing and tracking;

- Deep magazines (meaning long operating time without replenishment) and low operating costs.

Short-range and long-range applications require different power levels. An example of a classification is given in Table 4.3 below.

Table 4.3: Classification of HPM Weapons

	Case 0 Very Short Range Mobile	Case 1 Short Range Mobile	Case 2 Intermediate Range Transportable	Case 3 Long Range Fixed
Range [km]	0.1	< 1	1 – 10	100+
Pulse energy [J]	10 – 100	$10^2 – 10^3$	$10^2 – 10^4$	$10^4 – 10^6$
Average power [kW]	1	10	$10^3 – 10^4$	10000
Peak power [MW]	100	1000	10^4	10^5
Pulse repetition frequency [1/s]		$10^4 – 10^5$	$10^2 – 10^4$	pulse < 1 µs
Target energy [J/cm2] (range)		10 (200 m); 0.1 (2 km)	1000 (1 km); 10 (10 km)	1000 (10 km); 10 (100 km)

4.1.2   Common Technical Requirements for EPPS (Electrical Pulsed Power Supplies)

The above listed military applications will require technical characteristics of electrical components, systems and architectures in order to allow integration into a land vehicle. Moreover, there are electromagnetic compatibility considerations and safety aspects due to the high voltages and currents which are involved. In addition, advances in specific measurement technologies may be required, depending on the availability of diagnostics for the critical physical parameters of the EPPS to be developed.

Tables 4.4 and 4.5 summarize the State-of-the-Art (SoA) and the expected far term characteristics of some fundamental components of pulse-forming networks and pulsed power systems supplying electrical weapons. The need to improve some fundamental characteristics must be emphasized; mainly the energy and power densities of storage components and switching capabilities in terms of current variation, current density, action integral, blocking voltage, repetition rate and opening function.

Table 4.4: Characteristics of Some Energy/Power Storage Components

Storage Component	Function	Energy/Power Density SoA MJ/m^3 MJ/t MW/m^3 MW/t	Energy/Power Density Far term (2010) MJ/m^3 MJ/t MW/m^3 MW/t	Remarks
Magneto Dynamic Storage (MDS)	Intermediate energy storage	160 80 5 2.5	600 300 10 – 20 5 – 10	
Homopolar generator	Energy storage	100 30 5000 1300	150 50	low voltage (100 – 200 V) opening switch inductance
Pulsed disc alternators Compulsators	Energy and power storage	90 30 750 250	300 100 3000 1000	- deliver several GW for a few ms - deliver several successive shots
Fast discharge Capacitors (alone)	Power storage	$1 – 3$ $0.5 – 1.5$ $10^6 – 10^4$ $10^6 – 10^4$	$10 – 20$ $5 – 10$ $10^7 – 10^5$ $10^7 – 10^5$	new dielectric materials need to be developed
Coils (normal T)	Power storage and pulse forming	5 2	10 4	
Superconducting coils	Power storage	60 30 15000 7000	200 100 90000 50000	Need of high T superconducting materials
Super capacitors	Intermediate Storage	40	> 40	Pulse durations 1 ms to s
Batteries (e.g. Na/Ni Cl$_2$)	Intermediate storage	400 100 0.1 0.25		Long discharge times Low voltages
Batteries-Capacitors	Intermediate energy storage	600 300 4000 2000		Discharge times 0.2 s
MHD generators Flux compression	Pulse generators			Usually single shot devices No multi-shot capability

Table 4.5: SoA Characteristics of Some Switching Components

Switching Component	Function	Characteristics
Vacuum discharge	closing (opening)	1 kV – 100 kV 500 kA $> 10^{11}$ A/s
Si thyristors	closing (opening)	< 11 kV 150 kA $2 \cdot 10^{10}$ A/s
Si diodes	closing	< 12 kV > 100 kA $> 10^{10}$ A/s
GTOs	closing opening	6 kV switch-off current < 6 kA
Pseudo-sparks	closing (opening)	< 100 kV < 500 kA $5 \cdot 10^{11}$ A/s
Spark gaps	closing	200 kV 400 kA 10^{12} A/s

In the future semiconductor switches based on silicon carbide (SiC) technology may represent a new generation of switches, characterized by a higher working temperature (600 °C), repetition rate capability and blocking voltages about 10 times greater than those achieved with Si components. Research programs on hybrid mechanical/semiconductor opening switches and 1 MA semiconductor opening switches using IGBTs and diamond based systems are underway.

The electrical and thermal conductivities are greatly increased over silicon devices. Therefore SiC should enable more powerful switches with lower volumes and masses. The largest obstacle to the realisation of SiC power devices at present is the low quality of the wafer material. The density of defects (micropipes) is currently 5 cm^{-2}. Consequently the yield of large wafers free from defects is very low, making the wafers very expensive. Currently, SiC power devices are not larger than a few mm^2.

The first SiC devices have already been commercially produced, e.g. INFINEON are Schottky barrier diodes (SBD). These diodes have blocking voltages up to 600 V and rated currents up to 10 A. Prototype SBDs were demonstrated up to blocking voltages of 4.5 kV. They can easily be paralleled to achieve higher total current. A set-up consisting of three devices has been produced and shows a total current of 75 A. SBDs are extremely well suited when ultra fast switching is required, since their nearly-ideal switching behaviour leads to negligible diode losses.

Bipolar diodes have been realised in the laboratory with blocking voltages up to 4.9 kV and a forward voltage drop of 4 V at a current density of 1000 A/cm^2. A world record of 19 kV for blocking voltage was achieved

with a special pin diode. Compared to silicon diodes, SiC types show much lower transient losses, especially for reverse recovery. In terms of thyristor devices, a 500 V SiC-GTO operating at 400 °C has been produced.

SiC unipolar devices like MOSFETs and JFETs have shown better performance than silicon switches. SiC MOSFETs have been made with a specific on-resistance (R_{on}*A) that is more than a factor of 25 lower than is possible with a standard silicon MOSFET.

JFETs (junction field effect transistors) are the most promising SiC devices that have been developed, with a blocking voltage of 3.3 kV in the same package as that of a 600 V silicon device. In Table 4.6 the current records for the blocking voltage of different SiC switches are listed.

Table 4.6: Listing of Most Powerful SiC Devices Concerning the Blocking Voltage (V_b).

Type of Device	SBD	Bipolar Diode	MOSFET	JFET	IGBT	Bipolar Transistor	Thyristor
V_b [kV]	4,5	19	3,36	6,1	0,38	2,2	3,1

In conclusion, SiC power devices allow a significant reduction of switching losses, and conduction losses can be reduced compared to silicon devices. They can operate at higher temperatures since their physical limits are well beyond today's capabilities. SiC power devices may open a field of new ideas in power electronics system design which up to now were impossible because of the lack of suitable devices (see also section 6.3).

4.2   ARMAMENT SYSTEM ISSUES
Architecture of EPPS

4.2.1   Application to Electric Guns: ETC/EM

Some examples of the architectures of EPPS, which can be envisaged to supply electric guns, are shown in Figure 4.3.

a)

| Turbine, alternator, rectifiers | Batteries or rotating machine | Converter, transformer | Capacitors | Closing switches | Gun |

b)

| Turbine, alternator, rectifiers | Batteries or rotating machines | Converter, transformer | Superconducting coil | Opening switches | Gun |

c)

| Turbine, alternator, rectifiers | Homopolar generator | Closing switches | Storage inductor | Opening switches | Gun |

d)

| Turbine | Pulsed power alternator | Rectifier | Gun |

e)

Figure 4.3: Examples of EPPS Architectures for Electric Guns.

In the architectures a), b) and c) of Figure 4.3. The gun supply is divided into two sections:

- A high-energy storage section containing the energy for several shots;

- A high-power storage section containing the energy for one shot delivered with a power reaching up to 20 GW. The type of switch to be used depends upon the EPPS architecture – opening, closing or both. Typically, closing switches are easier to integrate into the EPPS design than opening switches. The interruption of currents ranging between several tens of kA up to several MA is obtained by using mechanical switches or explosively actuated systems to separate the electrodes. Research has been undertaken to use semiconductors or superconductors (SC) as opening switches.

The architecture shown in Figure 4.3e) avoids the use of switching components because compulsators deliver a burst of high-power pulses. Difficulties arising from the use of such systems are due to mechanical limits – strains and stresses generated by the fast rotating velocity and rapid deceleration lead to breaking of machine components. Improvements can be obtained by using materials with better dynamic properties.

The architecture shown in Figure 4.3b) uses, for the power section, superconducting coils which can be DES or breech fed connected to a launcher. An example is shown in Figure 4.4.
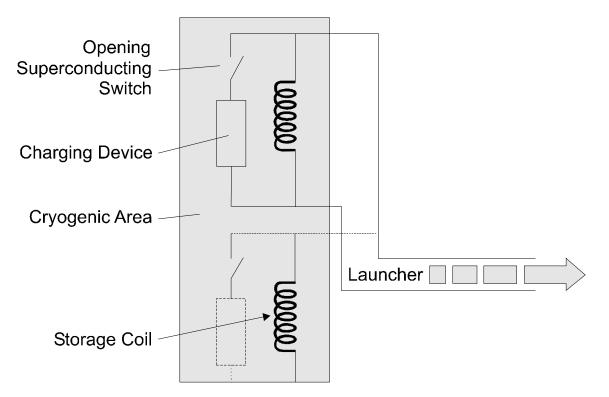
Figure 4.4: Modular Superconducting Inductive Pulse Power Supply.

The main difficulties encountered by using superconducting materials are due to the frequencies involved (≈ 1 kHz) and to the high currents/magnetic fields needed to supply a launcher. Moreover, the system energy densities have to reach >5 MJ/m^3 in order to allow integration into a vehicle.

A Superconducting Inductive Pulsed Power Supply (SCS) has the task of time-compressing the pulses, i.e. being charged at a moderate power level and being discharged in a short time with high power. An inductive device stores the energy in the magnetic field of a coil. The energy density achievable in an inductive energy storage device is higher than that in capacitors. For this, however, it requires the application of superconductors, which conduct the current flow free of resistive losses. For this cryogenic cooling is necessary.

Discharging an inductive storage requires an opening switch. The phenomenon "super-conductivity" can also be used to produce an opening switch. A superconducting material can "jump" from its superconducting state (resistivity zero) to the normal conducting state (resistivity non-zero), e.g. by warming up, so interrupting very high currents. Several laboratory units of a superconducting inductive pulsed power supply have been built. Two examples are described below.

- The first is a laboratory test set-up with a rated energy capacity of 0.5 MJ. It uses the "classical" superconductor NbTi (Niobium-Titanium), which is a so-called "low-temperature" superconductor. It requires cooling with liquid helium at T= 4.2 K. This set-up also contains superconducting NbTi opening switches. This is one of the test set-ups with which the technical concepts and the features of the components themselves as well as of the system of a SC pulse power supply were investigated. The complete set-up including the switch has a volume in the cryostat of about 600mm diameter and 600 mm height.

- The second is an example of a new so-called "high-temperature" superconductor. It is a stack of 24 pancake coils. Its main advantage is the fact that it can be operated at higher temperatures. It was tested at 27 K – the temperature of liquid neon. From the point of view of applicability, for instance in vehicles, this raised temperature is very interesting (even though the performance of the storage coil is presently less). The cryogenic effort for liquefying neon is more than one order of magnitude less than that for liquefying helium. A further benefit is the fact that liquid neon cooling in a military vehicle can be handled in a closed cycle system, whereas liquid helium would require an open system with refilling. To verify this, tests using a compact neon cryostat have been started.

Beyond that, different manufacturing technologies for superconducting switch topologies have been examined as well as the use of semiconductor instead of superconducting switches. A complete system of MDS with SCS has been built and tested, thereby investigating the principal behavior of the system and especially the effective charging of the SCS by the MDS.

4.2.1.1   Applications to Laser Weapons

Various laser systems are discussed and evaluated. Different concept studies have been pursued, which have led to different, even controversial conclusions in Europe or elsewhere. In some countries, chemical pumping concepts (particularly COIL) have found most widespread acceptance, not only for high-energy lasers, but also for the medium energy class of lasers. Preference for the medium energy range in other countries, in contrast was given to gas lasers or solid state lasers which both require "Electric Pulsed Power Systems" (EPPS) for efficient pumping and optical power extraction.

Table 4.7 summarizes some fundamental concepts using electrically stored primary energy, in a few cases also for chemical pumping schemes. The assumed optical energies (column 3) correspond either to published experimental results or to values, estimated by extrapolating experimental data up to a factor of ten. For simplicity, in all cases an irradiated area of 100 cm^2 has been taken into consideration in order to obtain a comparable evaluation of required fluences and fluxes to be handled during target interaction processes. Some further figures of merit, including typical efficiencies are summarized for the different lasers. In the case of electrical excitation, reference is made to EPPS requirements which are necessary to meet the indicated specific pumping conditions. The resulting complexity clearly shows the difficulties encountered in the past, to precisely define and suggest one single solution for a widely accepted operational medium energy laser demonstrator concept. This difficulty still exists today, as far as the definition of corresponding electric pulsed power systems requirements is concerned.

Table 4.7: Medium and High Energy Laser Candidates Data Comparison

Laser Wavelength El. Efficiencies Excitation	Temporal Mode of Operation	Assumed Optical Energy	Peak (Average) Power	Fluence (Across $100 cm^2$)	Power Density	Epps Requirements
Nd-Laser 1.06 μm $\eta_{electric} < 5\%$ electrical (flashlamp pumped diode pumped)	quasi-cw (range of s) ms-long pulses μs-range pulses (sub-) ns-pulses	10 kJ " " 0.1 kJ	10 kW 10 MW 10^4 MW 10^5 MW	< 100 J/cm^2 " " < 1 J/cm^2	10^2 W/cm^2 10^2 kW/cm^2 10^2 MW/cm^2 10^3 MW/cm^2	200 kW " " 2 kW
CO_2 10.6 μm $\eta_{electric} < 20\%$ electrical (cw, and pulsed) chemically pumped	quasi-cw (range of s) ms-long pulses μs-range pulses (sub-) ns-pulses rep. pulsed, 100 pulses 100 Hz, τ=10μ quasi-cw	500 kJ " 50 kJ – 5 kJ/pulse tot. 500 kJ > MJ	500 kW 500 MW $5\ 10^4$ MW – 500 MW (500 kW) > MW	< 5 kJ/cm^2 " < 0.5 kJ/cm^2 – < 50 J/cm^2 tot. 5 kJ/cm^2 > 10^4 J/cm^2	5 kW/cm^2 5 MW/cm^2 500 MW/cm^2 5 MW/cm^2 (5 kW/cm^2) > 10^4 W/cm^2	2.5 MW " 250 kW 2.5 MW
HF/DF 2.7/3.8 μm $\eta_{electric} < 2\%$ electrical (pulsed) chemically pumped	rep. pulsed, 100 pulses 100 Hz, τ$_p$=5 μs quasi-cw	100 J/pulse[1] tot. 10 kJ several MJ	20 MW (10 kW) several MW	1 J/cm^2 tot. 100 J/cm^2 > 10 kJ/cm^2	0.2 MW/cm^2 (100 W/cm^2) > 10 kW/cm^2	500 kW
COIL 1.3 μm chemically pumped	quasi-cw (few s)	hundreds of kJ	hundreds of kW	> kJ/cm^2	> kW/cm^2	

[1] Extrapolation by a factor of ten with respect to experimentally demonstrated values.

4.2.1.2   Applications to HPM

As an example, a pulsed power supply for case 2 of Table 4.3 will be described in more detail. The data for this example are listed in Table 4.8 and Figure 4.5 shows the corresponding pulse trains of the missions.

Table 4.8: Example of a HPM Mission

	HPM
P$_{out}$ *[GW]*	2
E$_{out}$/pulse *[J]*	200
t$_{pulse}$ *[μs]*	0.1
PRF [Hz]	1000
Efficiency	0.5
E$_{in}$/pulse *[J]*	400
P$_{in}$ [GW]	8
#pulses stored	1000
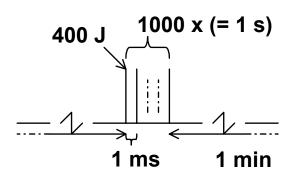
Figure 4.5: Pulse Train for the HPM Mission of Table 2.

Figure 4.6 shows a possible solution for the pulsed power supply. The HPM source is directly fed from a high voltage capacitor bank which stores the energy for one pulse. The capacitor bank is fed from a battery or flywheel which stores the energy for all the pulses of the 1 second burst. The battery or flywheel is charged from the vehicles high voltage DC network.
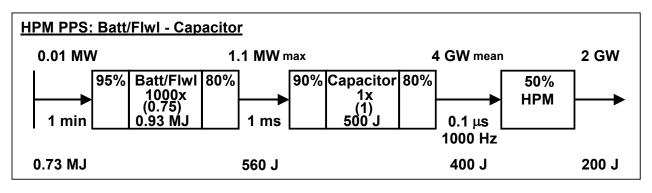
Figure 4.6: Energy and Power Levels of PPS with Battery or Flywheel IES and Capacitive PFN for HPM.

The charge and discharge efficiencies for the intermediate energy storage (battery or flywheel) of the PFN (pulse forming network) are given in the rectangles. The stored energy has to be multiplied by the number between the brackets because not all of the stored energy can be used. For instance, for flywheels the speed during discharge will drop to half; this means that only 75% of the stored energy can be used to charge the capacitors. This example shows that due to the pulsed power supply the power requirement for the vehicles network can be reduced form 4 GW to 10 kW.

A HPM source needs a very high voltage (200 kV up to 1.5 MV) to generate the required electron beam. The capacitor bank can be realised in the form of a Marx generator in which capacitors are charged in parallel and discharged in series. Figure 4.7 shows the flowchart of a Marx generator.
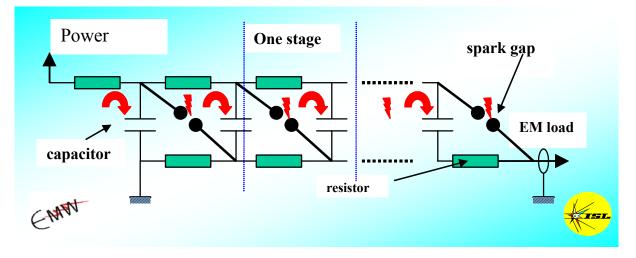
Figure 4.7: Marx Generator Flowchart. All the capacitors are electrically charged in parallel and discharged in series. The current flows through the EM load.

Typically a Marx generator has to meet the following requirements:
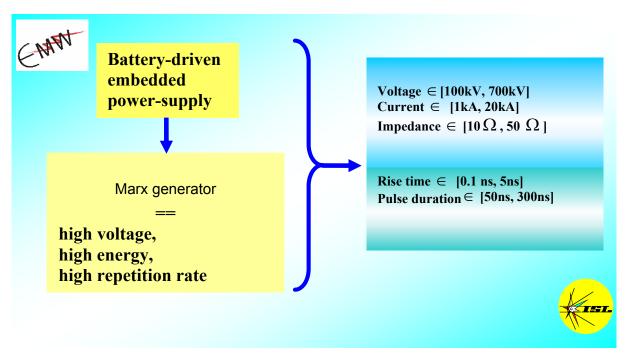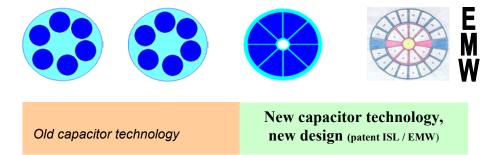
Figure 4.8: Electrical Requirements for the Marx Generator.

Table 4.9

Capacitor	Disk	Disk	Pie form 1	Pie form 2
700kV	Techno. 1	Techno. 2	Techno. 3	Techno. 3++
Voltage	40 kV	55 kV	65 kV	65 kV
Stage number	18	13	11	11
Capacitance	10 nF	7.5 nF	9.2 nF	28 nF
Energy/stage	8 J	11.3 J	19 J	59 J
Energy stored	144 J	147 J	213 J	650 J
Energy density	14.7 J/l	14.9 J/l	21.7 J/l	23.2 J/l

Old capacitor technology

New capacitor technology, new design (patent ISL / EMW)
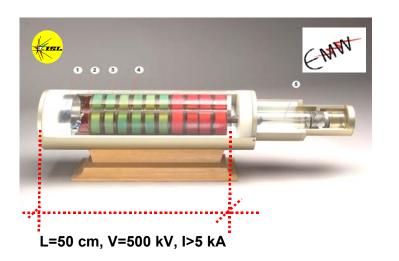
According to a new patent design of both the capacitors and the elementary stage we can reach the performances of Table 4.9. Depending on the capacitor technology, the Marx stored energy ranges from 144 J to 800 J. With this new technology, one can increase the stored energy without increasing dramatically the final volume of the generator. The results from Table 4.9 show that it is possible to build a rather compact Marx generator which can deliver 700 kV, 5 kA with a rise time less than 5 ns. Figures 4.9, 4.10, 4.11 and 4.12 show the state of the art of the studies performed by the ISL/EMW research team. With the technology presented here it is possible to build a 1.5 MV Marx generator.

Elementary 50 kV stage
150 mm x 30 mm

Embedded 50 kV high voltage power supply: DC-DC converter

Disk Techno. 2 (ref. Table 4.9)

Figure 4.9: View of One Elementary EMW Marx Stage.
Each stage includes the charging resistors and the two half-spark gap spheres.

*Disk Techno. 1
(ref. Table 4.9)*

L=50 cm, V=500 kV, I>5 kA

Figure 4.10: View of an EMW, Stand-Alone, 24 V Battery Driven Marx Demonstrator.

Figure 4.11: View of two different EMW Marx generators (disk techno. 2), the smaller can issue a 500 kV pulse (size: 680 x 220 mm) and the larger 750 kV (size: 880 x 220 mm). The Marx generator case is designed for RX flash radiography and to connect an HPM source easily. In this figure, an external high voltage power supply (50 kV max.) drives the Marx generator. The output voltage amplitude is controlled both through the number of internal stages and of course with the charging voltage amplitude.

*Disk Techno. 2 to
pie form 1
(ref Table 4.9)*

**Figure 4.12: Performances improvements through a new technology
associated to a new design: the stored energy increases, the capacitors
can be electrically stressed without damage (patent EMW/ISL).**

4.2.2   Aspects of Weights and Volumes; Integration of EPPS in a Weapon System

The aspects of volumes and weights are the most critical ones today for the high energy/power electric components and their association in pulse forming networks or/and in systems.

The ignition of powder by a plasma discharge needs low electrical energy (see Table 4.1) and, consequently, the integration of the EPPS can be envisaged in the foreseeable future (mass < 1 t, volume < 1 m^3).

4.3   SURVIVABILITY

4.3.1   General

Apart from the weapon presented in the previous paragraph, the following further applications are relevant for land vehicles (Table 5.1).

**Table 4.10: Requirements for EPPS Applied to Functions in a Land Vehicle.
These and additional functions have been described in TR/LTSS/43.**

Application	Description of function	Energy/ pulse	Peak power/ pulse	Pulse duration	Repetition rate	Average charging power/burst	Burst: No. of pulses
Electro-magnetic active armor	Launching of protective elements (250 m/s to 800 m/s and 4 kg to 30 kg)	5 MJ	10 GW	1 ms (damped sine wave)	Setup time 30 s	170 kW	2 to 3 (average power/burst 170 kW)
Launching of a propeller UAV or drone	3 m to 6 m 60 m/s 300 kg	540 kJ	2.7 MW	0.2 s to 0.3 s			

4.4 ACTIVE ARMOUR

The major problem for electric weapon systems is the lack of high energy density and low volume storage/switching devices, although good progress has been made during the recent years. The energy and volume needed by electromagnetic protective systems is relatively small because the required energy is relatively low.

This fact is shown using the simple nomogram in Figure 4.13. While the velocity range is defined following the experiences of reactive armour interactions, the masses of the active interception elements can be up to 20 kg. So it is possible to accelerate heavy protection plates in the future, as well as any terminal ballistic interception device like splinter or blast wave charges.
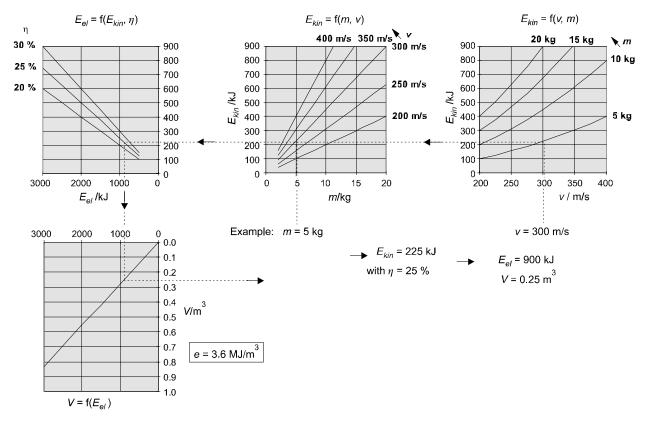
Figure 4.13: Nomogram for the Determination of Energy and Volume Needed by Electromagnetic Armour Launching Systems (capacitor energy density assumed: 3.6 MJ/m^3).

An interception element of 5 kg at a velocity of 300 m/s requires a kinetic energy of 225 kJ. For a mean efficiency of 25%, an electric energy of 900 kJ must be stored. Assuming a high-tech capacitor with an energy density of 3.6 MJ/m^3, a volume of 0.25 m^3 is required. This example is for an EPPS with capacitive energy storage, which provides a non-reversing current pulse with a crowbar diode configuration.

Three possible cases are given below for a power installation of 1000 kW inside a heavy weapon platform, with only 10% of this power available for the active protection equipment (to avoid a shutdown of the whole system). The charging time delays can be calculated from the kinetic energy and the stored electric energy and are shown in the following table:

Table 4.11: Parameters for Electric Armor Options

Mass	5	10	15	kg
Velocity	100	200	300	m/s
Kinetic energy	25	200	675	kJ
Electric energy	0.1	0.8	2.7	MJ
Charging time	1	8	27	s

This table intentionally presents a large energy range to cover as many applications as possible. In all cases the charging time delay is lower than half a minute. Additionally the enlargement of the restricted availability (10%) of generator power supply could further shorten the charging time.

The use of electric energy for the improvement of terminal ballistics protection provides several advantages. On one hand, this kind of energy can be turned-off and thereby high safety potential will be realized. On the other hand, a possibility of immediate electronic control exists for "intelligent" protective systems. Apart from high explosives, electric power is the only kind of energy which will act or react with sufficient speed considering future projectile velocities. For EM armors to be fielded in the near future, improvements in high energy density storage devices are required. However, the continual improvements in anti-armour weapon systems are forcing new adequate protective measures.

4.5 UAVs AS SURVIVABILITY AIDS

UAVs are already on the battlefield, and will no doubt continue to expand their range of uses. Their impact on electric vehicles will be similar to that on conventional vehicles. There is no universal modus operandi for a UAV, and they span a very wide range of sizes, weights and capabilities.

In general, size is related to potential range, so any vehicle mounted UAV is likely to be of small size – commonly known as a mini/micro-UAV. These have a useful range of only a few kilometres, there are VTOL options and fixed wing systems which could easily be launched using a mechanical catapult but recovery is much more difficult. They can overfly the local battlefield and transmit back information on local enemy movements. They have low power transmission capability, and may have limits on their operation in adverse weather. Work is ongoing to increase the efficiency of the on-board motive power systems, so as to extend the useful flight time and range. Such devices may be regarded as disposable one-shot devices. The smallest current experimental vehicles are typically 15 – 20 cm wingspan with larger variants available. Propulsion is by small i.c. or electrically powered from on-board batteries. The systems currently carry a small optical camera although other sensors such as acoustic, chemical and biological sensors have been proposed. Other experimental disposable systems have been suggested which are tube launched and could achieve longer ranges but there is little experience of these.

Larger UAVs with the ability to fly many tens of kilometres, with either optical seeking equipment or even some form of attack weapon, are too large to be launched by a combat vehicle designed to have a normal offensive capability. A dedicated vehicle or group of vehicles could be used, as could a land based launcher set-up. Their cost and complexity means that they are normally recovered and re-used. This effectively rules them out for front line attack vehicles. The US Pioneer system weighs up to 200 kg, with an altitude capability of 5000 m and endurance of 5.5 hours. However, it requires a dedicated group of vehicles and men, and is usually operated from behind the front lines, feeding information out to battlefield groups.

UAVs of any size have the potential to provide additional battlefield information to combat vehicles, though they are dependent upon good weather and visibility conditions. Their use with electric vehicles would be co-ordinated in the same way as with conventional vehicles. It is unlikely that they would increase the electrical load on the vehicle significantly, since they are relatively self-contained units and the main addition to the ground vehicle would be the communications link to receive data and permit control of the UAV and whatever additions to the operator system are needed to use the information.

4.6   SAFETY

Safety problems can arise from the presence and use of an EPPS. From the safety aspect, it should be recognized that high levels of voltage and current, electric and magnetic fields are inherent in the design of EPPS. It must be stressed that EPPS designers must protect the human body from contact or exposure to these factors, by shielding and bonding techniques. Maintenance personnel should be cognizant of these issues.

The factors to be taken into account are the following:

- Electric fields from 10^2 V/m to 10^6 V/m,

- Magnetic fields ranging from 0.1 T to 20 T,

- Magnetic field rates of 10^2 T/s to 10^7 T/s,

- Pulse duration between 10^{-6} s and 10^{-2} s,

- Currents of 10^5 A to several MA,

- High voltage 5 kV to 20 kV (DC and pulses).

With conscientious application of conventional techniques the associated hazards will be minimal. Nevertheless, a research program with the goal of studying the effects of pulsed electric and magnetic fields on personal health should be undertaken.

Chapter 5 – MODELING AND SIMULATION

5.1   INTRODUCTION

Potential benefits of hybrid electric drive for future combat platforms have been mainly identified in following points:

- Reduced fuel and logistics,
- Increased vehicle range,
- Improved modularity and architecture flexibility,
- Improved mobility (acceleration, off-road mobility through individual wheel-torque, skid steering, …),
- Reduced thermal and acoustic signatures,
- Reduced exhaust emissions,
- Improved reliability (redundancy, …).

The development of modeling and simulation in the field of electric drive is therefore a necessity to evaluate all the concepts and architectures and to compare improvements. Interests of modeling and simulation lie obviously in the following points:

- More alternatives in design process,
- Reduction of development time and risks.

The opportunity to build models to evaluate conventional as well as hybrid electric vehicle allows the study of various designs to compare advantages and disadvantages of each transmission particularly under the aspects of consumption, emissions and performance.

Combined with a components library provided by manufacturers or obtained from lab tests, modeling and simulation could become a reference to evaluate future concept with a great precision. That interest implies that component models should be available and shareable on a common platform like MATLAB®/ SIMULINK® for example.

This chapter contributes to the NATO task by gathering information about modeling and simulation tools used by each nation. Tools concerned are:

- VSP (Vehicle Simulation Program) from Belgium,
- ®™ from UK,
- PROSPER from France,
- TNO-ADVANCE from Netherlands.

These tools have been designed for different reasons and therefore provide different types of simulation.

5.2   VEHICLE MODELING

5.2.1   The VSP Simulation Programme

5.2.1.1   VSP Main Features

VSP, Vehicle Simulation Programme, is used in several European and national research programmes. In each project a special problem and drivetrain layout was studied resulting in a different system modeling. These models have to be uniform to result in one model that is applicable for all types of drivetrains and power algorithms. To be able to leave out, change or introduce components in the simulated drivetrain it was required to have a uniform definition of the different components.

The development of a standardized iteration process applicable on all kind of hybrid vehicles was harder than originally expected. While simulating on-road measured drive cycles different combinations of component operating limits in very exceptional cases occurred, which had lead the iteration process to an infinitive loop.

Due to the utilisation in different research project it was possible to debug the software and validate it based on real vehicle problems. Hence it was possible to develop a modular user-friendly interactive programme that allows simulating the behaviour of electric, hybrid and internal combustion vehicles. Nowadays VSP is a powerful tool to develop new concepts of different drivetrains. Existing vehicles can be compared or, due to the large library, components of the drivetrain can be substituted to improve the performance of the vehicle.

The flexible design of the software and the rather unique iteration algorithm allows the use of different simulation methodologies (cause-effect or semi-effect-cause) as well as of different database structures (mathematics formulae or statistical data based on measurements in equation form or look-up table) and of route profile types (standardised, measured or maximum allowed speeds).

The goal of the simulation programme is to study powerflows in drivetrains and corresponding component losses, as well as to compare different drivetrain topologies. This comparison can be realised at the level of consumption (fuel and electricity) and emissions (CO_2, HC, NO_x, CO, particles) as well as at the level of performances (acceleration, range, maximum slope). The general aim of the simulation programme is to know the energy consumption of a vehicle while driving a certain reference cycle. For thermal vehicle this energy consumption corresponds to fuel consumption and in the case of electric vehicles this is the energy drawn out of the battery. For hybrid electric vehicles fuel consumption as well as energy out of the battery is required. Based on models for battery charging, electricity production and fuel refinery, the primary energy consumption can be simulated.

To verify the models, input-output interfaces are developed as well as parameters tracers. During the simulation run the progress in vehicle status is displayed and can be controlled by the user. It is possible to compare measured values with simulated ones for exactly the same speed cycle. Hence it is possible to calibrate the models resulting in accuracy's within 5%. Most of the component models are based on experimental results and curve fitting, instead of mathematical models based on equivalent circuits. For this purpose a large amount of measurements was done with a self-developed "On road measurement system".

VSP can be used by a wide variety of users with different expertise like: engineers, transport operators and suppliers, energy utilities and decision-makers. It is mainly an engineering tool to evaluate different drivetrains, but due to the large database it can be used by all kind of people to compare different vehicles. Furthermore VSP has the possibility to be coupled to traffic simulation programmes allowing traffic planners to examine congestion and related emission problems.

The simulation programme is able to model any driveline structure without programme modifications. This degree of flexibility can be achieved only by formulating generally applicable program modules, which can be linked via defined interfaces. The interface, between the different components of this drivetrain, is very strictly structured. This allows the user to define and select the powertrain layout and the control strategy in an easy way. The modeling of the component itself is on the contrary very flexible to allow the use of different data sources.

It is not the scope of the simulation tool to simulate e.g. speed control algorithms (PID-controller, etc.). Also transient phenomena in the time domain of milliseconds are not relevant in this simulation tool.

In the following chapters user interface, programme language, calculation methodology and the main features are described.

5.2.1.2   Main User Interface

Figure 5.1 shows the main user interface of VSP. How to perform a simulation will be described below.
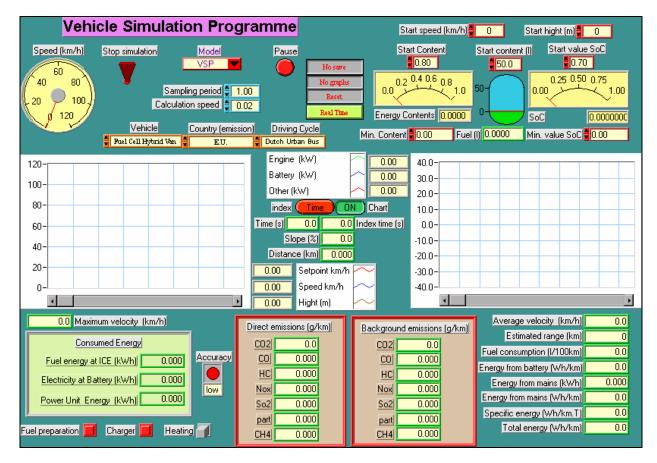

Figure 5.1: The Front Panel of the Vehicle Simulation Programme.

Before starting a simulation run the user has to select the desired vehicle, the imposed cycle it has to run and the country in which the background emissions, due to the production of electricity, have to be calculated.

The user can select if the speed cycle is defined in function of time or in function of distance. Furthermore the user can select the sampling period or better named the speed cycle time increment. The time increment is fixed during a run and should be chosen in relation with the chosen cycle. Indeed for range determination a time step of 10 s can be sufficient, whilst the ECE 15 cycle is best evaluated every second. The acceleration from zero to a constant speed requires a 0,1 s time increment if you want to determine the vehicle dynamics precisely.

The user has the possibility to select whether or not the results should be saved. If he is interested in the detailed values of the different parameters (speed, torque, power, current and voltage) in function of time of the different components, he has to enable the 'Graph' button.

During the simulation some error messages can occur when a component is not able to follow the imposed speed cycle. When in a next run this should not be displayed a second time the user should chose to disengage the 'Reset' button.

Some computers can be equipped with very fast processors; even so fast that the intermediate results changes to fast on the screen. The user can slow down the programme by selecting the 'Real time' button and the corresponding 'Calculation speed'. On the other hand when the user is only interested in the end results he can disengage the graphs, showing the speed and corresponding power levels on the main user interface.

Additionally some start and minimum values should be chosen before starting the simulation. These start value are the start value of the: fuel tank content, the battery state of charge, the State of Energy content of an optional additional power unit, vehicle velocity and level (height) of the road. The minimum values are these for the minimum state of charge and state of energy. Finally the user can select whether or not fuel preparation (refinery), battery charging and cabin heating should be taken into account and simulated.

Once this is selected one can start the simulation. At the left top of the panel a gauge indicator gives the momentary value of the actual speed.

At the right the state of charge of the battery is indicated as well as the contents of the fuel tank and the state of energy of an additional power unit.

A strip chart in the left middle displays the imposed speed and possible speed as well as the height of the road. The power level of the battery, engine and possibly of another unit is displayed in another strip chart besides. Between both graphs the interface shows the covered distance and actual slope.

Furthermore the actual time as well as the index used to define the next required speed out of the speed cycle is displayed.

The cluster at the left bottom corner contains the total energy consumption: the energy contents of the consumed fuel, the electricity out of the battery and out of another unit.

All indicators described up to now have their value changed once every sampling period. The following indicators have their value changed only after execution of a run, i.e. when, either the cycle is over, the battery is empty or the run is stopped with the toggle switch.

At the right bottom corner one can find the average velocity (km/h), fuel consumption (l/100 km), the energy from the battery (Wh/km) and the energy from the mains in kWh as well as in kWh/km. This is the total energy required at the mains to load the battery after the run to a state of charge (SoC) equal to its start value.

Dividing this energy by the average vehicle weight gives us a figure that is often used to characterise the performance of a drivetrain; it is called the specific energy (Wh/Tkm).

For hybrid electric vehicles the primary energy consumptions corresponding to electricity production (battery charging) and fuel refinery (fuel consumption) are added to have an idea of the total energy consumption (Wh/km). Based on the consumed fuel and/or battery energy and the corresponding covered distance the total possible range is estimated.

In the middle of the bottom the direct emissions (g/km) cluster gives the CO_2, CO, NO_x, CH_4, SO_2, hydrocarbon (HC) and particles emissions provoked by the vehicle at the place of operation. They are of course related to the use of ICE in a classic car or hydride vehicle. The heater of an EV can also emit direct emissions.

The background emissions (g/km) cluster gives the same kind of emissions provoked by the vehicle but not at the place of operation. They are related to the charging of the batteries from the mains and are depending of the composition of the electricity production park. Additional emissions can also be related to fuel refinery.

5.2.1.3   Program Language

The programme runs in a LabVIEW^{TM} environment. Different other programming languages could also be used like C++, MATLAB$^{®}$/SIMULINK$^{®}$, Delphi, etc. Traditional text based programming languages like FORTRAN, BASIC, C++, etc. are not flexible to use for a modular simulation programme. Modifications, other than changing parameter values, in this type of model will usually lead to a major reprogramming effort and reformatting of input files. Both LabVIEW^{TM} from National Instruments as MATLAB$^{®}$/SIMULINK$^{®}$ from Math Works have developed a graphical user interface (GUI) and corresponding programming language. Programme experience and cost were the decisive parameters to choose for LabVIEW^{TM}. Furthermore programming in C can be required when one wants to implement new functions in SIMULINK$^{®}$ [14].

This paragraph will describe the advantage and drawbacks of LabVIEW^{TM} used as a simulation tool. In the same time the specific LabVIEW^{TM} terminology will be explained. Hence the user could understand better the simulation models.

LabVIEW^{TM} is a general-purpose programming system, but it also includes libraries of functions and development tools designed specifically for data acquisition and instrument control. Most users do utilise it for measurement purposes. To programme the data-acquisition systems used to measure different components of the database LabVIEW^{TM} is also used.

LabVIEW^{TM} is a high-level programming tool, with the advantage of being a user-friendly interface with a high graphical performance. LabVIEW^{TM} is easy to learn and does not mandate special training. Within one week one can already develop simple programmes. LabVIEW^{TM} programmes are called **virtual instruments** (VIs) because their appearance and operation can imitate actual instruments. However, VIs are similar to the functions of conventional programmes. A VI consists of an interactive user interface, a data-flow diagramme that serves as the source code, and icon connections that set up the VI so that it can be called from higher level VIs.

More specifically, VIs are structured as follows [1]:

- The interactive user interface of a VI is called the **front panel**. The front panel can contain knobs, pushbuttons, graphs, and other controls and indicators. Using a mouse and keyboard one can enter data and then view the results on the computer screen.

- The VI receives instructions from a **block diagram** construct in LabVIEW[TM]. The block diagram is a pictorial solution to a programming problem. Such a diagram allows having a good overview of the structure of the programme. The block diagram is also the source code for the VI.

Contrary to text based languages like C or BASIC, LabVIEW[TM] uses a graphical programming language, like illustrated in Figure 5.2. This figure is a very simple example of a straightforward programme. Left one can see a traditional text based programme of a While loop in which several subprogrammes, simulating the components of an electrical drivetrain, are executed successively. The right part illustrates the same programme written in LabVIEW[TM]. When more complex structures should be written with several loops, one into another, and different parameters are used at different levels, the graphical programme will give a better overview of the programme structure than a text based programming language.


```
WHILE (iteration criteria) DO
    BEGIN
        Body;
        Wheels;
        Differential;
        Reductor;
        DC motor;
        Chopper;
        Battery;
    END;
```
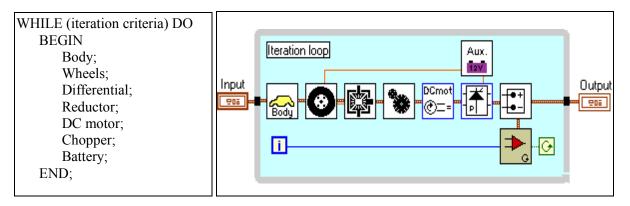
Figure 5.2: Example of 'While Loop' in Text Based Language and LabVIEW[TM] Graphical Language.

VIs are hierarchical and modular. They can be used as top-level program, or as subprograms within other programs or subprograms. A VI, when used within another VI, is called a subVI. The **icon** and connector of a VI work like a graphical parameter list so that other VIs can pass data to a subVI.

With these features, LabVIEW[TM] makes the best use of the concept of modular programming. An application is to be divided into a series of tasks, which can be divided again until a complicated application becomes a series of simple subtasks. A VI is build to accomplish each subtask and then these VIs are combined on another block diagram to accomplish the larger task. Finally, the top-level VI contains a collection of subVIs that represent application functions. In our case this top-level VI is the Vehicle Simulation Programme, **"VSP.vi"**, that contains as subVIs among other things the models of the different drivetrains and the different drive cycles.

Because each subVI can be executed by itself, separate from the rest of the application, debugging is much easier. Furthermore, many low-level subVIs often perform tasks common to several applications, so one can develop a specialised set of subVIs well-suited to future applications [1]. Graphical debugging tools enable the programmer to visualise the data flow and interpret problems. Simulation parameters can be changed while the program is running.

One of the big advantages of LabVIEW[TM], but also a specific difficulty is the fixed in- and outputs of each sub programme. Each component is modelled as a black box. It allows the construction of a very modular drivetrain. This means that every component can be replaced by another component of the component library.

E.g. in the same drivetrain a lead acid battery can be replaced by a nickel cadmium battery just by clicking with the mouse on it, without influencing the in- and output parameters.

The definition of these in- and output parameters is a very important issue of the development of the simulation tool, because once defined they should not change anymore. The use of global variable should be avoided to preserve the modularity of the programme.

Within each component of the drivetrain at the contrary the user has a large flexibility to implement the component's data. It is very difficult to find good component data. These data that could be found in literature are usually from different shapes and forms. A fixed predefined database does not allow an easy implementation of different data structures. This is why is chosen for a flexible database, integrated in the component model itself. A drawback of this approach is that there is no distinction between component model and component data.

Additional LabVIEW^{TM} terminology:

Frame: The sequence structure, which looks like a frame of a film, consists of one or more subdiagrams, or frames that execute sequentially. The sequence structure is used to control the order of execution.

Global: Global variables store data used by several VIs. Global variables have to be used judiciously because they hide the data flow of the diagram.

Cluster: A cluster is an ordered collection of one or more elements, similar to structures in C and other languages. Clusters can be used to group related data elements that appear in multiple places on the diagram, which reduces wire clutter and the number of connector terminals subVIs need.

5.2.1.4   Calculation Methodology

5.2.1.4.1   Different Approaches

In literature one can find different approaches to simulate the behaviour of a vehicle. One can try to describe the whole problem into *matrices*, where the solution is found using matrix linearisation and calculation. This is a very mathematical approach and requires rather simple models. The matrix approach can be interesting as an optimisation technique for a dedicated problem. However for every new problem (e.g. drivetrain topology) one needs to start almost from scratch again.

Another approach is based on the comparison of *frequency distribution* of operating point with efficiency curves. The calculation of the time independent frequency distribution for a given driving cycle requires that wheel speed and torque are known for the complete cycle. Since both quantities depend on different vehicle parameters, frequency distribution can only be applied to a specific vehicle. Integrating the product of frequency distribution and losses characteristics gives the average power losses. The energy losses result from the product of average power losses and cycle time. Figure 5.3 (left) illustrates an on-road measured driving pattern [2] (distribution of wheel torque in function of wheel velocity), which has to be correlated with the overall drivetrain efficiency, as illustrated in the example at the right side with the motor efficiency map (in the motor torque – speed plane).
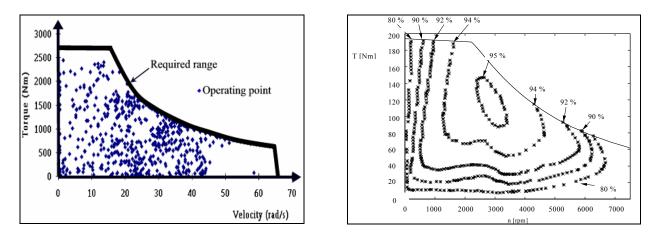
Figure 5.3: Frequency Distribution of Working Points.

Another approach is the *longitudinal dynamics simulation*, on which VSP is based.

5.2.1.4.2   *Longitudinal Dynamics Simulation*

The basic modeling strategy is the well tried and trusted method of dividing the drive cycle into a number of time steps and calculating the characteristics of the vehicle at the end of each time interval.

Longitudinal dynamics simulation serves to calculate the time characteristics of several quantities in a vehicle. Therefore it is a good tool to detect the weak points in the drivetrain and moreover to assess further improvements of single drive components [3]. The simulator approximates the behaviour of a vehicle as a series of discrete steps during each of which the components are assumed to be in steady state. The smaller this step, called time increment, the higher the accuracy. At each step the transient effects of changing current, voltage, torque, etc., are neglected. This allows the use of efficiency or other look-up tables, which are generated by testing a drivetrain component at fixed working points.

In handling the modeling process it is important that the direct energy flow can have a forward as well as reverse direction, corresponding with driving or braking the vehicle. The energy flow direction will be called "physical direction". The calculation direction of this energy flow can be different from this physical direction. Two main groups can be distinguished the forward calculation (cause-effect) and the reverse (effect-cause) method [4].

The first one starts at the setpoint set by a driver (acceleration pedal) or controller. With this setpoint one can calculate the force acting on the wheels (Figure 5.4). The speed profile of the vehicle is thus depending on the setpoint. This method is interesting to test control algorithms (for example PID-controller). Also the effect of the driver can be evaluated. Reproduction of exactly the same speed profile is not possible without a speed controller.
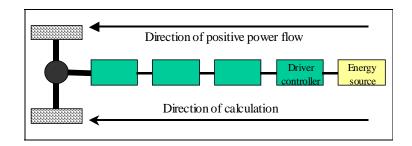
Figure 5.4: Direction of Calculation: Cause-Effect Method.

The other method simulates backwards (Figure 5.5). With an imposed speed cycle one calculates the forces acting on the wheels and simulate backward through the drivetrain up to the primary energy sources, which is either fuel or electricity. The driver's behaviour is not taken into account, since the cycles are followed precisely, gear switching occurs at fixed moments, etc.
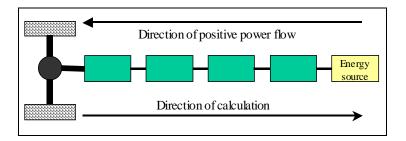
Figure 5.5: Direction of Calculation: Effect-Cause Method.

In VSP the calculation is performed using the procedure working backwards from the demand imposed by a required drive cycle, to calculate the properties of the powertrain components as they attempt to meet this demand. For a vehicle simulation typically the following steps are carried out [5].

The tractive effort required from the vehicle is calculated from the required acceleration and resistive forces such as aerodynamic and gravitational drag.

This tractive effort is converted by the wheels into the required torque and speed.

The torque and speed are transformed through the powertrain by the successively intervening system components (such as differential or gearbox) until a prime mover such as an engine or electric motor is reached.

The prime mover typically uses an efficiency map to predict its energy requirements (f.i. in terms of fuel consumption for an IC engine or power to be drawn from a battery).

This calculation is repeated at each time step during the vehicle cycle.

Figure 5.6 illustrates the longitudinal calculation algorithm. The left part represents a drive cycle and the right part is the resulting power drawn out the energy source.
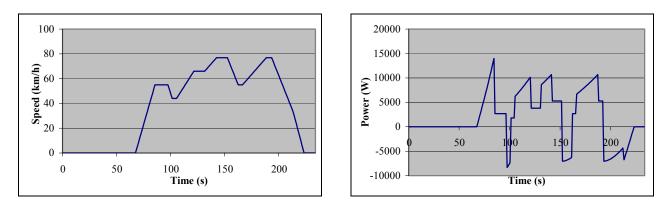
Figure 5.6: Longitudinal Dynamics Simulation (e.g. Japan 15 Reference Cycle).

5.2.1.4.3   *How to Describe the Forces Acting on the Vehicle?*

Using primary parameters for vehicle's body shell and chassis (e.g. cumulative mass of powertrain components, payload, body design characteristics, etc.) and route parameters (gradient, wind velocity, etc.), the programme calculates the forces acting on the vehicle.

The tractive force (F_{trac}) acting via the tyre contact surface of the driven wheels is determined by the engine or motor torque and by the gear ratios and inertias of the driveline. For level driving, the resistive forces acting in the direction of motion are the components rolling resistance (F_r) and air resistance (F_v). If the propulsion forces are not in equilibrium with the driving resistance at the considered steady speed, vehicle acceleration (a) or braking occurs, producing an inertial force (F_a), which acts at the vehicle centre of gravity [4].
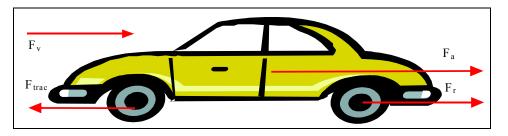
Figure 5.7: Forces Acting on the Vehicle.

When driving uphill or when there is a head wind (velocity v_w) additional forces are acting on the vehicle. The total resistive force can be expressed with equation [7].

$$F_R = \frac{1}{2}.\rho.S.C_x\left(\frac{v_{cur} + v_w}{3,6}\right)^2 + M.g.f_r.\cos(\alpha) + M.g.\sin(\alpha) \qquad (5.1)$$

For accelerating the vehicle an additional force corresponding to Newton's 3rd law of motion (5.2) has to be delivered by the traction system.

$$F_a = M.a_v \qquad (5.2)$$

The supplementary force corresponding to the inertia of the different components is taken into account within the components themselves.

5.2.1.4.4   Component Characteristics Modellisation

A component model can be as sophisticated or simple as the programmer's time and budget permits. Different parameters and even different modeling methods can be used to describe a component. Although there may be different types of models, the subprogrammes have the same interface, return predefined outputs and use the same predefined inputs.

Since the general aim of the simulation programme is to know the energy consumption of a vehicle, all parameters, which have an influence on this energy consumption, have to be defined. With the forces acting on the vehicle corresponds a certain power level. The battery or fuel does not only need to deliver this power, but also the losses of the different components of the drivetrain. A good description of these losses is thus required. The different parameters defining these losses should be calculated. The accuracy of the model will define the accuracy of the overall energy consumption.

a) Efficiency covering the whole working field

A lot of publications use a constant value for the efficiency of a component, generally corresponding to its maximum value. They multiply the different efficiencies to describe the overall efficiency. This approach is a very rough estimation and corresponds mostly to a very optimistic energy consumption. This is also the reason why one can find in literature so many different results on the energy comparison of different drivetrain. A more accurate solution would be to simulate the behaviour taking into account the whole map of working points.

b) Analytical Models

The components (electric motor, chopper, charger, etc.) can be defined by *physical equations* and equivalent circuit (analytical models) or by measured efficiency characteristics (statistical models).

Physical laws and equivalent circuits can describe the characteristics of a component. Such theoretical models can be used for different motors or inverters, only the component parameters are to be changed. However the component parameters are not always available. If they are received from the manufacturer, they are generally measured under laboratory conditions (sinusoidal voltage, standard measuring points, etc.). They can be fine-tuned while calibrating the entire vehicle model.

c) Statistical Models

On the basis of numerous measurements one can calculate statistical models for the components. These measured data can be stored in one or two dimensional *look-up tables* or arrays. Parameters can be calculated by bilinear interpolations on a network of two dimensional efficiency curves. The precision depends on the density of the points of the map. This approach is explained by example of Figure 5.8. The considered parameters can be emissions, fuel consumption, voltage, efficiency, etc.
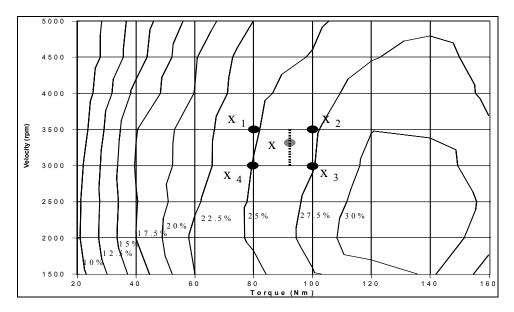
Figure 5.8: Bilinear Interpolation of a Two-Dimensional Efficiency Curve.

In the simulation programme a two dimensional model is mostly used. A parameter (efficiency, power, etc.) can be defined e.g. in function of torque and speed, or current and voltage. Other models can be a one-dimensional table of only one parameter, e.g. the maximum torque in function of speed. In some cases it can be necessary to have a multiple dimensional function. In this latter case, an interpolation in a look-up table will become very complex. The use of *statistical formulae* will be required. Using statistical equations has the benefit to use less memory and to allow a faster simulation. It is thus recommended to transform the look-up table into statistical formulae. This can be done with the help of mathematical programmes like MATLAB® or spreadsheet programmes like EXCEL.

Statistical piecewise models, derived out of the measurements data, have the advantage of being closer to the reality, and thus are mainly used, as an accurate input, in the database of the Vehicle Simulation Programme.

The more parameters used to define these statistical equations or look-up tables, the more complicated the simulation programme becomes and the slower the programme will run. It is thus advisable to determine those parameters, which have an important influence on the required end-result (the energy consumption).

d) Component Boundaries Modeling

Each system is identified by its operating limits (Figure 5.9). While simulating the behaviour of a drivetrain performing a chosen cycle, it is possible that one of the components cannot satisfy the demanded requirements. For instance a motor can reach its maximum torque or can come in overspeed, a battery or inverter can be overloaded. In that case it is interesting to reduce the required acceleration and hence to evaluate the maximum performance (possible speed) of the drivetrain. To ensure that all components operate within defined boundaries, corresponding to loading limitations, acceleration reductions are introduced. This *acceleration reduction* (AR) is used to iterate towards the possible vehicle speed domain. The limiting values can be either properties of the specific part or defined by the user.
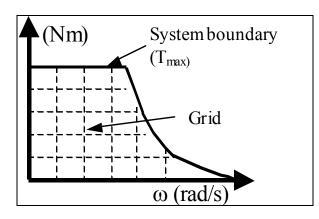
Figure 5.9: System Boundary.

Figure 5.10 illustrates the reduction of the required acceleration a_1, corresponding to a desired velocity v_1 into the possible acceleration a_2, resulting in a possible velocity v_2. By means of this higher simulation level it is also possible to simulate acceleration and maximum speed performance tests.
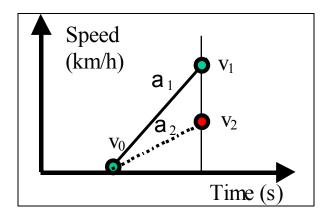
Figure 5.10: Possible Speed Calculation.

e) The iteration algorithm also allows a kind of semi 'cause-effect' calculation

Due to the use of this iteration algorithm it is also possible to simulate the influence of the driver or controller. Normally the *cause-effect* method or forward calculation method (see above) is used to simulate the effect of the driver. Nevertheless VSP uses the effect-cause method, which means that during the simulation the desired speed can be set to a maximum value that never will be reached by the drivetrain. In this way an acceleration reduction is always calculated. In a special model for the driver the acceleration reduction (AR) is implemented in the same way as it is done in all other components of the drivetrain. In the driver model a setpoint for power, speed or torque is evaluated as if it would be a maximum limit or boundary. Due to the iteration process the programme will calculate the speed corresponding with this setpoint.

In the graph, Figure 5.11, the controller algorithm is demonstrated. Normally out of the speed cycle the torque acting on the wheels is calculated. In this case, with same programme using its special iteration algorithm, one can change in real time a setpoint for the torque (dashed line). This setting is

coming for instance from an acceleration pedal. The actual speed is following this setpoint (straight line).
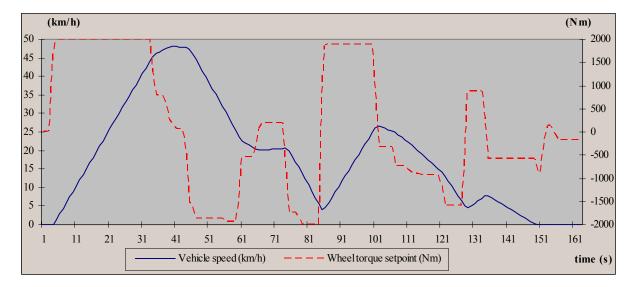
Figure 5.11: Demonstration of the Controller Algorithm.

f)   Powerflow Control Algorithm

The powerflow control strategy of hybrid drivetrains is implemented with the same iteration process as for calculating the vehicles performance. The power distribution between the several mechanical shafts or energy sources is controlled with the help of a *Power Distribution Factor* (PDF).

When exceeding the operating boundaries, instead of using an acceleration reduction, a *Power Reduction* (PR) will be introduced to regulate the power split (the PDF) in the different components that are in charge of the power division in the hybrid drivetrain (e.g. toothed wheel and DC-bus controller).

Opposite to the Acceleration Reduction the Power Reduction is not used to change the vehicle acceleration performance, but to control the powerflow in the hybrid drivetrain.

In more complex hybrid structures a *second PDF* and *Power Reduction* can be necessary: for instance in a series hybrid vehicle with a traction battery (AR), a generator (PR$_1$) and a Flywheel (PR$_2$). Until now the software is built up to simulate maximally third order hybrid systems. The software can easily be extended to higher order systems if necessary. Consequently additional Power Reduction factors have to be introduced.

In the case of hybrid vehicles the iteration process is much more complex: the PR can change the power split or the AR can reduce the acceleration. Due to the fact that several reductions can occur within one drivetrain an intelligent *iteration order* is required. Hence a *hierarchy* of different hybrid control strategies is developed and inherently implemented in the software. This means that the control algorithm is not a separate block of the simulation programme, but makes part of the different components on which it has an influence. This is necessary because there is a high degree of

interaction between component models, particularly with respect to operation limits, and powerflow control strategy.

The difficult challenge was to develop this iteration algorithm in such a way that it was applicable on all types of vehicles: electric, thermal, series and parallel and even complex hybrid vehicles. For this reason it was necessary to develop a *uniform* approach to introduce the Acceleration and Power Reduction for each type of operating limit (speed, torque, power, etc.) and to develop an iteration control module to tackle all these reductions.

g) Interchangeable Component Library

One of the purposes of the simulation programme is the ability to calculate the performance of a vehicle comprising any set of components that have been connected together in a physically sensible manner.

Components of the same type can be exchanged, e.g. a lead acid battery by a NiCd battery, but also components with the same function, e.g. a battery by a fuel cell. Table 5.1 illustrates the possible interchangeable components. Components that do not have an equivalent counterpart are the body, wheels, torque splitter, planetary gear, DC-bus controller and the auxiliaries. They can only be replaced by other components out of the database of the same type.

Table 5.1: Possible Interchangeable Components with the Same 'Function'

Transmission	Power Transformation	Energy Source
Differential	AC motor + inverter	Battery (all types)
Gear	DC-motor + chopper	APU
Reductor	Engine	Electric Flywheel
	Mechanical flywheel	Super capacitor
		Fuel cell

The model of the engine is developed in such a way that it can be used in an APU for a series hybrid vehicle as well as traction unit in an ICE-vehicle.

5.2.1.4.5   *Programming Structure*

The programming structure of LabVIEW^{TM} lends itself to a top down approach. The programme, VSP, therefore can be seen as a three level structure.

*   The top level is the main programme of which the user interface is described in a previous chapter. This level contains the icons of the subprogrammes for the different vehicles and also for drive cycles, electricity production, etc.

*   The second level is consequently the level of the different drivetrains. Each drivetrain is composed of different vehicle components. The manner these components are connected together will represent the topology of the drivetrain. This second level represents in fact the energy flow and conversion through the vehicle drivetrain. Each component is modelled as a separate subprogramme.

*   The third level is the level of the different component models.

The flow chart of Figure 5.12 gives an overview of the software. One can recognise two different simulation loops: one that defines each step a new required velocity in function of the chosen speed cycle and another that contains an iteration algorithm to define the possible vehicle performance in the case the vehicle is not able to follow the imposed speed cycle. Additionally there is a very small loop that is used to pause the simulation process.
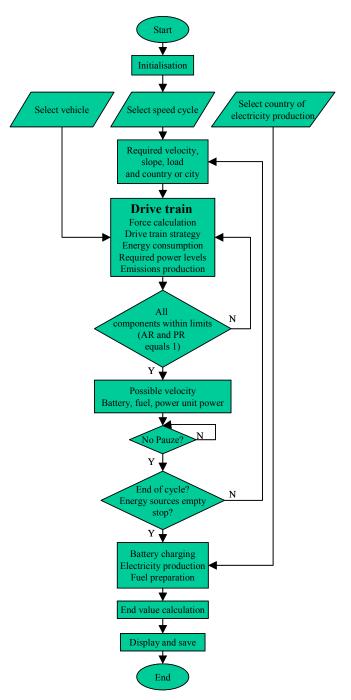
Figure 5.12: Flow Chart of Vehicle Simulation Programme.

After the initialisation phase the required velocity of the vehicle is defined by the speed cycle that the user has selected on the main user interface. The model of this speed cycle contains also the load of the vehicle, the slope of the road and whether or not the vehicle is driving in the city (centre). Based on these parameters and the characteristics and weight of the selected vehicle body and of the wheels, the forces acting on the vehicle can be calculated. In function of the powerflow in the drivetrain (the hybrid drivetrain power strategy), the component losses and the energy consumption from the battery, fuel tank or other energy source is processed. In the case of non-pure electric vehicles the direct emissions are simulated too.

When the end of the drivetrain is reached, this means one has processed all calculations from the wheels to the energy sources, the iteration algorithm checks if all components were able to deliver the required torque, speed, power, current, etc. If one or more components were out of data range, the required acceleration is adapted (via the acceleration reduction) and the drivetrain is simulated again until all components are within limits. Hence the imposed speed cycle is only exactly followed when all components are able to do so.

The power levels of the energy sources are visualised in the main user interface and the next required speed step is used to calculate the forces acting on the vehicle. If the speed cycle is completely simulated or all energy sources are empty or the user stops the simulation, the programme will go to the last part. In this part the battery will be recharged, the corresponding background emissions are calculated and possibly the additional energy consumption due to fuel refinery is defined. The end results are displayed and if wanted saved on hard disc.

5.2.1.4.6   Different Levels of Accessibility

To conclude this first part the different accessibility levels are described. VSP is a software tool that can be used by a large range of different customers, with different skills and desires. Different password protected accessibility levels are foreseen and allow the user to have admission to a certain level of information.

The *first level* corresponds with the front panel of the main programme, like described in paragraph "5.2.1.2 Main User Interface". At this level the user can select a vehicle of the database, to be driven at a speed cycle and some other features. At the end of the simulation the energy consumption and emissions are the most important results. This level is dedicated to novice users.

Level two gives access to the front panels of the vehicle and electricity production models. Especially for hybrid electric vehicles this gives the opportunity to define some general drivetrain power strategies, like whether or not the generator should be engaged and in function of which criteria. By choosing a certain country one select the way the electricity is produced to recharge the battery. The relative contribution of the different types of power plants in each country can be different. By having access to the front panel of this electricity production model one can change the pollution and energy losses of the considered country.

Level three is related to the vehicle components. Each drivetrain consists of different components. The major parameters describing the working of such a component can be found on its front panel. While having access to level three the user can change the parameters on the front panel of the different components of the drivetrain. Furthermore this level allows replacing a component of the drivetrain by another out of the component library or database. For this level some technical skills are required. Sometimes it can be difficult to get access to data. In this case standard values are proposed.
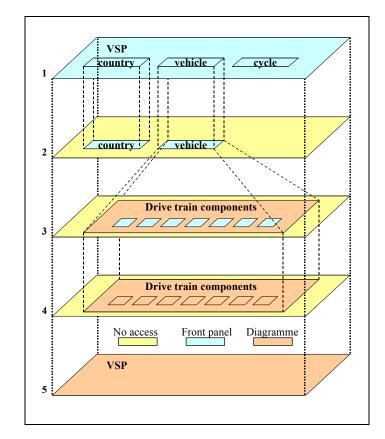
Figure 5.13: Different Accessibility Levels of the Simulation Programme.

The *fourth level* is related to the creation of new component models. Most component data can be found within the diagram of the component model. This diagram contains submodels, equations, case structures, etc. When one wants to make models of new components one should have access to this fourth level. Some engineering skills are required concerning characteristics and modeling of motors, engines, convertors, batteries, etc. The user must also be familiar with LabVIEW^{TM}. This level is more dedicated to expert users.

The last and *fifth accessibility level* gives admission to the whole software tool. At this moment the user can change any part of the software from main programme to detailed subprogramme. An in-depth knowledge and understanding of the simulation programme is required. How are all programmes related to each other? Which parameters will influence each other and via which process? Only when fundamental changes have to be made access to this level is obligatory. This most in-depth level is dedicated to users with engineering expertise.

5.2.1.4.7   *Comparison with Other Programs*

It is always interesting to evaluate what other researchers have already done. In this chapter other simulation programmes will be briefly described.

The last ten years simulation programmes dedicated for the evaluation of vehicles have known an important progress. Most simulation tools were originally designed to evaluate specific drivetrains and each model has been implemented for its own particular scenario. They were mostly written in text-based languages, with data

structures that were difficult to access. Admission to many of these programmes is limited by commercial considerations. Multimedia technology allows now relatively rapid development of highly graphical and interactive user interfaces.

In the following paragraphs examples of some important and recently developed programmes are described. These descriptions are based on the corresponding publications, but most of them could not be verified. All the programmes use the same fundamental principle, based on longitudinal upstream-looking quasi steady state time stepping algorithm. This algorithm has already proven its validity and will be described further on.

While reading the literature of the above-described simulation programmes the same remark systematically came back: 'due to lack of information', 'data is hard to find', 'the availability of the required information to implement is not a trivial point', 'parameters will not be easily at disposal'. It is clear that one of the problems of vehicle simulation software is the availability of data.

The Vehicle Simulation Programme (VSP) differs fundamentally from these examples:

- It has a unique iteration algorithm dedicated for the flexible implantation of different kind of hybrid drivetrain topologies and powerflow control algorithms taking into account the component operating boundaries or desired operating conditions.

- It has an in-depth worked out programme modularity in which almost all parameters are only accessible in the module of the component itself.

- It has a flexible database structure, integrated in the component models, allowing an easy implementation of different kind of component data in the form of look-up table, maps, theoretical equations, and empirical formula; in function of the available data.

a) Drivetrain Simulator (DTS)

Our first major experience with vehicle simulation software was in the framework of a JOULE II programme, funded by the Commission of the European Communities, as collaborator of the University of Kaiserslautern in Germany. Within this project a transparent simulation for electric and hybrid vehicles, called Drivetrain Simulator (DTS) was developed [6,7].

Thanks to the main user interface, the user does not have to deal with the source code of the main programme. This user interface shows a modular structure of the drivetrain. For each object the user has to decide which variables will be drawn during and at the end of a simulation, as well as how often tracing occurs. Every component is described thanks to an integrated programming language called DTS [8]. The DTS-source code looks in some regards like the PASCAL language. Simulation source code can be modified to create new components and to change the structure of the studied system. For some components, such as the drive cycle, data and characteristic curves are stored in tables, which can be changed. Thanks to a "diagram viewer" the tables of results can be converted into graphs. Limitations in components can be introduced in modules so that the demanded power is reduced if one or more components are overloaded.

b) SIMPLEV[®]

SIMPLEV[®] is an Electric and Hybrid Vehicle simulation program developed by the Idaho National Engineering and Environmental Laboratory (INEEL). The INEEL is a multi-program engineering and environmental laboratory doing research and solving national problems for the US Department of Energy (DOE). The software is available free of charge. SIMPLEV[®] is written in a traditional text

based programming language, QuickBasic 4.5, which runs under DOS. Its main use is as a vehicle performance simulation tool which capable of simulating vehicles having conventional, all electric, series hybrid, and parallel hybrid propulsion systems. SIMPLEV® provides second-by-second predictions of powertrain component performance parameters over any user specified speed-time or speed-distance driving regime. Vehicle propulsion system components are modelled by user-written ASCII data files of component performance [9].

c) EHVSP

The Electric and Hybrid Vehicle Simulation Programme is developed at the Department of Electrical Engineering at the University of Hawaii at Manoa, USA [10]. The software is developed using MATLAB® 4.2a and SIMULINK® 1.3a. The software has a user interface and a simulation toolbox. The toolbox currently uses statistical data and look-up tables to simulate several parts of the simulator. A friendly user interface has been added to the program in order to facilitate the user. The simulation toolbox was prepared for the Advanced Research Program Agency (ARPA). The first version of the programme is currently available for the ARPA coalitions. The inputs to the programme can be given by double clicking the appropriate input data module buttons. This feature enables the user to test different configurations. Several combinations can be structured. Finally, the output module facilitates the output of the data. The user by pressing the appropriate button can see dozens of graphs and results [11,12].

d) ELVIS

The Series Electric and Hybrid Vehicle Simulator (ELVIS) was developed at the Southwest Research Institute (SwRI) [13]. It has been developed using MATLAB®/SIMULINK® as well as in LabVIEW™, both graphical languages. They also had experience with SIMPLEV®, but it was found not very flexible due the text based programming language [14]. The simulator uses statistical data and look-up tables to simulate several parts of the simulator. Using this model, engineers helped the Advanced Research Projects Agency (ARPA) select and optimise auxiliary power units for series hybrid cars and buses. ELVIS calculates varying operations of pure electric vehicles, series and parallel hybrid electric vehicles and conventional mechanical drive vehicles [15], but only predefined drivetrain topologies can be simulated.

e) ADVISOR

The ADvanced VehIcle SimulatOR (ADVISOR) is developed by the National Renewable Energy Laboratory (NREL), Golden, CO, USA. The model was created in support of the hybrid vehicle subcontracts with auto industry for the US Department of Energy. It contains a set of models, data, and script text files for use with MATLAB® and SIMULINK®. It is suited for doing parametric studies to map out the design space of potential high fuel economic vehicles consistent with the goals of the Partnership for New Generation of vehicles (PNGV).

ADVISOR also provides a backbone for the detailed simulation and analysis of user defined drivetrain components [16]. It has been applied to many different systems analysis problems, such as helping develop the SAE J1711 test procedure for hybrid vehicles and helping evaluating new technologies as part of the PNGV technology selection process [17]. ADVISOR contains 'autosize' function to scale component data and 'optimiser' functions to adapt the size of components one to each other. Five vehicle configurations have been modelled. The software can be free downloaded from the Internet, but MATLAB® and SIMULINK® should be purchased anyway.

f) HYGEIA

HYGEIA is a vehicle mission tool for thermal, electric and hybrid vehicles developed in the framework of the FLEETS-ENERGY project. The Commission of the European Communities has sponsored this JOULE project. Our experience in the field of vehicle simulation could give some interesting inputs to this project via the collaboration of CITELEC, which was one of the main project partners. HYGEIA is a piece of software written at the Motor Industry Research Association (MIRA), Nuneaton, UK, which enables the modeling of a wide range of vehicles. Within the program, various vehicles can be designed including ICE, Electric, Fuel Cell and Hybrid vehicles. The software has been coded using Borland-Dephi. This language provides a visual programming system for developing the graphical user interface, includes the Borland Database Engine for development of the required data tables and has Object PASCAL for coding the modeling and calculation routines [18]. The database is a passive component that is used purely for data storage. An advanced development version is for sale at a price of 5000 Euro.

Dedicated mainly for the transport sector, where engineering skills are less required to evaluate the vehicles, it enables fleet operators and policy makers to predict cost of operating these vehicles in service, thus providing an analysis and decision making tool which can be used by different groups [19]. It uses generic control strategy for each type of hybrid, which limits the variation in hybrid layouts that can be modelled [20]. The software has achieved the compromise between allowing flexible vehicle design and operating hybrid vehicles. It allows the implementation of external control through telematics to improve vehicle and energy utilisation. Both forward and backward calculation methodologies are implemented (see further). It includes also models for thermal control, airco, heat transfer characteristics, etc.

5.2.2 $\circledR^{TM}$

$\circledR^{TM}$ is a simulation tool developed by QinetiQ and mainly dedicated to the evaluation of many possible combinations of power generation and of many operating scenarios. Technologies, component sizing and power management strategies combine to meet the whole range of operating scenarios applicable to the vehicle.

An important consideration in developing $\circledR^{TM}$ was the level of fidelity which was appropriate for the models. The approach adopted was to use ''look up'' tables of test data from real components wherever possible, rather than relying on purely theoretical models. Considerable effort has been expended to ensure that all sub-models are accurate. To that end laboratory testing of fuel cells, ultracapacitors, batteries and hub mounted electric drives have been conducted within QinetiQ. In cases such as the flywheel, detailed simulations were performed outside of $\circledR^{TM}$ using dedicated simulation packages to provide the necessary data.

5.2.2.1 Model Structure

5.2.2.1.1 *Power System*

The electrical power system consists of four major sub-systems: (1) the power management controller; (2) the primary power source(s); (3) the secondary power source(s) and (4) the dump resistor.

1) Specific examples of primary power sources were selected from the following categories:

   • Diesel engine with motor/generator;

   • Gas turbine with high speed motor/generator;

- Fuel cell operating from stored hydrogen;

- Fuel cell operating from a diesel reformer.

2) Similarly, the secondary power sources were selected from one or more of the following categories:

- Battery,

- Flywheel,

- Ultracapacitor.

In the case of the battery, there was also the option to select a separate Zebra^{TM} battery model, which included specific models of the battery management, heating and cooling systems.

3) The power management controller automatically started, stopped and set the power output of up to three primary power sources. It compensated for the state of charge of the secondary power source, applying thermostatic, load-following, rolling average or other strategies.

- **Thermostatic**: The primary power source output is either on, at a fixed power output, or off. The secondary power source is heavily utilized.

- **Load-Following:** The primary power source output power is set to follow the demand of the drives. The secondary power source is less heavily utilized but still stores recovered braking energy and "fills the gap" when the primary power source is not running. Less energy flows in/out of the secondary power source than with rolling-average strategy. This reduces the losses there but expense of operating the primary power source over wide range of outputs, where efficiency may be poorer.

- **Rolling Average**: The power generator output is set to the average power demand. The secondary power source provides the difference between this and the instantaneous demand at the drives.

Power limits were applied to ensure that the primary power source was kept within a chosen operating range and to avoid exceeding the dynamically varying power limits of the secondary power source. The controller itself was implemented in Stateflow^{TM}, and its settings were read in from the database.

4) Finally, the dump resistor was activated whenever there is more electrical power regenerated than could be stored in the secondary power source (e.g. when approaching 100% state of charge).

- **Vehicle and Tire Data:** it accounted for resistance to motion from gradient, rolling and aerodynamics mechanisms.

- **Drive System***:* The drive system was concerned with motors, electric drives, gear reductions and mechanical brakes. Power limits, torque limits and efficiency maps against torque and speed formed the basis of the power consumption calculations for the motor and drive. Efficiency losses in the gear reduction were also accounted for, including no-load losses. Mechanical brakes were applied whenever the required braking torque exceeded that possible using regenerative braking. The power consumed or generated then placed a demand to the electrical power system.

  To run a simulation, a driving cycle is associated to the model. More information is available in the simulation possibilities chapter.

5.2.3   PROSPER

PROSPER is mainly a 3D-road vehicles dynamic simulation software mainly dedicated to following applications:

- Vehicle project preliminary design,
- Forecast and extrapolation of real tests.

As hybrid electric drive is more and more considered for future applications, an electric module concerning electric motor and electric generation had completed the tool.

Vehicle modeling is done by using a components library with parameters or by entering the component main characteristics on an EXCEL sheet.

5.2.3.1   Model Structure

Vehicle Main Characteristics: Ground clearance, unsprung mass, mass per wheel or per track, height of center of gravity, width and wheelbase.

Aerodynamics: Three levels of aerodynamics are available from basis with Cx and S to detailed curve of aerodynamics characteristics according to vehicle evolution.

Engine: Torque map according to load and engine speed, consumption map according to load and engine speed and correction due to temperature and pressure.

Transmission: Architecture including I, H or Y transmission, passive and active differential, gearbox with efficiency map and shifting strategy, torque converter map.

Steering: From natural steer angle of wheels to dual steering combining classical steering to skid steering.

Braking: Braking torque according to driver's command including braking strategy.

Suspensions: Every layout can be described, from McPherson to trailing arm. Each suspension could be detailed by a complete kinematics, elastokinematics and dynamic map according to wheel travel and steer angle.

Tires: One of the most important component to model when it comes to longitudinal and lateral simulations. It uses different levels of Pacejka-type modeling using wheel speed input and longitudinal and lateral curves according to slipping rate and slip angle.

Various modules complete the main software and particularly an **electric module**. This module allows modeling of hybrid electric architecture.

Electric Module: It takes into account a main electric generation by diesel and a secondary electric generation by batteries. Various electric architectures are available to bring power to the wheels.

Engine/Generator: It is considered as an electric power generator delivering power according to speed and load. Consumption is calculated according to specific power.

Batteries: Batteries pack is defined by discharge and charge maps (V) and by nominal characteristics like Ah and pack voltage.

Electric Motor: Electric motors are defined by a torque map and an efficiency map according to load and motor speed. An overboost map can be combined to the nominal map. In that case, the overboost mode defined by an acceleration command, is allowed during a defined period and then unavailable during another period.

These motors can be combined with a mechanical architecture from a single reduction gear to a gearbox and differentials. This possibility allows various electric architectures for the vehicle.

Available electric architectures up to 10-wheel vehicle:

- 1 electric motor per wheel,

- 1 electric motor per axle + differential (I architecture),

- 1 electric motor per side + differentials (H architecture),

- 1 motor per wheel for the front axle and 1 motor per side for rear axles + differentials (Y architecture),

- 1 electric motor for the whole vehicle + differential.

Each motor can be combined with a gearbox and/or a mechanical reduction.

In cases such as one motor per wheel and one or many motors per side, these motors are driven for steering following torque or speed strategy. The speed control allows the combination of skid steering with natural angle of wheels. This strategy depends on vehicle speed.

In other case, an active differential allows the combination of both steering.

Figure 5.14: PROSPER Electric Architecture Module.

Braking: An electric braking provided by electric motor can be combined to mechanical braking. This electric braking is defined by a percentage in comparison with mechanical braking. This percentage depends on the electric motor speed.

PROSPER electric module allows the modeling of hybrid electric vehicle using the combination of diesel engine and batteries pack with a unique strategy of energy management. This module will undergo future development to fit military needs for future combat platforms, particularly in the field of energy management.

5.2.4   TNO-ADVANCE

TNO-ADVANCE is a modeling and simulation tool allowing the user to build vehicle models in an easy, flexible and modular way. It is based on the in-house TNO powertrain and vehicle dynamics simulation tools.

It contains adaptable, generic models of various parts of a vehicle, like the vehicle body, wheel suspensions, tires, engine, clutch, gearbox, differential, various electric machines, batteries, etc.

This section describes how TNO-ADVANCE can be used to build a car model consisting of a vehicle body, wheel suspension, and a complete powertrain. It also briefly touches upon the shortcomings advantages of the current library set-up. A description of the various powertrain and chassis library components is given in the proceeding sections.

Each car model is built by the constellation of various sub-models. Figure 5.15 schematically shows the modular set-up; the top panel (1) represents the complete vehicle model. The scheme then shows two branches, the left depicting the powertrain part of the vehicle model (panels (2) and (4)), the right representing the vehicle dynamics part (3) and (5)).
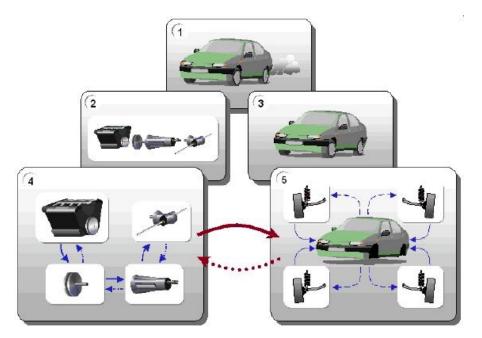
Figure 5.15: Schematic Representation of Modular Set-Up of a Vehicle Model.

Powertrain:

The powertrain is based on the already existing in-house Advance powertrain models (Van de Venne and Smokers, 2000). This is a modular simulation tool for the design and evaluation of advanced powertrains. A model of a powertrain is created by composing components from the powertrain library. This library comprises both conventional and advanced powertrain components and offers the user a wide variety of component modules. It presently includes dynamic and static models of:

- Otto and Diesel engines, gas turbines;

- Continuously variable transmissions (CVT), manual and automatic transmissions, clutches, torque converters;

- Batteries, fuel cell model;

- Permanent magnet electric machines, asynchronous electric machines, etc.

All component models are based on generic models in which parameters can be adjusted to fit desired component specifications. By selecting the desired powertrain components and attaching the appropriate signals, the user can quickly assemble a powertrain model.

Vehicle Model:

The chassis model is based on the in-house TNO-MoVe models. For most handling simulations of passenger cars the flexibility of the suspension components as well as the influence of bushings can be neglected. The relative motion of the wheel carrier with respect to the car body can then be represented by a movement over a smooth curved line in combination with rotations around this line. Based on experiments or multibody simulations the curved line and rotations around the line can be determined easily. By prescribing the vertical displacement of the wheel carrier with respect to the car body, fixing the rotations around the wheel axis, the remaining displacements and rotations can be determined, through a straightforward kinematics suspension analysis. Similarly the suspension effective stiffness and damping characteristics can be determined. The resulting effective joint with one degree of freedom is connected to both the car body and wheel carrier with tire.

Tire Model:

The default tire model is MF-Tyre (Delft-Tire, 1996). This pragmatic tire model is based on the latest version of the Magic Formula. Combined longitudinal and lateral slip conditions can be handled, e.g. braking in a turn.

First order transient effects are included by longitudinal and lateral relaxation lengths making the tire suitable up to an excitation frequency of 8 Hz. A single point contact approach is used which limits the usage to road undulations larger than tire circumference. Also the motorcycle tire model MF-MCFTyre can be applied which is based on the MF-Tyre but adapted to be able to describe large camber angles accurately. This tire model can be used to study possible roll–over situations of the passenger cars or SUVs. Smaller obstacles or higher excitation frequencies can be handled by the SWIFT model. This tire model is based on a rigid ring approach and thus applicable to the first eigenfrequency of tire belt. For passenger car tires this is typically around 60 Hz making the tire model not only suitable for active chassis control analyses, i.e. ABS, ESP, but also for vehicle ride and durability studies. Combined slip situations over road obstacles not smaller than 20 cm can be described accurately.

All tire models assume a rigid road surface, thus driving over soft soil can not be modeled using this approach. The soft soil could be modeled using finite element techniques but that would lead to unpractical computing times. For off the road applications, i.e. agriculture, construction or military, a pragmatic in-plane tire model can be developed. TNO Automotive has already developed a numerical model to simulate the behavior of a vehicle on deformable soil. The vehicle soil interaction model is based on the semi-empirical pressure-sinkage relations.
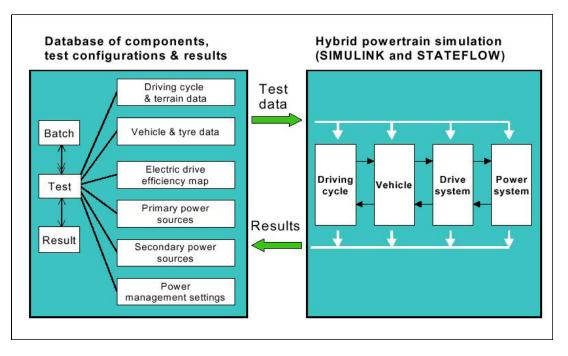
This method uses properties such as soil-wheel cohesion, soil internal friction angle, frictional modulus, normal force, contact surface, contact length etc. to determine variables such as wheel sinkage, soil compaction resistance, wheel slip and angular velocity and traction force. The model has also been used to apply inverse terrain characterization; from state of the vehicle (e.g. power delivered, acceleration) the model estimates soil parameters which can then be used to predict vehicle performance under such terrain conditions (e.g. maximum achievable slope, max. power required, etc.). Future developments would include validation, influence of different traction geometries (wheel or tracks), influence of the traction on soil characteristics (to predict behavior of the wheel on compacted soil), etc.

5.3   SIMULATIONS

5.3.1   ®™

PRINCIPLE OF ®™

- ®™ consists of a SIMULINK® model of the hybrid powertrain and an MS-Access database components, tests configurations and results, as shown in Figure 5.16. This arrangement separates the powertrain model from the underlying component data and test configurations, which simplifies the configuring each test condition and vehicle setup.

Figure 5.16: Simulation Principle (QinetiQ Copyright).

Driving Cycle: Definitions of driving cycles were stored in the database in a format compatible with DRIVE-C^{TM}, a conventional powertrain simulation package. This allowed the same speed and terrain data to be applied to the simulation of both hybrid and conventional powertrains. The ®^{TM} model determined coefficients of traction and resistance for off-road conditions, based on terrain properties and tire characteristics. These coefficients were calculated using validated mobility equations, previously derived at QinetiQ. During a simulation run, the driving cycle determined the acceleration demand on the vehicle, implemented using a proportional controller.

Vehicle: This part of the model determined the net force required to achieve the acceleration (and hence the velocity) demand by the driving cycle. It accounted for resistance to motion from gradient, rolling and aerodynamic mechanisms. It also calculated the vehicle velocity by monitoring the response of the drive system.

Drive System: The power consumed or generated then placed a demand to the electrical power system.

Power System: The power management controller automatically started, stopped and set the power output of primary power sources and compensated for the state of charge of secondary power sources following power management strategies.

®^{TM} tools mainly allow:

- Analyze fuel efficiency and acceleration performance;

- Store manufacturer and/or laboratory test data for powertrain components;

- Define tests using any combination of technology, operating scenario and control strategy;

- Allow simulation of multiple primary power sources (e.g. two mass-produced car diesel engines with generators instead of one large engine with generator);

- Allow simulation of mixed secondary power sources (e.g. a battery with an ultracapacitor);

- Run simulations either individually or as a batch;

- Store past results and with links to the associated test configurations;

- Link with automatic code generation tools, to provide a direct route from the simulated vehicle to the electronic control unit in a real vehicle.

EXAMPLE OF ®^{TM} SIMULATION

®^{TM} has been used in a technology trade-off study, examining options for an 18-ton wheeled vehicle. During the study, ten sets of primary and secondary power source options were considered, as shown in Table 5.2. The study aimed to analyze these with respect to cost, packaging, fuel efficiency and acceleration performance.

Table 5.2: Hybrid Powertrains – Technology Options Analyzed

Primary \ Secondary	Battery	Flywheel	Ultracapacitor
Diesel engine with motor/generator	✓	✓	✓
Gas turbine with high speed generator	✓	✓	✓
Fuel cell with hydrogen storage	✓	✓	✓
Fuel cell with diesel reformer	✓		

For each option, 4 candidate power management strategies were defined, making a total of 40 simulation test configurations. An example of one such test configurations is shown in Figure 5.17 as stored in the ®™ database. The ®™ tool was then used to assess the acceleration performance and efficiency of each of these, to inform the trade-off study.

For efficiency tests, the driving cycle consisted of a mixture of road and off-road driving, lasting 900 s. For performance tests, the time to go from 0 to 27 ms^{-1} (60mph) was measured for straight, flat road. At the start of performance tests, primary power sources were assumed to be running (at zero power) and the secondary power source was assumed to be 80% charged (as might be expected after a recent braking event).

For convenience, the tests were run in batches. The resultant.energy consumption and time to reach 27 ms^{-1} for each option was then compared with the conventional baseline vehicle.

Figure 5.17: Example of a Test Simulation in the ®™ Database.

Efficiency Saving

The efficiency results were found to be far more sensitive to the choice of primary power source than the choice of secondary power source:

- Best results were achieved with options based on the fuel cell with stored hydrogen, where the whole vehicle consumed ~47% less energy than the conventional vehicle. These results were achieved when power limits were applied to the fuel cell, which is more efficient at part-load. Without the power limit, results were closer to 40% saving. This, however, relies on the supply and store hydrogen, which has yet to be proven.

- Options based on diesel generators typically showed savings of 25%.

- The fuel cell with diesel reformer also gave savings, but marginally less than the diesel generator options at up to 18%.

- No efficiency savings were found in options based on the gas turbine. This was due to the relatively long start-up time, resulting in the need to keep the gas turbine running even when power demands were minimal (i.e. not taking full advantage of the hybrid operation). A higher capacity secondary power source would be required to overcome this.

Acceleration Performance

Based on the time to 27 m/s (60mph), all the hybrid options were shown to offer improved acceleration performance compared to conventional vehicle, due to the higher peak power. The maximum rate of change of primary power did influence results, as did the choice of power management settings. Power management settings which gave the best efficiency often gave the worst performance (and vice-versa). To demonstrate this, results obtained for the diesel generator and flywheel hybrid is shown in Figure 5.18. It clearly shows how the power management settings alter the balance between performance and efficiency.
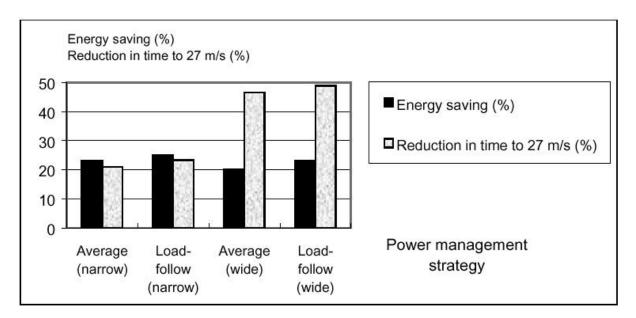
Figure 5.18: Example of Power Management Settings on Performance and Efficiency.

5.3.2   PROSPER

5.3.2.1   PROSPER Principle

PROSPER simulates the dynamic situation with all its complexity:

- Driver's command (throttle, hand-wheel, brake) versus time or distance,
- Atmospheric disturbances,
- Ground disturbances.

These 3 input types interact together in 3D open and closed loops simulations.

The number of degrees of freedom with mass is dependent on the presence of the trailer and the number of wheels. It is varying from 17 (4 wheels) to 29 (10 wheels) plus trailer (up to 27).

Beyond mass degree of freedom, there are differential equations of first order for control or transient, and the total order of the differential system is 90.

The main degree of freedom (for each vehicle) are:

- 6 body DoF;
- For every wheel, rotation speed;
- 1 engine rotation and one control;
- For every wheel, loaded radius;
- 2 steering DoF (rack and hand wheel angle) and 2 control for auto-driver (closed loop).

Other state variables without mass (first order equation) are per wheel:

- 2 tire transient per wheel;
- Brake pressure transient.

35 tests are preset concerning acceleration (performance acceleration, etc.), braking (performance braking, dynamic braking, etc.), steering (maneuverability, acceleration in cornering, etc.), straight line family, gradient and banking, side wind sensitivity, emergency simulation (braking in curve, etc.), ground (suspension test track like sinus, jump, step climbing, etc.), etc.
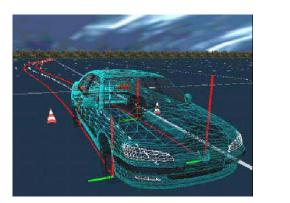
A general dynamic simulation is also available based on:

- Driver's command (throttle, brake, …) according to time or distance;
- Ground disturbances (slope, step , adherence) according to distance;
- Simulation option for post-processing.

The post-processing provides around 100 data graphs. Numerical and graphic zooms are available. Computed results are sent into EXCEL sheets.

A 3D animation is available to understand the movement.
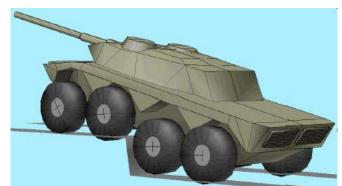
Figure 5.19: Example of Simulation and Animation.

5.3.3   TNO-ADVANCE

By applying the fast control options of MATLAB®/SIMULINK®, chassis and powertrain controllers can be developed and evaluated, i.e. *Rapid Control Prototyping*. Even interactions between vehicles, i.e. platooning, or new road transport systems, i.e. Intelligent Transport Systems and guided vehicles, can be studied effectively. MATLAB®/SIMULINK® offers possibility of real-time simulation. This enables the use of (parts of) a vehicle model for full-scale *Hardware-In-The-Loop*, thus allowing among others a thorough assessment of the controller robustness.

5.3.3.1   TNO-ADVANCE Principle

The powertrain components are mathematically represented by a set of differential equations, which can be solved when the driving resistance force is defined as a function of time, velocity and place. In relatively vehicle simulation models the set of differential equations is often solved by using the 'effect-to-cause' method. The vehicle velocity is then used to calculate the acceleration and the resulting driving force. Starting from driving force the simulation process is executed backwards through the powertrain up to the energy source. In the present powertrain model, however, the more sophisticated 'cause-to-effect' strategy has been implemented. The advantage of this strategy is that it uses a real-life approach. A driver (model) generates the accelerator and brake pedal signals. These, as well as the driven wheels rotational velocities, are used as input data for the simulation model. These signals are forwarded through the powertrain simulator from energy source up to the resulting, working torque on the wheels. The wheel rotational velocities, calculated in the vehicle dynamics branch, follow from the response of the vehicle to the powertrain action.

The vehicle dynamics branch shows that each wheel suspension is modeled separately and then kinematically coupled to the vehicle body. If the tire remains in contact with the road, the motion of the vehicle body (translations and rotations) determines the motion of the wheel carrier (Figure 5.15, panel 5, dashed arrows). Loss of tire road contact can also be handled. The forces on the wheels follow from the wheel accelerations, positions and motions of the wheels with respect to the road and vehicle body (spring/damper force, roll stabilizer force) and the tire-road interaction forces. From these forces and the wheel equations of motion, the wheel motion with respect to the vehicle body are determined (Figure 5.15, panel 5, solid arrows). These forces and moments – in turn – determine the vehicle's body translational and rotational accelerations, thus closing the computational circle for the vehicle dynamics. Not shown in the figure is the possibility to add a steering system thus allowing closed loop simulations (using a driver model) next to open loop simulations (using prescribed steering actions).

The MATLAB®/SIMULINK® vehicle model, created with standard library components, can be converted to real-time code using the Real Time Workshop module of MATLAB®/SIMULINK®. The motions of the vehicle can be monitored real-time during the simulation, and also off-line after the simulation.

5.4 VALIDATION

5.4.1 PROSPER

PROSPER is mainly used at ETAS for:

- Followings of design process,

- Evaluation of improvements on military vehicles,

- Evaluation of future concepts.

Modeling of existing military vehicle like VAB, AMX 10RC, VBL, LECLERC, etc. has been made to validate vehicle models by simulation before trying improvements on components.

In the field of electric drive, an hybrid electric VBL was used to validate the electric module comparing simulation with trials.
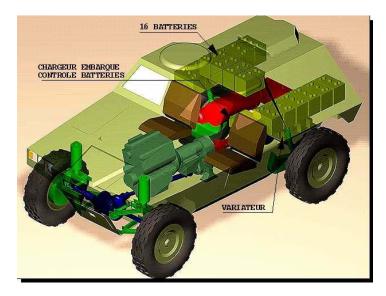
Figure 5.20: VBL Bi-Mode Example of Validation.

5.4.2 TNO-ADVANCE

In the past, this in-house tool has proven to be a flexible and valuable simulation tool for research and development. It has been used in various kinds of projects. These aimed, for instance, at the development of complete powertrains. Besides entire powertrains it is also used to investigate one or a combination of several components specifically . It has also been used in various research activities, in which not the design but the evaluation of specific advanced powertrain behavior was analyzed. A few examples of projects are given below.

1) System Specification

A vehicle with Continuously Variable Transmission (CVT) and Starter-Alternator (SA) was developed using the powertrain tool to determine system specifications. The SA was added to improve fuel consumption and performance. Starting from a desired, application specific Program of demands the complete electric assist system (SA and battery) was specified. Figure 5.21 shows the powertrain layout, the torque boost capability of the SA, and the type of results from simulation.
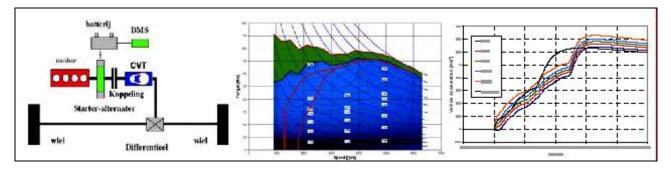
**Figure 5.21: Powertrain with CVT and SA, Torque Boost Capability,
and Results (i.e. the influence of different SA power on vehicle acceleration).**

2) System Specification

As part of the development of a complete vehicle, a series hybrid powertrain was designed and optimized using Advance for several of activities. This involved the specification of the powertrain components (engine, electric machines, and battery) according to performance targets (fuel consumption and acceleration). A second task was design of a powertrain management system that was implemented on the actual vehicle. Figure 5.22 shows several of the development stages.
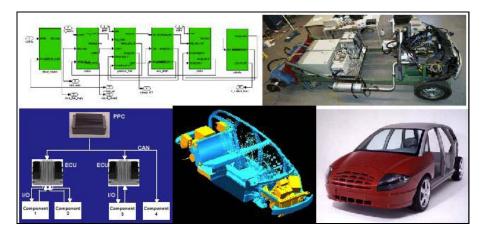
**Figure 5.22: Development Process; Simulation, Test Platform,
Controller Development, Vehicle Integration Prototype.**

3) Development of Test Procedures

In a project for the European Union (MATADOR, 2000) research was conducted on vehicles with advanced powertrains for the development of test procedures. Part of this research involved the analysis of system

behavior by means of computer simulations. For this, models of all electric, various hybrid electric (alo. Toyota Prius, Honda Insight), and fuel cell powertrains were modeled and analyzed. The results have been compared with corresponding measurements on several electric and hybrid vehicles. This validation showed that the simulation models very well predicted the behavior of the powertrains.
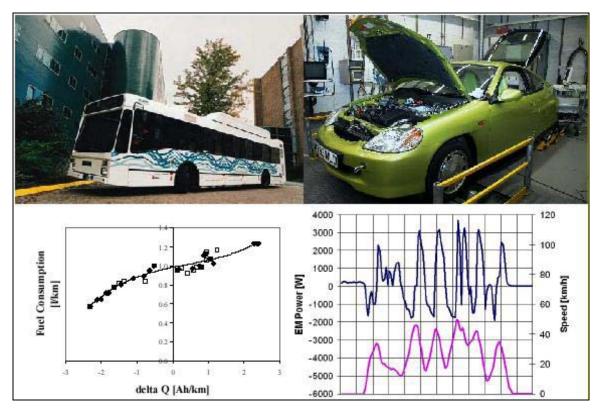
Figure 5.23: Two Hybrid Vehicles and Simulation/Measurement Results.

5.5   FUTURE DEVELOPMENTS

5.5.1   ®^{TM}

The ®^{TM} database and simulation models will continue to be updated as technologies develop and further test data is gathered. Further investigation of power management settings against a wider range of on and off road driving cycles is recommended, to ensure optimum performance across the full range of operational scenarios.

5.5.2   PROSPER

* PROSPER future developments for the electric drive module are mainly based on the use of MATLAB®/ SIMULINK® models for simulation. These developments should include, for the first step, the use of SIMULINK® models of:

  * Electric motors,

  * Batteries.

5.5.3   TNO-ADVANCE

In the previous sections some possible future developments have been indicated. A survey of possible extensions is the following:

1) Suspension Compliance

    The suspension model will be extended with effective compliance characteristics, which can be useful for detailed studies concerning vehicle handling.

2) Rigid Axle Model

    An additional module representing a rigid axle with two or more tires mounted on it will be developed for application in passenger cars as well as in trucks and buses.

3) Steering System Model

    In a modular vehicle model, a detailed steering system cannot be lacking. Because the steering system is quite a complex mechanical system, models of varying complexity can be made. Depending on the type of study to be performed, steering system modules of different levels of complexity/detail should therefore be available. The current direct steering input to the suspension or relatively simple steering system can be seen as the first step.

4) Powertrain Models

    In a powertrain library many different components have to be included. Depending on the type of simulation of application, different levels of detail are desired for the models. Components can be set up as relatively simple quasi static or detail, dynamic models. Several examples of components that will become available with different levels of complexity are the internal combustion engine, electric machine, gas turbines, and fuel cells.

5) Non-Rigid Models

    At this moment, the powertrain modules in the library assume rigid shafts/components. Models describing shaft stiffness, lash, etc. will be added to the library in the future. Other possible developments involve the implementation of the powertrain mounts (engine, transmission) in order to study the effect of powertrain movements on the chassis.

6) Driver Models

    The driver model creates a close-loop-controlled-system. Just like a real driver, the model performs several important tasks, like controlling the accelerator, brake and clutch pedal, as well as shifting and steering. These tasks have currently been implemented as (fixed) control logics. A series of driver models will be useful. These will include simple path following models (speed profile and circuit) which might evolve to self-learning driver models realized through neural networks.

5.6   REFERENCES

[1]   User Manual, LabVIEW^{TM} National Instruments^{TM}, Edition January 1998.

[2]   J. Van Mierlo, "Hybride elektrische drijflijn voor voertuigen: Addendum", Second year Report of IWT Research (930231a), "Hybride elektrische (brandstofcel) drijflijn voor voertuigen", Vrije Universiteit Brussel, Belgium, May 1996.

[3] P. Mauracher, "System-Optimization of the Drivetrain of Electric Vehicles to Reduce the Energy Consumption", Proceedings EVS-13, Osaka, Japan, 13-16 October 1996.

[4] J.W. Biermann, "Innovative Modular Computer Program for Calculation of Vehicle – Longitudinal Dynamics", Conference on Vehicle Dynamics and Power Train Engineering, EAEC N° 91066, Strasbourg, France, June 1991.

[5] J. Swann, "Reduced Energy Consumption and Environmental Impact from Road Vehicles Through the Development and Implementation of Simulation Tools", Summary Report SR3 of WP5 Modeling, Fleets Energy Programme, JOULE (JOE3960031), Fleets Energy Programme, JOULE 95 Motor Industry Research Association Ltd, Nuneaton – Warwickshire, UK, 1998.

[6] T. Walter, "Simulation Program for Electric and Hybrid Vehicles Programme", EC contract JOU2-CT92-200, University of Kaiserslautern, Germany, 1993.

[7] J. Van Mierlo, J-L. Maggetto, F. Van Haelst and H. Van Muylem, "Transparent Simulation for Electric and Hybrid Vehicles", Final Report, JOULE 2 CT92-0200, Vrije Universiteit Brussel, 1993.

[8] E, Rullière, E. Toutain and J.P. Yonnet, "A Simulation Program for Multi Energy Sources Electric Vehicles", Proceedings of EVS-14, EVAA, Orlando, Florida, USA, 15-17 December 1997.

[9] "SIMPLEV®, Simulation of Electric and Hybrid Vehicles", Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID 83415, USA. http://ev.inel.gov/simplev/desc.html

[10] http://www-ee.eng.hawaii.edu/, Department of Electrical Engineering at the University of Hawaii, Honolulu, HI 96822 USA.

[11] http://eve.ev.hawaii.edu/Simulation/HEVST/about.html, University of Hawaii, Honolulu, HI 96822 USA.

[12] http://eve.ev.hawaii.edu/ndc2.html, University of Hawaii, Honolulu, HI 96822 USA.

[13] http://www.swri.edu/, Southwest Research Institute, San Antonio, Texas, USA.

[14] "Development of a Hybrid Vehicle Performance Emissions and Efficiency Model" Final Report, SwRI IR&D Project 03-9788, Southwest Research Institute, San Antonio, Texas, USA, June 1995.

[15] http://www.swri.org/3pubs/brochure/d03/elhybveh/elhybveh.htm, Southwest Research Institute, San Antonio, Texas, USA.

[16] http://www.ctts.nrel.gov/analysis/advisor_doc/advisor_ch1.htm, Center for Transportation Technologies and Systems, National Renewable Energy Laboratory (NREL), Golden, CO, USA.

[17] K. Wipke, "Advisor 2.0: A Second-Generation Advanced Vehicle Simulator for System Analysis", NREL, Goldon, USA.

[18] J. Swann, "Reduced Energy Consumption and Environmental Impact from Road Vehicles Through the Development and Implementation of Simulation Tools", Summary Report SR4 of WP5 Quality,

Fleets Energy Programme, JOULE (JOE3960031), Fleets Energy Programme, JOULE 95 Motor Industry Research Association Ltd, Nuneaton – Warwickshire, UK, 1998.

[19] R. Noons, J. Swann and A. Green, "The Use of Simulation Software to Assess Advanced Power Trains and New Technology Vehicles", Proceedings of EVS-15, AVERE, Brussels, Belgium, October 1998.

[20] J. Swann, "Positioning EVs in the Marketplace", Proceedings of EVS-14, EVAA, Orlando, Florida, USA, 15-17 December 1997.

Chapter 6 – POWER GENERATION, MANAGEMENT AND DISTRIBUTION

6.1 PRIME POWER

6.1.1 Internal Combustion Engine Selection and Design Considerations

6.1.1.1 Diesel Engines

A hybrid power train incorporating an internal combustion engine is comprised of several new technologies (batteries, electrical motors, and power electronics). The differences in the requirements imposed on internal combustion engines employed in conventional and hybrid power trains result in the need for engines intended for hybrid vehicles to be selected, designed or adapted specifically to the purpose. The incorporation of a standard internal combustion engine in a hybrid vehicle would not make use of the full potential offered by hybrid propulsion as a means of clean and efficient transport.

A distinction can be made between two general categories of hybrid power train, i.e. series and parallel power trains.

In series hybrid power trains the internal combustion engine drives a generator, whereby the generator set delivers the average power demand for a journey. The positive and negative power peaks (e.g. acceleration and regenerative braking respectively) are accommodated by a load-leveling device (e.g. high-power batteries). As a result, the size of the engine can be considerably reduced. In addition, the engine no longer drives the wheels directly; as a result the engine can be employed at a limited number of operating points, thus, offering an opportunity to optimize the fuel efficiency and emissions performance at those operating points. The extent to which this optimization is feasible is limited by practical considerations, most of which pertain to the battery.

In parallel hybrid power trains the internal combustion engine is mechanically coupled with the wheels in the conventional manner (i.e. via the transmission). However the power train incorporates an electric machine that can provide additional torque to assist the engine. The electric motor and the engine usually run at proportional speeds, thereby offering an opportunity to uncouple the engine load from the vehicle load to the extent permitted by the electrical system, although the speeds of the internal combustion engine and electrical machine are determined by the vehicle's state. By virtue of this additional electrical power the internal combustion engine can be downsized such that it is largely used in high-efficiency operating areas. The efficiency is further increased by the use of additional features such as idle-stop, idle-launch and boost. An additional efficiency improvement in series-hybrid power trains can be achieved by the implementation of regenerative braking.

The following issues are of relevance to the implementation of internal combustion engines in hybrid applications:

- The general specifications (e.g. the cost, weight, dimensions, power, efficiency, emissions, noise) of the internal combustion engine, depend on the vehicle's schedule of requirements and the selected energy management strategy.

- The engine's operating points (the torque and speed) depend on the power-control strategy and the consequences of modifications to these operating points on the emissions and efficiency (sensitivity).

- The necessity for and feasibility of the optimization of the engine at this/these operating point(s):

  This may include the modification of the injection and ignition systems, the valve timing, and the intake manifold. Only a limited number of operating points are involved and almost no dynamic performance requirements are imposed on the internal combustion engine. As a result, significant improvements can be achieved by the optimization of the engine at these operating points.

- The engine's cooling system.

  Modifications may encompass the re-dimensioning of the cooling system, the integration of the engine cooling system with other systems in the hybrid power train (for the cooling of other components, dissipative electrical braking, etc.), the incorporation of engine and catalyst pre-heating features, and the provision of heating for the passenger compartment when the engine is not in operation.

- The exhaust after-treatment system (type, size, layout).

- The coupling of the internal combustion engine to an electrical machine (durability, vibrations, stability control, mechanical interface, the opportunity to omit the alternator and starter motor).

- Engine start/stop performance (noise, vibrations, turbocharger behavior, thermal management, wear, emissions, and efficiency).

It is evident that an integral approach is unavoidable. It is necessary to possess not only a knowledge of internal combustion engines, but also of real-world operating behavior (representative driving cycles, and worst-case situations), other power-train components (electromechanical components, power electronics, and batteries), and simulation methods (engines, power trains, and control systems).

6.1.1.2   Diesel Engine Characteristics

Diesel engines are characterized by their high fuel efficiency; modern direct-injection diesel engines can achieve full-load efficiencies of 40%. Reliability is also a major factor involved in the decision to employ a diesel engine. However diesels suffer from the disadvantage of high emission levels of nitrogen oxides (NO_x) and particulates (PM); at low air-fuel ratios (usually at high loads) the engine exhibits a tendency to emit high levels of particulates, whilst at higher air-fuel ratios (part loads) NO_x emissions can become a problem. In addition, the abrupt pressure development in the cylinders during the combustion stroke will usually create combustion-noise problems. These problems can be alleviated by the use of modern electronic injection systems and new after-treatment technologies. In view of today's preference for direct-injection rather than indirect-injection engines, the following discussion will review only direct-injection diesel engines.

The combustion process must be controlled to reduce the engine's emissions and noise. This control is affected by the adjustment of the timing and the duration of the fuel injection. A variety of potential systems have been investigated, i.e. electronically controlled distribution pumps, unit injectors and common rail systems. These studies have revealed that the largest reductions in noise and NO_x emissions and the greatest flexibility can be achieved by common rail systems, systems that distribute fuel to the injectors from a rail fed by a high-pressure fuel pump.

The main benefits offered by common rail systems are:

- Their capability of accurately delivering multiple pilot injections prior and subsequent to the main injection;

- The independence of the fuel delivery pressure from the engine speed and load conditions;

- The high injection pressure (up to 1500 bar) results in an appropriate atomization of the fuel, in turn resulting in low particulate emissions.

Although unit injectors (fuel injectors with built-in high-pressure pumps) do not provide for the accurate control of pilot injections, they nevertheless offer the advantage of operation at higher peak pressures as compared to common rail systems (up to 2000 bar).

Diesel and gasoline engines are required to meet emission standards. The future NO_x and PM emission standards listed in the following table (Table 6.1) clearly constitute a challenge for engine manufacturers. Compared with the current European standards, the manufacturers will need to achieve reductions of 60% and 98% in the NO_x and PM emissions respectively if they are to meet the standards for 2008.

Table 6.1: NO_X and PM Emission Standards

	Europe			USA
Year	2000	2005	2008	2007 – 2010
NO_x (g/kWh)	5	3.5	2	0.27
PM (g/kWh)	0.1	0.02	0.02	0.013

It is generally perceived that compliance with the future standards cannot be achieved solely by the implementation of improvements to the engine. For this reason development work is currently in progress on after-treatment systems; for example, particulate emissions can be reduced by the use of a particulate trap which collects and oxidizes these particles to form CO using active systems such as a burner, electric heater, or post-injection in combination with an oxidation catalyst. An alternative for these active systems is a passive system which oxidizes particulates by the use of a catalyst or fuel additives.

NO_x gases can be removed from the exhaust using a de-NO_x catalyst (which needs periodic regeneration; this catalyst is also referred to as 'NO_x storage catalyst'), an SCR system (in which ammonia is introduced into the exhaust stream to react with the NO_x), or plasma-assisted de-NO_x catalysts. Although the last of these systems is still in the development phase the initial results would appear to be very promising. The operating temperature of these catalysts (referred to as the 'light-off temperature') may result in the need for external heating during the start-up phase.

EGR, i.e. Exhaust Gas Recirculation, is an alternative process currently being employed to help reduce NO_x emissions. In this process the (pre-cooled) exhaust gases are mixed with the engine intake air prior to its entry in the cylinder, thereby providing for an effective reduction of NO_x emissions.

In general, although after-treatment systems are effective in reducing the power train emissions they tend to be detrimental to the fuel economy (in particular during regeneration or external heating) and/or to the running costs (because of the need to include an extra material to serve as the catalyst for the required chemical reactions). The reliability and durability of the after-treatment systems currently under development have yet to be demonstrated. Moreover a number of practical problems still have to be overcome, such as the distribution of Ureum for the SCR system and the availability of extremely low-sulfur diesel for the NO_x storage catalyst system in the event that manufacturers decide to introduce these specific technologies.

6.1.1.3   Gas Turbines

The use of Gas Turbines in ground military vehicle is minimal mainly because of the high cost of the turbine and the high fuel consumption as compared to the diesel engine, which thus far has been the most efficient power plant, and the loss of power at higher altitudes, and high speed which requires large gear reduction thus reducing the total system efficiency even lower. Nevertheless the gas turbine has several advantages, which keeps it at the forefront of prime movers whenever there is a new ground vehicle program. The main advantages of the turbine are its weight and its ability to run without any significant cooling system, which normally takes up a large space for the reciprocating engine and takes 10 to 15 % of the prime power to operate the cooling fans and pumps. Furthermore, the gas turbine is relatively quite, thus it does not present the noise or the thermal signature problems of the diesel engine.

The most difficult issue associated with the gas turbine for the military to deal with is its fuel consumption at BSFC (Brake Specific Fuel Consumption) level as high as 0.5 lbs/hp-hr as compared to 0.3 lb/hp-hr for a diesel engine. For a fleet of ground vehicles, the high fuel consumption presents a cost and logistical burden especially that the cost of a gallon of fuel in a battlefield scenario can be as high as $500 or more.

Hybrid applications provide a good opportunity to capitalize on the benefits of the turbine while reducing or eliminating its problems. In a hybrid vehicle the prime mover (engine) has to drive an AC generator to produce electric power and deliver it to the traction motors. The generator size is impacted by its shaft speed. A high-speed diesel engine maximum speed is about 4500 rpm. At this output speed the driven generator must be either large or matched to the engine with a gear reduction. A turbine output speed can be as high as 100,000 rpm and can be matched to smaller and higher speed generator thus reducing the weight and size and eliminating the need for reduction gears.

The fuel consumption penalty of the turbine occurs in the low speed range at part load. At higher steady state speed operation, the turbine can be as efficient as a diesel engine. The hybrid operation allows the turbine to be operated at its optimum conditions at almost constant speed, while the transient modes of operation are powered by the energy storage devices such as batteries. This power split can be used during most of the mission operation thus maintaining optimum fuel consumption while also retaining the low thermal and noise signature, two main characteristics of the gas turbine.

6.1.2   Fuel Cells

6.1.2.1   Introduction

Fuel cells generate electrical energy by an electrochemical reaction (i.e. without combustion). As a result, fuel cells offer a high potential efficiency, and emit exhaust gases comprised solely of water vapor. In contrast to the majority of prime movers, the efficiency of fuel cells is the greatest at partial loads rather than at full load. Consequently, other than is the case with internal combustion engines, it is not beneficial to down-size a fuel cell solely on the basis of efficiency considerations – for example, as a component of a series hybrid system (a relatively small fuel cell and a constant high load, instead of a large fuel cell usually subjected to a partial load). However, since the available fuel cells are still heavy and bulky – and, above all, expensive – many projects will nevertheless deploy a small fuel cell. The expected reduction in weight, volume and price will lead to a trend towards the use of fuel cells as a component of the power train. In view of the use of electricity produced by fuel cells to power vehicles the recuperation of the braking energy will continue to be of interest; this can be achieved by the use of a small battery to serve as a buffer, and consequently these systems will continue to be of a hybrid nature. The inherent inertia of reformers may result in the need for systems employing a reformer to make use of a hybrid power train so as to provide for a rapid response to the

operation of the gas pedal. Fuel cells are often regarded as a potential longer-term (several decades) serious alternative to the internal combustion engine. A number of manufacturers have announced plans to market fuel-cell vehicles within the near future (2003/2004), albeit on a very restricted scale.

Advantages and disadvantages:

- High potential efficiency,
- Low emissions,
- Opportunity to use hydrogen produced from sustainable sources,
- Possibly less maintenance as a result of the absence of moving parts,
- The opportunity to make use of the existing fuel infrastructure in combination with reformers,
- Hydrogen is extremely inflammable, and difficult to store,
- The complete absence of a hydrogen infrastructure for supplies to ordinary vehicles,
- High costs,
- The use of a reformer lowers the efficiency,
- Slow response of the reformer to varying loads,
- The power train can be of a substantial size,
- System integration.

6.1.2.2 Description of Technology

Fuel cells convert chemical energy directly into electrical energy. This process does not involve the Carnot cycle, and consequently extremely high electrical efficiencies (to 80%) are theoretically possible. The fundamental difference between fuel cells and batteries pertains to the fuel and the oxidant. In batteries the fuel and oxidant are stored in the form of a solid or a liquid in the battery (and are regenerated when the battery is charged), whilst fuel cells receive continual supplies of fuel and oxidant in the form of a gas (and sometimes as a liquid) from an external source. Consequently, in analogy with combustion engines, the range of vehicles propelled by fuel cells is determined by the content of the (separate) fuel tank.

Five types of fuel cells are currently in development; the electrodes, electrolyte, and separator/membrane it employs, as well as the relevant fuel cell's operating temperature characterize each type.

Table 6.2 lists the characteristics of the various types of fuel cells. The names assigned to the fuel cells usually pertain to the type of electrolyte.

Table 6.2: Fuel Cell Types

Type	Electrolyte	Temperature °C	Specific Power W/kg	CO_2 Tolerance	CO Tolerance	Reformer Required	Stage of Development
PAFC	H_3PO_4	150 – 200	50 – 100	Good	Fair	Yes	Commercial
AFC	KOH	50 – 80	50 – 100	Poor	Poor	Yes	Demo
PEFC	Membrane*	60 – 90	50 – 1000	Good	Poor	Yes **	Demo
SOFC	ZrO_2/Y_2O_3	800 – 1000	50 – 300	Good	Good	Yes **	Demo
MCFC	Li_2CO_2/K_2CO_3	600 – 650	50 – 100	Good	Good	Good	Demo
DMFC	membrane*	60 – 90	50 – 300	N/A	N/A	No	Lab

* fluorocarbon polymer which is selectively permeable to protons

** the reformer for SOFC and MCFC is much simpler, and sometimes unnecessary

PAFC	=	phosphoric acid fuel cell
AFC	=	alkaline fuel cell
PEFC	=	polymer electrolyte fuel cell
SOFC	=	solid oxide fuel cell
MCFC	=	molten carbonate fuel cell
DMFC	=	direct methanol fuel cell

The characteristic cell voltage of fuel cells varies from 0.5 – 0.8 V at current densities of 0.1 – 1 A/cm^2 (power densities of 0.05 – 0.8 W/cm^2). In general the performance is expressed in terms of the specific power, which ranges from 50 – 1000 W/kg.

Cells are usually grouped together in what are referred to as stacks, in which they are connected together in series to yield DC voltages that can range from 10 to more than 100 V per stack. In general, the term 'fuel cells' is understood to refer to fuel cell stacks. At present hydrogen is still the only suitable fuel for low-temperature fuel cells, and consequently other fuels (methanol, methane, liquid petroleum gas, diesel, gasoline, etc.) need to be converted into hydrogen before they can be supplied to the fuel cell. This conversion is effected using what is referred to as a 'reformer' (discussed in more detail in the relevant section). The gas mixture produced by the reformer (hydrogen, carbon dioxide, carbon monoxide, etc.) must comply with fairly stringent requirements. High-temperature fuel cells can operate without a reformer (natural gas), or at most need a partial reformer (for example, from diesel to natural gas).

6.1.3   Development Stage/Trends

Until now, most attention has been devoted to the development of methanol reformers, since methanol can be converted into hydrogen and carbon dioxide at relatively low temperatures (200 – 300 °C). As mentioned earlier, this technology is now approaching the stage at which it can be employed in vehicles. During the past few years a considerable improvement has been achieved in the conversion efficiency; the initial approximately 50% efficiency had increased to about 75 to 80 % in 1999, whilst levels of 90% are considered to be feasible within a few years time.

A great deal of development work has also been carried out on natural-gas reformers (in particular, on the somewhat larger units for stationary installations). These operate at a temperature of about 500 – 600 °C.

Similar temperatures are also required for the conversion of gasoline, diesel, etc. Serious development work on these reformers was begun by ADL in the USA, in collaboration with Chrysler. This development work has been continued by a separate company, (EPYX), which subsequently merged with De Nora Fuel Cells under the name NUVERA at the beginning of 2000. NUVERA has constructed and tested a power train based on a gasoline reformer. In part as a result of these developments the oil companies have developed a serious interest in fuel-cell technology – and not only from a perspective of the strategic/logistic issues, but also from the perspective of the reforming processes (which find use in oil refineries on a large scale). For example Shell, until recently in collaboration with DBB, is working on the development of its own partial-oxidation technology (CPO). Shell recently published the initial highly promising results achieved by this technology: a catalyst volume of about 100 ml (a 'tea-cup') is enough to produce sufficient hydrogen from gasoline for the needs of a fuel cell capable of producing 50 kW. However, Shell has not yet provided any information about the dimensions of the other components of the reformer (the shift reactor, gas purifier, etc.), as a result, the feasibility of the entire system is not yet apparent. For the purposes of comparison: most reformers currently in development readily require a volume of 50 l for the generation of 50 kW (inclusive of the shift reactor, gas purifier, etc.). The conversion efficiencies achieved in reforming gasoline are of the order of 70%, whilst levels of 80% are considered to be feasible within a few years time.

For the time being development work on diesel reforming is restricted to defense applications (in particular, ships).

Although progress is evidently being made, considerable efforts will still be required for arriving at an efficient, small, light, and affordable system. In view of the relative complexity of reformer/fuel cell systems (in comparison with the use of hydrogen as the fuel), a great deal of research being carried out in parallel with the reformer development work is investigating the feasibility of compact hydrogen storage systems (such as graphite nano-fibers). Consequently, it is as yet anything but certain as to which technology will ultimately be used in vehicles – i.e. either hydrogen, or a liquid fuel in combination with a reformer. Most parties (such as Shell) regard the use of fossil fuels for fuel cells as a transitional phase prior to the ultimate supply of hydrogen to vehicles for their fuel cells.

The efforts of the organizations engaged in the development of reformers are primarily focused on the following issues:

- The reduction of the response time from >10 min. to < 1 min;

- The increase of the specific power (W/kg) by means of the integration of the components;

- The reduction of the costs;

- The improvement of the efficiency.

It is evident that the use of hydrogen as the fuel will require (and certainly during the coming ten to twenty years) the deployment of the centralized reforming of (fossil) fuels (for example, as service stations). This reforming process can be affected in large installations in which issues such as the response time, compactness, etc., are much less critical, and in which higher efficiencies can be much more readily attained.

6.2 ELECTRICAL MACHINES AND POWER ELECTRONICS

Both battery-electric Vehicles (BEV) and hybrid electric vehicles (HEV)and fuel-cell vehicles employ at least one electric motor in the power train. This electric motor converts electrical energy into mechanical energy.

Virtually all types of electric motors can also convert mechanical energy back into electrical energy, i.e. they can serve as a generator. Consequently it is customary to refer to electric motors in the more general term 'electrical machine'. Electric motors are used as generators in hybrid vehicles and in the regenerative braking of BEVs and HEVs. In the latter application the braking energy that is normally dissipated in the form of heat is recuperated and converted into electricity that can be stored by the vehicle, in turn increasing the efficiency of the power train. In theory it is possible to recuperate up to 90% of the braking energy; however current systems are able to achieve the recuperation of between 30 to 40 % of the braking energy, depending on the system that is used. An additional 40% is lost in the event that the recuperated braking energy is reused in the power train. Higher percentages are regarded as feasible in the future by virtue of the development of high-power energy-storage media (flywheels, bipolar batteries, and supercapacitors).

The following table (Table 6.3) lists the various types of electrical machines.

Table 6.3: Classification of Electrical Machines

				Suitable for EVs:
AC	asynchronous (induction)			+
	synchronous	hysteresis		
		reluctance	stepper motor	
			standard reluctance	
			switched reluctance	+
		permanent magnet	stepper motor	
			permanent magnet synchronous motor	
			brushless DC (*)	+
DC	series			
	shunt (parallel)			
	compound			
	externally-excited	field winding		+
		permanent magnet		+

(*)= This AC motor is referred to by this name since the combination of the motor and the control electronics possess the same characteristics as an externally-excited DC motor.

Electric motors cannot be compared directly with each other, since they cannot be considered separately from the accompanying power electronics (together with the associated controller). Table 6.4 lists the advantages and disadvantages of the various types of electric motors that could be used in BEVs and HEVs. When examining this summary it is necessary to take into account the total system (motor and power electronics) because of the great dependency of the two components on each other in a specific design.

Table 6.4: Comparison of Electrical Machines

	top efficiency	efficiency	power density	max. rot. speed	reliability	necessary maint.	development stage	cost of motor	cost of controller	total costs	recycling	use in current EVs	use in future EVs
AC asynchronous	+	+	+	++	++	+	+	+	--	+	+	++	+
Switched reluctance	+	+	++	++	+	+	--	+	-	++	+	0	+
Brushless DC	++	++	++	+	+	+	-	--	--	--	--	+	++
DC independent ex.	--	-	--	--	+	--	++	-	++	++	-	0	0

In the past DC motors (either series, or independently excited) were perceived as the most logical choice for use in EVs in view of their advanced stage of development, their proven reliability, and their low investment costs. However they suffer from the disadvantages of their relatively large dimensions, maintenance requirements.

The asynchronous three-phase electrical machine is a suitable candidate for use in vehicles currently in development, or to be developed in the near future, since this type of EM possesses a relatively high efficiency – an efficiency which also remains high in a relatively large operating range – and a higher power density. The initially greater costs of the power electronics can be recovered by virtue of the energy savings accrued during use and the much lower maintenance costs. Vector control and liquid cooling can achieve a further optimization.

In addition to asynchronous motors, synchronous motors are also eligible by virtue of their greater specific performance and their good efficiency – benefits that are particularly applicable to permanent-magnet motors. Once again, the higher costs can be recovered by virtue of the savings in energy costs and the lower maintenance costs. Synchronous motors with permanent magnets in combination with a special inverter control are often referred to as 'brushless DC motors' – a version usually employed in EVs.

The switched reluctance motor is a relatively new type of motor that makes use of an unexcited rotor and simple power electronics. Originally these motors were employed solely as stepping motors; however they have been developed further in the past few years, and now possess a more constant torque and generate less noise. It is not yet clear whether this type of motor will make a breakthrough and become an alternative form of electric motor for vehicles, although manufacturers are currently studying this possibility.

Permanent-magnet technology can be employed in the construction of very compact generators capable of operation at high rotational speeds required for use in combination with gas turbines. In contrast to the situation with asynchronous motors, the development of permanent-magnet motors is focused on the actual motor rather than on the motor's electronics. Figure 6.1 displays the electric motor trends.

```
                              ┌────────────────────┐
                         ┌───→│  AC asynchronous   │
            ┌────────┐   │    └────────────────────┘
            │   DC   │───┤
            └────────┘   │    ┌────────────────────┐
                         └───→│    Brushless DC    │
                              └────────────────────┘
```
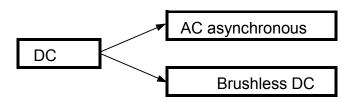
Figure 6.1: Electric Motor Trends for EVs.

When fitted with permanent magnets synchronous motors are ideally suited to installation in the form of wheel-hub motors. The advantages offered by hub motors in comparison with centrally located electric motors are:

- Space-savings in the vehicle (enlargement of the interior space);

- No mechanical differential and drive shafts (increased efficiency and reduced weight);

- Modular construction method possible (facilitates maintenance and repairs);

- Integration feasible with the vehicle's dynamic controls, such as Electronic Traction Control, anti-lock braking systems, and steering adaptation;

- Feasibility of skid steer which eliminates the space taken by the steer angle of Akerman steering, desirable feature for military vehicles.

However a number of disadvantages are also associated with the use of hub motors:

- Increased unsprung weight (reduced comfort and road holding);

- More motors are required, and consequently there is an increased risk of malfunctions – albeit with opportunities for redundancy;

- Neither the use of a gearbox nor simple final reduction gear is feasible (which can be both an advantage and a disadvantage).

Hub motors are ideally suited to use in buses, since they offer an opportunity to construct buses with a low floor over a large surface area. In spite of their complexity and costs it is expected that hub motors will play an increasingly important role in the future. However, it should be realized that a more economical intermediate form between hub motors and a centrally-located electric motor is also possible – in specific applications the electric motors can be located next to the wheels, thereby achieving sufficient savings in space to, for example, nevertheless be able to construct a low-floor bus.

As mentioned earlier, electric motors cannot be viewed separately from their power electronics. At a vehicle scale (power) electronics are also required in the power train of BEVs and HEVs. A number of the most important components are reviewed below:

Rectifier: Converts AC to DC;

Inverter: Converts DC power from the battery to AC power for an AC motor, and the reverse;

DC-DC Converter (chopper): Increases or reduces the DC voltage, for example as a substitute for the vehicle's 12 V battery;

Transformer: Increases or reduces the AC voltage;

Motor Controller: Microprocessor that controls the motor in the appropriate manner;

System Controller: Electronics which convert the inputs from the driver, into vehicle operations such as acceleration and deceleration, the flow of energy from the battery to the motor (speed control), the reversal of the motor's direction of rotation (reversing the vehicle), and the control of the regenerative braking; on-board charger: power electronics unit that ensures that the battery is charged in the appropriate manner; can make use either of induction or conduction.

A large number of developments can be expected in the power electronics field, such as improvements in their efficiency, and reductions in their weight, dimensions and, above all, costs. These costs will fall by virtue of mass production, although this does not necessarily need to be limited to EVs. Controllers or important components of controllers used in other applications will also benefit directly from the reduced cost.

Considerable improvements in the efficiency can still be achieved. In general the efficiency of power electronics can be increased by implementing a reduction in the variation of the voltage. Large fluctuations in the voltage result in higher (peak) currents, in turn increasing the cost of the controllers. The costs of the power electronics account for a substantial portion of the total costs of the power trains of BEVs and HEVs, and they constitute a major impediment to the mass production of HEVs and (to a lesser extent) BEVs. It is expected that these prices will be halved within the next ten years. Furthermore, the weights and volumes of the power electronics should not be underestimated, and the trend is towards increasingly compact units. New technologies (such as IGBT transistors) and integral cooling, in particular, will result in the achievement of higher power densities.

Development tasks pertaining to electric motors and power electronics are:

- Down-sizing, reduction of weight, reduced mass inertia, increased efficiency, lower costs (inclusive of the transmission);

- The achievement of a broad speed and torque range;

- Thermal management;

- The development of cooling methods that will provide for the achievement of increased power;

- Adjustments based on the measurements of acceleration, and regenerative braking;

- Improvements in the reliability and the useful life;

- The provision of electromagnetic compatibility.

Some of these improvements have already been made and implemented in current hybrid electric drive. However, thermal management of the power electronics remains a major concern for vehicle integrators. This is mainly due to the low operating temperature of the power semiconductor devices such as the IGBT (most commonly used switch). Although the power rating has greatly improved over the last ten years reaching voltage levels of 6500 V at 600 A (Eupec), and current levels of 2400 A for 1700 V devices (Eupec, Semikron), the operating junction temperature of the IGBT is 125 °C. To maintain the junction temperature at that level the coolant going into the base plate must not exceed 65 °C leaving a very small margin with the ambient temperature. Consequently the cooling system needed to meet these requirements is quite large.

In addition to the rating improvements, there has been an increase in the efficiency and a decrease in the conduction losses of the device. These improvements have allowed the increase of the voltage and current levels of the IGBTs.

Another major and innovative technique was recently introduced in the packaging of the IGBT switching device. The insulating layers were reduced from five to three, which brought the Silicon at the junction closer to the cold plate and reduced the Δt between the junction and the base plate (Figure 6.2). Consequently the coolant temperature was increased to 90 °C resulting in a reduction of the cooling system size.
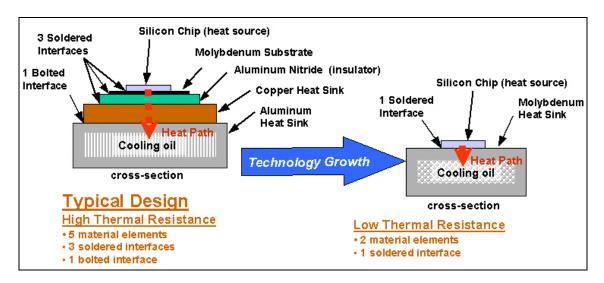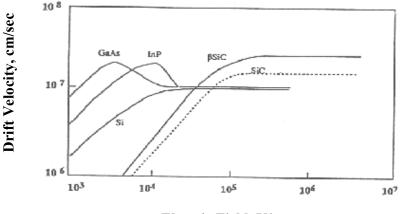
Figure 6.2: Isolating Layers Reduced from Five to Three.

Ultimately, the switching devices that will meet the performance and thermal requirements will be based on wide band gap materials, which can operate at much higher temperatures and high frequencies resulting in a more packageable system for hybrid vehicles. Silicon Carbide (SiC) has been identified in the early nineties as such material.

6.3   EMERGING SiC POWER ELECTRONICS

Silicon carbide, with its robust physical and electrical properties, is becoming an increasingly important semiconductor material in the advancement of high performance electronic devices. Silicon carbide's ability to function under such extreme conditions is expected to enable significant improvements to a far ranging variety of applications and systems. These applications range from greatly improved high-voltage switching for energy savings in electric power distribution for the public and electric vehicles to more powerful microwave electronics for communications to sensors and controls for cleaner-burning more fuel-efficient jet aircraft and automotive engines for the public and military applications. Its high electron saturation velocity, wide band gap, and high thermal conductivity, among other properties, make it highly attractive for high temperature and high-power applications. Much progress has been made in SiC for high temperature and high-power device applications due to the availability of high quality SiC substrates, advances in chemical-vapor-deposition growth of epitaxial structures, and the ability to easily dope the material both *n* and *p* type. The large saturation velocities in SiC are attributable to its larger optical phonon energies. SiC can function well at much higher electric fields than the conventional semiconductors (Figure 6.3).

Figure 6.3: Velocity-Field Relationships of Various Semiconductors. SiC illustrates the superior high-field electron drift velocities and breakdown field of SiC.

In the particular area of power devices, theoretical appraisals indicate that SiC power MOSFETs and diode rectifiers would operate over higher voltage and temperature ranges, have superior switching characteristics, and yet have die sizes nearly 20 times smaller than correspondingly rated silicon-based devices. With its very high thermal conductivity (~5.0 W/cm-°K), high-saturated electron drift velocity (~2.7 E10^7 cm/s) and high breakdown electric field strength (~3 MV/cm), SiC is a material of choice for high temperature, high voltage, high frequency and high power applications. There are many new technological prospects for SiC power electronic devices such as MOSFETS (Metal-oxide semiconductor field effect transistors), Schottky and PiN Diodes. SiC is making fast progress over the past decade. This characteristic makes it ideal for very high performance power MOSFETs since SiC is the only known compound whose native is SiO$_2$. SiC MOSFETs have achieved blocking voltages of 6.1 kV and performance figures increased at and average rate of 75% per year for the past eight years (see Figure 6.4).
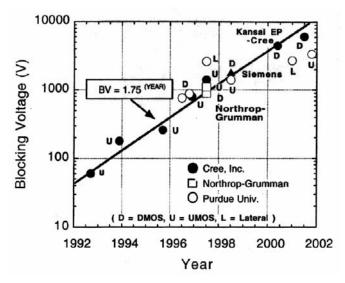
**Figure 6.4: Blocking Voltage versus Year for SiC MOSFETs.
Blocking voltages has increased at about 75% per year since 1992.**

However, SiC MOSFETs are not yet economically competitive with other silicon devices. There are two aspects of SiC MOSFET development that require further improvement. First, inversion layer mobility needs to be increased. This will require minimizing surface degradation due to implant anneals while reducing interface state density, possibly using post-oxidation annealing techniques now under investigation. Second, device size needs to be increased to provide absolute currents in the tens of amps instead of fractions of an amp, and a manufacturability process must be developed that can produce high performance devices with good yield at a commercial cost. Third, oxide reliability at high temperature and high field must be investigated further. Many researchers and scientist are still trying to determine the exact temperature that SiC devices can withstand. Many argue these devices are good up to 175 °C while others say they are good up to 200 °C. To ensure reliability operation, it is safe to de-rate them to 150 °C.

In addition, a 2.4 kV DiMOSFET in 4H-SiC has been successfully fabricated. The devices have a MOS channel mobility of 22 cm^2/V-s and a threshold voltage of 8.5 Volts. A forward voltage of around 2.4 Volts was observed and an on current of 10 Amps was measured for a 0.103 cm^2 device. The turn-on-time of 180 ns and a turn-off time of 220 ns was measured when controlling a current density of 52 A/cm^2 with 1000 volts supply voltage. The fast switching speed and excellent blockage capability of the devices ensure that these devices will enable high-voltage, high-frequency, and low-loss power switching applications, especially in electric vehicle applications.

Power diodes that are made with SiC have a high expectation to show high performance advantages compared with those made with other semiconductors. Fabrication of SiC power Schottky and PiN diodes have been shown to be quite comparable to the conventional technologies. Switching and high temperature measurements prove that SiC power diodes offer extremely low loss alternatives to conventional technologies and show promise of demonstrating efficient power circuits. SiC has an order of magnitude higher breakdown electric field ($2 - 4X\ 10^6$ V/cm) than conventional materials, and an electron mobility only 20% lower than silicon. This high breakdown electric field allows the design of SiC power diodes with 10X thinner and higher doped (100X) voltage blocking layers. The on-state voltage drop of this diode at high current density of 50 kA/cm^2 is 17 – 18 V (see Figure 6.5), PiN diodes are expected to be promising candidates for pulsed power applications for the development of hybrid electric vehicles.
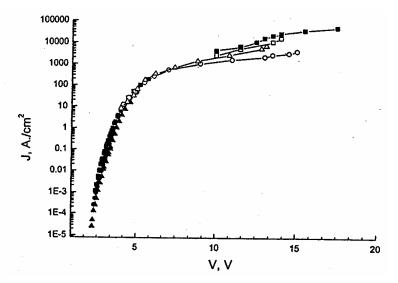
**Figure 6.5: Forward I-V Current Density of 50 kA/cm^2 on Many
5.5 kV PiN Diodes Shows Forward Drop of 17 – 18 Volts.**

Its larger band gap is also expected to result in a much higher operating temperature and higher radiation hardness. Thermal conductivity of n+ SiC is approximately >3.3 W/degree C-cm at room temperature which is 2 – 3X higher than silicon. High voltage Si PiN diodes are restricted to <50 kHz and <120 degrees C, thereby severely limiting the availability of advanced electronic hardware used for utility applications, energy storage, pulsed power, intelligent machinery and solid state power conditioning. The main features of the 4H-SiC PiN high voltage diodes are:

(1) A voltage drop in the on-state comparable to stacked Si diodes at sufficiently high current densities;

(2) Switching speeds that are at least 30 times faster than any of their Si counterparts because of the use of thinner epitaxial layers;

(3) And good high temperature operating characteristics.

In addition, a two orders of magnitude advantage in resistance is expected for Schottky based diodes in SiC over those in Si. This makes them attractive in the commercially lucrative 600 – 1500 Volt range where the Si PiN diodes are used. For voltages above 1500 and up to 3000 Volts, SiC Schottky-PiN hybrid rectifiers like MPS diodes are expected to replace Si PiN diodes used in this voltage range due to superior on state and switching characteristics. Beyond the 3 kV, SiC PiN diodes offer performance advantages over Si PiN diodes due to their fast switching and high-temperature stability. Above the 100 – 150 kHz frequencies, SiC Schottky diodes also become competitive with SiC PiN diodes at any blocking voltage.

A first successful attempt in the demonstration of a >5 kV 4H-SiC rectifier was done using a 4H-SiC n^- epitaxial layer with a thickness of 85 μm and a doping range of 1 to 7E14cm^{-3}. The on-state voltage drop of this diode at high current density of 50 kA/cm^2 is 17 – 18 V (See Figure 6.5), PiN diodes are expected to be promising candidates for pulsed power applications for the development of hybrid electric vehicles.

The design and fabrication of the highest current, 130 A, and highest voltage, 5 kV, for the SiC Schottky diodes show the applicability to many ultra-fast circuits. The measured results for the 5.5 kV SiC PiN diodes at high current densities prove over again that this application is essential for pulsed power applications. In addition, PiN diodes has shown to work at high temperatures up to 300 Celsius and their overall characteristics show enhanced stability at extreme operating conditions.

The capability of SiC PiN diodes for high frequency, low-loss operation at high voltages has been demonstrated at 30 kW in a capacitor charging DC-DC converter developed under the US Army TARDEC CHPS (Combat Hybrid Power Systems) program. The SiC diodes were connected to form a full-bridge rectifier. The rectifier blocked 2.7 kV and switched 12.5 A peak at 100 kHz. Northrop Grumman developed the rectifier, shown in Figure 6.6.
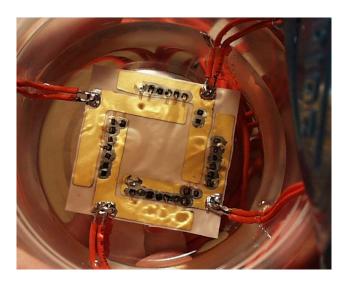
Figure 6.6: 30 kW SiC Bridge Rectifier.

The high-temperature operation of a silicon carbide gate turn-off thyristor is evaluated for use in switching circuits. Ability of SiC components, such as the thyristor, to operate at high temperatures and high power dissipations are crucial factors for their use in future power conversion/control systems. SiC is currently being investigated for the use in electrical power-control systems. Research has demonstrated that SiC gate turn-off thyristors can be used in switching devices in circuits driving resistive loads. This ability of SiC and all components to operate at elevated temperatures and high power dissipations are important factors for their use in future Army power conversion/control systems. For the operation of 600 V and 2 A is shown in Figure 6.7.
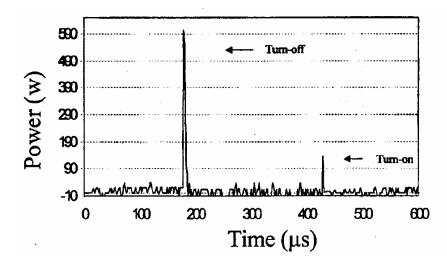
Figure 6.7: Instantaneous Power Dissipation in the GTO During Inductive Switching.

Power spikes of 600 W with full width, half maximum duration of 4 us are produced at turn-off where as spikes of 140 W with full width, half maximum duration of 2 us are produce at turn-on. The switching frequency of 2 kHz produces switching power loss of 5 W on average and conduction power loss of 3 W on average.

6.4   ENERGY STORAGE

6.4.1   Battery Energy Storage

6.4.1.1   Introduction

In a rechargeable battery (accumulator), chemical energy is converted directly into electrical energy, generally speaking by means of the "fuel" and "oxidant" present in the battery. In the lead acid battery, for example, the fuel is lead and the oxidant, lead dioxide. The reaction products of the electrochemical conversions in the battery (in the case of the lead battery, this is lead sulphate) are converted back into fuel and oxidant by applying a voltage (the charging of the battery). Because, in general, the battery also functions as a reservoir of fuel and oxidant, when used in an electrical vehicle, the amount of energy (expressed in kWh/kg), and consequently the range of the vehicle, is limited. More than 10 types of batteries are under development for hybrid and electric drive vehicles. The stage of development of these batteries varies from the laboratory phase (e.g. various types of lithium batteries) to commercially available (lead-sulphuric acid traction batteries).

The typical cell voltage of an electrode pair in a battery ranges from 1 to 4 V. Battery stacks of 6, 12 or 24 V are usually made by connecting cells in series. Series connection of larger numbers of cells, leading to higher stack voltages is, however, common.

Most batteries consist of what are known as monopolar cells, that is, the electrical connection between the positive and the negative plate takes place around the outside in series connection. This means that the electrical current must flow through the whole plate of the connecting strip. Consequently, the specific power (kW/kg) is limited, due to the necessary electrical conductors. By switching over to bipolar cells (the plate is positive on the one side and negative on the other, so that no separate conducting strips are required around the outside) much higher specific powers can be achieved (with more or less equal or slightly lower specific energies). The bipolar battery sets higher requirements with regard to sealing because there may be no contact between the electrolytes in the various cells. The bipolar battery is still at a relatively early stage of development.

In the development of batteries for BEVs, the emphasis has traditionally been on achieving a high specific energy (high energy content for sufficient range). These are usually monopolar batteries. Because the number of batteries necessary to achieve an acceptable range is relatively large, the (limited) power requirements of the vehicle are often automatically met. Since flywheels and super capacitors have a very low specific energy (compared with most types of batteries) they are less suitable for BEVs.

The battery requirements set for HEVs are totally different. In this case, the power usually determines the battery specifications to be delivered during acceleration and absorbed during braking, rather than the energy content. Bipolar batteries (and also flywheels and super capacitors) may be more suitable than monopolar batteries, although with the latter (wound) systems with thin electrodes, high specific powers are feasible.

In order to arrive at a sufficiently long life, the method used for charging the battery (from the mains or in the case of hybrid drive, from the on-board generator or by braking) is very important. There are large differences between the various types of batteries in this regard.

The electrical energy efficiency (as a result of losses during charging and discharging) of batteries depends to a large extent on the correct dimensioning and good coordination with the rest of the system. If these factors are optimal, efficiencies of 80% or more are feasible.

6.4.1.2   State of Development/Trends

As a result of the considerably increasing interest in (hybrid) electric drives and the accompanying increases in budgets (e.g. USABC with a budget of USD 300 million for battery development in 4 years) in the nineties, considerable advances have been made in the development of the promising types. This particularly applies to lead-sulphuric acid, nickel-cadmium, nickel-metal hydride and lithium battery types (Li-Ion and Li-polymer), which have been developed, and are still being worked on by many companies and institutes. Although the lead-sulphuric acid battery is, in fact, the least suitable battery for BEV application, due to its low specific energy which results from thermodynamic limitations, it is still being used a great deal, because of its low price and good availability. In addition, a reasonable amount of effort is being put into work on the sodium-nickel chloride battery and the zinc-air battery, although only 1 to 2 companies are working on each type respectively.

All of the above-mentioned types of batteries have been tested in demonstration vehicles with varying degrees of success. Despite all developments, it has become apparent that meeting the requirements set by the USABC with regard to the range and life of BEVs, is very difficult. Consequently, legislation in California has been relaxed with regard to the forced introduction of ZEV (zero emission vehicles), which has led to a considerable reduction in the efforts put into the field of BEV development and the batteries considered suitable for BEV. Large car manufacturers such as Daimler Chrysler and Honda have announced that they are discontinuing their efforts while many demonstration projects have now been terminated.

As a result, growing interest in HEVs has become much greater (no range problems, plus a high efficiency and low emissions) and focus has shifted to the batteries with a high specific power (1000 W/kg or higher) and high energy density. Attention has been concentrated particularly on lead-sulphuric acid, nickel-metal hydride and lithium-ion batteries. Lead acid batteries provide reasonable power density with relatively low energy density and is the most affordable type of batteries. High power, high energy density nickel-metal hydride batteries have been used in the Toyota Prius and the Honda Insight. While the Li-Ion batteries has been installed in some military vehicle demonstrators in the US and a in a commercial bus and a Toyota VITZ in Japan.

A general trend in the field of batteries is that, in addition to the lead-sulphuric acid battery which will continue to exist for a long time yet, and possibly also the nickel-cadmium battery, in the short and medium-long term, the nickel-metal hydride battery and the Li-Ion batteries are the most promising types, and in the long term, lithium-polymer battery will become a viable candidate. This trend started much earlier in consumer applications (portable equipment) in which, incidentally, contrary to the nickel-cadmium battery, the lead-sulphuric acid battery has never been used. In 2001 a European proposal to ban nickel cadmium batteries was, for the time being, rejected.

6.4.1.3   Li-Ion Batteries

The introduction of rechargeable lithium-ion cells suitable for the industrial market opens new possibilities for maximum battery performance in demanding applications. Lithium-based batteries offer the most long-term potential for commercially practical full-range electric vehicles (EVs) and hybrid electric vehicles (HEVs) because of their outstanding electrochemical characteristics. The electrochemistry consists of a carbon negative, a liquid electrolyte typically made up of carbonate solvent and $LiPF_6$ salt and a metal oxide positive. Lithium-ion batteries with a liquid electrolyte promise to fulfill the energy storage requirements for traction applications in the near future. They can achieve higher specific energies than lead and nickel based technologies. In EV designs, specific energies greater than 100 Wh/kg appear to be achievable, and peak specific powers in excess of 1000 W/kg have been reported for HEV designs. Its characteristics make the

lithium-ion battery an attractive energy-storage device for efficient operation of hybrid electric vehicles supplying the high power bursts demanded by vehicle acceleration and capturing those created by the release of regenerative breaking energy. Lithium-ion battery technology offers several advantages over the present state-of-the-art technology. Two important advantages are (1) the improvement in safety over rechargeable batteries using solid lithium as the negative electrode and (2) the high cycle life of hundreds to thousands of charge-discharge cycles.

The following tables (Tables 6.5 and 6.6) gives specifications of several types of batteries for two applications.

Table 6.5: Battery Specifications for a 320 V, 50 kW Peak System

Battery Chemistry	Specific Power [W/kg]	Specific Energy [Wh/kg]	Mass [kg]	Volume [dm^3]	Cost [kUSD]
Pb-A	70 – 380	28 – 32	110 – 707	46 – 320	8.1
NiMH	139 – 900	33 – 54	91 – 240	53 – 106	13 – 100
NiCd	200	14	600	490	15
Li-Ion	1150	66	90	88	465
Li-polymer	521	45	–	–	–
NaNiCl	325	>20	158	118	165

Table 6.6: Battery Specifications for a 560 V, 170 kW Peak System

Battery Chemistry	Specific Power [W/kg]	Specific Energy [Wh/kg]	Mass [kg]	Volume [dm^3]	Cost [kUSD]
Pb-A	70 – 223	30 – 36	1044 – 1900	475 – 2900	11 – 14
NiMH	205 – 800	54 – 66	380 – 984	230 – 450	28 – 100
NiCd	200	14	900 – 1500	260 – 532	64
Li-Ion	300 – 690	145	135 – 710	58 – 455	120
Li-polymer	521	45	204	456	–
NaNiCl	169	94	1000	1944	95

Good management of the battery is essential in both BEVs and HEVs in order to provide maximum performance in combination with an acceptable battery life.

The safety aspects of batteries are also critical. They include:

• Protection against overcharging;

• Collision proof etc. (shock tests, drop tests, behaviour in water, in event of fire etc.);

• Formation of hydrogen/oxygen (during charging) and other emissions;

• Consequences of (high) DC voltages (up to approximately 1000 V).

6.4.1.4   Availability and Price

Only lead-sulphuric acid batteries and nickel-cadmium batteries are commercially available. These primarily concern the types which have been developed for BEV application. The price of lead-sulphuric acid batteries is below EUR 10/kWh, while nickel-cadmium batteries usually cost more than EUR 500/kWh. Nickel-metal hydride batteries are slowly reaching the stage of commercial availability, although they are still very expensive (>>EUR 500/kWh). The USABC objectives for BEVs are usually used as guide numbers. Despite the fact that development in this framework has already been taking place for a number of years (primarily for BEV) there is still no indication in sight that these prices will be achieved, all the more because the large-scale application of BEV is more or less off the agenda. The prices most recently predicted for mass production all exceed EUR 200/kWh, which is considerably higher than USABC's mid-term and long-term objectives (EUR 150 and EUR 100/kWh, respectively).

The cost targets for HEV batteries vary greatly depending on the source. Values of EUR 500/kWh are given as the upper limit in a number of cases; lower values are also mentioned. The fact that the acceptable price is higher than that for a BEV is because the number of kWh installed in an HEV is much lower than in a BEV (typical values are 2 – 5 kWh for an HEV and >= 20 kWh for a BEV). So far, the BEV lead-sulphuric acid and nickel-cadmium batteries, which perform best with regard to specific power (maximum 200 – 400 W/kg), have primarily been used for application in HEVs. The nickel-metal hydride battery was taken into production by Panasonic when the Toyota Prius went into production and, more recently, the Honda Insight. This battery has a significantly higher specific power (up to 800 W/kg), but is much more expensive (estimated price is between EUR 2500/kWh and EUR 5000/kWh).

6.4.2   Supercapacitors

In electrical terms, supercapacitors are standard capacitors with an internal structure and materials of construction that yield a capacity of 1000 to 3500 Farad. The rated voltage is in the order of 2.5 V, resulting in the storage of energy in a range from 3 KJ to 10 KJ. The power density is in the range between 0.7 – 1 kW/kg.

These figures are applicable to discharge from the maximum voltage to half the maximum voltage within 6 to 8 seconds, where the discharge efficiency is on average 85%. The literature often cites higher figures for the energy density; these higher figures are applicable to higher currents, when the discharge efficiency is between 50 and 60 %. Another problem with the figures cited in the literature is that these figures are all applicable to different circumstances, as a result of which comparisons are of less significance.

As a result of the low internal resistance of 0.5 – 1 mΩ the energy can be charged or discharged with a high efficiency, even at high power. However the efficiency is significantly lower if the voltage drops to half the rated voltage. Consequently supercapacitors are usually not discharged further than to half the rated voltage, a level at which three-quarters of the stored energy is released. The maximum current is in the order of 300 – 500 A, as a result of which they can be discharged to yield an average power of 500 W per capacitor. Consequently the power/energy ratio is much higher than that of batteries, as a result of which supercapacitors are ideally suited to use in hybrid vehicles.

Supercapacitors can withstand more than 500,000 charge-discharge cycles, and consequently exhibit a much more linear performance than batteries. Moreover their performance does not decrease significantly at low temperatures to minus 40 °C, and for this reason supercapacitors are a serious alternative to batteries for use as an electrical-energy buffer in hybrid vehicles.

Supercapacitors can be employed either passively, when the DC voltage of the system depends on the state-of-charge of the capacitors, or in combination with a DC/DC converter, when the DC voltage is independent of the state-of-charge. The latter option simplifies the control of the system, but also increases the cost and the weight of the system.

The aforementioned data are applicable to double-layer supercapacitors, which is the most common type.

6.4.2.1   Cell Balancing

As a result of the low voltage per capacitor supercapacitors are always used in stacks, for example 20 for a 42 V system. It is important that all supercapacitors possess equal voltages, for which purposes a special balancing system is required. This balancing system is a relatively simple electronic unit which dissipates energy from supercapacitors with an excessive charge, or which transfers energy from one capacitor to another.

6.4.2.2   Efficiency

The internal resistance of supercapacitors needs to be as low as possible if the highest efficiency is to be achieved. Since the other properties of different makes of supercapacitors are comparable, the internal resistance is the most important factor involved in the selection of the suitable supercapacitors for a given application.

6.4.3   Combinations of Supercapacitors and Batteries

Supercapacitors can also be combined with batteries. The combination can be passive, when the supercapacitors are connected in parallel to the battery; as a result the battery will not be exposed to high-frequency pulses, thereby increasing the life of the battery.

Alternatively, the supercapacitors can be connected to the battery via a DC/DC converter, in which case the power flow to the supercapacitors can be controlled. This offers the opportunity to implement a control strategy focused, for example, on the optimization of the battery life, or the system efficiency, or the lowest lifecycle costs. However the inclusion of the DC/DC converter considerably increases the cost and the weight of the system.

6.5   HYBRID POWER MANAGEMENT

A trend becoming apparent with conventional vehicles is the move towards the monitoring and control of multiple functions in the vehicle, whilst taking account of their mutual interactions. This is what is referred to as 'system management' which is essential for HEV. Consequently a great deal of effort and research in the field of systems management is still required for the development of an optimum monitoring strategy which ensures the optimum performance of all the vehicle's functions in a broad variety of situations. All components will need to be harmonized with each other, both in terms of their functions and operating methods. The benefits that can be achieved with HEVs, and to a lesser extent with BEVs, depend largely on the approach adopted towards their control strategy.

System management encompasses both hardware and software issues:

Hardware: Monitoring and control electronics both for individual and mutual components, whereby the mutuality is intended to arrive both at the improved collaboration between the components and the integration of the components.

Software: The control of the individual and mutual components, depending on the signals from the surroundings, the driver, and the vehicle.

At the component level the primary control is often affected by the component's own controller. Internal combustion engines are equipped with a motor management that, for example, monitors, controls and directs the ignition and the injection of the fuel. An electric motor is controlled by its power electronics (for example, a voltage and a frequency controller). Often as many standard components as possible are selected during the development of an HEV, resulting in the integral adoption or, on occasion, slight modification of the frequently inseparable component-controller combination.

The level above the individual components is the level of collaboration between two components, such as the interaction between a catalyst and an internal combustion engine, or a generator and an internal combustion engine in the generator set of a series HEV.

However the situation is more complex at a vehicle level. A central computer monitors and controls a large number of diverse components, whereby major differences may also be exhibited in the relationships between the various components. This can result in the creation of an extremely complex network encompassing the battery management, the vehicle's voltage control system, the control of the internal combustion engine, the regenerative breaking, the ABS, and a large number of other functions. This inter-mutuality is, in particular for an HEV, much more pronounced than for an ICEV. This communications network can, for example, be implemented using a CAN bus that provides for the mutual exchange of data between different components.

The quantity of electricity on board EVs is restricted. Consequently any demand for a great deal of additional electricity for the vehicle's accessories, heating, lighting, control units and similar will be detrimental to the overall performance of the vehicle. This has resulted in a much greater need to develop energy-efficient components for EVs as compared to conventional vehicles. Examples of energy-efficient components are heat pumps for the air-conditioning, low-energy electrical power-assisted steering, heat reservoirs for the cooling water, heat-reflecting windows, gas-discharge lamps, etc. To address the ever-increasing demand of the electrical power onboard the ground military vehicles, high energy density storage devices are critical to meet future vehicle requirements. The power management and distribution system takes into account the available amount of energy, its depletion and recovery strategy based on a well defined and prescribed duty cycle. This must be accomplished under a system control strategy developed for the vehicle mission(s). This strategy must ensure that the hybrid power train delivers the required performance in the most diversified circumstances. At the same time, the strategy must also take account a large number of requirements, conditions, and restrictions.

The following list gives an indication of the issues to be taken into account in the control strategy for a series HEV:

- There are 24 different system states (each with a different direction of the flow of the power current) applicable to a series HEV's power train.

- The internal combustion engine must be turned on and off as little as possible, a requirement which is extremely stringent for gas turbines. For a diesel engine the frequent on and off operations results in an excessive NO_x emission especially when the engine is hot.

- A control strategy is almost always based on the instantaneous energy content of the battery, i.e. the State-Of-Charge (SOC). However the measurement of the SOC is not simple. Changes in the

energy content depend on factors such as the temperature (thermal management), and the manner in which the battery is charged and discharged.

- Electric motors can be overloaded. However both the extent to which they are overloaded and the duration of the overload depends on the cooling, the ambient temperature, the power electronics, and safety issues.

- All components must comply with the requirements for electromagnetic compatibility (EMC).

An example of the Power management and Distribution system is shown in Figure 6.8. This system was developed under the US Combat Hybrid Power Systems (CHPS) program. The power management consists of two power sources, a prime mover (Diesel engine, turbine etc.) driving a generator and energy storage system (battery). All the power generated is placed on a DC bus through PWM rectifier and system controller. The power delivered to traction motors also goes through the PWM motor inverters and the main controller to match the load requirements as commanded by the operator. The power generating and distribution station receives commands from the vehicle operator to deliver power on a continuous basis to various auxiliary systems such as propulsion, thermal management, and other continuous loads, or to the high pulsed power loads such as an ETC gun or EM armor. The power is delivered either simultaneously or in accordance to a precedence strategy as required for a particular mission.

Both the prime mover and the energy storage system provide the required power in the appropriate form according to the architecture software that regulates continuously the power split between the two sources.
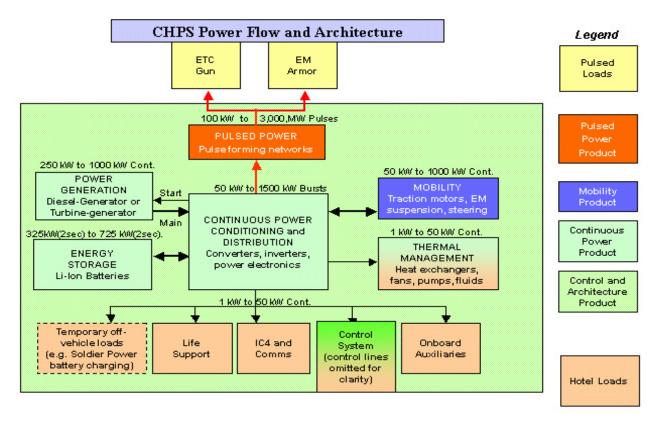
Figure 6.8: Power Management and Distribution.

6.5.1 Development Stage/Trends

The first steps have been taken towards system management and have also been demonstrated in some military vehicle prototypes; however in view of the complex nature of the problem a lot of work is still required. The present HEV prototypes certainly do not represent the ultimate power management. The results achieved in the vehicle's emissions, use of energy and drivability are not as good as predicted from simulation studies.

The success of HEVs, in particular, will largely depend on the extent to which success is achieved in the endeavors both to develop reliable and affordable control systems and to arrive at the integration of and communications between the various components of the power train for maximum efficiency and reliability.

6.6 THERMAL MANAGEMENT

The introduction of advanced traction motors and controllers have added new technical challenges to the thermal management of ground vehicles. The critical temperatures of magnetic materials and the silicon based power devices are the main criteria for the design of the cooling system. The coolant temperature must be maintained at a much lower level (65 °C) in order to keep the Si semiconductor devices (IGBT) from failing. Similarly, the permanent magnet motors which are desirable for traction because of their high efficiency must also be cooled below the temperatures at which they can partially demagnetize. These temperatures for magnets operation range between 140 °C and 180 °C.

6.6.1 Mobility Requirements

Military vehicle must be able to operate anywhere in the world, under extreme environmental conditions, from desert soft soil to hilly cross-country travel over rough terrain for long periods of time with little or no maintenance. The most critical mobility requirements under these conditions are:

- Vehicle top speed,
- Vehicle cross country speed,
- Gradeability (60%),
- Steering,
- Braking,
- Acceleration.

Figure 6.9 Shows the torque speed curve with emphasis on some severe conditions the vehicle can encounter. To normalize the loads under these conditions, we use the tractive effort to weight ratio TE/WT.
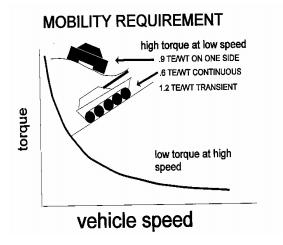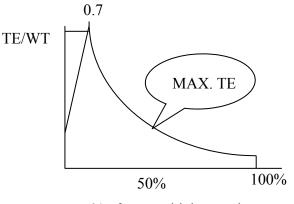
Figure 6.9: TE/WT vs % of Max Vehicle Speed.

Most of the losses in the power train occur during low speed high torque conditions during either transient or continuous operations. The traction motors and their controllers under these conditions must be able to withstand temperatures of 200°C without demagnetizing and without shutting off the system. The current electric drive vehicles using permanent magnet motors have thermal limitations well below the desired levels. The traction motors are designed to operate at a maximum of 150°C while the coolant temperature of the power electronics does not exceed 65°C. Thus, currently vehicle designers are faced with the burden of integrating at least two cooling circuits, one for the prime mover and the traction motors using probably oil for coolant, and one circuit for the power electronics using water ethylene Glycol. That by itself jeopardizes the space claim for the powertrain in addition to the cooling system size dictated by the relatively low temperatures for both the motor and its inverter.

6.6.2   Cooling Requirements

Military vehicles cooling systems must be designed such that under a continuous load of 0.7 te/wt all the components can operate without exceeding their thermal limits. This requirement is better described in Figure 6.10. Which shows the cooling envelope that defines to a certain extent the cooling system.

Figure 6.10: Cooling System Must be Designed for Continuous Load of 0.7 TE/WT.

Under these conditions, the vehicle can climb a 60% grade continuously and in the case of a wheeled vehicle continuous down hill braking on a 15% slope is feasible.

These cooling requirements are met by most of the current fleet vehicles. However, they do present a great challenge to the vehicle designer due to the limited space available for the needed cooling system. For electric drives, the challenge is a lot more complicated and more difficult to overcome.

6.6.3   Electric Drives

Electric and hybrid electric military vehicles must meet all the mobility and cooling requirements described in paragraphs 2 and 3. The electric drive system using advanced power semiconductors and advanced batteries such as NiMH or Li-Ion is capable of generating and delivering to the wheels or sprockets the required torque and speed which under steady state conditions does not present any challenges. Under increased loads the operating temperatures of the motor and particularly the power electronics can exceed their limits much faster than the mechanical systems due to their low tolerance level. For the traction motor the AC induction is more tolerant of temperature increase and can recover in a reasonable time, but for the more efficient Permanent magnet DC brushless type motor, the magnets on the rotor can loose their properties at elevated temperatures and will get partially or totally demagnetized if their temperature approaches the Curie temperature. (Curie temperature Neodymium Iron Boron is 310°C).

Permanent magnet designers have to select the magnet that will provide the required torque within the space constraints in the vehicle. In this effort, they must evaluate the trade-off between the energy product and the operating temperature that a reasonably sized cooling system can maintain. In order to get the highest possible torque and still operate at temperatures higher than 140°C the magnet must be limited in field intensity (H kOe) which imposes another restriction on the gap between the stator and the rotor.

Figure 6.11

The situation is a lot worse for the power devices as most Silicon based semiconductors have a limited junction temperature of about 125 – 150°C which dictates a coolant temperature at the base plate of no more than 65°C. In order to maintain such a low coolant temperature, the coolin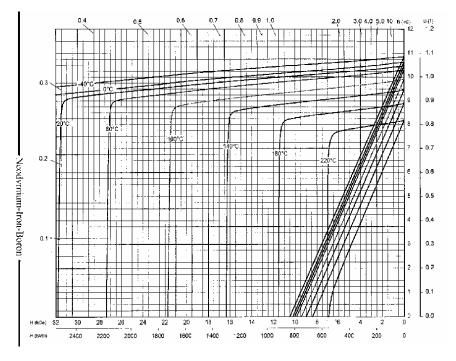g system will exceed its allocated space in the vehicle. To correct this situation, two solutions are being pursued. The first one would be to repackage the power devices so that the silicon is closer to the cold plate; the second is Silicon Carbide development with reasonably sized wafers free of voids and "micropipes".

Silicon carbide (SiC) is the most promising new semiconductor material for power devices in the near future (5 years) provided that material-related problems can be solved. Its wide-bandgap gives it the potential to operate at much higher temperatures than silicon devices, and its thermal conductivity is about 2.5 times greater. Associated with its wide-bandgap is an avalanche breakdown field about 8 times higher than silicon. This allows devices to operate at much higher voltages or electric fields. These properties may lead to a silicon carbide power device capable of operating at high temperatures and high switching rates with much lower losses than silicon devices, in the medium (1200 V) to high voltage range (>2500 V). Such devices would have significant performance advantages over silicon devices for traction and high power supply applications.

The wide band gap of silicon carbide, 3.25 eV for 4H-SiC vs. 1.12 eV for silicon, dramatically reduces the thermal generation rate of free carriers. The following equation describes the intrinsic carrier concentration (n_i) as a function of bandgap (E_g) and temperature (T in °K):

$$n_i \cdot N_s \, T^{3/2} \cdot \exp(-E_g/2kT),$$

where k is Boltzmann's constant. The temperature at which junctions become intrinsic and lose their blocking capability ("wash-out") is about 200 °C for silicon and above 900 °C for silicon carbide. Leakage current is also significantly less in SiC. Leakage current in SiC at 600 °C is on the same order as leakage in silicon at 175 °C. This high temperature capability has been partially realized. Prototype SiC thyristors and diodes have operated reliably at 500 °C.

Currently, MOS structures have not matured, and reliable high-temperature silicon carbide power MOSFETs and IGBTs are not yet available, but significant progress has been made on silicon carbide GTOs, JFETs, and rectifiers. Cree Research Inc. has reported 2.5 kV thyristors which have switched 12 A, and 12.5 kV rectifiers.

Significant developments in material growth and processing, device fabrication techniques are still required. The most significant problem is micropipe defects. These are "killer" defects, which occur, in high concentrations in SiC wafers; on the order of 10 – 50 per cm^2. Selected wafers have been seen with large micropipe-free areas. Using selected material, Cree Research, Inc. has been able to fabricate Schottky diodes with 1 cm^2 area, capable of 300 A operation. However, for an acceptable yield using currently available commercial-grade material, devices must be limited to about 1 or 2 mm^2. SiC devices of this size are rated at about 5 – 10 amps. Significant progress has been made in increasing wafer size. Two-inch diameter wafers are commercially available, and three-inch diameter wafers have been demonstrated in-house.

Almost all SiC device developers have attempted to overcome the current limitation by paralleling devices. These attempts have been successful to an extent, but the drawback of this approach is higher costs of material and fabrication.

The cooling system must be sized to keep the temperatures below their upper limits for all the components within a working system. It is desirable that one common cooling system handles the cooling loads for

the prime power i.e. engine/generator and the electric drive train including the energy storage system. Currently the batteries used in hybrid applications are air cooled by forced convection. The traction motors are liquid cooled by either oil or Water Ethylene Glycol (WEG) because of their low operating temperatures. Development of SiC based power devices will allow in the future to use one common coolant for the prime power, the motors and the power electronics, thus reducing the cooling size and capacity.

Thermal management is critical for military applications because of the harsh conditions the vehicles operate under. The thermal load during some transient modes of operation can shut down a vehicle system in few minutes if the cooling system is inadequate to handle such loads. In order for electric and hybrid electric drive systems to be viable for future military vehicles, permanent magnet materials must be able to operate at temperatures close to 200°C especially if the SiC materials are developed to the level needed for high power devices (1000 amps and 1500 volts). Once these developments are realized, then hybrid electric with its high payoffs will greatly support the mission of future combat and tactical vehicles.

6.7   INTEGRATION

Integration of the various components into a system is done at two levels. First level integration is done in a system integration lab where the components are assembled and connected so they can function according to a control strategy as they would in a vehicle. This preliminary type of integration is not restricted by the sizes and weights, as is the case in a vehicle. This part of the integration is very important as it provides an early assessment of the components viability in a system environment. It also provides an opportunity to test the technology and verify the models that preceded the hardware design. The second level of integration is into a vehicle within the weight and size constraints and according to the design concept; which dictates the packaging of the components and subsystems in the available space.

Example of vehicle integration is shown in Figure 6.12.

Figure 6.12: Virtual Prototype of Hybrid Electric System.

For a hybrid electric combat vehicle, integration includes propulsion system, gun system and armor. Each of these systems includes other subsystems that must also be integrated within the available space, which is very limited. For a C130 transportable vehicle, the available space a power train should be designed to is approximately 2.5 m^3. This space must include at a minimum the prime power, the power generating and distribution station, the controllers, the cooling systems, and the pulse-forming network. For a wheeled vehicle it is desirable to move the traction motors outboard and free the inside of the chassis for other components. Therefore in-hub pancake type motors are among the preferred candidates for wheeled vehicles. The same types of motors are also suitable for in-sprocket installation in the case of tracked vehicles.

Chapter 7 – AECV PERFORMANCE

7.1   BACKGROUND

The Engineering and Automotive Performance tests were conducted on two series HE-HMMWV conversions at the request of the Tactical Technology Office of the Defense Advanced Research Projects Agency (DARPA). The program was managed for DARPA by the US Army Tank-Automotive Research, Development and Engineering Center (TARDEC).

Testing consisted of a series of controlled engineering performance tests designed to measure vehicle performance under a variety of environmental extremes. Tests included vehicle characterization (weights and measures), acceleration, sustained speeds, tractive effort, gradeability, and fuel economy determination over a wide variety of terrain profiles and duty cycles. Hybrid vehicle performance was compared to conventional HMMWV performance where appropriate using a combination of historical data and side-by-side testing. Both vehicles were tested at the US Army Aberdeen Test Center (ATC).

7.2   TEST OBJECTIVES

The overall program objectives were to characterize the automotive performance of two series HE-HMMWV conversions with specific attention focused on fuel consumption, driveline power, efficiency, and overall vehicle ground mobility. Evaluation of potential mobility and agility improvements associated with individual wheel driven propulsion systems was also conducted. Furthermore, the hybrid electric demonstrators had been tested only on paved roads and on a limited basis. These tests were to provide information on the operation of the various components (Motors, controllers and batteries) in a military environment to verify the validity of the design approach or revise it as needed to meet the mobility requirements discussed in this report.

7.2.1   Description of Material

Two hybrid HMMWVs were used in these tests, one with two traction motors and one with four traction motors (one motor per wheel placed on the axles). The engine selected for prime power was the Volkswagen Industrial Engines AFD 1.9 l water-cooled, four cylinder, in-line, diesel engine with direct injection, turbo-charger, intercooler and oxidation catalyst (see Figure 7.1). The engine develops a maximum output of 66 kW (88 hp) at 4000 rpm. The generator selected was the Unique Mobility SR218H brushless DC motor operated in regenerative braking mode. The generator is rated at 32 kW continuous power and 55 kW peak power. SWRI test results of the APU show a peak efficiency of 33.2 percent at 25 kW and 30.7 percent at 55. The batteries were lead acid at 80 amp-hr and roughly 40 w-hr/kg.

Figure 7.1: Hybrid HMMWV Engine/Generator.

The test vehicles were the PEI HMMWV and CTC HMMWV in reference to the contractors who converted the two HMMWVs into hybrid electric. These vehicles will be referred to in the rest of this report as Vehicle 1 and Vehicle 2.

7.3   TEST SUMMARY

7.3.1   Vehicle 1

7.3.1.1   Physical Characteristics

Vehicle 1 was tested at a gross vehicle weight (GVW) of 8150 pounds. A 2416-pound (3696.78 kg) increase in the vehicle's curb weight was noted when compared to a standard M1037 HMMWV. An increase in the envelope dimensions of the HE-HMMWV was also noted when compared to the conventional M1037 HMMWV. A height increase of 5.2 inches (13.208 cm) was noted as a result of the body lift required to accommodate the Auxiliary Power Unit (APU) and the traction battery pack. A reduction in the center of gravity (CG) height was noted when compared to the standard HMMWV. This was attributed to the placement of the lead acid traction batteries and the removal of the conventional engine, transmission, and transfer case. The measured initial traction lead acid battery pack capacity was 50.94 ampere-hours (amp-hr). This was significantly less than the advertised battery capacity of 85 amp-hr.

7.3.1.1.1   Performance

VEHICLE 1 was capable of short-term operations at full power demand. Peak performance was available for the first 30 seconds of operation. After 30 seconds of operation the performance was degraded in an attempt to protect the traction motors from overheating. The maximum observed drawbar pull was 4525 pounds (2052.505 kg) at a road speed of 4.0 mph (6.44 km/hr). This was equivalent to a tractive effort-to-weight ratio

of 0.61. The maximum continuous drawbar performance was 2850 pounds (1292.738 kg); equivalent to a tractive effort-to-weight ratio of 0.40. The measured drawbar pull characteristics of VEHICLE 1 were significantly less than those observed with a conventional HMMWV at low road speeds. This was due primarily to the large difference in the available propulsion torque and the overall gear ratios. VEHICLE 1 started to show a significant increase in both drawbar pull and reserve power at speeds above 9 mph (14.48 km/h). This was attributed to the traction motor torque-speed characteristics.

Mobility limitations of VEHICLE 1 in standard obstacles were attributed to structural interference of the vehicle with the obstacle and current output limitations imposed by the battery control system. An increase in the ground clearance to the required 16 inches (40.64 cm) would improve the obstacle crossing ability. A significant improvement in obstacle negotiation was noted when the control system software was manually set and held to 100-percent state of charge (SOC). This allowed high current output and, therefore, more traction motor torque to be supplied during the maneuver.

The APU did not provide any additional power to supplement the battery power requirements during any of the obstacle crossings. This was a result of the artificially high battery SOC that was implemented on-site by VEHICLE 1 personnel to provide a look at the optimum performance potential of this vehicle operating in this scenario. The torque distribution between axles appeared equally split during the obstacle maneuvers indicating sufficient traction for both axles and good traction control algorithms.

Low-speed maneuvers such as step and ditch crossings require specific driving techniques that are handled in conventional vehicles by the simultaneous use of both the throttle and service brakes. Service brakes are applied while the engine is allowed to build the required torque necessary to overcome the obstacle. Use of this technique with a series hybrid electric drive vehicle would require simultaneous power and regeneration commands. The traction motors are not capable of operation in both scenarios at the same time. This results in a motor fault as experienced on the 18-inch (45.72-cm) wall negotiation.

Low-speed maneuvers that require high torque and power must be accomplished in a single attempt without the use of service brakes. VEHICLE 1 was equipped with a momentary switch to disable the regeneration feature of the vehicle.

The performance potential of VEHICLE 1 was clearly evident from the results of the sustained speed on longitudinal grade portion of the gradeability tests. Each vehicle exhibited superior sustained speed on grade performance for grades exceeding 20 percent.

The sustained speed performance of VEHICLE 1 on the Munson Test Area (MTA) longitudinal grades up to 40 percent was limited by the manual operational range selection capability of the vehicle. Use of low range for road speeds below 35 mph (56.33 km/h) allows for maximum vehicle performance without the automatic shifting of supplied electrical power within the motor controller. Selection of high range causes a shift to occur while negotiating a grade upon which speeds in excess of 35 mph are attainable. Use of low range also limits the top speed of the vehicle to approximately 35 mph.

Table 7.1: Sustained Road Speeds, Vehicle 1

Grade, % mph	Vehicle 1 mph	M1097 Speed Standard Vehicle
5	34.3	45.8
10	34.6	35.5
15	33.0	34.5
20	29.4	29.9
30	26.6	18.2
40	20.2	15.1

The ability of VEHICLE 1 to negotiate longitudinal grades exceeding 40 percent from a standing start was compromised by the fact that the service brake and the throttle cannot be used simultaneously while on the grade to insure a smooth transition to ascend the respective grade. Simultaneous brake and torque commands produce an unexpected mode of operation for most commercially available motor controllers. Similar performance issues were noted during the standard obstacle subtest.

While on the 50-percent grade, the loss of power assist for the service brakes due to a failure of the electrically driven hydraulic pump left the driver incapable of applying sufficient pedal force to hold the vehicle stationary. The need for reliability of any device that supplies power for both steering and braking is crucial for gradeability and control during low-speed maneuvers on longitudinal grades.

The maximum speed of VEHICLE 1 did not meet the maximum speed requirement outlined in the established specifications for this project. The measured speed was 2.0 mph (3.22 km/h) less than the 70 mph (112.65 km/h) requirement. The vehicle did however, exceed the maximum speed requirement of the standard HMMWV. The improvement in performance is especially impressive above road speeds of 40 mph (64.37 km/h). The only HMMWV configuration with similar performance was the M1097 HMMWV at curb weight. With a weight increase of 2350 pounds (1065.94 kg), VEHICLE 1 outperformed the M1097.

Acceleration times were adversely affected by the failure of the engine generator to quickly respond to the power demands of full throttle acceleration. The slow APU response coupled with the high current demand associated with full throttle acceleration, produced a battery pack load voltage low enough to cause the control system to limit the current output of the traction batteries. The current output was limited to prevent individual module voltages from dropping too low until the APU was able to develop the requested power. The final result was a change in the local slope of the time velocity curve. Acceleration times above the characteristic road speed of 18 mph (28.97 km/h) were affected. A time delay of 1.2 seconds was measured as a result of the APU delay.

The APU was capable of delivering a maximum output of 44 kW (59 hp) during acceleration tests. This output was available for 10.7 seconds. The power output was reduced to 30 kW (40.23 hp) for the remainder of the acceleration test. The power reduction was not caused by any thermal limitations.

Table 7.2: Acceleration Performance (Vehicle 1)

Speed Interval, mph	Time to Speed, sec
0 to 10	1.5
0 to 20	4.0
0 to 30	6.2
0 to 40	8.8
0 to 50	12.2
0 to 60	17.3
0 to 68.3	29.4

The engine generator control algorithm had some effect on the cruising range performance between 20 and 40 mph since at those speeds the APU is operating at a power output significantly less than its continuous rating. The vehicle was charge sustaining at speeds up to 20 mph. The cruising range was limited by the fuel consumption of the APU and the usable fuel capacity of the vehicle for the charge-sustaining condition. Since there is some reserve power available from the engine generator below 40 mph, the calculated cruising range may be considered somewhat conservative. At 40 mph and above, the APU is producing electrical power at or near its continuous rating; however, that output is significantly less than the required road-load power to maintain the vehicle at speed. The additional power must come from the traction batteries at the measured rate. The cruising range associated with VEHICLE 1 ranged from a maximum of 412 miles (663 km) at road speed of 10 mph (16 km/h); thus exceeding the specified range of 300 miles (482.8 km) for the standard vehicle, and down to 17 miles (27.36 km) at its maximum speed.

The APU operation during the acceleration tests was such that minimal fuel was required up to road speeds approaching 40 mph. This was a direct result of the time response of the APU and the total available power characteristics of the vehicle. Fuel consumption remained low for the remainder of the test as the APU operated at its peak rating for a very short portion of the acceleration test. The compensated fuel consumption reflects the required use of the traction batteries during acceleration.

7.3.1.2   Hybrid Range

The hybrid vehicle range goal of 300 miles (482.8 km) was met for specific operating conditions explained in the test findings portion of this report. During the level road tests, the fuel consumption of VEHICLE 1 ranged between 8.5 and 23 mpg (3.6 – 9.72 Km/l) for the speed range of 50 to 20 mph (80 – 32 km/h). VEHICLE 1 showed a distinct improvement in fuel economy especially for the 20 to 45 mph (32 – 72 km/h) interval.

While the reduced fuel consumption of the vehicle is an attribute, the battery energy required maintaining vehicle speeds above 35 mph (56 km/h) became the major factor limiting sustained operations. It was noted that the APU was operating near its continuous rating for road speeds above 35 (56 km/h). The road-load power required to maintain the vehicle at speed exceeded the output of the APU at approximately 20 mph. The remaining power was provided by the traction batteries. Based on the measured depletion rate of the traction batteries and the finite battery capacity, the cruising range was significantly reduced compared to a conventional HMMWV over much of the usable speed range.

The full-load fuel consumption of VEHICLE 1 showed a marked improvement in fuel economy compared to the standard HMMWV over the majority of the usable speed range where full-load operations would be expected. The APU fuel consumption characteristics were nearly identical for the continuous and peak conditions measured during the full load testing. Additional power, as required for propulsion, was provided by the traction batteries.

VEHICLE 1 was charge sustaining on the Munson standard fuel course for speeds less than 12.5 mph (20.12 km/h). This produced a theoretical cruising range over this terrain of over 250 miles (402 km). The low continuous available power production of the APU resulted in a marked reduction in the cruising range once the vehicle failed to maintain its charge sustaining status. The average APU power was similar for clockwise (CW) and counterclockwise (CCW) directions even though significantly more power was required to negotiate the course in the CW direction as a result of ascending the 30-percent grade. The traction batteries provided the additional power necessary for propulsion. The higher percentage of battery use in the CW direction was also reflected in the reduced cruising range in that direction compared with the CCW direction.

The initial SOC or the direction of travel did not appear to have a significant impact on the compensated fuel consumption of the vehicle. Although the APU fuel consumption varied with SOC and power production once the effect of the traction battery energy and/or capacity was factored in, the "corrected" fuel consumption did not show any significant variation. The best observed fuel economy during operations on the standard fuel course was 14.0 mpg (5.91 km/l) at a sustained road speed of 21 mph (33.78 km/h). The calculated cruising range at this speed was 69 miles (111 km) in the CW direction and 83 miles (133.56 km) in the CCW direction. This direction sensitive performance was attributed to the variation in traction battery use as a function of terrain induced power requirements.

Performance of VEHICLE 1 exhibited similar characteristics over the Cross Country terrain as it did on the Munson standard fuel course. The load requirements imposed by the Cross Country terrain were much more severe than the standard fuel course. Its additional grades and the length of many of those grades gave the vehicle opportunities to recover energy by traction motor regeneration.

At a sustained road speed of 10 mph (16 kph) on cross-country course, the vehicle was charge sustaining and the cruising range was determined by the fuel consumption of the APU only. Above that speed, the traction batteries provided a significant amount of the power required traversing the terrain and the cruising range suffered accordingly. It was also noted that the initial SOC had a significant impact on the fuel consumption and the distribution of power between the APU and the batteries. Operations starting at or near 100-percent SOC caused the traction batteries to provide more of the required power especially at the slow and moderate speeds depleting the battery pack at a rate which could not sustain vehicle operations for a significant time period. This characteristic resulted in a wide variation in cruising range dependent on the initial SOC of the traction batteries. Tests initiated at a lower SOC produced a greater cruising range for all conditions and speeds.

The best observed fuel economy was measured at a sustained speed of 20 mph (32.19 km/h) over the Cross Country terrain. The fuel consumption rate was 9.0 mpg (6.5 km/l). This proved to be an improvement over the standard M1097 HMMWV that was tested at the same time over the same terrain.

7.3.1.3   Fuel Efficiency Driving Scenario

Based on the observed totals of distance, time, and energy, the following performance indices were computed for the array of test course operation presented in the fuel efficiency driving scenario with VEHICLE 1.

1) The overall fuel consumption for the driving portion of the scenario was 7.4 mpg based on the APU fuel consumption and equivalent fuel volume calculated from battery energy use. Using the battery capacity values, the observed fuel consumption would be 6.7 mpg.

2) The overall fuel consumption measured during the driving cycle including the silent run portion was 0.13 gal/h (.5 l/h) using the measured APU fuel consumption and the equivalent fuel volume calculated from battery energy use. Using the battery capacity values, the observed fuel consumption would be 0.14 gph (.53 l/h).

3) The fuel used by the APU to complete this driving scenario was 6 percent of the usable fuel capacity of the vehicle. The battery capacity required to complete this scenario was 328% of the best observed battery capacity and 196% of the advertised battery capacity.

4) Excluding the silent watch portion of the driving scenario, the battery capacity required to complete this scenario was 64 percent of the best observed battery capacity and 39 percent of the advertised battery capacity.

7.3.2   Vehicle 2 – PEI HE-HMMWV

7.3.2.1   Physical Characteristics

VEHICLE 2 was tested at a gross vehicle weight (GVW) of 9100 pounds (4155 kg), which was marginally less than the imposed weight requirement of 9160 pounds (4128 kg). A 2460-pound (1116 kg), increase in curb weight was noted when compared to a standard M1025 HMMWV. An increase in the envelope dimensions of the HE-HMMWV was also noted when compared to the conventional M1025. A height increase attributed to a 4-in (10-cm), nominal body lift required to accommodate space for the auxiliary power unit (APU) and the traction battery pack. The vehicle length was increased to accommodate the traction motors. The vehicle width increased due to the addition of exhaust snorkel component of deep water fording kit. The measured initial traction battery pack capacity was 62.68 ampere-hours (amp-hr). This was much less than the advertised battery capacity of 85 amp-hr.

7.3.2.1.1   *Performance*

During the tractive effort tests vehicle 2 was not capable of continuous full power demand operations due to thermal limitations of the APU and traction motors. The maximum observed drawbar pull was 6125 pounds (2778 kg), at a road speed of 8.6 mph (13.8 km/h). This was equivalent to a tractive effort-to-weight ratio of 0.67. The drawbar power of vehicle 2 and the M1097 was similar up to a speed of 5.5 mph (8.9 km/h). At speeds above 5.5 mph (8.9 km/h), vehicle 2 developed much more drawbar power than the standard HMMWV. This was attributed to its nearly constant drawbar pull characteristics across the entire tested speed range.

Table 7.3

Grade, %	Veh2 Road Speed, mph/kph	M1097 Speed, mph/kph
5	48.8/78.5	45.8/73.7
10	44.6/71.8	35.5/57.1
15	38.6/62.1	34.5/55.5
20	35.8/57.6	29.9/48.1
30	34.6/55.7	18.2/29.3
40	20.2/32.5	15.1/24.3

Vehicle 2 easily negotiated all of the standard obstacles that it could physically approach. Failure to negotiate the 22-in (55.9-cm) vertical step was a result a physical interference between the left front traction motor and the leading edge of the wall. The 67 kW peak power requirement resulted in a total traction motor torque requirement of 1225 lb-ft (1661 N-m). The APU was operational during the obstacle negotiations and did provide traction battery charging during the vertical wall obstacle negotiation. Battery control algorithms were adequate to provide sufficient power and torque to negotiate the obstacles. The APU control was responsive to the high power demands made of the traction batteries and supplied some recharging during the maneuver. This helped keep the state of charge (SOC) near the optimum design operating condition of 85 percent.

Low-speed maneuvers such as step and ditch crossings require specific driving techniques that are handled in conventional vehicles by the simultaneous use of both the throttle and service brakes. Service brakes are applied while the engine is used to build the required torque necessary to overcome the obstacle. Use of this technique with a series hybrid electric drive vehicle would require simultaneous power and regeneration commands. The traction motors are not capable of operation in both scenarios at the same time.

The sustained speed performance of vehicle 2 on the longitudinal grades up to 40 percent was limited by the length of the grades and the approach angle of the 30 – 40 percent grades. The addition of a protective guard for the forward most drive motor reduces the approach angle and speed.

Vehicle 2 exhibited a control issue associated with the simultaneous use of the brake and accelerator pedals when attempting to negotiate longitudinal grades from a standing start. Standing start attempts on longitudinal grades exceeding 40 percent were unsuccessful due to wheel spin. This low-speed maneuver requiring relatively high torque produces an operational condition to which the motor controllers react by shutting down power to the motor. During time periods of power request and no displacement, the motor controllers will cycle power to the motors.

During acceleration tests the maximum speed of vehicle 2 was 79.8 mph (128.4 km/h). Acceleration performance for 0 to 50 mph (80.6 km/h) in hybrid mode at variable initial states of charge (SOC) and pure electric vehicle (EV) mode were between 7.3 and 8.4 seconds. Typical acceleration performance is listed in Table 7.4.

Table 7.4: Acceleration Performance Vehicle 2 HE-HMMWV

Speed Interval, mph/kph	Time to Speed, sec
0 to 10/16.1	0.9
0 to 20/32.2	2.0
0 to 30/48.3	3.3
0 to 40/64.4	5.1
0 to 50/80.5	7.5
0 to 60/96.6	10.8
0 to 70/112.7	15.6
0 to 78.1/125.7	27.8

Acceleration performance was not significantly affected by the initial SOC. Acceleration times were generally comparable for testing conducted between 85 and 72 percent SOC. Distribution of the energy between the traction batteries and the APU did show some distinct differences based on the initial SOC. Operations at an initial SOC of 85% resulted in the lowest energy contribution from the APU over the vehicle's usable speed range. As the initial SOC was lowered, the portion of battery energy contributing to propulsion increased, especially at road speeds above 60 mph (96.6 km/h) where the road-load power significantly increased due to aerodynamic effects.

The performance of the traction batteries showed a decrease in pack voltage as the initial SOC decreased. The battery control unit (BCU) limited the current on all acceleration runs regardless of SOC. The battery recovery times as a result of the current limits were also variable, test-to-test. The battery recovery rate affected the length of time during each test that maximum current and power were delivered. Battery recovery times ranged from 5.8 seconds at 80-percent SOC to nearly 24 seconds at 85-percent SOC. These recovery times become significant after looking at the exceptional acceleration characteristics of this vehicle. The variable battery recovery rate may explain some of the variability in the 0 to 60 mph (96.6 km/h) and above acceleration times. The controller appeared to limit the battery output based on the rate of current draw rather than a lower pack voltage limit. Operations at lower initial SOC resulted in lower pack voltage under load. The battery power fluctuations were countered by allowing the engine generator output to reach its set point faster for the lower initial SOCs. Performance of the vehicle in terms of acceleration times appeared generally unaffected by the cycling traction battery power.

Battery capacity was sufficient to provide reserve power in excess of that required for road-load propulsion. This was evidenced by the EV performance. Acceleration times and maximum speed were not significantly different for hybrid mode versus pure EV mode. The EV only tests were conducted with the batteries near their optimum capacity. Reduced capacity would quickly affect the ability to operate at significant speeds for extended time periods.

Vehicle 2 was capable of delivering 47 kW of electrical power from the engine generator during the hybrid mode acceleration tests. The APU was capable of delivering that power on a continuous basis throughout each test. The time to reach the maximum continuous output was a function of the initial SOC. When the vehicle was at the optimum SOC of 85 percent, the APU took 15.4 seconds to reach the continuous power output. At the lower SOC, the time was reduced to between 5.2 and 6.8 seconds.

7.3.2.2   Hybrid Range

During the Hybrid range tests vehicle 2 met the cruising range criteria of 300 miles (483 km) for specific operating conditions and environments. For level road test conditions fuel economy of vehicle 2 ranged between 6.5 and 16.3 mpg (2.76 and 6.93 km/l), for the speed range of 76 to 21 mph (122 to 34 km/h). Vehicle 2 showed a significant improvement in fuel economy compared with the standard HMMWV especially for the 20 to 45 mph (32 to 72 km/h) interval. Vehicle 2 and the M1097 HMMWV showed comparable fuel consumption characteristics for the usable speed range of the M1097 HMMWV. From 45 mph (72 km/h) to the maximum speed, the fuel economy characteristics of the two vehicles were comparable. As currently configured, vehicle 2 exhibited superior cruising range compared to a conventional HMMWV for speeds less than 25 mph (40 km/h) on level roads. At speeds above 25 mph (40 km/h), the cruising range was limited by the depletion rate of the traction batteries instead of the fuel consumption of the APU.

While the reduced fuel consumption of the vehicle is an attribute, the battery energy required to maintain vehicle speeds above 45 mph (72 km/h) became the major factor limiting sustained operations. In addition to the required battery energy, a reduced battery capacity (compared to the advertised capacity) was realized for the duration of testing. It appeared that the APU generally operated at two set power points. The low setting was approximately 12 kW while the high-power setting was near its continuous power rating of 25 kW. The road-load power and the APU power output began to diverge at about 25 mph (40 km/h). At speeds above 25 mph (40 km/h), the batteries provided the additional power required for propulsion. The rate of traction battery depletion was the limiting factor for the operational range of the vehicle.

The full-load fuel consumption characteristics of vehicle 2 were significantly different than those of a conventional HMMWV. Fuel consumed by vehicle 2 was significantly higher than that of the standard HMMWV for speeds up to 6.5 mph (10.5 km/h). At speeds above 6.5 mph (10.5 km/h), the APU was operating near its peak rating resulting in less traction battery use during the test. Sustained operation at the peak rating was not possible due to thermal limitations of the power electronics and the oil temperature of the engine. Above that speed, vehicle 2 exhibited better fuel economy than the conventionally powered HMMWV.

The best-observed kW-hr corrected fuel economy during operations on the standard fuel course was 17.2 mpg (7.3 km/l) at a sustained road speed of 15.4 mph (24.8 km/h). The average kW-hr corrected fuel economy increase for vehicle 2 as compared to the M1097 HMMWV traversing the standard fuel course was 36.6 percent combined for the clockwise and counter clockwise directions. Vehicle 2 was charge sustaining on the standard fuel course for speeds less than 17 mph (27 km/h). This produced a theoretical cruising range over this terrain approaching 400 miles (644 km). The low continuous available power of the APU resulted in a marked reduction in the cruising range once the vehicle failed to maintain its charge sustaining status.

Performance of vehicle 2 exhibited similar characteristics over the cross-country terrain as it did on the standard fuel course. The load requirements imposed by the cross-country terrain were much more severe than the standard fuel course. The additional grades and the length of many of those grades gave the vehicle opportunities to recover energy by traction motor regeneration.

At a sustained road speed of 11 mph (18 km/h) on cross-country course, vehicle 2 was charge sustaining and the cruising range was determined by the fuel consumption of the APU only. Above 11 mph (18 km/h), the traction batteries provided a significant amount of the power required to traverse the terrain and the cruising range suffered accordingly. Also noted the initial SOC had a significant impact on the fuel consumption and the distribution of power between the APU and the batteries. Operations starting at near

85-percent SOC allowed the traction batteries to provide more of the required power especially at the slow and moderate speeds, depleting the battery pack at a rate which could not be sustained for a significant time period. This characteristic resulted in a wide variation in cruising range dependent on the initial SOC of the traction batteries. Tests initiating at a lower SOC produced a greater cruising range for all conditions and speeds.

The best observed kW-hr corrected fuel economy of vehicle 2 was 8.4 mpg (3.57 km/l) calculated for the speed range of 10.5 to 16.4 mph (16.9 to 26.4 km/h) over the cross-country terrain in the counter clockwise direction. The average kW-hr corrected fuel economy increase for vehicle 2 as compared to the M1097 HMMWV traversing the course was 5.7 percent in the clockwise direction.

7.4 GERMAN PROGRAMS ON ALL ELECTRIC COMBAT VEHICLE (AECV) DEMONSTRATION

7.4.1 General

Modern electric propulsion and transmission systems are used in a lot of field applications with ambitious requirements and they are on the way to replace more and more some of the mechanical-hydraulic transmission systems in both commercial and military sectors. This trend is the result of significant advantages of the electric drives which is augmented by the rapid improvements of the electric and electronic component technologies. These technologies are gradually leading to an All Electric Combat Vehicle systems (AECV).

Since 1985 the R&D Programs of the German Government resulted in developing and manufacturing of permanent magnet machines and the appropriate power and system electronics which have the characteristics and potentials for vehicle applications. They show the highest torque and power values at minimum volume and weight together with best efficiencies and optimal control features. Figures 7.2 and 7.3 show some wheeled and tracked vehicles running with Multiple Electronic permanent magnet propulsion systems.

Figure 7.2: Electric Drive System in Wheeled Vehicles.

Figure 7.3: Electric Drive System in Tracked Vehicles.

There are a number of characteristics required for future military vehicles which have a direct or indirect connection to the propulsion system and which can be met or positively influenced by electric drive systems. The following list summarizes the most important features of electric systems and their impact on the vehicle as a whole:

- Reduction of weight and volume of the power transmission in the overall system.

- Flexible integration of the drive components feasibility of new vehicle concepts and modular platforms:
    - Optimal operation of the Diesel engine (power optimized; no more torque optimized);
    - High overall efficiency in driving cycles/missions.

- Infinite variable drive and steering operation, e.g. skid steering and pivot turning ability for wheeled vehicles:
    - Modular design technology;
    - Improved reliability due to low wear and tear of the system components;
    - Multiple sprocket propulsion for tracked vehicles.

- Simple realization of automation, energy management, power control, drive-by-wire, remote control and robotics:
    - Available power and electric energy supply for internal and external consumers;
    - Low life cycle costs due to maintenance free components;
    - Basic electric supply for all future electric weapons and electric armor systems.

Wheeled vehicles show the enormous advantages of the electric drive technology which are much more obvious in such vehicles than in tracked ones. The electric drive motors with the integrated gear are installed within the wheel hubs having only flexible electric and coolant connections to the chassis, Thus the chassis is completely free of all mechanical devices like drive shafts, transmission and differential gear units,

clutches etc. which are necessary in a conventional wheeled vehicle. The silhouette and the outside volume of the electrically driven vehicle can be significantly reduced which gives many benefits for the deployment of such vehicles. For illustration see Figure 7.4 which presents the comparison between an electrically and a conventionally driven vehicle and which proves the above given arguments: The electric version is significantly shorter and lower compared to the mechanical one although having the same exploitation volume. The detailed elaboration made for this comparison also showed a weight reduction of approximately 10% which e.g. can be used for improved armor. In addition the electrically driven vehicle has higher and easier maneuverability and better handling due to skid steering and pivot turning ability.

Conventional Mechanic Drive Version   Electric Drive Version
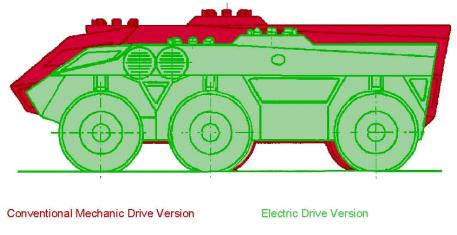
Figure 7.4: Reduction of Vehicle Silhouette by Use of Electric In-Hub Drives, Example 6x6 (Study MM/Mak).

Using the electric drive modules an adjustable height wheel suspension can be realized to provide maximum clearance for the vehicle. Thus the detection probability by mine sensors can be minimized and the damage from the mines to the vehicle is significantly reduced.

As a prime power supply, the Diesel engine used in electric drive systems is not designed for peak torque demand dictated by the driving conditions, as is the case with mechanical systems. This provides opportunities for engine designers to introduce new diesel engine development for optimized power output.

In conjunction with powerful electric energy storage a hybrid electric system can be realized. Its power reserve and power redundancy opens a lot of other benefits for the vehicle and its function:

• Decisive improvement of the maneuverability especially in heavy terrain;

• Increased acceleration;

• Quick position change ability, jump out of the cover position;

• Stealth operation;

• Underwater operation without Diesel engine running;

• Energy saving and regaining of braking energy;

• Electric energy supply of all consumers of the vehicle;

• Option for future internal and external high power consumers.

The energy storage is mainly intended to support the on-board power supply and the power averaging of the main bus. The Power generating and distribution station in a hybrid electric vehicle is bi-directional and therefore can provide or receive electric power from the various consumers such as drive motors, secondary consumers, electric armaments or electric armor. The block diagram in Figure 7.5 represents such a system. In a pure Diesel-electric system the Diesel engine has to cover all high-power actions. A powerful energy storage like the MDS can replace the prime power source for periods of time. The complete vehicle is operable at full performance with the engine shut down. Also for all other operating conditions the energy storage improves the performance and offers the possibility for an effective power management during varying power demands as can be expected in future battlefield scenarios. In unexpected combat situations a conventional vehicle would lose valuable seconds until the Diesel engine is ready to deliver power. A Hybrid electric vehicle system is able to overcome such a situation.
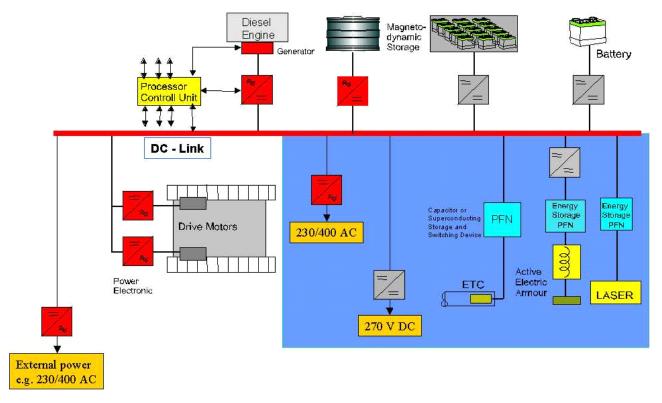
Figure 7.5: Block Diagram of a Future Hybrid-Electric AECV.

The MDS as a central storage system possesses enough power to supply all the consumers in the AECV, i.e. the electric drive, the pulse forming unit of electric weapon systems, active electric armor as well as any other secondary internal and external consumers. The MDS has sufficient energy to replace or back-up the primary power supplier for a period of seconds up to minutes, depending on the power requirement of the consumers.

From that a number of system advantages for AECVs arise, which enhance significantly the tactical system performance in the areas of:

- Fire power
- Mobility
- Survivability.

These are in detail:

- Jump from cover and rapid change of position with Diesel engine shut down;
- Significantly increased acceleration at all speed ranges;
- Rapid start-up of Diesel engine;
- Silent and Stealth movement and observation;
- Redundant system if the Diesel engine or the generator should fail;
- Supply of active electric armor;
- Full combat readiness as all systems are supplied by the MDS with Diesel engine shut down;
- Sufficient power for internal and external secondary consumers with Diesel engine shut down.

7.4.2   Programs for Tracked Vehicles

7.4.2.1   Demonstrator SPz-Marder

In 1985 the realization of a tracked vehicle with diesel electric drive was investigated. The SPz-Marder, which is the current German Armoured Infantry Fighting Vehicle, was selected as demonstrator platform (Figure 7.6). The aim was to demonstrate and prove the feasibility of mobility capabilities of the diesel-electric drive for tracked vehicles and to get specific experience for improved design characteristics.

Figure 7.6: APC-Prototype MARDER with Diesel-Electric Propulsion.

The electric drive in this vehicle was installed to directly replace the HSWL 194 hydro mechanical drive. The MTU diesel engine MB 833 Ea 500 as prime mover is still used providing a maximum power of 440 kW. This power is converted to electric power by a PM-generator that is coupled directly to the diesel engine. Two PM-drive motors of 750 kW maximum power rating drive the sprockets via the original final drive gears. The high power demands result during the regenerative steering operation.

A maximum speed of 72 km/h was measured, and the maximum tractive force is approx. 300 kN. The tested tracked vehicle is equipped with GTO (Gate Turn Off Thyristor)-power electronics units which were available in the mid-eighties. Compared to the present State-of-the-Art they only allowed a rather poor power density of 2.5 kVA/dm^3.

7.4.2.2   Demonstrator Wiesel LLX

Based on the lessons learnt, the light CH-53 – air-transportable weapon carrier Wiesel was chosen as Technology Demonstrator in 1996 (Figure 7.7). In Germany the Wiesel LLX is the most recent tracked demonstrator for a diesel electric drive system. It is presented at the NATO AVT-098 Demonstration of all electric vehicles in Belgium (Brussels and Brasschaat) in April 2003.

Figure 7.7: Demonstrator Wiesel LLX.

In contrast to the solution in the SPz-Marder, the possibility to integrate the electric motors together with the reduction gear in the roadwheels of such a vehicle was investigated. It allows more integration volume inside the hull. Furthermore, the electric Wiesel LLX was the first military vehicle to be equipped with the advanced MED-drive components with magnetic flux concentration design and advanced power electronic system now based on IGBT technology providing the power density of 28 kVA/dm^3. It is understood that this was the status of 1996. Today's technology is in the range of 42 kVA/dm^3.

A further aim was the integration of an electric power supply module with the purpose to make the full diesel power available for various internal and external electric consumers also providing different DC and AC voltage levels (Figure 7.8).

Figure 7.8: LLX-Prototype Wiesel with Diesel-Electric Propulsion and External Power Supply (DC/AC).

The Wiesel LLX demonstrator weights 2.7 tons. It is powered by a 1.9 l turbo-charged VW diesel engine of 65 kW with integrated Magnet-Motor-PM generator (Figure 7.9).

Figure 7.9: Diesel Engine Integrated PM Generator.

The operational data of the generator is:

- Dimension: length 115 mm, diameter 360 mm;
- Rated power 64 kW at 4500 rpm;
- Floating voltage from 500 V – 700 V supplying the DC main bus via power electronics;
- Separated power electronic (volume 17 l, weight 19 kg).

Two Multiple Electronic Permanent magnet Motors are integrated into the right and left roadwheel (Figure 7.10). This is the first application where a final drive for tracked vehicles is placed outside of the hull.

Figure 7.10: Roadwheel Integrated PEM Motor.

The operational data of each motor is:

- Max power 150 kW;

- Permanent torque 650 Nm;

- Max. torque 950 Nm for steering operations;

- Dimension: length 200 mm, diameter 562 mm;

- Max. speed 3380 prm;

- Separated power electronic (volume 44 l, weight 48 kg, max. current 400 A).

The structure of the main components is given in Figure 7.11. The electric components are shown in red (generator – drive motors – electric brake resistor – power electronics for drive components and power module for external consumers). The system control units for driving, braking, diesel operation and external power supply are given in green.
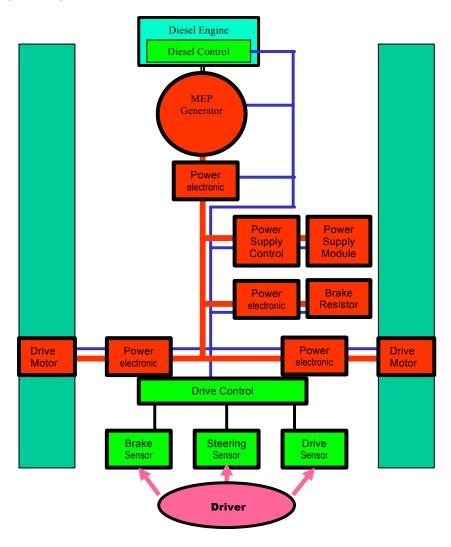
Figure 7.11: Structure of the Wiesel LLX.

The control system is designed to implement and optimize the benefits of electric drive system with respect to diesel operation, mobility and external power supply.

The Wiesel LLX demonstrator passed all initial tests successfully. It proved that this vehicle significantly challenges the mechanical version with respect to mobility and handling. The power supply of external users – directly supplied from a military vehicle – was also successfully demonstrated for 24 V DC and 3-phase 50 Hz consumers.

Figure 7.12 shows the Wiesel LLX Demonstrator on a 60% slope where it can be operated fully electrically from a stand still position, as well as in, in downhill movement.

Figure 7.12: The Wiesel LLX in a 60% Slope.

Even in humid and rugged conditions like mud the vehicle performed safely (Figure 7.13).

Figure 7.13: Wiesel LLX in Heavy Terrain.

The Wiesel LLX vehicle demonstrates the following features by realization and testing:

- Integration of available drive modules especially integration of the drive motors into the roadwheel;

- Functionality of electric drive for tracked vehicles;

- Ruggedness of the electric drive components, even outside the hull;

- Maximum tractive effort of 3,3 kN;

- Maximum torque even at zero speed;

- Sufficient torque and power at each roadwheel for steering and traction allowing more than 70 km/h of road speed;

- Maneuverability/agility comparable or even better than conventional drives;

- Infinite variable traction forces for drive and steering;

- Pivoting and quick change of direction;

- Full performance of electric braking;

- Power supply for external consumers (DC, AC);

- EMI protection, no critical magnetic stray fields.

Detailed investigations concerning licensing of electric drive on system and subsystem control have been conducted. The required safety has been achieved and the licensing according to the regulations of the German Federal Armed Forces and traffic authorization for wheeled and tracked vehicles will be feasible for military electric vehicle drives.

7.5   PULSE POWER

7.5.1   Pulse Power Supply for Electro Thermal Chemical (ETC)

In Germany experimental investigations of electrical requirements for a 120mm ETC-gun have shown that the required electrical energies for ignition are lower than 500 kJ. Based on these results a compact 120 kJ pulse power supply module was developed and tested. The module includes a high energy density capacitor, high power crowbar diodes, an optically triggered thyristor switch and a toroidal pulse forming inductor. The volume of the module is 128 l and the weight 165 kg. It is charged from a 22 kV high power density charger. The schematic is shown in Figure 7.14.
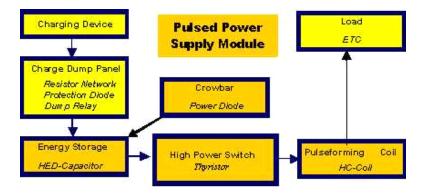
Figure 7.14: Schematic of Pulse Power.

To verify the system compatibility between the electric system of a AECV and the ETC-gun pulse power supply the high power density charger was connected during experiments to the electric system of the Wiesel demonstrator LLX situated aside the 120 mm gun.

In 2002 the pulse power supply was built by Rheinmetall W&M GmbH, Unterlüß and in cooperation with Magnet Motor GmbH, Starnberg for the high power density charger. Figure 7.15 shows the hardware realization and the measured pulse diagram. The module is presented at the NATO AVT-098 Demonstration of all electric vehicles in Belgium (Brussels) in April 2003.
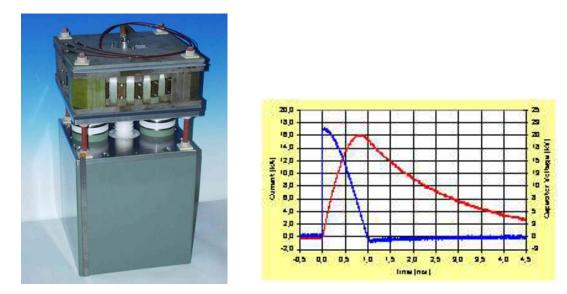
**Figure 7.15: Pulse Power Supply Module for ETC Gun
Systems and Pulse Diagram for Voltage and Current.**

The test results certified the integration of pulse power modules for ETC guns into an AECV system with sufficient pulse power. This is a big step towards the realization of ETC concepts.

In combination with the progress of ETC Technology in the field of ignition and propellant characteristics the complete ETC experiments proved that ETC concepts provide the potentials for significant increase in gun performance beyond conventional approaches.

7.5.2   Outlook

The results of the German R&D activities in the field of AECV prove the realization and potential benefits of electric vehicle systems for individual program needs. Further work is still necessary in this area and power electronics especially based on SiC Technology, energy management and storage systems.

7.6   MDS EXPERIENCES

7.6.1   Bus Applications

The MDS K3 (2 kWh/150 kW) has been used in bus applications in urban transport since 1988. Two examples, operated in Diesel-electric buses in the German cities of Munich and Bremen are shown in

Figure 7.16. Public transport requires typical operation times up to 19 hours per day. Presently the MDS operation experience amounts to more than 300,000 hours in customer application. The operation time of a single MDS amounts to more than 25,000 hours, equivalent to about 0.5 Million. charge/discharge cycles. The maintenance interval of the MDS K3 is currently defined to 3,500 operation hours.

Figure 7.16: Diesel-Electric-Storage Buses for Public Service in Munich (left) and Bremen (right).

7.6.2 Demonstration in an Experimental Tracked Vehicle

In order to investigate practical aspects of the mechanical and electrical integrability of MDS in AECV systems tests of an MDS on a 30 tracked vehicle MARDER with Diesel-electric drive were carried out. For simplicity of the experimental set-up an available MDS K3 was placed in the tower hole of the MARDER (Figure 7.17). The peripheral components of the MDS system, i.e. inverters, vacuum and cooling components were installed in the interior of the MARDER.

Figure 7.17: MDS K3 Integrated in APC-Prototype MARDER with Diesel-Electric Propulsion.

Test runs were made on flat asphalt and gravel roads as well as on roads with grades up to 12%. The test runs showed as a main result that with this comparable "small" MDS, as a sole energy source, a quite normal drive behavior in speed ranges up to about 20 km/h is possible for a short time operation. The power and energy

ability of this MDS even allows pivot turning. The MDS energy was sufficient for a test run at a speed of about 20 km/h over a distance of 350 meters. For this run an energy amount of 5.4 MJ from the MDS was consumed.

Although the bus type MDS used in these experiments is not fully adequate to the MARDER drive system, important information concerning mechanical and electrical integrability could be obtained.

7.6.3   Shock Tests and Mechanical Periphery

Crash tests with shock amplitudes up to 6 g on the suspension frame and up to 12 g on the MDS were conducted under full MDS speed. Figures 7.18 and 7.19 show the experimental setup of the MDS on a rail vehicle as well as one of the measured shock curves.

Figure 7.18: Shock Test Set-Up of the MDS K3.

The shocks caused no damage and no malfunction of the MDS. These tests were one reason why the MDS K3 received the approval for operation in public buses.

In the frame of development work for the military application further shock tests, especially with the MDS K6 are scheduled to be carried out in the next few months.
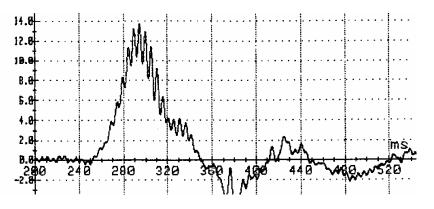
**Figure 7.19: Signal of the Sensor at Top of the MDS Looking
in Forward Direction [x-axle: ms, y-axle: g].**

Extensive practical experience is available for tilt angles up to about 12 degrees in civil vehicles. A further development focus concerns the high tilt angles, which occur in military vehicles. Experiments using cardanic frames, allowing tilt angles of about 45 degrees have been started. Figure 7.20 shows a corresponding experimental setup.

Figure 7.20: Experimental Cardanic Frame for High Tilt Angles.

7.6.4 Tests with an MDS on an 8x8 Vehicle

First tests with an MDS were conducted on an 8x8 Diesel-electric vehicle (Electric Transmission Demonstrator, ETD) equipped with a bus type MDS K3 (2 kWh/150 kW). For these tests the MDS was mounted on the loading floor of the ETD (see Figure 7.21).

Figure 7.21: Electric Transmission Demonstrator (ETD) with MDS Test Equipment.

The ETD is equipped with a Diesel engine coupled to a 350 kW PM generator. All eight wheels are driven through PM wheel drive units. The vehicle mass at the start of the tests (driver and full fuel tank) was 16,040 kg. The main aims of the tests were to quantify the increase in vehicle performance and to evaluate the gyroscopic behavior of the MDS during driving.

- **Acceleration and Overtaking Acceleration**

The acceleration tests demonstrated that the drive performance of the vehicle is significantly enhanced with the addition of the MDS. Acceleration times are improved by 20% to 36%, whilst the acceleration distance is reduced by 21% to 39%. The overtaking performance of ETD is improved by up to 38% when the MDS is activated. Table 7.5 gives an extract of the measurements.

Table 7.5: Listing of Acceleration Measurements at Various Speed Intervals Without as well as With MDS

Speed interval	Engine only		Engine and MDS	
[km/h]	Time [s]	Distance [m]	Time [s]	Distance [m]
0 – 20	2.8	8.6	2.3	6.8
0 – 40	7.5	48.6	5.7	35.8
0 – 60	16.0	168.9	11.3	116.1
0 – 80	31.4	474.3	21.0	304.7
0 – 90	43.3	755.4	27.5	461.9
20 – 40	5.4	44.7	4.2	34.5
40 – 60	9.2	128.3	6.5	90.2
60 – 80	15.8	310.5	9.8	192.4

- **Distance Driven with MDS only, at Constant Vehicle Speed**

For this test the MDS was fully charged by driving the vehicle at constant speed and the distance covered with only the MDS was measured. Tests were executed between 20 km/h and 60 km/h constant speed. The tests showed as expected that the distance covered by ETD is not sensitive to the vehicle speed. At each velocity the covered distance was between 1000 m and 1050 m.

- **Gyroscopic Behavior**

During a ride at the maximum attainable speed over a heavy terrain, the MDS angular motion was recorded. The cardanic frame allows the MDS to tilt against a spring/damper system which has to inhibit the tilting of the MDS as well as to readjust the MDS axle to the vertical direction after being tilted by the movements of the vehicle. A ring around the MDS capsule constrains it to angles less than 15 degrees. Figure 7.22 shows the record of one round in two different views. It can be seen that the maximum allowable motion is utilized by the MDS. Angles of more than 15 degrees result from the track not being leveled at the starting point of the vehicle. It could be demonstrated that the existing civilian bus type MDS is well suited to operate under heavy terrain conditions of the VTF track.
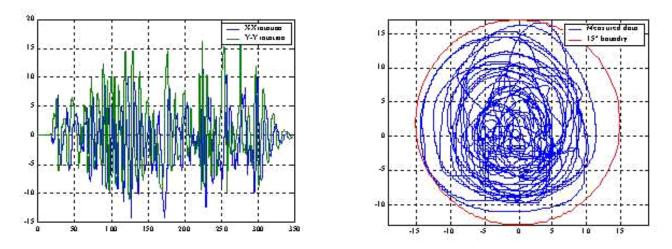
Figure 7.22: Record of the Tilt Angles of the MDS Against Verticalness During a Test Run.

Summarizing, the tests demonstrated that, compared with the vehicle requirements this even comparably weak MDS enhances the drive performance of the vehicle significantly and that its mechanical behavior on the test track is rather robust.

Chapter 8 – STANDARDIZATION AND DUAL USE

VEHICLE ENGINES: Towards Improvements in the Propulsion Technologies. (Civilian) All Electrical Vehicles

Les technologies génériques communes aux marchés civils et militaires sont d'importants contributeurs à la révolution dans les armements

F. Heisbourg, 1997

8.1 INTRODUCTION

A linear correlation between the gross national product of a Country and its car density has been observed in Europe, the United States, Japan and a series of other 'rapidly industrialized and developing countries such as China, East Asia, Central and Eastern Europe. This substantial growth of the global vehicle population (production of more than 50 million motor vehicles/year today) begins to play a major role in the air pollution and the so-called greenhouse effect: the vehicles emit significant quantities of carbon monoxide (incomplete combustion of carbon-based fuels), nitrogen oxides (origin of acid rains and eutrophication of waters), indirectly produce photochemical oxydants (ozone), lead, etc. This pollution has two consequences:

(1) The definition of recommendations and directives regarding the pollutant emissions.

(2) The development/use of alternative energy sources as well as the increasing use of new technologies.

8.2 RECOMMENDATIONS AND DIRECTIVES

8.2.1 Two Major Conferences Defined the Actual Evolution of the Design of Thermal Engines and of the Cars Using Them

In May 1997, the G8 endorsed the phase out of leaded gasoline in the 1997 declaration of Environmental Leaders of the Eight on Children's Environmental Health. In December 1997, a large number of Countries adopted the Kyoto protocol requiring 38 industrialized Nations to reduce their 'greenhouse' gas emissions: the EU should reduce them by 8%, the USA by 7% and Japan by 6%. This accord only takes effect if it is ratified by 55 nations and it is binding on individual countries only after their governments' ratification: the new US Administration (2001/2004) denied this Kyoto protocol.

8.2.2 However Significant Progresses Have Been Registered [23]

The US EPA (Environmental Protection Agency) in close cooperation with the CARB (California Air Resources Board) adopted a series of LEV (Low Emission Vehicle) standards (reducing the NO_x to 0.012 g/km in 2004 (for Gasoline and Diesel), the fuel sulfur levels to 15ppm, the exhaust particulate matter (PM) to 0.006 g/km, etc.); the EU has adopted a series of EURO regulations; EURO 5 foresees a reduction of NO_x to 0.08 g/km, PM (particulate, mixture of solid particles and liquid droplets, result of condensed sulphur dioxide, nitrogen oxides and volatile organic compounds – HC) to 0.025 g/km.

8.2.3   Negative Observation

It is also observed that no one country has adequately addressed the problem of the CO_2 emissions: Europe and Japan envisage to reduce the fuel consumption by 25% in the next decade while the car fuel economy in the USA seems to have stabilized.

8.3   NEW TECHNOLOGIES

To reduce the pollutant effects of the combustion, it appears essential to optimize the combustion processes. Four areas are targeted by the future developments in this domain: (1) the introduction of high-pressure direct injection in combination with turbocharging in the Diesel: This has already reduced the fuel consumption of this kind of engines. (2) the turbocharging combined with an engine downsizing is also promising for the gasoline engines as well as (3) the direct gasoline injection (10% fuel savings) and (4) throttle-free load regulation.

The exhaust treatment remains obviously an unavoidable complementary solution: NO_x and desulfurization accumulator catalytic converters will be provided.

The next tables summarize the objectives announced by the US (TIER 2 standards to be adapted in 2004), Japan (JAPAN 2002), European Union (EURO 4) if such efforts are pursued:

Pollution STANDARDS or objectives	USA/2004	Japan/2002	EU/2005
Passenger Car Nitrogen Oxides g/km (gasoline) – Trier 2/Japan/Euro	0.043	0.08	0.08
Passenger Car NO g/km (Diesel) – T/J/E	0.043	0.28	0.25
Passenger Car PM (Diesel) g/km – T/J/E	0.006	0.05	0.025
Car Passenger CO_2 g/km			150

Some observations indicate that the ZEVs (Zero Emission Vehicles) production becomes a new challenge and will re-orientate the choices of the propulsion energy. As an example, the California Air Resources Board (CARB) required some fleet operators to start using ZEBs (Buses) in three years. the regulation moves forward in several steps over the next ten years, requiring cleaner engines, cleaner diesel fuel, choosing to use alternative fuels such as compressed or liquefied natural gas, propane, methanol, *electricity, fuel cells* or other advanced technology.

In Europe, light and heavy duty vehicle and engine standards have been substantially tightened over the past few years and further tightening may not be expected. Evolution towards new energy sources may be foreseen as short term solutions.

8.3.1   Electrical Transmission Technologies

Obviously, reductions in fuel consumption may still be expected from an optimized design of the transmission: this one assumes the role of adjusting torque and engine speed in order to bring the torque provided by the engine in line with the vehicle's requirement for tractive force. The so-called AMT or Automated Manual Transmission, characterized by a very high gear efficiency factor, should set the ideal

engine and transmission operating point for all desired power requirements, during driving operations and without affecting the comfort of the driver. Such a transmission could bring about fuel savings to order of 20% [24] over drivetrains currently in use.

Despite the fact that the future of the Gasoline and Diesel engine still has a great potential (hybrid solutions will be the first alternative ones), the conflict of interests between *a reduction in consumption and emissions on the one hand and the requirements of reliability, weight and costs on the other will further escalate: the ratio of reachable benefits to additional effort (investment) will continue to decrease*: it's consequently necessary to focus on alternative energy sources and alternative drive systems.

8.3.2   Fuel Cell Drive

The fuel Cell drive system has undergone some promising development over the past few years. Its higher efficiency and its characteristically low emission and noise levels are the main advantages of this drive system. The series NECAR 1…4 presented by Daimler-Benz clearly showed the possible autonomy (more then 450 km) for a passenger car size. Obviously, the power-to-weight ratio must be further improved and the size of the cell unit reduced as well as new complementary electronic technologies and new materials will help to sustain this innovation; furthermore methanol can be derived from organic waste and produced from biological products such as wood on a CO_2 neutral base.

The aim of Daimler Benz, in cooperation with the Californian Fuel Cell Partnership, the California Air Resources Board and partners from the Petroleum Industry is to launch the first fuel-cell powered vehicle on the market by 2005.

8.3.3   Hybrid Drive Systems

Advantages can also be derived from a combination of two different systems in the so-called hybrid vehicle. In the series hybrid drive system, an internal combustion engine drives a generator; one or more powerful electric motors use the electric current thereby generated to propel the vehicle. Excess electrical energy and the energy generated during braking are temporarily stored in a large battery: the combustion engine can then operate in steady-state mode, in a more efficient manner than in conventional operation with regard to fuel consumption and exhaust emission.

In parallel hybrid operation, an internal combustion engine and electric motors fed from a needed large accumulator battery, operate independently of each other. Both systems or one of them may be used depending on the applications. However, weight as well as production costs of such vehicles are considerably higher and the insufficient life of the accumulator batteries still presents an obstacle to large-scale manufacturing. Clearly, the high LCC (Life Cycle Cost) hinders the progress in this matter.

However, progress may be expected to increase. Daimler Chrysler, for example, combined the electrical powering of one of the vehicle's axles with the 'combustion engine' powering of the other one, synchronizing both speeds via the wheel-to-road frictional connection. Toyota PRIUS adapted the same hybrid system too.

8.4   TRENDS IN TRANSPORTATION

8.4.1   Rail Transportation

The electric transmission of railtrains is well known. Railroad engineering has seen major advances and the evolution now includes the very high-speed travels. The Super Speed Maglev System (GE Trans-rapid

International GmbH – Berlin [25]) gives, among other systems, a precise idea of the future trends in this domain. Electromagnetic fields replace the wear-prone elements of wheel and rail and enable levitation: the propulsion system is not mounted in the vehicle but in the guideway playing the role of the stator of an electrical motor, fed through a three phase windings with a traveling magnetic field of variable frequency (speed regulation) and possible reversing capabilities (braking). Operating speeds of the train can reach 500 km/h, guideways-elements vary from 78 m to 148 m long and can adapt to the landscape.

8.4.2   Aircraft Propulsion

The present-day conventional turbofan engine has reached a very high degree of reliability and one expects a 5% more fuel-efficiency with lower costs of operation. This propulsion will dominate the air fleets until 2030. The increasing fuel prices and ecological requirements will lead to still higher by-pass ratios (12/15) and an optimized design of cooled turbine blades with development of recuperative heat exchangers. Although Liquid hydrogen and methane are regarded as possible alternative fuels to reduce the CO_2 emissions, several technical problems have to be solved, among which the treatment of low fuel temperatures and the higher emission of condensed water, not to mention the considerable investments in the worldwide airport infrastructure.

The only 'electrical' addition may be expected in the introduction of electrical linear or rotary actuators instead of hydraulic cylinders ensuring the working of the control surfaces (governors).

8.4.3   Ship Propulsion

8.4.3.1   All Electric Ship

In an all electric ship concept all energy consumers, not only weapon and sensor systems, ship service and auxiliary systems, but also propulsion systems use electricity as their power input. Examples of current research programs are: the DD21 destroyer of the US navy, the Type 45 destroyer of the Royal Navy, the Klasse 212 submarine with fuel cells of the German Navy and the Landing Platform Dock (LPD) of the Royal Netherlands Navy which is already in service (Figure 8.1).

Figure 8.1: LPD HMS Rotterdam of the Royal Netherlands Navy with 15 MW Propulsion.

Also civil ships, primarily cruise liners, tend to apply electric propulsion more often. Here the application of a podded propulsor (unit with propulsion motor and propeller) under the ship results in less noise inside the ship, increased available space and higher fuel economy.

8.4.3.2 All Electric Ship (AES) Benefits

There are two primary benefit areas of the AES: increased war fighting effectiveness and reduced life cycle cost (LCC).

Increased War Fighting Effectiveness

War fighting capacities can be improved by the AES concept, since the power management that controls the distribution of electrical power to the loads can be extremely rapid and flexible. If all energy sources and all loads aboard a ship are electrical, the responsiveness of the ship to any long or short-term change is enhanced.

This leads to:

- Improved survivability: Automatic, near instantaneous pre-hit and post-hit reconfiguration of the distribution system will assure that all surviving vital loads, including propulsion, are adequately and uninterruptedly powered during and after damage according to mission priorities. "Fight-through" capability will be enhanced.

- Reduced signatures (acoustic, infrared, magnetic): In electric propulsion there is no need for a noisy gearbox, therefore significantly reducing the acoustic signature. Because of optimum loading of the power generators and prime movers, the thermal emissions (IR signature) can be kept to a minimum. Automatic power flow control can be used to minimise the electromagnetic signature as well.

- Reduced vulnerability: The prime movers can be divided more easily over different zones and compartments and the propeller shafts can be much shorter with full-electric propulsion.

- High power weapons, sensors and other consumers: Future electrically powered sensors, weapons and other pulsed loads can draw power up to the installed electric power capability, alternatively used for propulsion. The AES is ready to be fitted, now or later, with directed energy weapons.

- The possibility of using podded propulsion: The use of pods gives benefits in manoeuvrability, space requirements and cost.

- Increased range: By keeping prime movers and power generators at the most efficient operating point, fuel consumption will be reduced.

- Ready to be fitted with direct energy weapons.

Reduced Life Cycle Cost

Electricity is the common means of energy transport in an all electric ship. So substantial life cycle cost savings can be achieved through increased commonality, efficiency, automation, and reduced maintenance, manning and pollution.

- Electrical power sources and loads are easy to interface to a common power distribution system. This enables commonality of equipment across platform types and with the industrial world.

- The assembly of a ship will be easier (cheaper), because of a greater modularity.

- The cost of substituting new technology (new modules) into existing systems will be reduced if only electrical interfacing is required.

- The number of prime movers can be less than in the case of separate propulsion and generation, still maintaining the same level of redundancy. The number of prime movers running can be minimised, operating them in their most efficient point. This will result in maintenance cost reduction, fuel savings and emission reductions.

- Improved survivability, automation and reduced maintenance (less mechanical components) will result in reduced manning cost.

8.4.3.3 AES Research Topics

Figure 8.2 shows the most important research areas of the All Electric Ship. Many of these topics are also relevant for the All Electric Combat Vehicle.
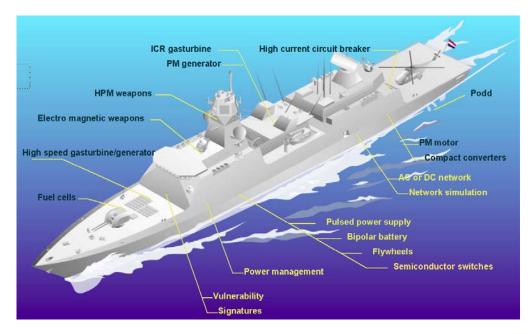
Figure 8.2: AES Research Topics.

As for the AECV many of these research areas profit from research for civil applications (fuel cells, batteries, semiconductor switches, etc.). The development of electric weapons is equally important for vehicles as well as for ships and is for both platforms one of the motivations to go to "All electric".

8.5 THE AEV: CIVILIAN MARKET. PROSPECTS 2000/2010 [25]

The next analysis allows a useful comparison between the AECV concepts, design-criteria/options, etc. and the similar concepts developed in the 'civilian' market (AEV). R&D activities merge today both concepts and common equipments are resulting from this generalized market.

8.5.1 Structure of Pure Electric Vehicles

The electric drive system consists, in the simplest case, of battery (1), converter (2), motor (3), changeable or fixed gear (4) and differential gear (5) (Figure 8.3) [1]. Besides the torque splitting with assistance of the

differential gear, a two (or four) motor propulsion (3) is also possible (Figure 8.4) [2,3]. The motors are placed in the wheelhubs. But in this case, each motor needs a separate converter (2) with speed and torque control, which guarantees the necessary torque splitting in each condition. A superposed slip-control is possible. The advantage of a wheelhub motorization relies on the ease to realize a four wheel drive system but mainly for buses in the design of low floor solutions.
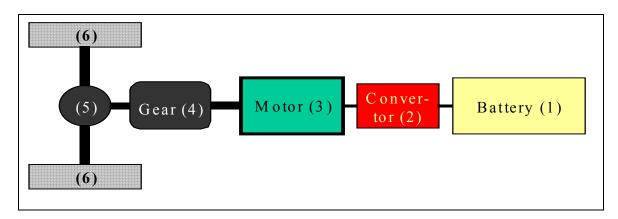
Figure 8.3: One Motor Drive for Electric Vehicles.
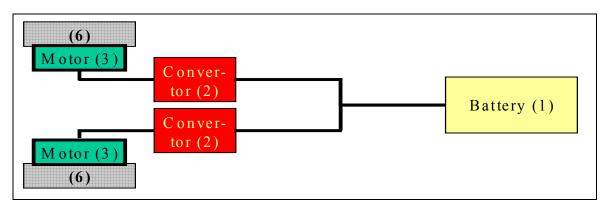
Figure 8.4: Two or Four Motor Drive for Electric Vehicles.

8.5.2   Structure of Hybrid Electric Vehicles and Fuels Cell Electric Vehicles

The implementing range of an electric vehicle can be extended by an additional energy transforming system, i.e. an internal combustion engine/generator group or fuel cell. For the sake of simplicity the vehicle will be named hybrid electric vehicle (HEV) and fuel cells electric vehicle (FCEV). Two main structures are defined in hybrid electric vehicles: series hybrid and parallel hybrid.

The series hybrid (Figure 8.5) is a combination of energy sources. The traction is obtained by only one central electric motor or by wheelhub motors. The on-board total energy source results from the combination of two or more energy sources. Hence a decoupling of the operation of the energy source from the required traction power is possible. The rated power of the engine-generator group can be designed different ways depending on the applications characteristics.
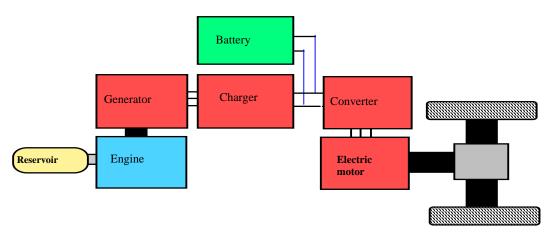
Figure 8.5: Series Hybrid.

The fuel cell hybrid structure in Figure 8.6 is a series structure in which the engine/generator group is replaced by a fuel cell system producing electric energy starting from stored hydrogen or from a fuel tank feeding a reformer to produce hydrogen. The excess of electricity produced by the fuel cell can be stored in a buffer battery. The series hybrid concept can also be chosen for a two motor propulsion, four-motor or multi-motor propulsion in the same way as for pure electric vehicles.
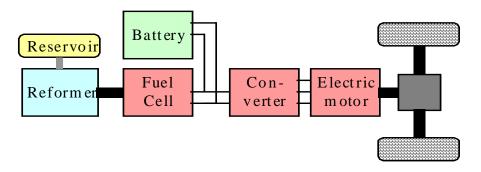
Figure 8.6: Fuel Cell Hybrid.

The parallel hybrid Figure 8.7 is a combination of traction systems. A combination of electric machines and internal combustion engine, being part of two or more driveshafts, providing the traction. Each driveshaft has to be associated with an energy source. The parallel hybrid drives realize a purely mechanical power addition. Clutches can disconnect each motor. This way, it is possible to drive only with the electric motor, only with the internal combustion engine, with both motors or with the internal combustion engine driving only the electric machine to charge the battery. Solutions with completely disconnected motors driving each one axle are called dual mode hybrids.
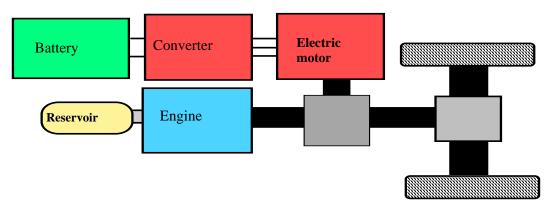
Figure 8.7: Parallel Hybrid.

All topologies different from the series and parallel hybrid electric vehicle shall be called complex hybrid vehicles. Hence complex hybrid vehicles include series hybrid with peak power units (Figure 8.8), parallel hybrids with flywheel mechanically connected via e.g. a continuous variable transmission (CVT) or combined hybrid vehicles.
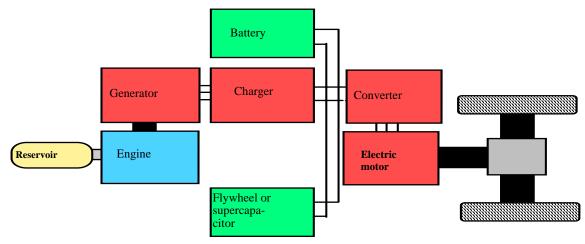
Figure 8.8: Series Hybrid with Peak Power Unit.

A combined hybrid Figure 8.9 is a combination of a series and a parallel hybrid drivetrain. By adding a mechanical connection in a series hybrid between the internal combustion engine and the electric motor a combination of series and parallel hybrid working mode can be realized. This solution allows benefiting from the parallel as well as from the series hybrid concepts. Thermal engines are usually petrol or diesel.
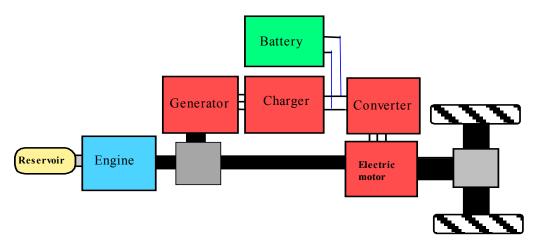
Figure 8.9: Combined Hybrid.

Hybrid drive systems need a good power source. Normal traction batteries are not suitable for hybrids. The energy management systems of all hybrid structures will play a fundamental role because of its influence on the global energy efficiency and the emissions. Therefore a good data acquisition and control system becomes a key element of the drive structure.

8.5.3   Performances of Electric Vehicles

An electric vehicle should fulfil all demands of the urban and suburban traffic. These demands are different and depend on the vehicle kind and size. It is not possible to assess and conduct evaluations on one type of vehicle and utilisation pattern representing all together the different segments of the automobile population. The different market segments can be: small passenger cars or second family car, the family car or intermediate car segment, high class segment, commercial delivery vans, trucks, minibuses and urban buses; but also electric bicycles and scooters.

Generally the maximum and continuous velocity, gradeability, acceleration and range describe the vehicle characteristics. The driving range of a pure electric vehicle is defined by the battery energy content. The desired continuous speed on a flat road is used to design the battery and the components of the drive system for the continuous power rating.

Regenerative braking is a main feature of electric vehicles. For this, a sufficiently high enough brake torque and battery recharging current must be available to fulfil the requirements. Figure 8.10 shows the "throttle" pedal characteristics of an electric vehicle.
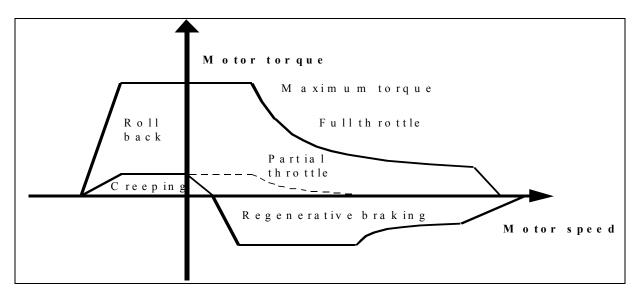
Figure 8.10: Driving Torque Curve.

The driveability is very important, which requires a high starting torque at standstill, a quick and stable response of the motor and an efficient controllable regenerative braking. To have a smooth gentle start, the rate of power increase of the motor should be limited.

A tractive effort – vehicle speed diagram [4], directly derivable from the motor torque-speed characteristics, is the main characteristic for a vehicle drive. For a better comparison between passenger car, van, minibus and urban bus the tractive effort is referred to a vehicle mass of one ton.

Figure 8.11 shows also the minimum power per mass for different types of electric vehicles.
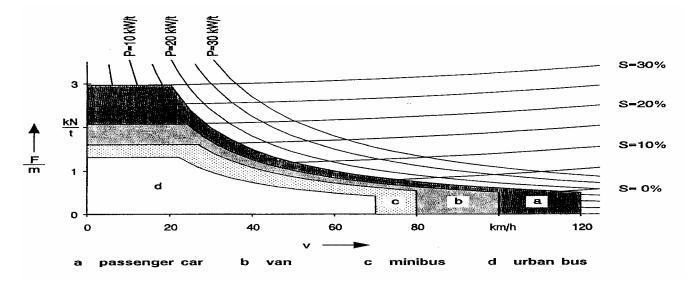
Figure 8.11: Tractive Effort Diagram for Electric Vehicles.

In the past, these specifications did not show such high values everywhere in the world. Often, low speed (60 – 70 km/h) and low gradeability (15 – 20 %) made the EV not comparable to petrol or diesel driven vehicles in city and highway traffic.

Table 8.1 shows vehicles characteristics realisable with short-term or even today's most advanced batteries. The most popular solutions on the today's European market are the cars (106 and Saxo) and the vans (Partner and Berlingo) of the PSA group.

Table 8.1: Present Reachable Goals for Electric Vehicles

	Passenger Car	Van	Mini-Bus	Urban Bus
Range [km]	120 – 250	100 – 150	140 – 200	150 – 300
Max. Speed [km/h]	100 – 120	80 – 100	80	70
Continuous Speed [km/h]	100	80	60	60
Gradeability [%]	30	20 – 25	15 – 20	12 – 15
Acceleration 0 to 50 km/h [s]	7 – 10	10 – 15	12 – 18	15 – 20

8.5.4   Performances of Hybrid Electric Vehicles

8.5.4.1   Rate of Hybridization

Some definitions are given to better understand the hybrid concepts.

8.5.4.1.1   *Order of Hybridization*

The order of a hybrid system is the number of different systems necessary to build the drivetrain [5].

In the case of an electric or thermal vehicle there is only one motor or engine driving the vehicle. These drivetrains are from the first order. Also fuel cell vehicles without a battery are first order systems.

A parallel hybrid built up with one engine and one motor is a second order hybridisation as well as a series hybrid electric vehicle containing a battery and another energy source.

When a peak power unit, like a flywheel or super-capacitor, is added to the drivetrain, the vehicle is from the third order. All complex hybrid drivetrains are third or higher order systems.

A combined hybrid drivetrain (Figure 8.7) can also be seen as a third order hybridisation. Although there are only two energy sources, there are three shafts: one connected to the engine, one to the generator and one to the electric motor. All three are mechanically connected to the wheels.

8.5.4.1.2   Electric Hybridization Rate (EHR)

The Electric Hybridisation Rate (EHR) gives an indication of the performance, and above all, the range in protected areas. This means the 'more battery'; the longer one can drive without generator or engine, the higher the electric hybridisation rate. It is the ratio between the electric power and the total traction power (equation 1), and is expressed as a percentage. The higher this rate, the more the vehicle tends to a pure electric vehicle.

In the case of a series hybrid electric vehicle, the traction power corresponds with the nominal electric motor power, since this motor is in charge of all traction effort. The electric power is the maximum continuous battery power. This maximum power is difficult to define and is to be related to a discharge rate (one hour, two hours…). Consequently the EHR for a series hybrid is given by equation 2.

For a parallel hybrid electric vehicle, the EHR is equal to the ratio of the electric motor power to the overall power (equation 3). This overall power is the sum of the engine power and motor power, since both are in charge of the traction exertion.

$$EHR = \frac{electric\ power}{traction\ power} \tag{1}$$

$$EHR = \frac{P_{bat}}{P_{mot}} = \frac{P_{mot} - P_{gen}}{P_{bat} + P_{gen}} \tag{2}$$

$$EHR = \frac{P_{mot}}{P_{ICE} + P_{mot}} \tag{3}$$

8.5.4.1.3   Combustion Hybridization Rate (CHR)

To have an idea of the relative contribution of the internal combustion engine a complementary definition to the Electric Hybridisation Rate can be introduced: Combustion Hybridisation Rate (CHR). It is the ratio between the thermal power and the total traction power (equation 4), expressed as a percentage. The higher the rate, the more the vehicle tends to a pure thermal vehicle.

In the case of a series hybrid electric vehicle, the thermal power is defined equal to the rated generator power and hence the CHR is defined by equation 5.

For a parallel hybrid electric vehicle, the CHR is equal to the ratio of the engine motor power to the overall power (equation 6).

$$CHR = \frac{thermal\ power}{traction\ power} \tag{4}$$

$$CHR = \frac{P_{gen}}{P_{mot}} = \frac{P_{mot} - P_{bat}}{P_{bat} + P_{gen}} \tag{5}$$

$$CHR = \frac{P_{ICE}}{P_{ICE} + P_{mot}}$$

(6)

The relation between HER and CHR is expressed by equation 7:

$$EHR + CHR = 1 \text{ (or 100 in \%)}$$

(7)

8.5.4.1.4   Rate of Hybridization (ROH)

The Electric Hybridisation Rate or the Combustion Hybridisation Rate don't express the degree of hybridisation itself, but rather how much a vehicle leans against the electric vehicle side or respectively to the thermal vehicle side.

The Rate of Hybridisation (RoH) describes the relative contribution of each energy source (in the case of series hybrid electric vehicles) or traction system (in the case of parallel hybrids).

If both systems have an equal contribution to the traction effort, the RoH is defined as equal to one (the maximum). If the contribution of the thermal system is higher then the electric system, the rate of hybridisation (RoH$_{th}$) equals the ratio of the electric power to the thermal power and vice-versa (RoH$_{el}$) (equation 8). Hence first order systems always have a rate of hybridisation that equals zero.

$$If \quad P_{el} < P_{th} \quad \Rightarrow \quad RoH_{th} = \frac{P_{el}}{P_{th}}$$

$$If \quad P_{th} < P_{el} \quad \Rightarrow \quad RoH_{el} = \frac{P_{th}}{P_{el}}$$

(8)

8.5.4.1.5   Classification

Based on these definitions, a diagram representing a panorama of second order hybrids can be constructed (Figure 8.12). This user-friendly diagram is based on reference [5] and is pointing out the different possibilities of hybridization in terms of power by varying progressively the electric and combustion hybridization rate. It is possible to show which continuum exists in the global field.
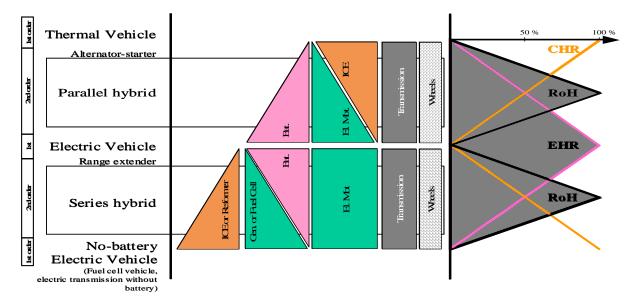
Figure 8.12: Different Hybrid Electric Vehicles Classification.

Looking at Figure 8.12 from top to bottom, we see, first, the thermal powered vehicles, the family of parallel hybrids, the electric vehicle, the family of series hybrid, ending with the fuel cell or the so-called diesel-electric transmission structure.

Back to the top, the starting point is the thermal engine in its classical structure. It assumes that no battery is present onboard these vehicles, with the auxiliary battery not taken into account.

The first step to hybridization is in the parallel hybrid group and is represented by the "Alternator-starter" solution integrating the charging alternator and the electric starter motor in the motor flywheel. With an increase in size (power and energy) of the auxiliary battery, recuperative braking becomes possible.

Going further down, we observe an increase in the power of the battery as well as the electric motor's power while the power of the ICE is decreasing. If pure electric range is desired, the increase in power of the battery has to be complemented with an increase of accumulated energy, consequently an increase in weight. We can more or less locate the PRIUS solution in this group with a (RoH) of 33 kWel/53 kWth = 0,62 (or 62%). The thermal motor power is still dominant.

Still further down, we see the increase in the electric motor's power, and power of the battery, whilst there is a decrease in the thermal motor's power. At the bottom of the parallel hybrid block we naturally meet the pure electric vehicle solution. Going further down, we enter the family of series hybrid characterized by a full electric motor traction system.

The first indicated step is the so-called "range extender solution". This small thermal motor-electric generator group is providing complementary energy to the battery or traction system, thereby extending the battery vehicle range.

Further Increase of the ratio of thermal power to battery power, we reach a structure without a battery and with 100% electric power generated by a thermal engine-electric generator group. This is the so-called "diesel-electric" transmission system.

To the series hybrid block naturally belongs the fuel cell hybrid structure with a power partition between the fuel cell and the battery. At the bottom the battery disappears as we have a 100% fuel cell powered drive system.

We see that the number of possible solutions is infinite but will not all demonstrate the same value neither economically nor with respect to efficiency emission but in the end with respect to a weighted mix of these criteria. To evaluate these criteria a software has been developed at the 'Vrije Universiteit Brussel' as a result of a fundamental PhD work which can be consulted at: http://etecnts1.vub.ac.be/VSP/.

8.5.4.2   Component Requirements

At present, the choice of the structure of a hybrid vehicle is a strongly evolving matter because of the more or less rapid but steady evolution of the component technology and performance. It is out of the scope of this paper to try to give an extensive overview of the characteristics of all possible components for all possible configurations but some among the most classical can be briefly discussed.

8.5.4.2.1   Batteries

Compared with the electric vehicles the batteries for hybrid vehicles are characterised by a reduced energy contents and higher power requirements.

A specific energy of at least 50 Wh/kg and a specific power of at least 500 W/kg is a must for an efficient design. For electric vehicles the power specifications should be 100 W/kg continuous up to 300 to 500 W/kg for one minute.

8.5.4.2.2   Petrol, Diesel and Gas Engine/Electric Generator.

The maximum power of the thermal engine depends clearly on the rate of hybridization. The acceleration power is mainly delivered by the battery. For the electric generator the tendency goes clearly towards the implementation of permanent magnet generators which efficiency at constant power working point is between 90 and 95%.

8.5.4.2.3   Fuel Cells

Fuel cells can replace the thermal engine/generator group. The associate hybrid structure is always the series one. Maximum efficiency around 60% can be expected with which the efficiency of hydrogen production (e.g. the reformer) has to be multiplied. The ways to produce hydrogen considered today are multiple:

- Electrolysis of water in countries with hydro energy (e.g. Canada, Norway) or nuclear power plants (e.g. France);

- Electrolysis of water with electricity produced by wind or solar energy;

- Reforming of methane (natural gas – CH_4), methanol (CH_3OH) or other hydrocarbon fuels (e.g. those classically used today);

- Reforming of ammonia (NH_3).

The global energy efficiency related to these different ways and/or the resulting CO_2 emissions, remains an open question as well as the necessity, or not, to use a buffer battery.

8.5.4.2.4   Electric Motor

Two main types seem to emerge. The asynchronous (induction) motor has the advantage of its higher robustness. The permanent magnet motor leads to a more expensive solution with a somewhat higher efficiency. It is the solution to be implemented in case of integration of the motors into the wheels. Due to their low cost, reluctance motors can be a good choice in the lowest EHR field.

8.5.4.3   Segmentation

To plan a suitable hybrid vehicle, the usage of the vehicle must be clearly defined. One way of doing this is to use the segmentation of the automobile market. The basic criteria is the price, which is justified by technical performance, but in the future the price of energy, the reduction of consumption and emissions will play an increasing role. The standard use per segment is very important for selecting, but also for defining the type of hybrid vehicle, as its price alone cannot really be representative.

8.5.4.3.1   Second Family Car Segment

The second (or third) family car segment, also considered as "ladies" or "young persons" car is characterized by a frequent use in town, a relatively low daily mileage and a great maneuverability in urban areas. Long trips are performed only occasionally, therefore some reduced comfort is acceptable. Due to the frequent use of the car in urban areas the use of the thermal engine in variable regime leads to a dramatic loss of efficiency (even lower than 10%). Therefore the series hybrid drivetrain with a rate of hybridization up to 20 – 30 % (CHR) seems to be a realistic approach despite the fact that in the series hybrid all losses (thermal engine or reformer, generator or fuel cell, converter, electric motor) are accumulated. The range in the all electric mode could be around 50 km.

Electric vehicles with a range extender unit (up to 300 km with a NiCd battery and probably more with a Lithium-ion battery) fits fully in this segment. They could lead to the solution for all psychological obstacles related to the acceptance of EVs.

8.5.4.3.2   Intermediate Car Segment

The intermediate car population segment is a very versatile car used frequently in town, with a good road performance, often used as the main and even sole car. Long trips are performed regularly therefore comfort is taken into consideration.

Therefore, as shown by simulation, the competition for this segment between series and parallel solution is high, the efficiency of the parallel hybrid being better on long trips. It could be the field of combined hybrid structure as implemented in the Toyota PRIUS which is on the market now (EHR of 62%, 3.8 l/km in low duty service up to 5.5 l/km in high duty service, in the CITELEC-AVERE 2nd TransEuropean demonstration trip from Monaco to Hanover) and the field of the fuel cell car as implemented in the NECARIV, based on the Mercedes class A car, which arrival on the market could happen within 5 to 10 years.

8.5.4.3.3   High-Class Car Segment

The high-class car population segment has excellent road performance, high technical performance and top comfort, it is not at all adapted for town use and is often the first car of a family with several cars. In this case the parallel hybrid solution seems to be definitely the best one because of the long highway trips. The electric hybridization rate could be around 35% to give the minimum backing to the ICE. This class could also be a

field of implementation of the fuel cells which is in fact a full electric solution. This type of car is often used as a taxi, in which case the series hybrid is more justified.

8.5.4.3.4   Small Delivery Vehicles Class

The small delivery vehicles are used in a similar way as the second family car, the comfort is usually somewhat sacrificed to add additional practical facilities. The series hybrid drive train with the same characteristics as the second family car segment is the realistic approach for this case. The electric Renault Kangoo equipped with a range extender using a 3 cylinder, 600 cc, ICE engine is a very promising realization. This could be an ideal solution for postal and goods delivery services.

8.5.4.3.5   The Citybus

The classification of the bus population is quite simpler because of the specific use i.e. urban public transport with the 6 m, 9 m, 12 m and articulated structure or tourism. The performances for city public transport are quite modest if one refers to the realizable medium speed in most cities, about 15 km/h, but the range must reach 250 km and sufficient power for acceleration and hill climbing is necessary. The maximum speed will range between 60 and 80 km/h. The increased weight imposed by the hybrid (and even electric) structure may have to be translated in a reduced number of passengers i.e. in a reduction of exploitation capacity. The tourism or long range buses are to be compared with vans and lorries. The service of a bus on a public transportation line is clearly a heavy duty service characterized by a big number of stops, acceleration and braking phases. Constant speed is becoming a rare event.

The series solution is once more the best solution here with a rate of hybridization within the step 30 – 50 %. The most popular realizations on the European market are the IVECO-ALTRA Europolis (7,2 m) and Cityclass (12 m) buses.

Higher rates can be implemented (greater than 50%) but in that case the working mode can dangerously approach the working mode of a pure diesel (thermal motor) generator group with a strongly variable load and consequently a poor gain (if even existent) in efficiency and emission level. Gain could exist if the efficiency of the mechanical transmission (gearbox,) demonstrates to be poor.

8.5.4.3.6   Lorries and Long Range (Tourism) Buses

This is currently, the field of diesel engine where the latter develops its best efficiency. Parallel hybrid structure can be considered for city use. The fuel cell find here one of its best promising application.

8.5.5   Batteries and Other Energy Sources

Energy for vehicles can be delivered from different sources. Thermal energy from gas and fuel has to be converted into mechanical energy but this is done with low efficiency. Oxygen comes from the air, exhaust-gas is emitted into the air. Burned material cannot be reactivated [6].

Electrochemical energy is stored in batteries or produced by fuel cells. The battery is the most important part in an electric vehicle. Energy density and power density are the first battery parameters to be considered. Table 8.2 shows the main characteristics of available and advanced batteries for electric vehicles.

Table 8.2: Characteristics of Batteries for Electric Vehicles

(Figures in brackets are the lowest and highest working temperature)

	Pb-PbO$_2$	Ni-Cd	Ni-MH	Na-NiCl	Li-Ion
Working Temperature °C	0 – 45 (-20 – +60)	0 – 50 (-40 – +60)	-40 – +50	300 – 350 (250 – 370)	-40 – +60
Specific Energy Wh/kg	161	236	300	794	275
Specific Energy (2 h discharge) Wh/kg	20 – 30	40 – 55	50 – 60	80 – 100	90 –140
Energy Density Wh/l	60 – 80	60 – 90	100 – 150	110 – 120	150 – 200
Specific Power W/kg	75 – 100	120 – 150	140 – 200 500 – 1000 (for hybrids)	150 – 200	350 – 400
Cell Voltage V_o/V (charged)	2,1	1,35	1,35	2,58	3,6
Lifecycle	500	2000	1000	1000	1000

The **lead-acid battery** is the best known. For maintenance-free batteries the electrolyte will be stored in a fleece material or in a gel [7]. New types with bipolar cells are in tests. This battery is heavy but cheap. With a good battery management system the lifecycle (500) can be secured.

The **nickel-cadmium battery** [8] has a high power density and a high cycle life. Completely sealed cells with gas recombination are in production. This battery is equipping most of the European electric vehicles on the market.

In **nickel-metal-hydride batteries** an alloy storing hydrogen will be used for negative electrodes instead of cadmium (Cd). Energy density and power density increase compared to the NiCd battery [10].

The **sodium-nickel chloride battery** is a hot battery. Its controlled working temperature (270°C) eliminates any influence of outside temperature. This battery demonstrates very good applicability for EVs [10,11] and HEVs in daily fleet service. It is known as the ZEBRA^{TM} battery.

An advanced battery is the **lithium-ion battery** [12]. Small cells are already strongly used in the portable electronic market. Batteries for EVs are under development. A first prototype for an EV was shown at the 13th Electric Vehicles Symposium, Osaka 1996 and prototype demonstrations (Peugeot 106 and Ford Ka) have got a range of more than 200km in the Michelin 'Bibendum Challenge 2000'. The real marketing is now announced around 2004.

The development of **fuel cells** goes back to the last century, with the invention by GROVE (UK). It was stimulated by the wish to produce energy independently from the Carnot law. The alkaline fuel cell was developed in Europe and mainly used for space exploration and satellite.

The power density of **proton exchange membrane fuel cells** (PEM) is significantly higher than that of alkaline fuel cells and the PEM is able to work at ambient temperature. Most of the car companies are making big efforts to integrate the PEM fuel cells in a small part of the car body.

The most advanced development in the field is realized by Daimler Chrysler with a Ballard fuel cell. The fuel cells need hydrogen as basic fuel. The production of hydrogen by means of a reformer for methanol (or another type of hydrocarbon fuel) could solve the problem of fuel infrastructure, which could then remain practically unchanged. The marketing is also announced around 2004 but this has only the value of a very optimistic market announcement in a field with very hard competition.

Developments of metal-air batteries like **zinc-air** or **aluminum-air** were started in the mid sixties. Since few years Electric Fuel Ltd., a company in Jerusalem, Israel, and an institute in Karlsruhe, Germany, developed new zinc-air batteries [13]. Zinc-air is now abandoned in Germany but efforts are still developed in Italy by the EDISON company.

Energy can be stored also in a **flywheel**. The mechanical energy is transformed into electric energy by a generator driven by the flywheel. In some application the flywheel-generator set can be a booster for high power.

Still in development are **supercapacitors**, which also can be used as short time power source.

8.5.6   Traction Motors

Table 8.3 gives a comparison of different motor types: asynchronous motor (ASM), permanent magnet motors (PM), switched reluctance motor (SRM), direct current motor (DCM) and synchronous motor (SYM).

Table 8.3: Comparison of Different Motor Types

(0 Is Neutral, + Means Better, – Means Less Good)

	ASM	PM	SRM	DCM	SYM
Motor Size Mass	0	+	0	–	0
High Speed	+	+	+	–	–
Endurance Maintenance	+	0	+	–	–
Efficiency	0	+	0	–	0
Controller Size Mass	0	0	0	+	0
Controllability	+	+	–	+	0
Number Power Devices	0	0	+	+	0
Reliability	0	0	0	0	0
TOTAL	+++	++++	++	– –	– –

Motors should always be evaluated as a function of needs and application. For instance, each of the different motors can be less efficient than the others in some regions of operation, and it can be more efficient than the others is some other regions. To make a good comparison, one must not compare maximum efficiencies,

but relate the efficiency map to a certain speed cycle. The table shows an advantage for the permanent magnet motor as traction motor for electric vehicles. Indeed, on the level of performance the permanent magnet motor has a lot of interesting features. But considering the production cost, one must take into account the high price of the magnets and the more complex construction of the motor. Regarding the price, the global result will probably be in the advantage of the asynchronous motor but in the last published information and development programs, the switched reluctance motor is earning a lot of interest.

8.5.7   Power Electronics for EV and HEV Drives

Thanks to power electronics and microprocessor-based control devices the performance and control of all the traction systems used in land transportation sector are becoming more and more efficient. From today's view, the IGBT will be the common switching device for EVs. Only converters for low battery voltages (< 100 V) and converters with very high frequencies (DC/DC converter, charger) will be equipped with MOS-FETs [14,15,16].

Today's inverters for electric vehicles will be designed with modules of bipolar transistors, MOS-FETs or IGBTs. Three-phase full bridge modules are available at reasonable prices. The inverter control-unit has to generate the three-phase voltage.

Regenerative braking or reverse driving is performed by the converter control unit without any additional switches [17,18]. Compared with DC chopper circuits with relatively low frequency, inverters need a big filter capacitor to reduce the current pulses in the battery.

To provide 12 V auxiliary power and to charge the auxiliary battery during operation, a DC/DC converter is necessary. In most cases DC/DC converters are made with single-ended forward converter or with push pull forward converter. In some new development flyback converter with very high frequencies are used.

8.5.8   Chargers and Charging Infrastructure for EVs and HEVs

Electric vehicles batteries need to be recharged. For hybrid vehicles the situation can be quite different depending on the structure of the drive system. Indeed for the diesel structure (without battery) and for the combined hybrid structure used in the Toyota PRIUS no external charging is required. The basic question discussed by associations promoting EVs and HEVs is: "Is it more efficient or is it necessary to recharge the battery of an HEV at the mains (external charging) to get the best results with respect to energy consumption and emission?" The debate is still open but the answer can be a matter of economy and/or infrastructure.

Electric vehicles are largely independent of the charging place if they are equipped with an on-board charger connectable with any AC outlet. A 230 V/16 A outlet can supply an apparent power of more than 3.5 kVA. Such an outlet can be installed everywhere e.g. in public parking or in home garages. A battery of 15 kWh can be charged in less than five hours (main charging) with a charger having a unity power factor [19,20]. Electric utilities in Europe are nowadays demanding more and more consumers with low distortion and reactive power requirements. From the AC power supply system a quasi-sinusoidal current with a low harmonic content, at unity power factor, can be easily obtained.

In Europe, three-phase feeding is used for powers higher than 3.5 kW. This is a line normally separated from the usual AC single-phase distribution.

Even considering that most electric vehicles can be charged at home garages, the provision of public charging stations is as necessary as it is for the refueling stations for classical vehicles.

In countries like France, Germany, Italy, Switzerland, United Kingdom and Finland public charging stations have been developed.

The cost of the energy used during charging is much lower (85%) than normal downtown parking fees and could easily be included in this fee.

The development of an public charging infrastructure must be done with particular emphasis on safety aspects and standardization.

Half fast (7 – 10 kW) and fast charging stations (25 kW and more) can help creating confidence in the use of electric vehicles. They allow recharging in less than two hours or in a few minutes, thus eliminating the fear of running out of battery power.

The only charging infrastructure used until now in Europe is of the conductive type i.e. with a galvanic connection to the mains. In the USA and Japan inductive charging systems have been developed and are becoming popular.

The basic idea of the inductive system is quite straightforward: the main transformer of the battery charger is split into two parts. The primary is fixed on the ground, the secondary is mounted on the vehicle. It will now be sufficient to place the primary adjacent to the secondary to "re-assemble" the transformer and to allow on energy transfer from the grid to the battery.

Due to its particular characteristics of user-friendliness and safety, inductive charging is well suited to a large number of electric vehicle applications. Because of the infrastructure needed, it seems likely that initially fleet applications will be the most important. To make an automatic rent-a-car system attractive and successful, it must be reliable, safe and easy to use. The manipulations to be done by the driver should be as simple as possible: ideally, only identifying himself to the system (e.g. with a credit card), board the vehicle and drive away (the credit card could serve as "ignition key"). Any additional activities, such as unplugging and storing a cable, are clearly undesirable. In this viewpoint, inductive charging systems are particularly attractive for this application.

City centers are the usual operation theatres for taxi fleets, which makes them particularly attractive for electric traction. The daily mileage of taxis in big cities however can be quite important (150 – 200 km) and may exceed the range of a typical electric vehicle.

This problem may be countered through the use of opportunity charging, which can be easily implemented taking into account that taxis usually spend an important lot of time waiting at taxi lines. Having to disconnect the charging cable takes some time however and will make the electric cab less popular with the customer, which in most cases will be in a hurry. Inductive cable-free charging is the solution.

Commercial vehicles (i.e. light goods vehicles) are one of the most obvious potential applications for electric vehicles in urban areas. The ubiquitous British milk floats are a well-known example; furthermore, advanced electric vehicles are used in a growing number of European cities for goods distribution and service applications. The utilization of inductive charging systems on such vehicles has obvious advantages. On one hand, the operations to initiate charging become much simpler and user-friendly, which is particularly interesting when frequent charging intervals are used (opportunity charging). On the other hand, the simplicity of the charging operation will ease the acceptance of the system by the personnel.

Electric buses offer a quiet and fully emission-free public transport in city centers. The daily mileage of a typical city bus however usually exceeds the range of an electric vehicle on a single battery charge. Battery exchange is a potential solution, but can be a cumbersome operation taking into account the heavy weight of the batteries. Opportunity charging is much easier, and when it can be inductively done, without cables or plugs, it offers the most attractive solution.

The present state of the art of inductive charging system shows several approaches related to the use of the working frequency (50 Hz, 400 Hz or more then 20 kHz), and which have led or may lead to industrial developments.

For all the above mentioned applications the basic charging power level is 3 kW but a half fast charging procedure with 6 to 10 kW power level is very easy to implement. The electric power levels used in buses are higher of course. The proposed technology is however fully suitable for power levels up to 100 kW.

8.5.9 Fueling Infrastructure

The way towards hybrid and fuel cell hybrid vehicles will very probably be accompanied by a fundamental change of the fueling infrastructure. Indeed, as stated in the introduction, today there is general concern about the increase in oil prices and it is generally agreed that the era of cheap oil is nearing its end.

Do we have alternative energy sources to compensate for this situation and allow further development, or indeed further maintain the mobility capacity in the world? The number of alternatives is quite large but each has its own limitations.

LPG is cleaner but is a by-product of oil distillation and accounts for only a complementary ten percent of fuels produced for transport. The distribution infrastructure for LPG is, due to the liquid form of this gas under pressure, quite easy to install and is already implemented. Most of the safety aspects have been solved.

CNG shows big reserves but with a situation similar to that of oil, even if the delay is a bit longer. It is a questionable solution with respect to efficiency. The distribution infrastructure is generally associated with the already existing one for domestic applications. CNG need to be compressed up to 200 bars and this costs electric energy. In the slow fill procedure the filling time takes hours, as is the case for the battery of an electric vehicle. The quick fill procedure requires a heavier compressing installation with accumulation boosters. Recharging is possible in less than fifteen minutes. This solution is acceptable for fleets particularly for bus fleets as popular in Northern Italy (Ravenna).

Bio Fuels has the problem of costs and efficiency at the level of production. The distribution infrastructure is very similar to that of the classical hydrocarbon fuels but raises more problems of safety in the case of methanol (burns without light production, more corrosive, dissolution in water table in case of leak).

Hydrogen is considered today as a major solution for the future but its production, distribution, its global energy efficiency and CO_2 balance remain an open question. Distribution under gaseous or liquid form has practically to be totally solved, despite the existence of some industrial distribution networks for gaseous hydrogen. This could be easily organised for fleets in association with a local production of hydrogen. A demonstration of a fuel cell bus fleet in ten European cities will probably be an effective approach to assess such alternatives. The case of production of hydrogen by reforming a "classical" fuel (methane, methanol, hydrocarbon fuel, etc. …) leads the distribution infrastructure back to the problems mentioned above. This way seems to attract the biggest attention of the classical energy providers in the field of land transportation.

Electricity is probably the cleanest and most efficient energy source to use but it is a secondary energy source and has to be produced using the other sources. Opposite to the traditional centralised production, decentralised production is becoming popular (e.g. solar photo voltaic plants, windmills, combined heat and electricity production, fuel cell power plants). Installation of a general or a local network is very easy.

Consequently, the path from primary energy to the wheel is generally a multi-stepped one and raises the question of balance between emissions, efficiency, access to energy source and economy. Considering the future's needs, it is clear that the solution is not a unique one but a mix of different ones.

8.5.10   Standardization of Electric Vehicle Charging

The wholesale introduction of electric vehicles and their acceptance by the public will lead to a situation which is unique with no historical precedent: a high-power connection (3 kW for normal charging, up to 25 kW or more for fast charging), made daily, in outdoor conditions, by members of the general public which are not electrically trained. One may think that the public has learned to live with electricity which has been our major source of energy for over 100 years now, and such power levels are quite common in household installations, but the conditions of use here are quite different:

- Connections of high powered electrical devices (washing machines, water heaters, cookers, ovens....) are made only once when the machine is installed, often by a qualified electrician; electrical vehicles however are on the move daily;

- The use of electrical equipment in outdoor, all-weather conditions is normally not performed in an ordinary household environment;

- Potential electric vehicle drivers, which are members of the general public, including specific groups such as elderly people, disabled people and mothers with small children, usually have not received a specific training about dealing with high power electrical equipment; the idea alone of "high electric power" may actually frighten them off from electric vehicles.

The connection of the electric vehicle to the charging network must be performed with a very high level of safety and reliability in order to gain acceptance by the public.

In normal conditions the energy transfer between the supply network and the vehicle shall be operating safely, causing no danger to persons or surroundings, even in the event of carelessness that may occur in normal use.

Furthermore, the introduction of public charging infrastructure, in order to be economically viable, must be able to accommodate a wide range of different vehicles. In order to obtain a sufficiently high operational flexibility, the vehicles themselves must be able to use as much different kinds of charging infrastructure.

Hence the need for specific standardization of electric vehicle charging is clear and can be considered in two categories: Onboard charging and or charging stations.

8.5.11   Energy Consumption of Electric Vehicles and Environmental Impact

The energy consumption at the mains of electric vehicles can be reflected by two mathematical expressions describing the state of the art of today's technology and the impact of the drivers.

For medium to high energy consumption we get

$$C = 150 + \frac{100}{W}$$

For normal to low energy consumption we get

$$C = 80 + \frac{80}{W}$$

where C the consumption in kWh/Tkm and W the weight expressed in tons.

To get then the environmental impact, the production mix of electricity has to be considered for each country and for each local production of electricity. This can lead to a very extensive discussion but will surely have a fundamental impact on the way of producing electricity for EV and HEV. Table 8.4 gives an example for the situation in Belgium for 1.200.000 EV replacing 800.000 petrol vehicles and 400.000 diesel vehicles.

Table 8.4: Total Daily Emissions Taking into Account Electricity Generation (ton per day)

	Petrol Cars (800.000 pieces)	*Diesel Cars (400.000 pieces)*	All ICE Cars (1.200.000 pieces)	Electric Cars (1.200.000 pieces)	**Difference: Advantage of Electric Cars**	
CO	*202,2*	*16,8*	219,0	1,0	**218,0**	*-99%*
NO$_x$	*26,2*	*17,9*	44,1	9,6	**34,5**	*-78%*
SO$_2$	*2,7*	*3,4*	6,1	21,6	**(15,5)**	
KWS	*27,6*	*3,5*	31,1	0,5	**30,6**	*-98%*
Dust	*0,5*	*2,0*	2,5	0,6	**1,9**	*-76%*
CO$_2$	*7104*	*3344*	10448	4800	**5648**	*-46%*

8.5.12 The Market

In collaboration with the European Union RTD Programs, studies have been performed (1994 – 1996) about the opportunities for electric and hybrid vehicle introduction in European cities. The selection of these cities takes into account the commitment towards electric transport of each city on one hand and the choice of a "palette" of cities with different characteristics on the other hand. This way, it has been possible to give a thorough description of the main activity and policy domains where electric and hybrid vehicles could be used in Europe.

These studies have confirmed the results obtained in the COST 302 study [21], in the EDS study for the European Parliament [22] and in the inquiries performed by CITELEC among its members. The studies all concluded in a market between 10 to 30 % for EV and even 70% in city administration fleets as defined by AVERE France in a recent inquiry.

The Californian market defined for 2003 provides 10% for EV, 25% for ULEV i.e. HEV and the rest for LEV (low emission vehicles). The Californian mandate has been recently confirmed.

But the real future will probably be a mix of EVs, hybrid ULEV and fuel cells vehicles. The time needed for this is projected to take between 10 to 20 years.

8.5.13   Automation in the Automobility: Other Electric(onic)al Dual Future (Auxiliaries)

Furthermore, the first World Engineers Convention (WEC) , held at Hanover, Germany, drew the attention on the emerging automation of the Transportation: in recent years, a large number of systems aimed at improving active safety in vehicles has been introduced under the general heading of Driver Assistance. From 2000 to 2020, one may expect, besides the progresses of the passive safety, considerable evolutions of the Dynamic Stability Control or DSC, the Adaptive Cruise Control (ACC), the Electric Power Steering (EPS). Full control of the vehicle's functions. Also, the transportation problem concerns more than one vehicle and Intelligent Transportation Systems (ITS) are currently developed and tested in Europe, in the USA, Japan, etc. Furthermore, the Telematics, defined as the convergence of the Automobile, telecommunications and consumer electronics, will also assist the driver with a continuously updated map database transmitted to the vehicle through a packaged wireless network. All those innovations will imply an increase of the user's acceptability and will have their impacts on the education level of the developers and the users. The actual R&D focuses on the electronically assisted safety of the vehicles (manually driven or not) and the upgradeability of the new Telematics systems. No doubt that those techniques will be developed through the research activities focusing on the unmanned ground and aerial vehicles (another promising branch allowed by the generalization of electrical technologies).

8.5.14   European Programs

A number of RTD actions are running in the ending fourth framework program, JOULE-THERMIE and BRITE EURAM. They are devoted to the development of batteries (Li), the testing of batteries (Pb, NiCd, NMH, Li-Ion, Li-Polymer), the testing of EV or HEV fleets (ZEUS, JUPITER, SAGITTAIRE, EVD-POST, ELCIDIS,...).

Important integrated RTD efforts for hybrid and fuel cell vehicles are further supported in the now running fifth framework program (PRAZE, E-TOUR, ENIGMATIC, ELEDRIVE, FUCENAV, ...).

8.5.15   Conclusion

EV, HEV and FCEV are existing technologies but many development efforts are still needed to put valuable products on the commercial market. The demand of research development and design effort in the field of drives, energy sources and charging infrastructure is becoming enormous and a challenging field for the European Community.

The future of the access to energy, the environmental and climate problems and the need to solve the mobility problems in the cities are all fields in which electric, hybrid and fuel cell vehicles offer a large number of interesting and necessary solutions.

AECV AEV Dual Use strategy [26]

"A tighter linkage with commercial markets can SHORTEN the cycle time for weapon system development and reduce the COST of inserting technological improvements into our weapon systems. We cannot afford a 15-year acquisition cycle-time for our defence systems when comparable commercial turnover is every 3 – 4 years. The issue is not only cost but security. The military advantage

goes to the nations who have the best cycle-time to capture technologies that are commercially available, incorporate them in weapon systems and get them fielded first."

8.6   REFERENCES

[1]   U. Görlach, The Relation Between Efficiency and Range of Electric Vehicles, Elektrot. Zeitschr. A Vol. 94 (1973) pp. 632-636.

[2]   J. Langheim and J. Fetz, Concept of an Electric Citybus with Two Induction Machines, EVS-10, Hong Kong, (1990), pp. 254-271.

[3]   H. Shimizu et al., The Concept and Simulation of a High Performance EV "IZA", EVS-11, Florence, 1992.

[4]   H. Kahlen and G. Maggetto, Electric and Hybrid Vehicles, EPE-97, Trondheim, Norway, (1997).

[5]   J. Beretta, PSA Peugeot-Citroën, France, New Classification of Electric Thermal Hybrid Vehicles, EVS15, Brussels, Belgium, 1998.

[6]   M. Barak, Electrochemical Power Sources; IEE Energy Series 1, Peter Peregrinus London, 1980.

[7]   H. Kahlen, Batterien, Vulkan Verlag (1992).

[8]   F. Haschka and D. Schlick, High Power Nickel-Cadmium Cells with Fiber Electrodes (FCN), 32nd Power Sources Symposium 1986.

[9]   S.R. Ovshinsky et al., Ovonic Ni-Metal Hydride Batteries for Electric Vehicles, 24th ISATA, Florence, 1991.

[10] J. Coetzer, A New High Energy Density Battery System, Journal of Power Sources, Vol. 18 (1986).

[11] D. Sahm and J.L. Sudworth, Lifetime and Reliability Testing of ZEBRA^{TM}-Batteries, EVS-12, Anaheim, 1994.

[12] M. Broussely, P. Flament, Ch. Morin and G. Sarre, Lithium-Carbon Liquid Electrolyte Battery System for Electric Vehicle, EVT-95, Paris, 1995.

[13] B. Koretz, J.R. Goldstein, Y. Harats and M.Y. Korall, A High-Power, Mechanically Rechargeable Zinc-Air Battery System for Electric Vehicles, 25th ISATA, Florence, 1992.

[14] B.Y. Baliga et al., The Insulated Gate Rectifier (IGR): A New Power Switching Device, IEEE IEDM-Digest Abtr. 10.6 (1982).

[15] V.A.K. Temple, MOS Controlled Thyristors, IEFE INt. Electron. Dev. Mat. Digest, Abt. 10.5 (1984) pp. 282-285.

[16] R.D. King et al., Comparison of Power Darlington, IGBT and MCT Switch Losses in ASD PWM Inverters, Power Conv. and Int. Motion, 1990.

[17] H. Bausch et al., Road Vehicle with Full Electric Gear, EVS-10, Hong Kong, 1990.

[18] B. Hexamer, A 33kW Electric Drive Based on a Switched Reluctance Motor, EVT-95, Paris 1995.

[19] C.K. Patini and L. Perier, Optimised Power Stage for High Frequency 380/400V AC Medium Power Switch Supplies, IEE 3rd Int. Conference on Power Electronics and Variable Speed Drives, London, 1990.

[20] J. Barret, Schaltnetzteile mit 10kW für den Betrieb am 380V und 400V Netz, Elektron. Ind. 10, (1984) pp. 88-96.

[21] F. Fabre, A. Klose and G. Somer, Technical and Economic Conditions for the Use of Electric Road Vehicles, Cost 302, Commission of the European Communities DG VII, Brussels and Luxembourg, 1987.

[22] G. Maggetto, P. Van den Bossche and H. Van Muylem, Advanced Electric Drive Systems for Buses, Vans and Passenger Cars to Reduce Pollution, EDS, Commission of the European Communities DG XII and AVERE, Brussels, 1992.

[23] Motor Vehicle Population Growth, Causes and Implications for the Environment, Michael P. Walsh (USA).

[24] Future Vehicle and Airplane Engines, Prof Klaus-Diter Vörhinger (Daimler Chrysler, Germany).

[25] Super Speed Maglev System: Dipl Ing Gerhard Wahl (WEC, 19-21 June 2000).

[26] Development of Dual Use Technologies and a Strategy for Application, Minister P.G. Kaminski (US, MoD 1997).

Chapter 9 – LCC OF AECV

"Procurement of equipment that represents value for money is not a responsibility I take lightly. After all, at the end of the day the products we provide could mean the difference between life and death for those who operate them and the success or failure of military operations."

Sir Robert Walmsley (Chief of Defence Procurement at the MoD, 1996 – UK)

"We do underestimate the economic side of military investment decisions for the future opportunities and for the future investments. Therefore, we should try to integrate, more than we are ready to do now, the economic aspect with our military decisions."

Minister Dr Werner Fasslabend (Austria – 1997)

9.1 GENERAL

The Life Cycle cost includes the development, the production and the Operation & Services and Maintenance Costs. Till the end of the eighties and the support by the (NATO) States of a Defense Industry, little attention was paid to the Production and Development costs: starting from the needs expressed by the (military) Operational Authorities, R&D was funded, technological progresses rapidly grew and were transferred to the military equipments. But the end of the 80's changed the geostrategy and results in significantly reduced defence spending. This has led in all our Countries to consolidation of industries, down-sizing, plant closures and increasing competitions on the market. This in turn has led to extreme pressures to improve productivity, to reduce the time and cost of bringing a product to market and to reduce the cost of supporting it after deployment [6].

The total yearly budget affected to the US Defence approaches 300 B$ for a population of about 270 millions and a military strength of 1,4 million people; 160 B$ in Europe for a population of 375 millions and a military strength of 2 millions people. The Defence budget of a Country like BE reaches $2,5 B/yr with a 'yearly LCC' of the Combat Ground mobility reaching about 2,5% of this budget. Assuming a same percentage for the US and the European entities should lead to $12 B (the defence budget of 5 'small' countries): that underlines the necessity to effectively integrate the economic aspects in our study.

9.2 INTRODUCTION LCC (SAS-007 CONCLUSIONS) [1]
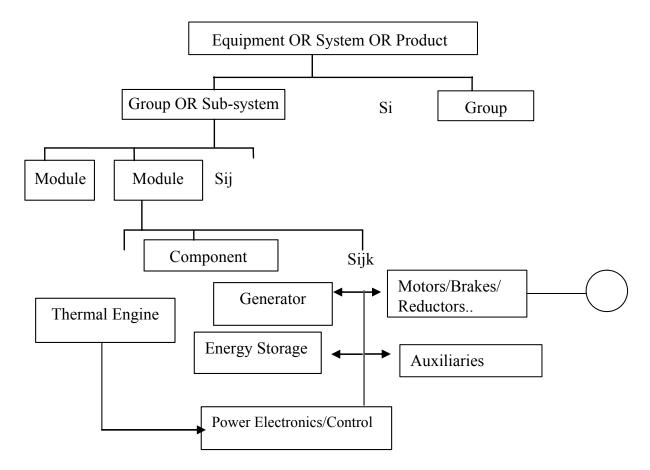
9.2.1 Background

From March 1997 to November 1998, a first LCC study (LTSS/50 or SAS-007 with the participation of BE, FR, GE, NL, UK and US) was conducted and may be summarized as follows:

- It had been decided to compute the LCC of a notional (conventional and all electrical) tracked combat vehicle of **50-ton weight class**. In order to develop the LCC, US and GE-LCC models were used for computing the <u>development and production</u> costs and the FR-CESAR program to compute the <u>maintenance-operations</u> costs. Initially, the study, considered as a first step a comprehensive LCC study including all aspects of an AECV (mobility, lethality, survivability) but was redirected to only focus on the MOBILITY.

The AECV has been considered as an equipment or system, represented by a TREE structure of elements, where each element is broken down into its components.

An agreement was reached, among the experts participating in the study, to consider the minimal tree structure for MOBILITY-related equipment comprised of the following components:

Table 9.1: Mobility Components

CODE	GENERAL DENOMINATION	EXAMPLE on Fig. 1
S1	**Prime Mover**	Diesel Engine or Turbine
S2	**Transmission Group**	
S21	Generator	Generator, MM Generator
S22	Traction Motors	Propulsion Motors, Drive Motors
S23	Brakes	Mechanical Brakes, Brake Resistors
S24	Controllers	Generator Power Conditioner, Motor Power Conditioner, Engine Controller Power Electronics, Drive Control (Brakes, Steering and Propulsion)
S25	Gear Reduction	Steering Differential, ..
S3	**Final Drive**	to Sprocket, Track, Wheel
S4	**Control Software(s)**	
S5	**Active Suspension**	
S6	**Energy Storage**	

Subsystems that could be common to both conventional and electrical vehicles (tracks, mechanical structure, crew-station, weapons, etc. have been excluded.

Integration was to be included in the cost of each component.

- In order to evaluate the LCC comprising the development, production, operation and service costs, it was decided to gather data on notional and/or existing vehicles both conventional and/or electric drive. Among the existing LCC models, three particular ones were chosen: the US model for the development and production of a notional AECV or conventional 50-ton vehicle, the German model for the development of adapted conventional and AECV (with and without energy storage) of the same class (starting with the existing Leopard II), and finally the CESAR model proposed by France for the computation (simulation) of the operation and service costs of two Combat vehicles with comparable performances (conventional and electric drive).

- CESAR Model: common assumptions were accepted and/or proposed, as mentioned in the Table 9.2.

- NL and BE had developed a statistical study on Leopard I and Leopard II (first and second generation of CV) in order to adapt some data or furnish missing data.

Table 9.2: Assumption for the LCC Model

A . General data.

The development, production and acquisition schedule is:
- 2000/2003: definition, demonstrator
- 2004/2007: development (12 prototypes)
- 2005/2013: production (50/150 then 300 vehicles per year)

(b) Technologies are available in 10 years
(c) **Technologies are scaleable to 50 T**
(d) Vehicle life : 20 years
(e) Production rate: maximum 300/year
(f) Total production: 2000 vehicles
(g) **Peace-time mission** profile: vehicles will operate 1500 km/year

B. Data for the Operation-Service Costs

Aspect	Value
General Environmental Data:	
Administrative delay time	2 hours
Maximum delay at corrective maintenance workshop	1 day
Maximum delay at workshop without corrective maintenance	1 day
General data for each module: delay times:	
Replenishment periodicity	6 months
Procurement lead time	9 months
Maintenance policy:	
% exchange at level A (ops unit)	15 %
% restoration at level B (log unit)	85 %
Repair performed at industry or at level C	100 %
Economical data:	
Restoration cost (% of unit production cost)	15 %
Repair cost at level B (id)	20 %
Repair cost Industry or level C (id)	20 %
Maintainability:	
Duration of exchange = duration of restoration = duration of repair at level B = duration of support equipment	
Duration of repair (industry - all modules)	180 min
Reliability:	
MTBF, min and max margin (all electrical)	**450 H, 20 %**
MTBF min and max margin (all hydro-mechanical)	**1000 H, 10 %**
Discard rate	**2 to 8 %**

Table 9.3 summarizes the cost-estimations provided by the partners of the SAS-007 study.

Table 9.3: Cost Summary

Module (1)	AECV US	CCV US	AECV GE	CCV BE	CCV NL – GE
ALL Mobility	4400 (2)	3266 (2)	1373 (3)(4)	818	1066 (NL)
S1 Engine	2150	2150	267	375	597 (NL) 300 (4)
S2 Transmission	587	254	157	443	426 (NL)
S21 Generator/ Powershift	175	93	39 (4)		100 (4)
S22 Traction Motors	125		39 (4)		
S23 Contr/Brakes	25	14	11 (4)		28 (4)
S24 Controller	250	133	57 (4)		19 (4)
S25 Gearing	12	14	11 (4)		
S3 Final Drive	10	20	161 2 (4)		42 (NL) 18 (4)
S4 Integration					
S5 Software	5	5			
S6 Active Suspension	**125**	203			
S7 Energy Storage	**401**		143		
Tooling	170	170	1		
Others	352	235	31		

1) Development + Production / Veh or Unit Price (Acquisition) / Veh in current **K US $.**

2) This high value includes the development and the production of a new engine 2500 HP.

3) This lower value excludes the development of new engine and considers the adaptation of the existing engines.

4) Values introduced in the CESAR model for the computation of the operation and maintenance costs.

(**Note**: The major difference lies in the costs of the engine: one observes a clear difference between the US assumption based on the development of a NEW engine of higher power (thus taking into account the other functions (lethality/survivability) of the AECV) and the GE assumption based on the adaptation of the actual engine. Another difference lies, as previously said, in the modules S6 and S7, depending on the technology used (see previous chapters).

Based on those assumptions, cost/price estimations, and after analysis of several realistic combined hypotheses, the study SAS-007 concluded:

Criterium	CCv	AECV
Availability	80%	78%
Cost/Hr	615.36 $/Hr	615.12 $/Hr

- **That the AE Technologies, at this stage of their implementation on AECV, will not offer a lower LCC: this is essentially due to the development/production costs.**

- **That the availability doesn't vary: the lower MTBF of electrical components may be explained by the relative novelty of some technologies (see previous chapters).**

9.3   LIFE CYCLE COST (SAS-028 CONTRIBUTION) [2]

9.3.1   The Use of LCC

The use of LCC must, whatever the phase of the program, inform the process by which managers can plan for future expenditure, manage existing budgets and make the best decisions on options presented to them.

Life Cycle Costs of a system consist of all costs to be made by the owner of the system to acquire, exploit against the required performance requirements and dispose of the system. This is a rather generic definition of LCC and does not give a decisive answer whether some cost elements or expenses can be attributed to a system. Furthermore, throughout the world many different phrases are used to define LCC. Sometimes also different names are used to define the same thing.

Finding unity in definitions and terminology used in the area of Life Cycle Costing was one of the tasks of TG SAS-028.

9.3.2   LCC, TOC and WLC

A distinction has been introduced between the life cycle cost (LCC), the total ownership cost (TOC, equal to LCC plus linked indirect fixed costs such as common support equipment, common facilities, personnel required for unit command, administration, supervision, operations planning, fuel and munitions handling) and the whole life cost (WLC, equal to TOC plus non linked indirect fixed costs such as family housing, medical services, ceremonial units, basic training, headquarters and staff, academies, recruiters): in this study (and the previous one SAS-007) we clearly limited ourselves to the LCC.

LCC consists of all direct costs associated with the acquisition, O&S and disposal of the product plus indirect-variable costs: these latter may include linked costs such as additional common support equipment, additional administrative personnel and non-linked costs such as new recruiters to recruit additional personnel. All indirect costs related to activities or resources that are not affected by the introduction of the system are not part of LCC.

9.4 LCC PROGRAM MANAGEMENT PLAN (LCC-PMP) AND LCC EXPECTATIONS

Taking into account the fact that the current phase of the AECV program may be considered as a development phase, that cost-data will not appreciably differ from the data exploited in the SAS-007 study and that the SAS-028 methodology has recently been proposed but was not available during the planned TG-047 activities, we decided to limit the LCC part of this report to the next three analyses and/or recommendations.

9.4.1 LCC-PMP

It is recommended to now form a LCC sub-group in charge of a detailed exploitation plan of the FR proposal described in Annex A of this chapter. The SAS-028 report is now available [3]. Such a SG could start his activities in 2003.

9.4.2 LCC AE-APC, IFV

The SAS-007 study considered a 50 T vehicle but the first operational AEVs will probably belong to the categories of Armoured Personnel Carriers (APC) and Infantry Fighting Vehicles (IFV) of lower weight-class. The missions entrusted to the NATO armed Forces (Peace-keeping/Peace-holding missions) confirm the priority of such development/acquisition program for most NATO Countries. Table 9.4 gives an idea of the actual performances of such vehicles [4].

Table 9.4: Vehicle Performance Summary

Vehicle Country	Crew Seating	Mass (kg)	Engine Power Output (kW)	Autonomy Fuel Cons/ 100 km	Max Speed km/h	Particular Use
PANDUR Austria	2 8	13.000	Diesel 195	600 km 50	100	6x6 multi-purpose CV
BDX APC Belgium/Ireland	2 10	10.700	V-8 Petrol 135	900 km 28	100	Belgian Air Force & Federal Police (dual use)
AMX 10P IFV France	3 8	14.500	V-8 Diesel 225	600 km 88	65	(also Ambulance, Repair Vehicle, Artillery observation..) Tracks
Panhard M3 APC France	2 10		4 HD petrol 68	600 km 28	90	4x4, Various uses (carrier, ambulance, mobile command..)
Transportpanzer 1 FUCHS APC Germany	2 14	17.000	V-8 Diesel 240	800 km 49	105	6x6, various uses (carrier, battlefield surveillance, etc.)
Shorland S 55 APC UK	2 6	3.600	V-8 petrol or Diesel 100	630 km 23	120	(from Lrover) (variants exist)

M113 APC US	2 11	12.150	V-6 Diesel 207	480 km 75	66	and variants (tracks) used by about 50 countries)
GDLS/AHED US/GE-2008	min 8 T payload	12.000	Hybrid		105	8X8 dr-in-wheels
MRAV GE/UK/NL (2006)	2 6	max 33.000				Production of 2000 units (?) Treatment and Evacuation missions, ambulance, command, …

The BDX APC, 123 ex for BE Air Forces/Police.

The PANDUR (BE Ground Forces).

The Well-Known M113 (used in about 50 countries).

The Shorland LR S 55 APC.

All those vehicles (and other vehicles of the same type) have an acquisition price varying from $US 400.000 to $US 650.000.

Extrapolating the US/GE data and BE/NL statistical data and from other (BE) sources, that the comparison between a conventional vehicle (Petrol/Diesel Engine and mechanical transmission) and a hybrid electric version using the same engine adapted for driving a generator and feeding electrical traction motors, in this category of vehicles, could be expressed by the next table.

Module	LACV (IFV,APC..) in $US (K) BE Sources	LAECV in $US (K)
All Vehicle	650	870
S1 Engine	182	247
S2 Transmission	255	95 (Generation : 39)
S3 (Active) Suspension	10	18
S4 Energy Storage		60
Others	203	450

The acquisition costs include the development and the production costs. The implementation of the new electric drive technologies imply an unavoidable increase of the acquisition price (under our assumptions, leading to an underestimation of the production).

Statistically, 58% defectiveness is of electrical/electronical origin on LACV, and 42% of hydro-mechanical origin. Furthermore, the O&S and maintenance costs reach about 35% of the acquisition costs under a life-assumption of 20 years for a conventional vehicle [5].

If we assume that the ratio mechanical/electr(on)ical defectiveness remains the same for AECV, and if we assume that the O&S and maintenance costs will be the same for LACV and LAECV except for the modules S1 to S4, we obviously must accept an increase of the LCC. Assuming the acquisition price could be reduced to the level of the LACV, the LCC-increase could be limited to 3%.

However, the acquisition price of a vehicle of this smaller category (light armoured combat or combat-support (electrical) vehicles or LA(E) CV) may be limited by harmonized US and European requirements: those ones could offer productivity benefits flowing from shared development costs and increased production runs. The cooperation opens the door to the economies of scale necessary to procure this type of advanced equipment. Indeed, one of the most benefits of cooperation (inducing a higher production-rate) is the sharing of NON-RECURRENT costs and reduced unit costs. '[7]: one has computed that 1/3 of the estimated development/production costs could be saved.

Under this realistic assumption and the same O&S constraints (and a.o. an equivalent fuel consumption LACV/LAECV and O&S costs reaching 35% of the acquisition costs), the LCC of a LAECV could be reduced down to 2%.
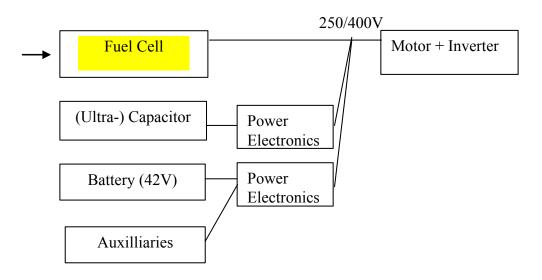
The LCC of a unit has been extrapolated with the next formula:

LCC of a LAECV = Acquisition-cost + 0.35 (0.58*(S1+S2+S3+S4)+0.42*(S5)

LCC of a LACV = Acquisition-cost + 0.35*042*(S1+S2+S3+S4+S5)

so that the LCC of LACV should reach $US 745K/unit or 3.852 $/kW, while the LCC of a LAECV should reach $US 731 K or 3500 $/kW.

A same computation (1) limited to the specific transmission-mobility-modules (from the generation to the traction, including regenerative/storage capacities and power control) lead to a LCC of 1020 $/kW for the LAECV and limited to the generation (generator.) to a LCC of 263 $/kW.

(Note [8]: Continuing Cost studies for PEM-fuel-cell (PEM=Proton-Exchange-Membrane) automotive propulsion systems estimate today (2001) the LCC to be approximately $500/kW for a production of ***500.000 units/year and a mean power-output of 50 kW***. *This note (1) underlines the importance of the production-scale-effect on the costs, and consequently the future impact that the introduction of the All-electrical technologies in the civilian automotive sector will have and (2) confirms **that the solution 'electrical generator' actually leads to the best economical solution, although the future cost impacts will strongly depend on the current R&D and political investments in the Automotive Industry.***)

In the previous scheme, equivalent to the AEV-scheme, replacing the FC by the Generator, power may flow to and from the capacitor while the auxiliaries are only fed from the batteries (charged by the Fuel-Cell, via a second power unit).

The LCCs comparison (263 $/kW versus 500 $/kW) gives the difference Generator/Fuel-Cell at this stage of the assumed production.

A detailed study, according to the proposal formulated by FR, and focusing on all possible combinations allowing the use of electrical energies remains necessary and will have to be completed by an Economy-Risk/Uncertainty study.

However, the next paragraph underlines the possible significant reduction of the TOC and WLC (both for hybrid and Fuel Cell solutions). And in the context of the 'Dual Use' development of the Industry of the Armament, the TOC, should be, at least, a better indicator of the cost-analysis of the production of new technologies.

9.4.3   LCC – Qualitative Considerations

Near the expected quantitative equivalence of the LCC, qualitative advantages, that cannot be easily expressed by a direct or an indirect cost, have been underlined *and are now confirmed by the US-AECV trials (see previous chapters – Trials/Simulation) and by the trends observed in the civilian sector (see Chapter 9).*

a) **Affordability:** Fleet commonality: Commonality is defined as the ability to use the same subsystems in multiple vehicle types. This results in economies of scale for basic components and reduction of the maintenance costs and the logistical burden.

Dual use: electrical and electronics devices, whether developed for the commercial market or for military applications, are for the most part interchangeable. This is particularly true for solid state semiconductors. This also implies economies of scale and (future) lower development costs.

Modularity: several subsystems can be assembled from basic modules: examples: batteries, capacitors, power controllers, generators and motors. Again, an approach that would yield lower production and maintenance costs.

b) **Operational Benefits:** The following advantages will allow more operational capabilities.

The power generating unit and the power controllers can be positioned anywhere in the vehicle. This allows several design strategies depending on the established mission of the AEV such as reduction of the vehicle profile, and rear crew access for Infantry Fighting Vehicles (IFV).

The electrical energy storage will improve the overall powertrain efficiency, giving reduction in fuel consumption, and thus increasing the range of the vehicle.

The electrical energy storage allows the vehicle to operate in STEALTH mode for short distances (1 to 2 km), which provides considerable reduction of the thermal and acoustic signatures.

c) **The Logistical Support:** The realization of modular components leads to fewer part counts, quicker parts replacement and a reduction in transportation and maintenance cost.

Use of electrical technology leads to improved diagnostics, due to the continuous fault detection feature inherent to electric systems. This will predict potential failures and thus will reduce the **down time and repair cost** by optimizing the scheduled maintenance.

d) **Technical Considerations:** The AECV concept provides an opportunity to reduce the size of the prime mover (engine) and to optimize the operation of the engine/generator and traction motors to meet all the requirements of the vehicle. The different components are described in details in the previous chapters of this study.

Propulsion Systems: tracked vehicles with conventional transmissions use complex multi-ratio mechanical gearboxes containing the steer mechanism with cross shafts. **They are complex and costly**, containing a large number of high precision gears, shafts, bearings, friction plates, etc. The use of electric drives greatly simplifies the transmission chain, increases the packaging flexibility and simplifies the control of the drive

system. This normally will induce a decrease of the production costs, and, consequently, the acquisition costs and O&S ones.

Power Control Units, Electronic Switching: Silicon Carbide is an emerging semiconductor material which will be superior to Si based devices in the domain of power electronics. SiC power devices can have higher operating temperatures (up to 400 °C), thus allowing a smaller cooling system which positively impact the total cost of the vehicle. However, the rate of progress is limited by the SiC wafer diameter and micropipe defect density, and is currently inadequate for device manufacturability at the required power ratings.

Energy Storage: the drive system is approximately 1 to 1.5 MW for a 50/60-ton battle tank and 200/300 kW for a 10/20-ton combat-support vehicle. The addition of storage devices will allow:

- Increase of acceleration at all speed ranges;
- Increase of the maximum speed in all kinds of terrain and grades;
- Reduction of fuel consumption;
- Stealth operations (limited silent mobility and silent watch);
- Redundancy in case of engine failure.

9.5   CONCLUSIONS

The AECV, and more particularly the LAECV have the potential to meet the allowable cost and performance targets (reduction of LCC) provided successful demonstrations prove the technology, both in the military as in the civilian sector: it is indeed essential, that for the current technologies to be commercially successful, especially small-capacity markets, high production volumes will have to be reached.

The BE Minister of ND recently [9] confirmed this point of view by identifying 5 particular weaknesses of the so-called 'European Defence-Industry':

- The breakdown into individual requirements: example: 13 different Ground Combat vehicles in Europe against only 3 in the US;
- The balkanization of the production/Supply: example: 4 project managers for Ground Combat Vehicles in Europe against 1 in the US, as consequence an overcost of about 20% by the acquisition of such equipments;
- The drastic reduction of the re-equipment budgets (about 25%);
- The loss of exportation-competitiveness (56% US, 27% Europe);
- The decrease of the R&D in the military sector.

Weaknesses that justify a detailed LCC study: we strongly recommend to adopt the FR proposal in the next phase of this study.

9.6   REFERENCES

[1]   SAS-007 Report (RTO-TR-13, AC/323(SAS)TP/10 (March 1999).

[2]   SAS-028, Note G. Seguin, Ann A and App A (March 2002).

[3] SAS-028 Report.

[4] Fighting Vehicles, APC and IFVs, T.J. O'Malley, Greenhill Military Manuals (ISBN 1- 85367-211-4).

[5] Etude des coûts d'exploitation des hélicoptères à la D.N. (TFE Slt Neckebroek, JP, ERM, 1986).

[6] 'The European Defence Industry: Perspectives from European Industry' M. Ian MacFarlane (RTO, UK Delegate EDIG/NIAG).

[7] 'The Advent of a Need for a Weapon System: From the Nation to Europe' Sir Robert Walmsey, 1996 (Chief of Defence Procurement at the UK Ministry of Defence).

[8] 'Fuel Cell Auxiliary Power Systems: Design and Cost Implications' C.J. Read, J.H.J.S. Thijssen and E. Carlson, 2001.

[9] Technology, Defence and Economy: New Dimensions, New Stakes (Symposium RMA/BE November 1997): 'allocution de clôture'. J.P. Poncelet, BE MoD.

a. LCC: PRICE

Chapter 9 – ANNEX A: AECV – LCC PROGRAM MANAGEMENT PLAN (LCC-PMP) FOR *CURRENT* PHASE

LCC Program Management Plan describes the way the costing activity is to be managed and carried out during the current phase of the program.

It is anticipated that this document will be updated on a regular basis as the phase evolves. Changes in document issue will be subject to agreement and ratification by the *nations involved* representatives of LCC Sub-Group of the *EACV*.

> *PROPOSAL*

A.1 INTRODUCTION

General Presentation of the Program

The Life Cycle Cost Program Management Plan (LCC-PMP) and the documents to which it refers are harmonised between the various participating nations. LCC-PMP is a "living document" and will be updated as necessary.

Aim of LCC-PMP

The aim of this LCC-PMP is to define and specify the various aspects related to the implementation of LCC during the current phase. Those aspects refer to:

1) The use of LCC;
2) The organisation and the role of each parties involved;
3) The activities to be performed by the government side;
4) The methods, data and tools;
5) Communication rules between the various parties;
6) The schedule.

Those points are addressed in the following Sections.

A.2 CONSIDERATIONS ON THE USE OF LCC

A.2.1 General Considerations

Life Cycle Cost (LCC) represents all the costs that will be borne during the life of a System (Main System and Support System) to acquire it, operate it, support it and eventually dispose of it. The list of cost items is defined and organised in a LCC Breakdown Structure (LCCBS).
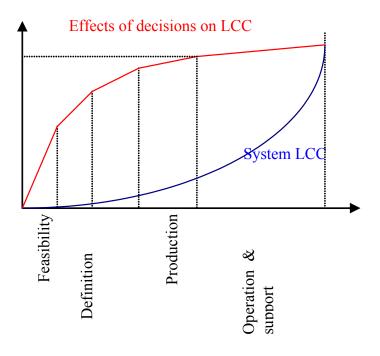
The cost of maintaining a Weapon System in service can be significant and often exceed the acquisition cost of the System. Procurement decisions must therefore not be based solely on acquisition costs.

During the current phase, LCC will be used for several purposes:

1) To optimise the design (industry task);

2) To compare several options;

3) To produce a Government LCC estimate.

A.2.2   Optimisation of the Design

Life Cycle Cost is to be used as a benchmark against the value for which money options can be measured during the acquisition process, bearing in mind that the greatest opportunities to reduce LCC occur during the early stages of the Program.

Figure 9A.1

The bottom curve represents the cumulated expenditures measured during the life of the system. The top curve represents the expenditures induced by the decisions taken during the program.

As showed in Figure 9A.2, the design options determine the characteristics (modularity, reliability, maintainability, testability, etc.) of the system and delimit the possibilities of optimisation of the maintenance policy and its organisation.
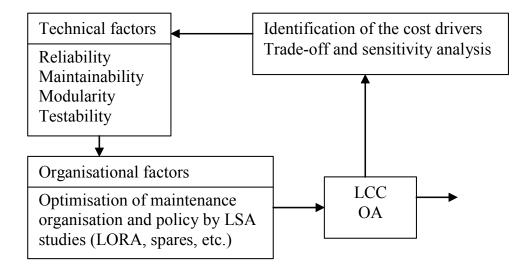
Figure 9A.2: Design Optimisation Process.

Remarks

1) The various options must be compared in a cost/effectiveness approach. Effectiveness criteria is represented by operational availability (OA). As LCC is defined by LCCBS, OA must be defined in an unambiguous way.

2) When comparing various alternatives, LCC may have a relative value. Costs, that are approximately equal for each case, sunk costs and negligible costs may be left out.

3) When comparing various alternatives, LCC must be discounted over the life of the system.

4) This optimisation process is related to ILS and mainly LSA activities.

A.2.3   Comparison of Several Options

To be developed.

A.2.4   Production of a Government LCC Estimate

To be developed.

A.2.5   Risks and Uncertainty

To be developed.

A.3 PARTIES INVOLVED

Both Government and Industrial parties are involved in life cycle cost.

A.3.1 Industry

Manufacturers are in charge of the design, development and production of the system (main system and support system). For that they permanently select options concerning technical and economic factors[1] (unit production cost, etc.) that have an impact on LCC. That is why they must take into account LCC considerations and demonstrate that their solutions are the most cost-effective. They must identify and evaluate possible cost risks based on the technologies being used and manufacturing process.

Taking into account LCC is not a side activity, independent of other tasks carried out within the contract. It is an integral part of concurrent engineering.

Industry LCC estimates must be based on organisational parameters provided by Government side (See GDAL).

Results to be Provided

Most of the technical and economic parameters related to LCC are the result of industrial activities. That information must be provided to the Government side for its own life cycle costing activities (See LCC questionnaire).

Industry must establish and provide LCC results for the solution(s) they propose. Those results must be supported by any useful considerations. LCC estimates must be presented in a format consistent with the cost breakdown structure suggested by Governments.

Although most of organisational parameters are on the responsibility of Government side, contractor must (or may) propose the most appropriate maintenance policy for the technology being used (interaction with ILS activities in particular LORA).

A.3.2 Government

Governmental (or independent) cost estimates are indispensable for the dialogue with industry and for economic and financial considerations. Government side will carry out life cycle costing activities to:

1) Verify, as far as possible, that the solution provided by industry results from a real optimisation of the system;

2) Use LCC to compare alternatives related to organizational factors (repair policy, spares community, etc.);

3) Prepare its own (independent) estimates of LCC.

To carry out these activities, a Life Cycle Cost Sub-Group is set up.

A.4 THE TASKS OF LCCSG

The LCC Sub Group has several tasks:

1) To produce documents related to methodological and technical aspects of LCC;

2) To review and comment on the Industry estimates;

3) To provide Program Managers with LCC estimate and analysis.

---

[1] See Appendix AA.1

A.4.1   Production of Documents

In order to efficiently conduct its business, the LCC Sub Group establishes, produces and maintains the following documents during the assessment phase:

1) LCC Programme Management Plan (LCC-PMP),

2) Government Data and Assumption List (GDAL),

3) LCC Questionnaire (LCCQ),

4) Life Cycle Cost Breakdown Structure (LCCBS).

The LCC-PMP defines the programme of work to be carried out and is the reference document for this work.

The **GDAL** recapitulates the list of data and assumptions to be provided by the Government side and necessary to estimate LCC. They describe, among other things, a common O&S scenario agreed by the participating nations. The initial version of this document is the one prepared for the previous feasibility phase. It has been updated at the first LCC meeting. It has been recognised that this document, specific for LCC studies, is different from the "Use Study" prepared for ILS studies.

LCC Questionnaire describes the list of data to be produced and provided by Industry and necessary to estimate LCC. This document concerns hardware development and production costs, software development (and maintenance?) costs and hardware life support costs.

Life Cycle Cost Breakdown Structure defines and organises all the cost items to be included in LCC.

A.4.2   Review of Industry LCC

The Sub-Group will review and comment the LCC estimate and the corresponding work performed by Industry. This includes the following tasks.

Validation of the Data

The Government side must, as far as possible, validate the data used by the Contractor and presented in the "LCC questionnaire". This validation concern the technical (reliability, maintainability, etc...) and economic (unit costs) factors of the system.

Several approaches may be used for the validation, ranging from rough judgements to the use of specific models. It is decided that the LCC-SG will use any convenient means to accomplish this task.

Validation options	
No validation	Some data provided by Industry will be used as they are.
Analogy with similar systems	Validity and realism of some data will be examined by analogy with similar equipments. These equipments must be identified and the data collected.
Use of specific models	Specific models will be used to validate some data.

One result of the data validation activity is to provide information for risk and uncertainty analysis.

Comment on the Results

The Sub-Group will review and comment the LCC estimate and the corresponding work carried out by Industry.

A.4.3   Production of Independent Estimates

The Sub-Group will elaborate independent estimates of the LCC using:

a) Data provided by Industry, including possible changes resulting from the validation activities;

b) The costs provided by the contractor;

c) Computation models if necessary.

The final report will include the following elements:

• LCC provided by Industry, additional information and/or modifications made by Industry in answer to questions raised by the Sub-Group;

• Justification of data or cost changes made by the Sub-Group;

• LCC estimates provided by the Sub-Group, analyses and justification of the possible variations between the results produced by Industry and the Sub-Group;

• Comments on the work and the results provided by the Contractor.

A.5   METHODOLOGY, TOOLS & DATA

It is anticipated to use the following models:

Object	Model
Hardware development and production costs	PRICE-H
Software development (and maintenance) costs	PRICE-S
Hardware Life Support Costs	CESAR, PRICE-HL?, EDCAS?
Risk and uncertainty analysis	@Risk
LCC	LCCBS on EXCEL

Data will be provided by GDAL, LCCQ and Program Management (PM). Additional information will be required to calibrate the model PRICE and/or to permit validation or estimation by analogy. The information will be collected and provided by the national members of LCC-SG.

A.6 COMMUNICATION

LCC-SG is set up by and report to PM.

All technical documents dealing with LCC activities can be directly exchanged between the national members of LCC-SG.

A.7 LCC PLAN SCHEDULE

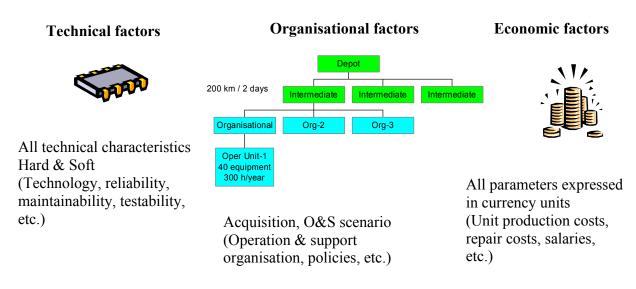The following plan defines the milestones of LCC-SG, agreed with PM, to meet its goals.

To be defined.

Appendix A – Life Cycle Costing

AA.1   COSTS FACTORS

LCC is generated by three categories of factors, which are not independent:

Technical factors

All technical characteristics
Hard & Soft
(Technology, reliability,
maintainability, testability,
etc.)

Organisational factors

Acquisition, O&S scenario
(Operation & support
organisation, policies, etc.)

Economic factors

All parameters expressed
in currency units
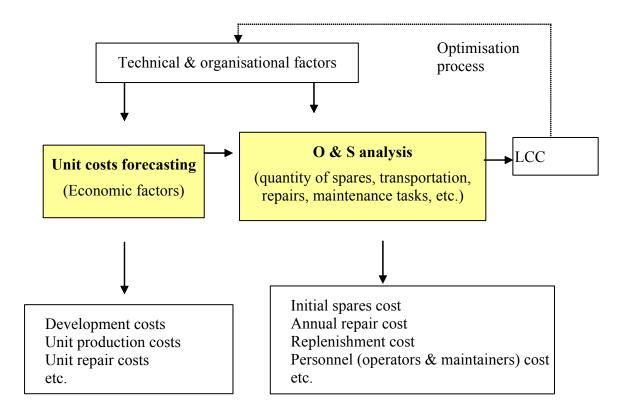(Unit production costs,
repair costs, salaries,
etc.)

- Most of technical factors result from the options chosen by industry throughout design, development and production phases to meet the customer requirements.

- The user (Government) defines most of organisational factors.

- Most of economic factors are market dependent. Some costs are usually available in the organisation (salaries, etc.) and others may result from a cost forecasting activity (unit production costs, etc.).

Generally, a life cycle cost element is equal to the unit cost of the entity considered (object or activity) multiplied by the corresponding quantity. The analysis of the operation and the support of the system usually determine this quantity.

AA.2   TWO TYPES OF ACTIVITIES

Life cycle costing is a set of techniques for modelling, predicting and analysing the LCC of a system, at any stage of its life. As shown in the following figure, the evaluation of LCC, and thus the various cost elements that constitute it, rests on two types of activities. The first one concerns the production of "unit cost" estimates. The second one, mainly based on operation and support analysis, permits to assess the quantities of objects or activities.

```
                    ┌ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ┐
                    ┆                                                    ┆
        ┌───────────────────────────────────┐        ┌──────────────
        │  Technical & organisational factors│        Optimisation
        └───────────────────────────────────┘        process
             │                    │
             ▼                    ▼
```

| **Unit costs forecasting** (Economic factors) | → | **O & S analysis** (quantity of spares, transportation, repairs, maintenance tasks, etc.) | → | LCC |

Development costs
Unit production costs
Unit repair costs
etc.

Initial spares cost
Annual repair cost
Replenishment cost
Personnel (operators & maintainers) cost
etc.

These two types of activities are complementary but may involve skill, tools and data of different natures.

AA.3   FORECASTING METHODS

Several methods can be used to produce a cost estimate. The choice of a method depends on the nature of the cost element and the quantity and the quality of available data. The three main methods are the following:

1) Method by analogy with similar objects or activities. This approach is used when there is little information on the entity to be considered.

   This approach is generally used for unit costs (UPC, etc.) for the major components of LCC. It doesn't need a lot of information about the future system but requires costs of similar objects or activities. It is based on opinions of experts. It doesn't permit sensitivity or trade-off analysis with the factors that generate costs.

2) Parametric methods use elaborate mathematical equations based on information collected on comparable systems. They require a limited number of information.

   Parametric methods are generally used to estimate development and production costs.

3) Analytical methods are based on the description of the tasks to be realised. These methods often require detailed information on the system.

   The analytical methods are generally used to estimate recurring and non-recurring in-service costs (O&S). They permit sensitivity or trade-off analysis on every data element (the factors of cost) used to describe the system.

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's References	3. Further Reference	4. Security Classification of Document
	RTO-TR-AVT-047 AC/323(AVT-047)TP/61	ISBN 92-837-1110-6	UNCLASSIFIED/ UNLIMITED

5. Originator	Research and Technology Organisation North Atlantic Treaty Organisation BP 25, F-92201 Neuilly-sur-Seine Cedex, France

6. Title	All Electric Combat Vehicles (AECV) for Future Applications

7. Presented at/Sponsored by

The RTO Applied Vehicle Technology Panel (AVT)
Task Group AVT-047 (WG-015).

8. Author(s)/Editor(s)	9. Date
Multiple	July 2004

10. Author's/Editor's Address	11. Pages
Multiple	234

12. Distribution Statement	There are no restrictions on the distribution of this document. Information about the availability of this and other RTO unclassified publications is given on the back cover.

13. Keywords/Descriptors

Computerized simulation	Energy storage	Military vehicles
Electric batteries	Ground vehicles	Mobility
Electric drives	Hybrid electric systems	Performance
Electric power demand	Hybrid propulsion	Requirements
Electric vehicles	Lethality	Silicon carbide batteries
Energy recovery	Life cycle costs	Storage batteries
	Lithium ion batteries	Survivability

14. Abstract

Based on preceding studies of the last 10 years new electric technologies, technology requirements, systems for mobility, survivability and lethality of All Electric Combat Vehicles AECV were analysed, including pulse power requirement and energy storage. Enabling technologies were identified and potential payoffs were balanced against technical issues. A vehicle demonstration was performed. The general result is that further developing electric vehicle drives will be of advantage. The study dealt in detail with:

- Requirements
- Mobility
- Lethality and Survivability
- Modelling and Simulation
- Power Generation, Management & Distribution
- Performance
- Standardization and Dual Use
- Life Cycle Cost

of AECV.

CENTRES DE DIFFUSION NATIONAUX

ALLEMAGNE
Streitkräfteamt / Abteilung III
Fachinformationszentrum der
  Bundeswehr (FIZBw)
Friedrich-Ebert-Allee 34, D-53113 Bonn

BELGIQUE
Etat-Major de la Défense
Département d'Etat-Major Stratégie
ACOS-STRAT – Coord. RTO
Quartier Reine Elisabeth
Rue d'Evère, B-1140 Bruxelles

CANADA
DSIGRD2
Bibliothécaire des ressources du savoir
R et D pour la défense Canada
Ministère de la Défense nationale
305, rue Rideau, 9e étage
Ottawa, Ontario K1A 0K2

DANEMARK
Danish Defence Research Establishment
Ryvangs Allé 1, P.O. Box 2715
DK-2100 Copenhagen Ø

ESPAGNE
SDG TECEN / DGAM
C/ Arturo Soria 289
Madrid 28033

ETATS-UNIS
NASA Center for AeroSpace
  Information (CASI)
Parkway Center, 7121 Standard Drive
Hanover, MD 21076-1320

FRANCE
O.N.E.R.A. (ISP)
29, Avenue de la Division Leclerc
BP 72, 92322 Châtillon Cedex

GRECE (Correspondant)
Defence Industry & Research
  General Directorate, Research Directorate
Fakinos Base Camp, S.T.G. 1020
Holargos, Athens

HONGRIE
Department for Scientific Analysis
Institute of Military Technology
Ministry of Defence
H-1525 Budapest P O Box 26

ISLANDE
Director of Aviation
c/o Flugrad
Reykjavik

ITALIE
Centro di Documentazione
  Tecnico-Scientifica della Difesa
Via XX Settembre 123
00187 Roma

LUXEMBOURG
Voir Belgique

NORVEGE
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25, NO-2007 Kjeller

PAYS-BAS
Royal Netherlands Military
  Academy Library
P.O. Box 90.002
4800 PA Breda

POLOGNE
Armament Policy Department
218 Niepodleglosci Av.
00-911 Warsaw

PORTUGAL
Estado Maior da Força Aérea
SDFA – Centro de Documentação
Alfragide
P-2720 Amadora

REPUBLIQUE TCHEQUE
DIC Czech Republic – NATO RTO
LOM PRAHA s. p.
o.z. VTÚL a PVO
Mladoboleslavská 944, PO BOX 16
197 21 Praha 97

ROYAUME-UNI
Dstl Knowledge Services
Information Centre, Building 247
Dstl Porton Down
Salisbury
Wiltshire SP4 0JQ

TURQUIE
Milli Savunma Bakanlığı (MSB)
ARGE ve Teknoloji Dairesi Başkanlığı
06650 Bakanliklar – Ankara

AGENCES DE VENTE

NASA Center for AeroSpace
** Information (CASI)**
Parkway Center, 7121 Standard Drive
Hanover, MD 21076-1320
ETATS-UNIS

The British Library Document
** Supply Centre**
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
ROYAUME-UNI

Canada Institute for Scientific and
** Technical Information (CISTI)**
National Research Council
Acquisitions, Montreal Road, Building M-55
Ottawa K1A 0S2, CANADA

Les demandes de documents RTO ou AGARD doivent comporter la dénomination « RTO » ou « AGARD » selon le cas, suivie du numéro de série (par exemple AGARD-AG-315). Des informations analogues, telles que le titre et la date de publication sont souhaitables. Des références bibliographiques complètes ainsi que des résumés des publications RTO et AGARD figurent dans les journaux suivants :

Scientific and Technical Aerospace Reports (STAR)
STAR peut être consulté en ligne au localisateur de ressources uniformes (URL) suivant:
  http://www.sti.nasa.gov/Pubs/star/Star.html
STAR est édité par CASI dans le cadre du programme
NASA d'information scientifique et technique (STI)
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
ETATS-UNIS

Government Reports Announcements & Index (GRA&I)
publié par le National Technical Information Service
Springfield
Virginia 2216
ETATS-UNIS
(accessible également en mode interactif dans la base de données bibliographiques en ligne du NTIS, et sur CD-ROM)

NORTH ATLANTIC TREATY ORGANISATION

BP 25
F-92201 NEUILLY-SUR-SEINE CEDEX • FRANCE
Télécopie 0(1)55.61.22.99 • E-mail mailbox@rta.nato.int

RESEARCH AND TECHNOLOGY ORGANISATION

**DISTRIBUTION OF UNCLASSIFIED
RTO PUBLICATIONS**

AGARD & RTO publications are sometimes available from the National Distribution Centres listed below. If you wish to receive all RTO reports, or just those relating to one or more specific RTO Panels, they may be willing to include you (or your Organisation) in their distribution.

RTO and AGARD reports may also be purchased from the Sales Agencies listed below.

Requests for RTO or AGARD documents should include the word 'RTO' or 'AGARD', as appropriate, followed by the serial number. Collateral information such as title and publication date is desirable.

If you wish to receive electronic notification of RTO reports as they are published, please visit our website (www.rta.nato.int) from where you can register for this service.

NATIONAL DISTRIBUTION CENTRES

BELGIUM
Etat-Major de la Défense
Département d'Etat-Major Stratégie
ACOS-STRAT – Coord. RTO
Quartier Reine Elisabeth
Rue d'Evère
B-1140 Bruxelles

CANADA
DRDKIM2
Knowledge Resources Librarian
Defence R&D Canada
Department of National Defence
305 Rideau Street
9th Floor
Ottawa, Ontario K1A 0K2

CZECH REPUBLIC
DIC Czech Republic – NATO RTO
LOM PRAHA s. p.
o.z. VTÚL a PVO
Mladoboleslavská 944, PO BOX 16
197 21 Praha 97

DENMARK
Danish Defence Research
Establishment
Ryvangs Allé 1
P.O. Box 2715
DK-2100 Copenhagen Ø

FRANCE
O.N.E.R.A. (ISP)
29, Avenue de la Division Leclerc
BP 72
92322 Châtillon Cedex

GERMANY
Streitkräfteamt / Abteilung III
Fachinformationszentrum der
Bundeswehr (FIZBw)
Friedrich-Ebert-Allee 34
D-53113 Bonn

GREECE (Point of Contact)
Defence Industry & Research
General Directorate, Research Directorate
Fakinos Base Camp, S.T.G. 1020
Holargos, Athens

HUNGARY
Department for Scientific Analysis
Institute of Military Technology
Ministry of Defence
H-1525 Budapest P O Box 26

ICELAND
Director of Aviation
c/o Flugrad, Reykjavik

ITALY
Centro di Documentazione
Tecnico-Scientifica della Difesa
Via XX Settembre 123
00187 Roma

LUXEMBOURG
See Belgium

NETHERLANDS
Royal Netherlands Military
Academy Library
P.O. Box 90.002
4800 PA Breda

NORWAY
Norwegian Defence Research
Establishment
Attn: Biblioteket
P.O. Box 25, NO-2007 Kjeller

POLAND
Armament Policy Department
218 Niepodleglosci Av.
00-911 Warsaw

PORTUGAL
Estado Maior da Força Aérea
SDFA – Centro de Documentação
Alfragide, P-2720 Amadora

SPAIN
SDG TECEN / DGAM
C/ Arturo Soria 289
Madrid 28033

TURKEY
Milli Savunma Bakanlığı (MSB)
ARGE ve Teknoloji Dairesi Başkanlığı
06650 Bakanliklar – Ankara

UNITED KINGDOM
Dstl Knowledge Services
Information Centre, Building 247
Dstl Porton Down
Salisbury, Wiltshire SP4 0JQ

UNITED STATES
NASA Center for AeroSpace
Information (CASI)
Parkway Center, 7121 Standard Drive
Hanover, MD 21076-1320

SALES AGENCIES

**NASA Center for AeroSpace
Information (CASI)**
Parkway Center
7121 Standard Drive
Hanover, MD 21076-1320
UNITED STATES

**The British Library Document
Supply Centre**
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
UNITED KINGDOM

**Canada Institute for Scientific and
Technical Information (CISTI)**
National Research Council
Acquisitions
Montreal Road, Building M-55
Ottawa K1A 0S2, CANADA

Requests for RTO or AGARD documents should include the word 'RTO' or 'AGARD', as appropriate, followed by the serial number (for example AGARD-AG-315). Collateral information such as title and publication date is desirable. Full bibliographical references and abstracts of RTO and AGARD publications are given in the following journals:

Scientific and Technical Aerospace Reports (STAR)
STAR is available on-line at the following uniform
resource locator:
http://www.sti.nasa.gov/Pubs/star/Star.html
STAR is published by CASI for the NASA Scientific
and Technical Information (STI) Program
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
UNITED STATES

Government Reports Announcements & Index (GRA&I)
published by the National Technical Information Service
Springfield
Virginia 2216
UNITED STATES
(also available online in the NTIS Bibliographic
Database or on CD-ROM)

ISBN 92-837-1110-6