Condition-Based Maintenance (CBM) Prescriptive Analytics for Military Vehicles

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ABSTRACT

Condition-Based Maintenance (CBM) is one way to solve the issue of optimizing operational availability (Ao) and readiness across a fleet of assets. CBM focuses on replacing components based on their relative condition rather than a mileage or time duration. It delivers a further 8% to 12% improvement over normal time or cycle-based preventative maintenance, and it decreases unforeseen breakdowns by 70% to 75% with a 35% to 45% reduction in downtime. In a military context, Ao is paramount, and CBM can make great strides at achieving optimal Ao and readiness. Lone Star Analysis (LSA) has developed MaxUp™ Fleet, Vehicle CBM software, that monitors every aspect of a vehicle from air intake to exhaust and all points therein. It provides continuous diagnostics, predictions, and prescriptive actions so that personnel can focus on making precise adjustments to optimize the operational availability (Ao) of a military vehicle fleet. The sensors diagnose, predict, and prescribe maintenance actions on up to nine (9) major Vehicle System Failure Modes, thereby enabling comprehensive, proactive intercessions. The system evaluates frequently, which ensures that rapid onset issues are identified prior to failure. MaxUp™ Fleet delivers problem prediction and solution prescription, foresees catastrophic failure to critical systems, improves maintenance planning and associated cost estimation, reduces unplanned maintenance impacts, improves safety performance, and maximizes fleet utilization, efficiency, and service life.

1.0 INTRODUCTION

Lone Star Analysis (LSA) is a provider of applied decision intelligence and engineering solutions. We harness predictive and prescriptive analytics, artificial intelligence, and inherent knowledge to enhance innovation, create economic strength, and make the world safer. LSA has developed Evolved Artificial Intelligence (Evolved AI™), which overcomes limitations associated with Universal Approximation Theorem (UAT) and can solve nonlinear, nonconvex, and discontinuous (logic) problems. Evolved AI™ is less greedy for data and processing power; it runs on a laptop. Data may be discrete, continuous, deterministic, stochastic, or any combination therein. Our methods are agnostic; simulations and mathematics are not tied to any specific domain. LSA uses two interrelated approaches: (1) the Little Questions® approach (influencing much larger Big Questions that impact customers), and (2) a stochastic approach.

LSA Evolved AI™ delivers the ability to capture uncertain possible outcomes and reconcile those outcomes through Monte Carlo simulations and LSA patented platforms. The uncertainty can be captured to the degree of fidelity that the user has available, and the combined use of the Monte Carlo engine and statistical distributions will allow for all possible scenarios to be considered and the degree at which they are likely to happen.

LSA delivers predictive and prescriptive solutions that integrate enterprise, facility, staffing and process level solutions that enable customers to achieve transformational value through decision analysis using two flagship platforms, (1) TruNavigator (TruNav®) and (2) AnalyticsOS (AOS®). These platforms are highly configurable to meet customer defined challenges, are user friendly, designed to ensure the model manipulation is easily understood, and outputs are highly accurate, producing actionable results enabling informed decisions faster.

TruNav® is an analyst-in-the-loop simulation and predictive decision support platform that is designed to address virtually any problem, and particularly those problems with significant analytical and organizational complexity. AOS® applications automate predictive and prescriptive analysis through real-time integration with streaming datasets. AOS® has broad applicability to automate or semi-automate many of the challenging analysis problems associated with military maintenance. Both analytics platforms provide clients with a clear visual understanding of "cause and effect" for complex problems with high degrees of uncertainty to enable easier decision-making, while architected to be transparent, scalable, and easy to use. TruNav® and AOS® were designed to deal with uncertainty and effectively attack complex real-world problems.

1.1 Operational Availability (Ao)

The Operational Availability Handbook defines Ao as a function of reliability, maintainability, and supportability. The simplified equation is:

$$Ao = \text{UP Time} / \text{TOTAL Time} (\text{UP Time} + \text{DOWN Time})$$

Ao, therefore, denotes the supportability of a system, or equipment, in terms of predicted reliability, which is called the Mean Time Between Failure (MTBF), the maintainability, as Mean Time to Repair (MTTR), and the designed supportability or Mean Logistics Delay Time (MLDT). This creates a more specified formula for Ao:

$$Ao = MTBF / (MTBF + MTTR + MLDT)$$

It is therefore paramount to minimize MTTR and MLDT to the greatest extent possible to achieve a high Ao once a system, or equipment, has been fielded and is part of the Order of Battle. The best way to accomplish that task, without embarking on engineering upgrades to improve reliability, is to foresee and plan maintenance while predicting the logistics support required for that maintenance to the greatest extent possible.

LSA understands this integral requirement and has developed a vehicle CBM solution that will deliver the enhanced Ao while streamlining logistic support and reducing maintenance costs and impacts on mission accomplishment. MaxUp™ Fleet is powered by AOS®. This paper will describe how MaxUp™ Fleet will improve Ao for the warfighter.

1.2 Mission Readiness of Military UxVs

Every vehicle fleet operator struggles to ensure that assets are productive, maintenance and repair costs are minimized and the replacement of consumable items, such as tires and brakes is optimized. When dealing with military vehicles, there is added stress to maintain the Ao of the vehicle fleet; failure to achieve and maintain a high Ao can result in operational mission failure or casualties, neither of which is acceptable. There are too many interacting variables for a maintainer to effectively monitor all these issues; personnel can only provide cursory monitoring of historical data for vehicle fleets, but these systems require constant evaluation that is predictive in nature. In a growing environment of fiscal austerity that is exacerbated by the introduction and acquisition of technologically expensive components and an ever more dangerous world, the requirement to foresee and preclude costly maintenance actions is crucial to both mission accomplishment and budget and finance (BUDFIN) stewardship.

Traditional vehicle maintenance follows the path prescribed by the original equipment manufacturer (OEM) or the military in-service engineering agent (ISEA). In the case of most military equipment, both the OEM and ISEA test the equipment to best anticipate availability impacts based on projected operated environments. Component service life is established during this testing and is conversative to ensure that component failure does not catastrophically impact the system or personnel operating it. This time-based maintenance has proven to be unreliable based on operating in environments not anticipated during acceptance testing which is addressed with even more conservative life cycle estimations. Components have demonstrated considerable service life remaining when inspected after removal. This presents both operational and cost impacts to units.

1.3 MaxUp™ Fleet Vehicle CBM

MaxUp™ Fleet provides Vehicle Condition-Based Maintenance (VCBM) software for military vehicles and is powered by the AOS® disruptive advanced analytics platform that advances decision-making to the next level. LSA developed MaxUp™ Fleet Vehicle CBM to address areas of concern to military vehicle maintainers and operators. It delivers optimal Ao by constantly monitoring key elements of a vehicle, understanding the relationships between those elements, and thereby enabling consistent vehicle health. MaxUp™ Fleet VCBM delivers problem prediction and solution prescription, foresees catastrophic failure to critical systems, improves maintenance planning and associated cost estimation, reduces unplanned maintenance impacts, improves safety performance, and maximizes fleet utilization, efficiency, and service life.

2.0 CONDITION-BASED MAINTENANCE

Condition-Based Maintenance is one way to solve the issue of optimizing operational readiness across a fleet of assets. Conventional methods of maintenance include the two broad categories of “Reactive” and “Preventative” maintenance. Preventative maintenance, according to the US Department of Energy, reduces cost by 12% to 18% over reactive maintenance methods. CBM represents a significant improvement over both categories and can be thought of as an enhancement to preventative maintenance. CBM focuses on replacing components based on their relative conditions rather than a mileage or time duration. It delivers a further 8% to 12% improvement over normal time or cycle-based preventative maintenance. In addition to that, it decreases unforeseen breakdowns by 70% to 75%, and a 35% to 45% reduction in downtime. In a military context, operational readiness is the ultimate goal, and CBM can make great strides at achieving that goal.

2.1 MaxUp™ Fleet Systems Coverage

The current LSA MaxUp™ Fleet product sub-systems covered include:

- Internal Combustion Engine
- Transmission/Gearbox
- Suspension/Chassis
- Air Intake/Turbocharger System
- Electrical System
- Exhaust System
- Cooling System

- Fuel System
- Lubrication System
- Lighting System

Each area is continuously monitored using LSA's AOS® platform, which will be covered later. The analytics performed on each sub-system are based on known physical relationships and equations, either commonly accepted or utilized directly from well-regarded texts and data sources within the automotive industry.

2.1.1 MaxUp™ Fleet Technical Details

Looking at a few of the sub-systems as examples, the Internal Combustion Engine sub-system can track the air-fuel ratio and monitor the ranges it operates in while filtering out operational states, i.e., we expect a different air-fuel ratio at low engine speeds and throttle openings than at maximum engine speed and torque demand. Additionally, when not available from the vehicle's engine control unit (ECU), the engine load is calculated and tracked over time. Expected brake horsepower and torque are computed, as well as Brake Specific Fuel Consumption and Theoretical Brake Mean Effective Pressure (BMEP). Operational observations are also made, such as tracking idle time, or time spent at full throttle near the engine's peak torque output. Engine-specific rules can be applied as well, such as if the engine has specific shutdown idle-time criteria to be met. In addition to all the above, the mileages of major components are tracked, such as the valve cover gasket, serpentine belt, and other components. Where a condition that advances the degradation of a particular component is known, that degradation rate is applied to the component when the condition is met. Any calculations performed in the areas of the Internal Combustion Engine plus supporting systems (air intake, exhaust, cooling, fuel, lubrication, etc.) can be found in both Dixon (2009) and Heywood (1988).

The Suspension & Chassis system is one of the areas that separates Lone Star's software from other CBM products. This area of the solution utilizes known suspension parameters to create an understanding of the fundamental characteristics of the chassis dynamics. Texts such as "Suspension Geometry and Computation" by John C. Dixon (2005) and "Race Car Vehicle Dynamics" by William & Douglas Milliken (1995) are widely regarded as excellent information sources on understanding chassis dynamics, tire dynamics, and anything relating to the chassis and suspension system. The formulas discussed in these texts apply to all sizes of vehicles, as they are fundamentally kinematics problems that describe a spring-mass damper system in the context of a vehicle. Inputs such as vehicle weight, added weight (passengers), vehicle dimensions, and some basic suspension dimensions are required to provision the solution. Using these parameters, we can estimate the vehicle's roll angle and pitch angle using only an accelerometer as a sensor. Based on Table 16.1 from within Milliken & Milliken (1995), we know that we can expect roll gradients in a range of 8.5 deg./g up to 6.0 deg./g for typical consumer vehicles. AOS® is set up to alert when pre-defined roll angles are exceeded. Given additional performance parameters for components like dampers and anti-roll bars, we can estimate the level of degradation a damper is experiencing and track that degradation over time. If the customer requests it, the solution already computes some fundamental chassis balance metrics to understand the roll & pitch stiffnesses and distributions of the vehicle, and these can be made available. In addition to that, the solution also monitors the combined g-load on the vehicle and alerts to excessive vertical or combined lateral & longitudinal g forces. Tire pressures are monitored, and in the event of a slow puncture, the solution will predict when the tire pressure hits a critical threshold. In the circumstance where a tire is used while it is under-inflated, this will increase the rate at which the tire wears and will accelerate the remaining useful life calculation until the tire pressure is brought back to acceptable levels. Brake pressure monitoring is available as well, and the system can monitor the brake pressure channel biasing to detect and isolate failures in either the front braking system or the rear braking system.

Other systems, such as the transmission/gearbox system, focus mainly on the temperatures and pressures seen in the system and monitor them for anomalies. If a temperature is trending to cross a critical threshold, AOS® will predict when that value will cross the threshold and prescribe action to prevent it. In situations where the data is available, AOS® can also compare data such as GPS speed, transmission vehicle speed, and wheel speed. This gives insight into sensor failures, which can cause faulty error codes and other issues. In the case of a failed wheel speed sensor, this will often cause a failure of any anti-lock braking system, stability control system, and traction control system.

System failure correlation is also performed where relationships are well-known. For example, a tire with a low-pressure issue will have a higher rolling resistance, increasing the fuel consumption above the normal operating range. Rather than pointing to the engine operating in a degraded state, the root cause can be identified here as the issue with the tire pressure. In situations where sensors are not available to determine the root cause, the prescription issued for the event will still suggest a manual inspection of other components for functionality to isolate the root cause. A second example might be in the situation of a high engine coolant temperature, the solution will also look at the engine load, ambient temperature, and other factors that would increase the stress on a cooling system. In some circumstances, the prescription may be to just reduce the load on the engine by reducing speed.

In all systems, a defined health state is applied individually based on the operating characteristics of that system. In the instance of the electrical system, the system health is based on the performance of the alternator and the charge of the battery, whereas in the lubrication system, the system health is based on oil & oil filter life but can also be affected by oil pressure. If oil pressure drops while the engine is running, the system automatically goes into a critical health state. The overall asset health is an aggregation of all the systems' health states.

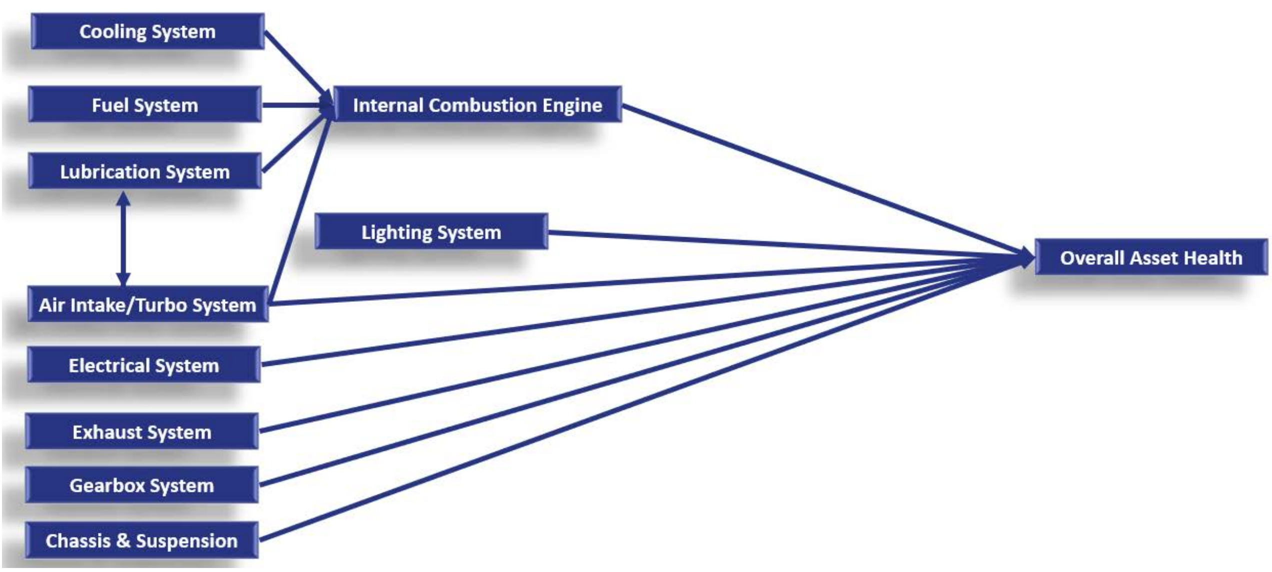

Figure 1: Health State Aggregation & System Interaction

2.2 AnalyticsOS®

AnalyticsOS® supports these analytics in real-time, processing the data as it comes in, executing the model, and then delivering the results to a database, where they can be viewed in visualization tools like Grafana. AOS® is a real-time analysis tool that utilizes the Monte-Carlo method to understand and capture uncertainty in the inputs. In the context of CBM applied to vehicles, the Monte Carlo method offers several advantages. In the example of estimating the center of gravity height of a particular vehicle, it is reasonable to assume it is between 0.5 and 0.65 meters, with a likely range of 0.55 to 0.58 meters. These ranges are based on the NHTSA's data published by the Society of Automotive Engineering's Heydinger, Bixel, Garrott, Pyne, Howe, and Guenther (1999). AOS® can capture this range and apply Monte-Carlo simulation techniques to estimate the likelihood that a 1G cornering event would cause excessive roll angle. Additionally, if the need to do "batched" data exists, AOS® can process time ranges of data as distributions to reduce computational costs and evaluation frequency. The evaluation frequency should be such that the fastest transient event being monitored can be isolated. For instance, in the event of a gradual loss of tire pressure, it will likely take anywhere from 5 to 15 minutes for the tire pressure to drop to a critical threshold. Given this, the evaluation frequency should be set to less than 5 minutes to capture the behavior. Evaluating faster provides better fidelity and a higher degree of accuracy in short-term predictions.

2.3 Evolved AI™

An additional element included in the roadmap for future offerings, Evolved AI™ can play a big part in improving CBM effectiveness by reducing asset running costs and maximizing uptime.

Evolved AI™ may be thought of as operating on principles of neural nets, but only in the sense of an underlying model being adapted to input data. LSA has used Evolved AI™ to solve the fundamental machine learning problems: supervised regression, supervised classification, unsupervised clustering, and for this application, model-based reinforcement learning. Evolved AI™ does not require input, hidden, and output layers or nodes, nor does it require activation functions. While LSA has implemented neural net architectures, we have found it more efficient for the model to represent the problem at hand. In short, Evolved AI™ addresses neural net critiques by removing the opaqueness of machine learning "black boxes" so users can easily interpret the results and fully explain how the transparent system works.

Instead of implementing backpropagation, which is typically done for neural nets, LSA implements our own (patent pending) approach to optimization. This technology is stochastic in three ways: (1) inputs to models may be any probability distribution the practitioner desires, (2) the underlying algorithm leverages probabilistic methods, and (3) the practitioner may run multiple Monte Carlo iterations. Benefits of this approach include the lack of gradients which would otherwise pose numerical challenges to the practitioner. Because gradients are not involved, LSA models can include discontinuities in addition to nonlinearities and nonconvexity. Also, with Monte Carlo methods, the optimal result is available as well as other feasible solutions. This enables the practitioner to explore the conditions that might lead to a feasible solution, thus uncovering potential Black Swans to improve situational awareness. With regard to Evolved AI™, the results of our trained models are based on various statistical measures which allow for the handling of real-world data.

In practice, Evolved AI™ can be used to optimize the maintenance costs within a given timeframe based on the risk posed by having different component failures. For example, if it costs a flat starting fee of $500 every time a vehicle goes in for servicing, some components may be allowed to remain in a critical state until other issues requiring maintenance arrive. Additionally, it may be beneficial to replace other components early while the vehicle is out of operation to save future costs. Evolved AI™ can enable this by assigning point metrics to the replacement of individual components to determine the best time to service a vehicle. In practice, implementing

Evolved AI™ would be done during model development in TruNav®, where the weights of the biases would be tuned to optimize whichever parameter would be targeted, and then that model would be transferred into the real-time environment of AOS®.

3.0 DATA AGGREGATION & VISUALIZATION

One of the biggest challenges posed by CBM is obtaining the data. A CBM system can be parameterized to support any vehicle with sufficient documentation, but if all the vehicle's Controlled Area Network (CANBus) reports is engine speed and vehicle speed, then there is not much the system can provide in terms of useful analytics. Utilizing the available sensor suite to the maximum is a critical aspect of enabling a solution to be effective. When it comes to collecting the data, there are a few viable options. A popular option in the commercial sector is to go through telematics companies like Geotab, CalAmp, or Verizon Connect. These companies produce hardware that plug directly into a vehicle's Onboard Diagnostics (ODB)-II port or other diagnostics port and stream the data via cellular connection. To deploy a CBM solution such as MaxUp™ Fleet, minimizing the physical interaction with the vehicle is best. Devices such as those built by CalAmp and Geotab require only a few minutes to connect to the vehicle's diagnostic port, and then immediately begin transmitting data. These devices can be updated remotely, so once they are installed, there would be no need to remove them except in rare circumstances. In cases where the vehicle diagnostic port is non-standard, or not directly supported by available devices, there are options to hardwire the device into the vehicle's ECU wiring loom. This option will require a higher level of interaction, and in the commercial sector, is usually performed at an approved supplier of the hardware.

3.1 Visualization

For visualization of the analytics, AOS® can support integration of most third-party visualization software. Grafana is a commonly used solution with a high degree of configurability and supports different user access levels for operational compartmentalization. If a user already has a dashboard/visualization solution in place and wants to incorporate the analytics directly into an existing platform, this can also be done and is a common occurrence in the commercial sector. Aggregating the analytics in the right fashion and in the right places is critical to maximizing the benefits of VCBM, but also can depend on the asset type, asset operator, and the type of operations in which the asset is expected to participate. Operators should be able to, immediately, observe the status of the entire fleet and see the operational status of each asset. If any asset has an issue, an alert would be issued that displays the required action on that particular asset.

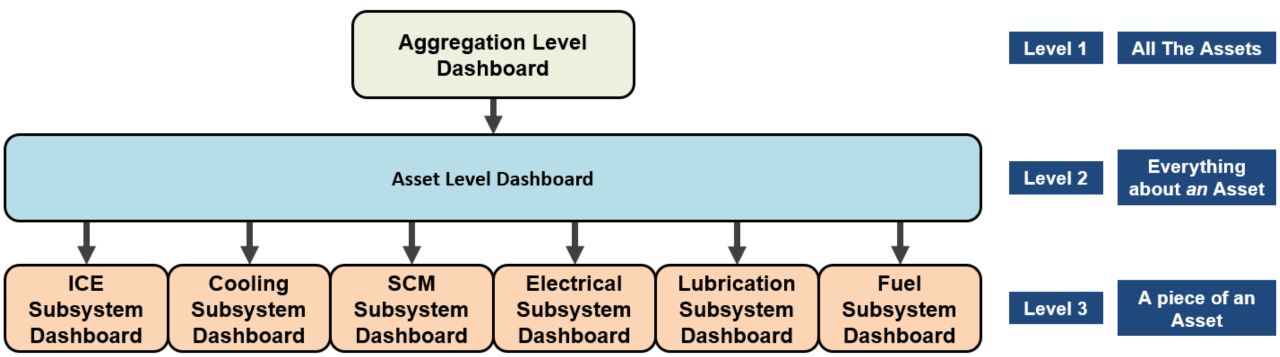

Figure 2: Dashboard Hierarchy

4.0 DEPLOYMENT METHODS

Some devices have computation abilities embedded, allowing for reduction of external computing costs, or for the ability to avoid the need to stream the data altogether. In this situation, the deployment would be entirely local to the asset, and would require either an additional display for the operator, or some other way of communicating the analytics. An additional option is collecting and storing the data while the asset is deployed, and then "dumping" the data upon the asset's return. This reduces the risk posed by having a signal emitted from the asset but would eliminate the possibility of a CBM solution capturing any immediate failures and risks. The most common deployment method in the commercial world is to have the hardware stream the data and perform the analytics in the cloud. This enables users to remotely view the status of every asset in the fleet, make decisions about supply chain logistics, and plan service intervals well in advance.

The typical cloud topology is displayed in Fig. 3. In this scenario the solution model is hosted on a Lone-Star owned server, but this can be adapted to customer needs and supported remotely.

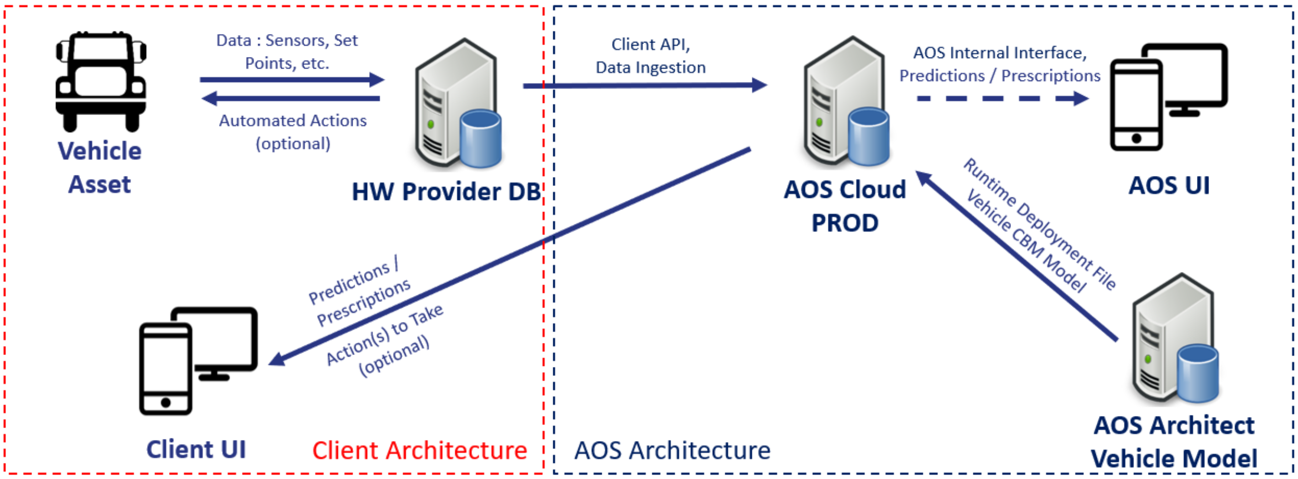

Figure 3: Cloud System Topology

In practice, this system has been tested on several light-duty commercial vehicles and will be tested on heavy-duty commercial vehicles as well. The largest challenge with the light-duty vehicles is the commonality of data between different vehicle types. For example, Ford may make different data available over the vehicle BUS than what Chrysler offers. To combat this, hardware providers have methods of reverse-engineering the vehicle BUS configurations to understand what data the vehicle can ultimately produce. So far in testing, this system has proven its ability to collect the data, push the data through the model, produce the expected results, and push those results to dashboards configured specifically for end-users.

The feedback that this system provides is real-time, but it is not a control system – any results that the system provides will always require operator intervention to implement any recommended maintenance changes or operational behaviour changes. In the sense that the system is real-time, it will provide results at a set frequency that is configurable and defined at model deployment. In practice, frequencies ranging from 30 seconds to 5 minutes have been tested and have shown success – in the instances where the end-user wants to capture events that happen over a matter of minutes, the model evaluation frequency will need to be set in the faster end of this range. It is possible to evaluate less often than 5 minutes, but fewer failure modes will be captured.

5.0 CONCLUSION

Operational Availability and mission readiness are complimentary to each other and are crucial elements to mission success. LSA has developed MaxUp^{TM} Fleet, which provides Vehicle CBM software that will decrease unforeseen breakdowns by 70% to 75% and provide a 35% to 45% reduction in downtime of vehicle fleet assets. MaxUp^{TM} Fleet covers all the major sub-systems of a typical vehicle and has the capability to expand to additional systems at the request of the user. The analytics performed on each sub-system are based on known physical relationships and equations, either commonly accepted or utilized directly from well-regarded texts and data sources within the automotive industry. In all systems, a defined health state is applied individually based on the operating characteristics of that system. The overall asset health is an aggregation of all the systems' health states.

MaxUp^{TM} Fleet runs on the AOS® platform that automates predictive and prescriptive analysis through real-time integration with streaming datasets. As a real-time analysis tool, AOS® utilizes the Monte-Carlo method to understand and capture uncertainty in inputs. Evolved AI^{TM} is complementary to all AOS® applications and will be integral going forward to improving CBM effectiveness in reducing asset running costs and maximizing uptime. In practice, implementing Evolved AI^{TM} would be done during model development in TruNavigator®, where the weights of the biases would be tuned to optimize whichever parameter would be targeted, and then that model would be transferred into the real-time environment of AOS®.

Data collection is crucial to the success of CBM. It is best to use hardware that plugs directly into a vehicle's Onboard Diagnostics (ODB)-II port or other diagnostics port. To deploy a CBM solution such as MaxUp^{TM} Fleet, minimizing the physical interaction with the vehicle is best. Devices require only a few minutes to connect to the vehicle's diagnostic port, and then immediately begin transmitting data. These devices can be updated remotely, so once they are installed, there would be no need to remove them except in rare circumstances.

Visualization and deployment methods must be considered and utilized that best support users' access levels for operational compartmentalization. Deployment methods need to be balanced against operational risk when vehicles are in direct contact with adversaries or operating in other non-permissible environments. Data can then be streamed via the Cloud, saved, and downloaded when circumstances permit, or deployment kept local to the respective asset.

Finally, NATO is seeking an improved understanding of the maintenance needs for UxVs to enable CBM in place of scheduled maintenance. MaxUp^{TM} Fleet provides the physics-based predictive methods, advanced data analytics for enhanced situational awareness and proactive, condition-based maintenance. As NATO and Allied Nations as well as potential adversaries significantly increase the utility of UxVs, it is crucial to understand and develop strategic approaches to all these aspects. LSA offers MaxUp^{TM} Fleet as an answer to these requirements.

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