

Integrated vehicle health management in the automotive industry

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1. Introduction

The advent of integrated vehicle health management (IVHM) in the auto industry promises to provide significant new capabilities to enhance the overall customer ownership experience with their vehicles. In essence, it provides a means to essentially redefine “reliability” by being able to proactively deal with future problems before they actually inconvenience the customer and, thus, largely mitigate the negative impact of those problems. IVHM provides an important building block upon which these innovative new features can be implemented. In addition, IVHM provides an improved framework to better manage the life cycle maintenance for such vehicles which in turn provides an immediate saving opportunity for all vehicles. Traditional maintenance schedules in automotive use have typically been time or mileage based but this can lead to negative consequences in multiple ways. The maintenance intervals can be too conservative for some operating conditions and therefore potentially waste the owner’s time and money as well as wasting valuable natural resources. On the other extreme, under certain operating conditions, the time or mileage based approach may signal a maintenance action too late to avoid a service issue of some kind. By tracking actual usage patterns, we can dynamically adapt the maintenance intervals to more appropriate periods based on the actual needs. This has been shown to result in significant benefits.

2. IVHM in the New Paradigm

IVHM is all about active management of the automotive vehicle’s health, as it relates to the performance of key vehicle functions, to meet the customer’s need for reliable transportation. It is instructive to consider the broad ramifications of IVHM in the context of the new paradigm the auto industry has entered. This is important because the assumptions and limitations implicit in today’s designs will simply no longer apply as this new paradigm takes hold.

In the early days of the auto industry at the start of the twentieth century, the paradigm was truly one of “craft manufacturing.” Even though the notion of interchangeable parts had been successfully applied in the gun manufacturing business, the same concept was

considered totally impractical relative to much more complex products such as automobiles. Henry Leland, founder of Cadillac, set out to prove otherwise and won the prestigious Dewar Trophy in 1908¹ with the successful demonstration of interchangeable parts held for the Royal Automobile Club of England (RAC). This second paradigm in turn laid the foundation for the third paradigm later introduced by the other Henry [Ford] who popularized the concept of the assembly line² based in part on what he learned from the meat packaging business. The assembly line paradigm dominated the industry for many years until Toyota's Taichi Ohno introduced what has since become known as Lean Manufacturing³. He got those ideas in part from the grocery business and its obsession with waste reduction driven by the perishable nature of their product and their very thin profit margins. But, just as lean built upon the assembly line which built upon interchangeable parts, we have now entered what I call the paradigm of "real time optimization."

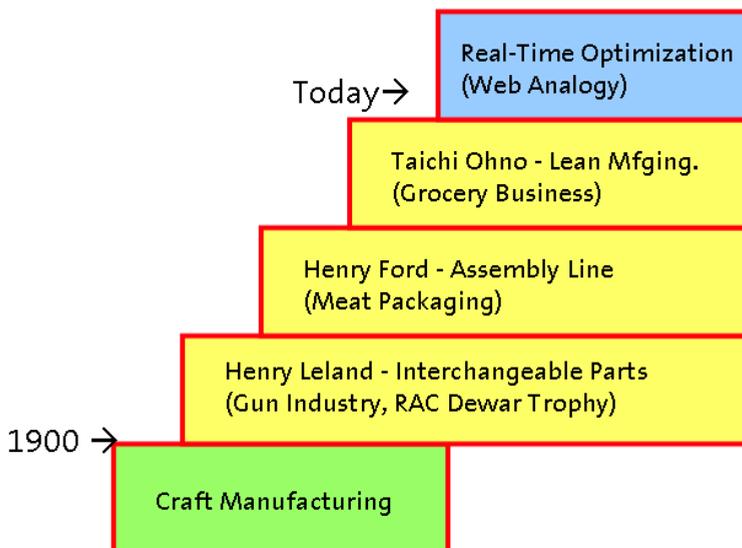


Fig. 1. Automotive Manufacturing Paradigms

The "real time optimization" paradigm draws heavily upon the lessons learned in the creation of the World Wide Web. There were a number of prerequisites before the web could explode into becoming the global phenomena that it represents today. I believe that reaching critical mass in both computational power and communication bandwidth was perhaps even more important than the advent of the browser. In automotive manufacturing today, we now have computers embedded in nearly all key manufacturing equipment such as robots, material handling systems, control systems (PLCs), ordering systems, supply systems, etc. Equally important is that we now have both high speed wired or wireless communications between all these smart machines or functions. Thus, we have begun witnessing a similar kind of explosion of capability in manufacturing as seen previously with the Web.

Just as lean manufacturing was to spill over into all aspects of business operations, so it is the case for the real time optimization paradigm.

This paradigm beyond “lean” is being driven by the availability and exploitation of real-time information across the enterprise to optimize the value chain from the suppliers through manufacturing plants, and into the distribution channel.

IVHM as we conceive it would not be possible without the real time optimization paradigm. It is precisely the elements of this paradigm which provide a means for knitting together all the engineering and business processes which taken together provide us our vision for IVHM. Modern vehicles already have upwards of 50 microprocessors on board to control the various subsystems of the vehicle. The software codes that deal with engines, transmissions, overall vehicle coordination, etc. already exceed one million lines of code each. The data storage on board to support entertainment and navigation systems typically requires gigabytes of data. This complexity will only continue to grow as the electrification of automobiles goes mainstream in the market and as sophisticated computer controlled safety systems advance⁴.

3. Customer Needs & Wants

It is essential to consider customer needs and wants as we prepare to provide fundamentally new services through IVHM technologies. One important analysis of that topic comes from J.D. Power and Associates studies on how customers themselves evaluate the various elements that impact their overall satisfaction. As shown in Figure 2, *Quality and Reliability* is the single biggest factor typically accounting for 38-41% of the overall score. It is not surprising that it is the single most important factor but one should take note that it does not by itself tell the whole story. The next factor is *Vehicle Appeal* at 22-26% of the score – this includes performance, design, comfort, features, etc. *Ownership Costs* represent about 18-20% and includes fuel consumption, insurance and costs of service/repair. Lastly, *Dealer Service Satisfaction* typically accounts for about 16-19% of the score. Clearly, there is no single factor and thus one needs to be mindful of all the areas. IVHM is very interesting as a new automotive concept as it has the potential to positively impact all four elements of customer satisfaction.

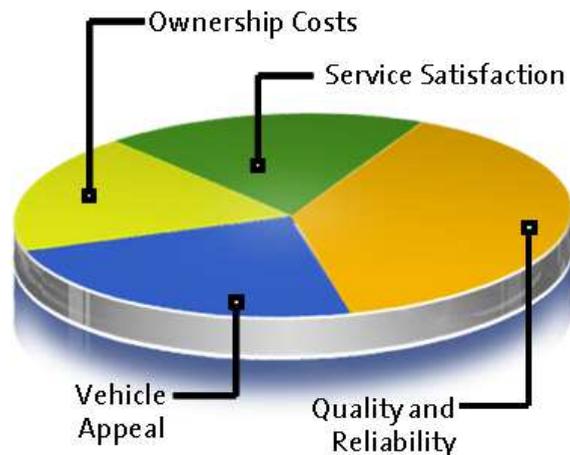


Fig. 2. Elements of Customer Satisfaction

We know from surveys that our customers do understand and appreciate currently available prognostic features such as GM's oil life monitor which is available on most of our products. The remaining useful life of the engine oil is monitored by onboard computers and is calculated based on actual driving conditions. People who drive only short distances with a lot of "stop and go" city driving may need to replace their oil after only 2,500 miles whereas those that tend to do mostly longer distance highway driving may be able to comfortably go 12,000 miles or more before a change. This is perhaps one small example but the point is important. That is, the amount of oil you can potentially save over the entire fleet of vehicles offers a significant societal benefit. In addition, there is a huge collective cost savings which accrues directly to customers by avoiding the expense of unnecessary oil changes and wasted time. The oil life monitor relates to just one of the consumables needed by typical vehicles but, of course, the same approach might apply to the other normal, time-based or mileage-based maintenance schedules. Looking to the future, we believe it is important to go beyond the normal maintenance items and be able to deal proactively with the health of all major systems onboard the vehicle as this specifically is what leads to significantly enhanced reliability as experienced by the customer.

As automotive technology has improved over the years, we have observed a trend of achieving higher and higher levels of quality, reliability and durability (often referred to as QRD). There is little question that this is important to prospective buyers and therefore important to the manufacturers as well. All manufacturers need to keep sharply focused on this need but QRD statistics alone do not tell the whole story. If we can exploit prognosis to predict problems before they negatively impact the customer, we will have essentially created an opportunity to redefine what reliability means from the customer's point of view. That is, if we can detect future problems at a point early enough to allow us to intervene on behalf of the customer and proactively resolve the issue before the customer is inconvenienced, we have essentially achieved this redefinition of reliability.

4. Automotive IVHM

Prognosis advances are creating new opportunities for applying IVHM in the automotive business. It clearly needs to be managed from a life cycle perspective and from a total business point of view as illustrated in Figure 3. Looking at warranty costs alone is too narrow a scope. As shown in the figure, the life of a given vehicle being in service will typically extend considerably beyond the warranty period. Often, it is in the later years of the ownership experience that IVHM may become most valuable to the customers. In addition, it may be precisely then that the customers are considering their next replacement vehicle which makes it very important to the manufacturer as well. Of course, one of the big advantages of applying IVHM in the paradigm of real time optimization is that the available linkages back to manufacturing, validation, and product developments allow one to reap even greater rewards. Not explicitly shown in the figure but equally important are the linkages out to the supply chain for issues like coordination of spare parts availability, scheduling of service, or feeding requirements back into the supplier community whenever performance or quality issues arise.

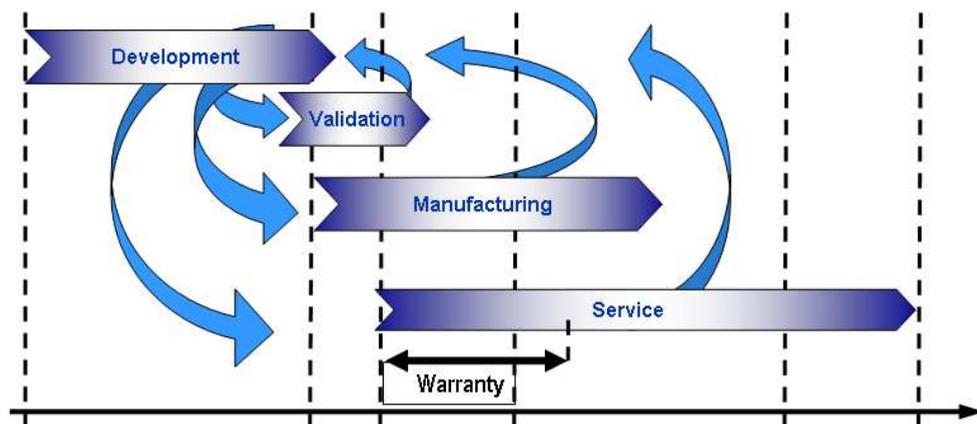


Fig. 3. Total Life Cycle Perspective

We generally consider our diagnostic and prognostic efforts in three broad categories which represent different situations—"enhanced diagnostics", "managed maintenance" and "prognostics". Some devices or systems do not warrant the application of sophisticated prognosis—they are well served by the ability to simply detect and diagnose the root cause of any problem. For example, very inexpensive items or extremely reliable items often fall in this class where the addition of sensors or software to prognose future behaviour may not be justified. These situations may still benefit from enhanced diagnostics. The managed maintenance area refers to the set of normal maintenance items on the vehicle. Instead of using traditional time or mileage based approaches to schedule maintenance, we instead use simple forms of prognosis to adapt the maintenance schedule to actual driving conditions and/or performance. A requirement for achieving low false positives is not necessary for this approach to do substantially better than pure time or mileage based approaches. Typically, we would still build in fairly conservative assumptions to mitigate concern for false negatives as well. Finally, areas including safety systems, fuel economy systems, emissions systems, or ones with sophisticated computer control are the target for advanced prognostics.

5. Sensor-Based Diagnosis & Prognosis

With the advent of higher and higher levels of electronics in today's products, there has been an increasing emphasis in on-board diagnosis to quickly detect faults and isolate their root cause[s]. The new technology frontier is clearly prognosis which adds the predictive element to what has gone before^{5,6}. This new technology seeks to be able to identify problems before they happen so that corrective action can be taken prior to loss of service.

A primary focus is concentrated on key systems providing for enhanced safety, improved fuel economy, stringent emissions control, or hybridization/electrification of the vehicle. These kinds of systems are specifically targeted because of their obvious importance and because their successful implementation is typically dependent upon heavy use of electronics, controls technology and software (ECS) to achieve the required levels of performance. ECS systems can offer greater challenges in terms of both diagnostics and

prognostics. They typically require a stringent systems engineering approach, and this is precisely what IVHM methodologies can provide.

On-Board Diagnostic (OBD) systems were originally mandated by the US government to ensure that emissions systems were performing as mandated throughout the vehicle's life. Nearly all aspects of engine and transmission operation have the potential for impacting emissions levels. The current generation of on-board diagnostics known as OBD-II has been fully in operation since the 1996 model year of vehicles sold in the US. Over time, the use of these diagnostic systems has expanded well beyond just emissions control to today where you find sophisticated diagnostics being used throughout the vehicle.

With prognosis, we are raising the bar and need to be able to reliably determine the state of health (SOH) or remaining useful life (RUL) of key components or subsystems essential to the performance of the product. The emphasis on "reliably" here is very important as rough prognostic assessments are usually not actionable in the field. We need to ensure a low level of false positives and false negatives if we are to drive better decision making and thus achieve the benefit.

For onboard diagnostics, we use the term diagnostic trouble codes, or DTCs. In other industries, DTCs are referred to by other names such as Built-in Tests (BITs) but the concept is the same. A DTC is basically a software subroutine that runs at some appropriate interval and looks for indications of specific problems being present. A DTC subroutine typically begins with first verifying that a set of preconditions are satisfied before proceeding—this is to ensure that it is appropriate to run the desired check and that the needed parameters are available and defined. If the specific problem is detected, the DTC is set to an "on" state. Should a DTC be set to "on" incorrectly indicating a problem which is actually not present, this is referred to as a Type I error. This is the same as an " α error" or a false positive. Similarly, if a DTC fails to set and the problem is actually present, we call this a Type II error, or a " β error", or a false negative. In a simple case where the value of just a single parameter is being used to classify whether a given problem is present or not, you can imagine the situation with two overlapping distributions along that parameter's range of possible values as shown below in Figure 4. Ideally, the distributions would be widely separated but this is not always the case. The point at which you establish the parameter threshold value as shown below provides you a means to trade-off between Type I and Type II errors. A test with a high *specificity* has a low Type I (false positive) error rate. A test with high *sensitivity* has a low Type II (false negative) error rate. Let's consider the implications for an automotive example dealing with the vehicle's battery. If we have an assessment algorithm that generates very many false positives, we may be causing unnecessary battery replacements which in turn will result in the waste of both time and money. On the other hand, if our algorithm generates many false negatives, we risk inconveniencing the vehicle's owner by having the car not starting or operating properly. In the example below, the threshold has been set such that nearly all bad batteries are caught but at the expense of calling quite a few good batteries bad. In real applications, the classification is normally multidimensional.

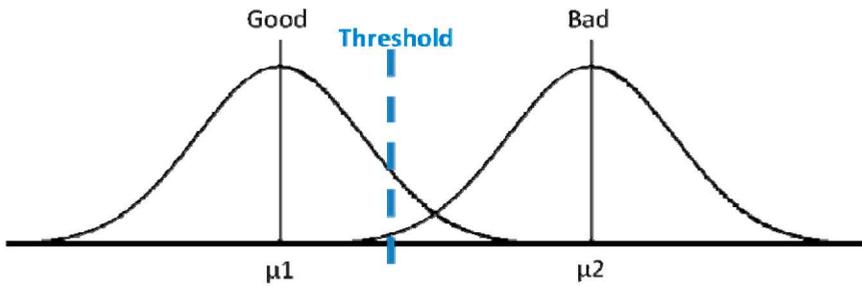


Fig. 4. Overlapping Distributions Forces Trade-off between False Positives & Negatives

Figure 5, as described by Professor Krishna Pattipati of the University of Connecticut, illustrates one conceptual view of the process for fault detection, fault isolation and control. There are many alternative ways to think about the problem. The model shown assumes that the system or subsystem being monitored makes available key sensory information or computed variables. These are in turn compared with expected or nominal values based on the operating regime of the system. The residuals or deviations can then be tested to provide input into an inference module that is preloaded with some kind of fault model. The results of these inferences together with the observed deviations allow an assessment of the problem severity. Finally, this can drive needed repairs or possibly real-time compensations to allow the system to maintain some minimum acceptable level of performance until such time as the ultimate repairs can be performed.

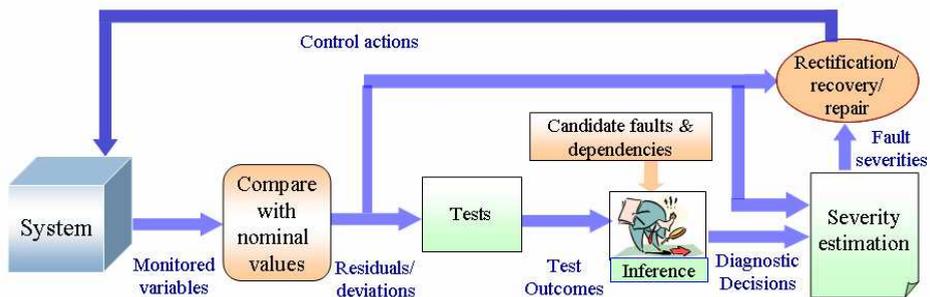


Fig. 5. Fault Detection, Isolation and Control

Most of the effort toward onboard diagnosis and prognosis has been pursued by using information available from within the operating vehicle itself. However, in cases where we can gather aggregate information from across an entire fleet of similar vehicles, we open up new possibilities that are not available with the just the vehicle specific information alone. For example, with aggregate fleet information, we are in a position to detect problems earlier in their life cycle while the total impact of those problems is still low and the cost of resolution is still correspondingly low. Further, if we were to look across the entire fleet and study performance of similar vehicles operating under similar driving conditions, we could learn useful information to send back to specific vehicles to focus performance monitoring on areas which were found to be at risk based on the overall fleet information.

6. Health Ready Supplier Components

In the context of automotive IVHM, no single company can or does make all components and subsystems for the final product as the consumer sees it. Cooperation with the global automotive supply base to clearly specify the kinds of information needed from the various subsystems to facilitate overall health management initiative goals and objectives must occur well in advance of the actual production needs, to allow for designing in of such features in an orderly and cost effective manner. This includes deciding what kinds of information are to be provided as outputs of the subsystem controllers, how often that data will need to be transmitted, how detailed it should be, and in what format it should be sent. Focusing on these important interface issues, should allow the OEM to more quickly and less expensively converge on a consistent framework to implement “health ready” components, resulting in a win-win-win situation for the automotive OEM, the suppliers and the customer. We recognize that various suppliers have invested a great deal of time and money to achieve their level of performance. This intellectual property is often unique to the specific supplier so careful attention must be paid to ensure that this intellectual property is protected and not allowed to be inadvertently communicated beyond its intended audience. It is to all constituents’ advantage to protect the intellectual property and to encourage creativity and advancement of the health management capabilities. The specification and bidding process must be designed to ensure these needs are being met.

7. Future Directions

Integrated vehicle health management as it applies to the automotive industry is a specific example of how diagnostics and prognostics technology can improve the products we sell and enhance their value to our customers. This is of course precisely our goal. If one looks to different industries such as aerospace, rail, trucking, computers, data storage, printing, farm equipment, mining equipment, etc., we find many innovative examples of how prognosis is growing in application and importance. Together they provide a rich set of real world examples where solutions have been found relative to associated business issues, privacy issues, financial issues, etc.

This chapter began by looking at the evolution of the major paradigms in the automotive industry and how that positions us to peer into the future and envision how the new *real time optimization paradigm* opens up new opportunities. In a sense, it was the emergence of the web that provided the model for the new paradigm we have entered. Similarly, as we look to the evolution of the web itself, perhaps we can better see some of the future opportunities for IVHM. The original web applications (Web 1.0) were all static information displays. Web 2.0 which is now fairly common brought us more dynamic information and, very importantly, the ability of a large user community to share information in new ways. In the case of IVHM, this suggests tapping into fleets of vehicles which represent large comparison populations operating under similar conditions, in similar geographic environments, in similar climates, etc. This would allow us to go beyond what could ever be known or experienced by any single vehicle, to benefit from the richer experience of the full fleet of similar vehicles operating in similar conditions. Web 3.0 as it is currently conceived is intended to add semantic tagging to web based information – this along with some kind of reasoning capability opens the door for more effective use of the vast amount of available

data. This external reasoning will be very powerful in an IVHM context and allow us to effectively use both the vehicle specific information and the available aggregated population information more easily. Web 4.0 promises to deliver agent-based technologies which provide the needed foundation for enhanced automation and new kinds of services – being performed autonomously by remote computers without the need for as much human intervention. IVHM services will be created and deployed in a similar fashion to increase their effectiveness, speed their performance, and provide new services not feasible given today's technological limitations. The future is bright indeed.

8. Conclusions

The time has come to port integrated vehicle health management concepts originally pioneered in aerospace and other domains into the automotive industry.

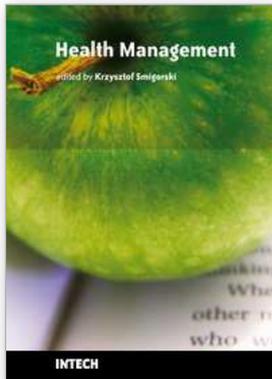
- The successful automotive manufacturer must remain highly customer-focused to ensure delivery of high value at an affordable price.
- IVHM success will require partnering between the automotive manufacturer, its suppliers, as well as external technology providers located in private industry, academia and governmental labs ...on a global basis.
- IVHM applied to automotive products illustrates the power of the new real-time optimization paradigm which is emerging as the successor to the venerable lean paradigm.
- IVHM will require a fresh look at the associated business processes and systems which have evolved over the years.

9. Acknowledgments

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Possibilities of medical intervention have thrived over the last decades. Our knowledge about mechanisms of the development of diseases and factors influencing it has increased. Effective treatment requires a holistic approach that takes into consideration aspects at first sight not related to a course of a specific disorder. This book contains a few chapters focusing on issues related to health management. The chapters are arranged in an order reflecting multidimensionality of issues constituting this theoretical and practical area - starting from the studies focusing on a general, administrative level, to considerations related to situations of individuals suffering from a specific illness. The discussed problems concern different age groups - children, adults and the elderly. We hope that readers professionally engaged in healthcare - both theoretically and clinically - will find it interesting, useful and inspiring.

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