

Design and Run-Time Information Exchange for Health-Ready Components

RATIONALE

This SAE Recommended Practice was created to help reduce existing barriers to the successful implementation of Integrated Vehicle Health Management (IVHM) technology into the aerospace and automotive sectors by introducing health-ready components. Health-ready components are augmented either to monitor and report their own health or, alternatively, ones where the supplier provides the integrator sufficient information to accurately assess the component's health via a higher-level system on the vehicle. The principal motivation for health-ready components is to facilitate enhanced IVHM functionality in supplier-provided components that better meet the needs of end users and government regulators in a cost-effective manner. Underlying this motivation is the assumption that market forces will drive the need to achieve IVHM's benefits, which will in turn drive new requirements that suppliers must ultimately meet. This SAE Recommended Practice has two primary objectives: (1) to encourage the introduction of a much greater degree of IVHM functionality in future vehicles at a much lower cost, and (2) to address legitimate intellectual property concerns by providing recommended IVHM design-time and run-time data specification and information exchange alternatives in an effort to help unlock the potential of IVHM.

SAE JA6268 has been reaffirmed to comply with the SAE Five-Year Review policy.

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1. SCOPE

This Surface Vehicle & Aerospace Recommended Practice offers best practices and a methodology by which IVHM functionality relating to components and subsystems should be integrated into vehicle or platform level applications. The intent of the document is to provide practitioners with a structured methodology for specifying, characterizing and exposing the inherent IVHM functionality of a component or subsystem using a common functional reference model, i.e., through the exchange of design-time data and the application of standard vehicle data communications interfaces. This document includes best practices and guidance related to the specification of the information that must be exchanged between the functional layers in the IVHM system or between lower-level components/subsystems and the higher-level control system to enable health monitoring and tracking of system degradation severity. The intent is to provide an IVHM system that can robustly report the degradation of a given component before it reaches the point where it goes outside its operational performance envelope by providing sufficient advance notice to deal with the issue. This document does not specify or address how each layer in the IVHM system produces or uses the data available for exchange.

1.1 Purpose

This recommended practice aims to address two primary objectives in order to help unlock the potential of IVHM: (1) to encourage the introduction of a much greater degree of IVHM functionality in future vehicles at a much lower cost, and (2) to address legitimate intellectual property (IP) concerns by providing alternative strategies for the supplier. The document offers several different design-time data specification and exchange alternatives by which a supplier can choose to deliver the required IVHM functionality while still protecting its legitimate IP.

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3. ABBREVIATIONS

ACARS: Aircraft Communications Addressing and Reporting System

ACMS: Aircraft Maintenance System

AG: Advisory Generation

AMS: Aircraft Maintenance System

ARINC: Aeronautical Radio, Incorporated

ARP: Aerospace Recommended Practice

AUTOSAR: AUTomotive Open System ARchitecture

BIT: Built-In Test

BITE: Built In Test Equipment

CAGE: The Commercial And Government Entity (CAGE) Code is a five-character ID number

CAWS: Caution Advisory Warning System

CBM: Condition Based Maintenance

CCND: Customer Complaint Not Duplicated

CDR: Critical Design Review

CEL: Check Engine Light

CI: Condition Indicator

CMS: Content Management System

CND: Could Not Duplicate

CPU: Central Processing Unit

DA: Data Acquisition

DAQ: Data Acquisition

DM: Data Manipulation

DTC: Diagnostic Trouble Code

DTS: Data Transfer System

DUNS: Data Universal Numbering System or D-U-N-S® Number

EAI: Enterprise Application Integration

ECU: Electronic Control Unit

EU: European Union

FAI: First Article Inspection

FDE: Flight Deck Effect

FMEA: Failure Mode & Effects Analysis

FMECA: Failure Mode Effects & Criticality Analysis

FTA: Fault Tree Analysis

HA: Health Assessment

HI: Health Indicator

HRC: Health Reporting Code

IBIT: Initiated Built-In Test

INCOSE: International Council on Systems Engineering

I/O: Input/Output

IRM: Integrated Reference Model

ISO: International Standards Organization

IVHM: Integrated Vehicle Health Management

JA: SAE designation for cross-industry recommended practice documents

LRU: Line Replaceable Unit

MIL: Malfunction Indicator Light

MIL STD: Military Standard

MIMOSA: Machinery Information Management Open System Alliance

MSG: Message

NFF: No Fault Found

NTF: No Trouble Found

ODX: Offloaded Data Xfer [Transfer]

OEM: Original Equipment Manufacturer

OSA-CBM: Open Systems Architecture for Condition Based Maintenance

OTX: Open Threat eXchange

PA: Prognostics Assessment

PAI: Proactive Alert Identifier

PDR: Preliminary Design Review

PLR: Performance Life Remaining

PWM: Pulse Width Modulated

RCV: Recirculating Valve

RMS: Root Mean Square

RUL: Remaining Useful Life

SD: State Detection

SDRL: Supplier Data Requirements List

SOH: State of Health

SysML: System Modelling Language

VHM: Vehicle Health Management

XML: eXtensible Markup Language

4. INTRODUCTION

The recommended best practices and guidance provided in this document are strictly advisory in nature and are suggested for use in concert with other IVHM recommended practices and the relevant organization's engineering design practices. There will be situations where good design requires that these guidelines be extended or modified to maximize use of the component, subsystem, system or the vehicle's inherent (health-ready) design functions and to optimize the benefits of the IVHM system solution. Figure 1 provides an overview of the overall concept behind the recommended practice. As shown in Figure 1, this document supports (1) the design and data integration process and (2) the integration of IVHM related run-time messages. Design-time integration uses data developed by suppliers and provided to the system integrator (upper area highlighted in light beige) in order to provide more complete implementation of IVHM functionality and to facilitate the integration of this functionality. Run-time messages are collected by the Health Management System and used by higher level reasoning functions to provide the best possible component health state advisories and support services to the various user communities (lower area highlighted in light red).

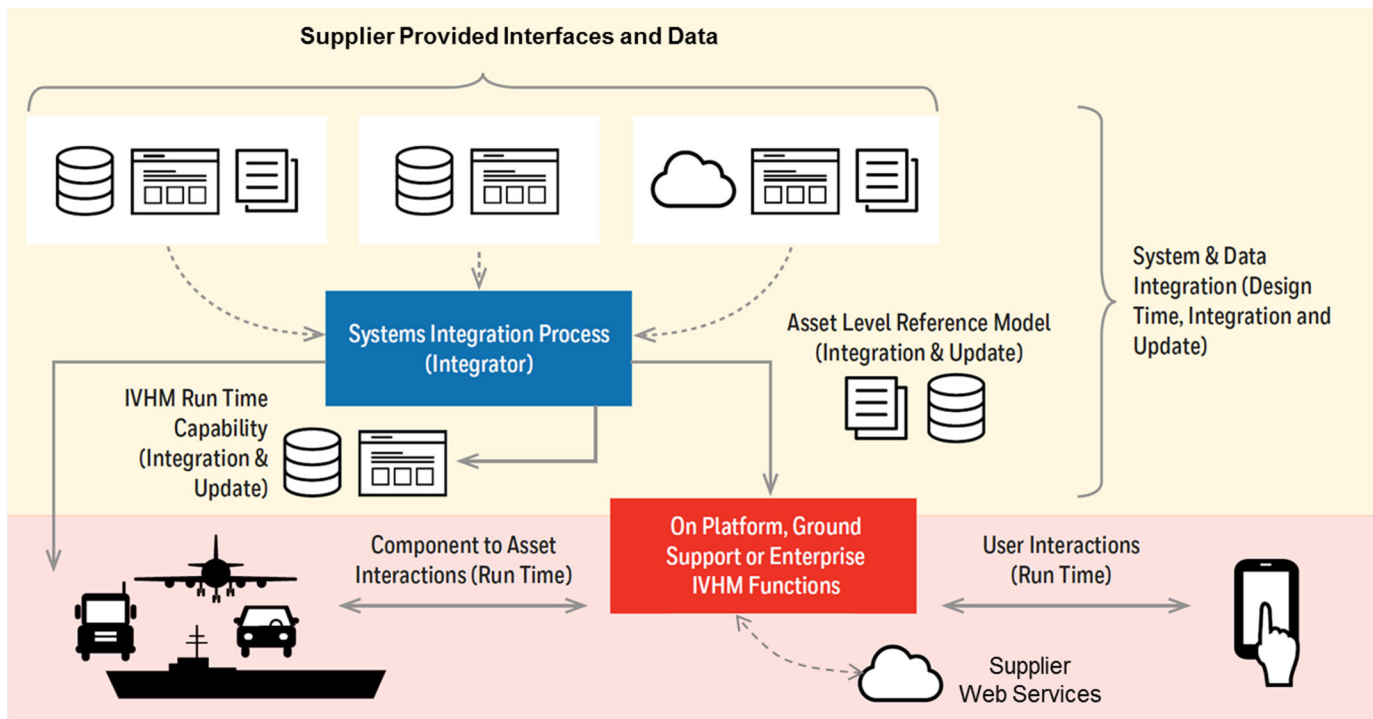


Figure 1 - Overview of IVHM deployment process with JA6268

It is important to note that this document provides recommendations for the integration of both the Design-time data and the Run-time messages. As discussed at length in this document, a supplier may choose to achieve a “Health-Ready” designation for its components through a process that relies primarily on providing additional Design-time data, additional Run-time messages or a combination of both.

Overall, JA6268 seeks to provide uniform requirements, practices and methods to address the sharing of critical component/subsystem design-time information to facilitate real-time platform level communication and the implementation of supplemental IVHM functions. In the past, component suppliers were primarily operating in the *diagnosis-only* paradigm in which the focus was to facilitate the detection and identification of the root cause(s) once a failure had occurred. In the new IVHM or prognostics paradigm, the supplier must also facilitate health monitoring and tracking of system degradation severity to prevent a given component from experiencing an unreported degradation to the point where it goes outside its operational performance envelope. As noted in Figure 1, suppliers may provide any combination of components, controllers, software and services. With health-ready components, they are accompanied by descriptive data that allows these functions to be integrated to produce a coherent picture of the overall health status of the asset and an estimate of the cost/benefit associated with the implementation or enhancement of the component/subsystem health-ready functionality.

A very important selling point of prognostics is that it can have a significant impact on “perceived” reliability from the end-user’s point of view. Consider the fact that if the vehicle health system can reliably predict 90% of a component’s actual field failure incidents, this means that only 10% of the expected faults are left to happen without warning. These high coverage rates may be somewhat easier to attain in the automotive space but recent aerospace programs have had the stated goal of reaching as high as 95 to 99% coverage. Note that from the end-users point of view, achieving a 90% prediction rate is analogous to a ten-fold improvement in raw reliability because 90% of the expected field failures would be transformed into simple maintenance events and never actually allowed to *become* a failure. Of course, 90% coverage may be difficult to achieve in all cases since some failures are not associated with wear-out mechanisms and can be difficult or even impossible to predict—the attainable level is application specific. It is nevertheless still extremely important for design engineers to do all that is practical to make a component’s true reliability be as high as possible. But, no matter what level of reliability is achieved through the application of good design practices, the added opportunity for a significant improvement from the customer’s point of view should be carefully considered. Care must also be taken that false alarm rates are not allowed to go up alongside detection rates.

Finally, this recommended practice allows for maximal flexibility for the supplier to determine the best way to provide the required IVHM functionality. In some cases, the supplier will implement nearly all the functionality and then be required only to provide structured data to inform the larger IVHM system how to interact with these functions and use their results. In other cases, the supplier may decide that it is better to provide additional design data to allow the integrator or a third party to implement the required functionality. In either case, or with a combination of them, the recommended practice calls for the supplier to provide their data in a machine-readable format that this document will reference as a “model”. It is important to note that the “model” includes a series of interface definitions, also information to interpret results or data provided by the supplier and, possibly, information required to allow a third party to implement required IVHM functionality. A major objective of the recommended practice is to provide flexibility to suppliers and integrators so that they can decide the best approach for each application.

4.1 The IVHM Development Process

The SAE IVHM Standards Committee (HM-1) is creating a set of recommended practice documents to provide guidance at various stages in the IVHM development process. This should be considered as a realization of the general system engineering process or the more domain specific IVHM Systems Engineering Process (INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, 2015) (NASA Engineering Innovations, Systems Engineering for Life Cycle of Complex Systems, 2011) (Jennions, 2011). Generally speaking, one starts by determining the organizational goals of the sponsoring and using communities. The requirements for the system should evolve somewhat naturally from these goals, and a system architecture is created that provides the framework to support the system requirements. A detailed system design process is then undertaken that should lead to a robust and efficient implementation which will support organizational goals and requirements for the planned life of the system. At each step along the way, there are numerous “reality checks” to ensure one is aligning with the constraints of previous steps, and these lead to iterations in the process where one revisits the previous steps as the design space is explored and new possibilities and constraints are revealed.

The HM-1 committee has created guidance for each of these major IVHM system development activities, as shown in Figure 2. It is the expressed goal of HM-1 to maximize the use of existing standards which are already available (OSA-CBM, 2010) (OSA-EAI, 2014) (AUTOSAR, 2003) (Mil-Std-1553, 1978; S1000D, 2017) (ODX.OTX, 2010) (SAE J1939, 2013) (Felke, KMS, 2009) (Bird, Christensen, Lutz, & Scandura, 2005) (ISO13374, 2002) (ITU-T, 1994). The document tree in Figure 2 reflects the configuration of the current SAE IVHM documents already planned as of the date of this publication (SAE ARP6407, 2017) (SAE ARP6275, 2014) (SAE ARP6803, 2016). Additional documents which are subsequently developed and released will be included in the tree in future updates of this document.

The goal of this JA6268 Recommended Practice is to provide the framework for health-ready components, which relates to the “System Requirements” step. It also has relevance to the subsequent “System Architecture and Detailed System Design” steps and the “Verification & Validation” step. The reader is directed to the other recommended practices for information on the other process steps.

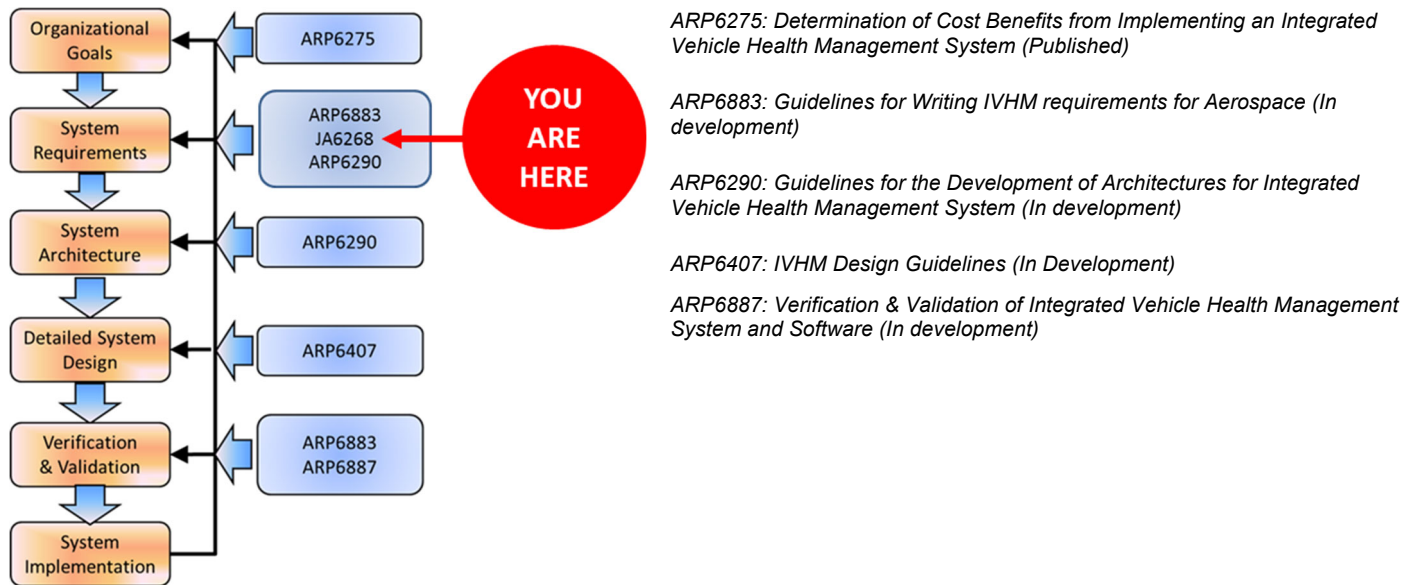


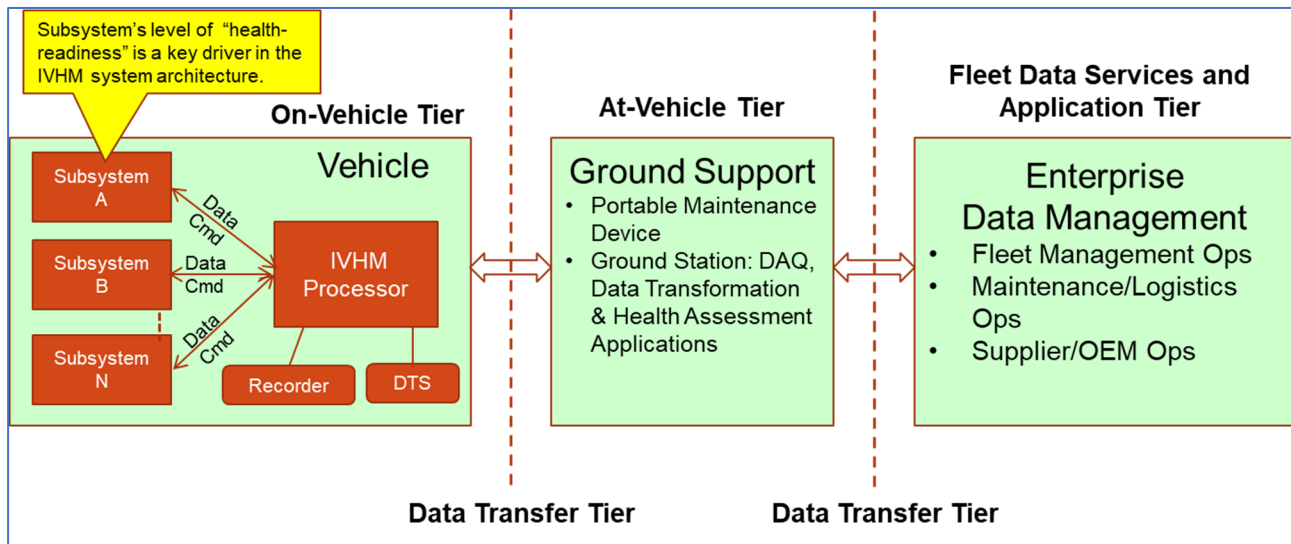
Figure 2 - SAE HM-1 document mapping to the IVHM development process

4.2 Concept of “Health-Ready Components”

The notion of “health-ready components” was first coined in the context of high volume aircraft manufacturing (Keller, 2007). However, it is equally applicable to both aerospace and automotive platforms (Holland, 2008), where typically an Original Equipment Manufacturer (OEM) is responsible for the design and build of the total vehicle but is also highly dependent upon suppliers or component manufacturers for a wide variety of components or subsystems essential to the final vehicle. With the advent of IVHM systems, it became apparent that OEMs could not fully deliver on the potential of IVHM without the active help and support of their component suppliers. The greater burden of IVHM solutions properly falls on the OEM, which is generally responsible for performing the vehicle integration function. However, to create total IVHM solutions with minimal duplication of effort and greatest efficiency of operation, suppliers need clear, consistent guidance on how best to support the integration of their health-ready components into an overall IVHM solution. In this context, “health-ready components” are those components which provide all the functionality to allow them to be integrated into the overall vehicle IVHM solution. This functionality includes critical design information as well as run-time information available in an operating vehicle. Health-ready components are expected to embody the following features to varying degrees:

- **Sensor mechanisms** to continuously monitor critical component functions and environmental parameters;
- **Raw sensor data acquisition and data processing** to produce data related to the state of health (data can be raw or processed to indicate state of health);
- **State detection and health assessment functions** to synthesize health state information and indicate conditions by which **component degradation** severity levels (e.g., normal, warning, critical) should be identified;
- **Prognostic algorithms** – where performance and usage data can be used for predicting the “Remaining Useful Life” (RUL), also known as “Performance Life Remaining” (PLR), for the degraded system;
- **Built-In Test (BIT)** to provide the status of power, electronics and sensors at start-up, periodically or at the request of the vehicle level system (a BIT is equivalent to a Diagnostic Trouble Code, or DTC, in the automotive sector);
- **Enhanced diagnostic functions** that correlate health state data including Built-In Test (BIT) results across component functions;
- **Communications interface module** to transmit raw, health state, condition and prognostics data from the component to a higher-level data subsystem or vehicle via wired or wireless links.

As noted in Figure 3 below, a subsystem's level of health-readiness is a key driver in defining the IVHM system architecture for aerospace/automotive applications. In fact, it is the starting point of the architectural design. Specifically, the IVHM system design options depend on the level of component "health-readiness," the enabling functions within the vehicle (On-Vehicle Tier), and the functionality of the off-board elements (At Vehicle, Fleet Data Services & Application Tiers). Therefore, it is important to characterize and specify [for component suppliers] the specific design-time and run-time data elements and interfaces that enable the level of health-readiness in components and subsystems which are recommended to achieve the IVHM objectives derived from stakeholder needs.



Note: DTS = "Data Transfer System"; DAQ = "Data Acquisition"

Figure 3 - General IVHM system architecture view

Leveraging "health-ready components" in the IVHM strategy calls for practitioners to focus on identifying and defining the information which must be exchanged between the layers in the IVHM system (or between lower-level components, subsystems and the higher-level vehicle system). It should also be noted that a particular program implementation may choose to utilize all or just a portion of the health-ready functions inherent in the component. This recommended practice does not specify how each layer in the system produces or uses the data available for exchange but rather focuses on the rationale and process for such exchanges. IVHM systems are usually independent of control systems, which are often subject to stringent governmental regulations. In cases where IVHM functionality is needed for control purposes, those functions should be moved inside the control systems and be subject to the same stringent processes. Whether IVHM is integrated with or partitioned from control systems, the integration of the IVHM software and hardware into the vehicle can be a major factor in the design and the cost of safety-critical applications such as aerospace because of the size, weight and power impact, as well as verification and validation considerations.

The SAE's IVHM Standards Committee has defined a progression of IVHM Capability Levels as shown in Figure 4. These levels offer a harmonized classification system which:

- Identifies six levels of IVHM system capability from essentially "no automation" at level 0 to "self-adaptive health management" at level 5.
- Provides definitions and levels based on functional aspects of the technology.
- Describes representative categorical distinctions for a step-wise progression through the levels.
- Is consistent with current industry practice and future directions.
- Reduces confusion and is useful across numerous disciplines (engineering, legal, media and public discourse).

- Helps to educate a wider community by clarifying for each level the role maintenance technicians have in performing vehicle repairs.

A key transition occurs between levels 2 and 3, where prognostics and predictive analytics are brought to bear to significantly enhance the capabilities of the system. These levels as shown in the chart are descriptive rather than normative and technical rather than legal. They imply no particular order of market introduction. Elements indicate minimum rather than maximum system capabilities for each level. A system may, in fact, have multiple IVHM features which could operate at different capability levels depending upon the feature(s) that are engaged.

SAE Level	Vehicle Health Capability	Narrative Description	Participation in Repair Actions	Key Data Resources	Availability of Logged &/or Real-Time Data	Use of Supporting Models	IVHM System Characteristics
Manual Diagnosis & Repair Process performed by Technician							
0	Limited On-Vehicle Warning Indicators	Service actions for scheduled maintenance or when Operator notices problems or is alerted by indicator lights or simple gages.	Operator/Driver & Service Tech	On-Vehicle Measurements & Observation	N/A	Paper-based Manuals	Only Manual Diagnostic Tools & No Condition-Based Services
1	Enhanced Diagnostics Using Scan Tools	Service techs gain added diagnostic insight using automated scanners to extract vehicle operating parameters & diagnostic codes.	Operator/Driver & Service Tech	On-Vehicle & Service Bay/ Depot Tools	Logged Diagnostic Codes & Parameters available to Service Tech	Paper-based Manuals	On-Board Diagnostics Available
2	Telematics Providing Real-Time Data	Service techs gain real-time vehicle data via remote monitoring of vehicle to more completely capture issues.	Operator/Driver, Service Tech & Remote Support Center Advisor	On-Vehicle, Service Bay / Depot & Cloud Data	Telematic Data Available to Service Tech with Diagnostics Info	Paper-based Manuals	On-Board & Remote Data Available
Diagnosis & Repair Augmented by Prognosis & Predictive Analytics							
3	Component Level Proactive Alerts	Operator and service techs are provided with component health status (R/Y/G) before problem occurs. Limited condition-based maintenance.	Operator/Driver, Service Tech & Cloud-Based Services	On-Vehicle, Service Bay & Cloud Data	Telematic Data Available to Service Tech with Diagnostics Info	Addition of Component-Level Health Models	Component-Level Health Predictions
4	Integrated Vehicle Health Mgmt.	Operator and service techs are provided with system or vehicle level health indicators before problems occur with remaining useful life estimated. Condition-based maintenance.	Operator/Driver, Service Tech & Cloud-Based Services	On-Vehicle, Service Bay & Cloud Data	Telematic Data Available to Service Tech with Diagnostics Info	Addition of Vehicle-Level Health Models	Vehicle-Level Health Management
5	Self-Adaptive Health Mgmt.	Self-adaptive control and optimization to extend vehicle operation and enhance safety in presence of potential or actual failures.	Operator/Driver, Service Tech & Cloud-Based Services	On-Vehicle, Service Bay & Cloud Data	Telematic Data Available to Service Tech with Diagnostics Info	Addition of Vehicle-Level Health Models	IVHM Capability Integrated into Vehicle Controls

Figure 4 - IVHM capability levels for aerospace and automotive applications

4.3 Health-Ready Component Considerations

4.3.1 A Common Strategic Goal (Win-Win-Win)

OEMs and suppliers share a common goal of producing the best possible vehicles which ultimately satisfy the needs of the customer base which, in turn, drives more business to the OEM and to the suppliers in the long term. This common bond creates the basis for a win-win-win situation. First, the OEM achieves a more capable and efficient process to create a higher quality product with built-in IVHM. Second, the supplier has one basic approach whereby it produces the needed information for all its OEM customers. Lastly, the end customers get a better product that is more reliable, less costly to maintain, and/or better meets their needs.

The move toward health-ready components does not address the fact that various suppliers may always be able to meet the integrator's requirements using fundamentally different component designs which therefore may possess some unique failure modes. However, in so far as the recommendations for health-ready components are adhered to, the goal is to minimize the complexity to achieve those ends.

4.3.2 Paradigm Shift from Diagnosis to Prognosis

Throughout the history of the automobile and aerospace industries, OEMs have designed increasingly reliable products built on top of increasingly reliable components and subsystems. The introduction of electronics and computer-based control resulted in the need for more sophisticated diagnostic systems because traditional maintenance approaches were no longer adequate. This happened because service technicians could no longer directly observe how various components were performing. For the purpose of this document, diagnosis is defined as the process to identify the root cause of a failure once a problem has occurred—specifically, what part or parts require replacement and/or what repair action (e.g., reseating a controller board) is required. The diagnosis paradigm has served these industries well for many decades. However, an argument can be made that the current diagnosis paradigm suffers from unacceptable rates of No Fault Found (NFF) or No Trouble Found (NTF) incidents. The advent of the prognosis paradigm offers the means to reduce NFF/NTF occurrences since knowing more about the component's state of health may prevent or reduce unnecessary component replacements.

In today's world, systems are being designed with ever higher levels of electronics and computer-based control. There's a continuing shift toward the electrification of the various subsystems, with electronic or electromechanical devices supplanting traditional mechanical solutions that were previously employed. This has created an increased need for health monitoring to mitigate the inherent risks of increased usage of electronics, controls, and software which tend to drive both incidents and intermittents. Similarly, increased usage of certain advanced materials may necessitate new forms of health monitoring. These design innovations in electronics and advanced materials have proven to be a highly effective approach to meeting the demanding needs of governmental regulations related to safety, emissions, fuel efficiency, etc. This, in turn, is driving the need for moving from the diagnosis paradigm to the prognosis paradigm. The goal of prognosis is to track degrading aspects of the overall design to predict deviation. Generally, we define prognostic systems as ones that compute remaining useful life (RUL), performance life remaining (PLR) or state of health (SOH) with sufficient fidelity and sufficient advance notice to allow a maintenance action well before an operational failure. It is important to note that from the customer or end user point of view, detecting and then correcting problems before they result in loss of function essentially eliminates the impending field failures and replaces them with preventive maintenance actions instead.

4.3.3 Need for Logical Abstractions of Physical Systems

One critical aspect of more effectively designing and applying health-ready components has to do with the establishment of clear and precise logical abstractions which align well with the represented physical systems. This allows better designs and better communications between the OEM and its suppliers. It becomes the essential underpinning for building good models of these systems and how they behave. In the physical world, there are a multitude of failure modes which lead to performance degradation and ultimately to failure of the given component or subsystem where it no longer meets design specifications. For example, physical seals can leak and contamination can occur or a fault may be caused by an open circuit or a short circuit. Creating logical abstractions for all these physical systems allows practitioners to understand them, model them and describe their operation. These functional models can incorporate diagnostics as well. In some cases, suppliers provide Failure Mode and Effect Analysis (FMEA) information or possibly a Fault Tree Analysis (FTA). This information correlates symptoms of a failure to the corresponding failure and its root cause, which then facilitates fault isolation and reduced "Could Not Duplicate" (CND) situations. The FTA can provide a method to evaluate the effects (and the probabilities) of failures of the components on the vehicle system as a whole. The FMEA will always be valuable and some of its content will clearly be required for health-ready components. In fact, the FMEA process itself could be enhanced to better meet the needs of IHVM and prognostics by identifying relevant parameters and relationships that could be used to detect the onset of each possible failure mode.

4.3.4 Diagnostic Codes and Prognostic Codes

Over the years, industry has developed a set of built-in tests (BIT) as commonly used in aerospace, or automotive diagnostic trouble codes (DTC), for Cautions, Warnings and Advisories. These may indicate a suspected trouble or problem area and are intended to guide and facilitate the correct service procedure. The diagnostic codes are implemented as computer algorithms which are often executed in a loop to monitor operating conditions with the intent of detecting the occurrence of real problems that might not be possible to observe otherwise. These algorithms typically run only after certain preconditions are satisfied. For example, it is not desirable for a diagnostic algorithm to run before the software has been properly initialized or before the system supply voltage has stabilized. Similarly, one would not want to run the code during system state transitions where some parameters are undefined. These precautionary approaches to avoid inappropriate setting of BITs or DTCs are also essential with respect to Health-Ready functionality.

Since DTCs are meant to capture problems once something has already gone wrong, it is proposed that there be Proactive Alert Identifiers (PAIs) as well. PAIs should behave similarly to DTCs but instead be used to indicate that something is about to fail (or go outside its normal window of operation). Each PAI needs to be defined in terms of accuracy and confidence and preferably in terms of the nominal Remaining Useful Life (RUL) at the time of the PAI being issued or set.

4.3.5 Reasoners and Advanced Diagnostic/Prognostic Algorithms

IVHM reasoners are software modules that reason about data from diverse sources, draw meaningful conclusions about the health state of the component or vehicle, and support advanced diagnostics. The addition of more data sources typically enables better, more specific fault isolation and a higher level of confidence. Reasoners therefore provide a form of knowledge integration to support advanced diagnostic (or prognostic) algorithms. Reasoners could also be used to drive a diagnostic process by building upon available data to determine what additional sensory data or test data will be necessary to more effectively and efficiently execute the diagnostic process and reach the likely root cause. Reasoners can reside on-vehicle or off-vehicle. Health-Ready component data represents key input parameters to the reasoners, which are designed to enhance the fault isolation and troubleshooting of the relevant component.

Advanced prognostic algorithms calculate either remaining useful life, performance life remaining or state of health based on parameters from the vehicle. Often these parameters are created during design of the vehicle to allow the system or vehicle to be properly controlled or to aid in the root cause diagnostic process. In some cases, these parameters are specially created to supplement the diagnostic parameters to enhance the accuracy of the prognostic calculations. These custom created parameters should be selected based on insights of the designer and/or based on field failure data. The parameters may capture raw sensor outputs, sensor outputs scaled to appropriate engineering units, or be a function of multiple sources of information. The prognostic algorithms themselves can be based on physics or engineering models of the relevant component or, alternatively, data-driven based on captured field data alone. Physics-based models are sometimes called white box models because the underlying physics are being explicitly modeled and is thus visible. Data-driven models are known as black box models since the underlying computations cannot be easily explained with respect to underlying engineering and/or physics. In practice, most models end up being gray box models that either started as white box but got calibrated or adapted by using field data or alternatively started as black box but were subsequently enhanced by the imposition of realistic physical assumptions (models).

4.3.6 Need for Semantic Data from Suppliers

To implement a Health-Ready Component/Subsystem into the IVHM system integration strategy, it is important for the supplier to identify and specify the health state data parameters, messages and their meaning (i.e., semantics) which must be provided for the component/subsystem to provide the critical IVHM interfaces. In case the supplier does not wish to implement all of the recommended functionality, the supplier may instead choose to provide additional design data to allow the integrator to do so.

Suppliers should provide understandable, machine readable formulae to permit the translation of raw sensor outputs into specific, appropriate engineering units. The machine-readable aspect is very important because simple textual descriptions are highly error prone and frequently complicate the use of the information or, worse yet, lead to incorrect conclusions as the data is used.

4.3.7 Model-Based Engineering

The cost of obtaining equipment-specific IVHM design characteristics could be greatly reduced if the suppliers of the equipment provided more of their design data in a machine-readable format. The increasing use of model-based design engineering tools across the industry will facilitate the exchange.

It is worth noting that the presence of these models goes well beyond just defining the interface between the component and the higher-level system which is going to access the data. It must also give insight into what is happening within the component or subsystem. Specifically, it should allow the data to be interpreted in the correct manner at the vehicle level. Ideally, these models will become more comprehensive and useful as time progresses. In the interim, a less demanding alternative is to share just the relationships between provided parameters which are deemed important by the designer in terms of detecting degradation—for example, identifying the critical parameters along with their normal ranges and the relationships or ratios involving those parameters that are best used to warn of the onset of specific failure modes.

4.3.8 Standardized Communication Interfaces

A critical aspect of the implementation of many Health Ready Components is the use of communication interfaces (ARINC 429, 629, IEEE 1553, CAN, FlexRay, etc.) through which run-time messages can be exchanged with the larger IVHM system. The physical nature of these interfaces continues to evolve quite rapidly and it is important to use the same communication abstraction techniques in the implementation of IVHM functionality as is typically used in the implementation of the functional aspects of the device. This approach allows the majority of the implementation of the IVHM functionality to be unaffected even its physical interfaces are changed in later revisions.

5. HEALTH-READY COMPONENT DEVELOPMENT METHODOLOGY

An overview of the methodology recommended for developing and integrating health-ready components is provided in Figure 5. As noted in the diagram, the methodology has four principal components:

1. Determining the **Inherent IVHM Functionality**: This involves determining the degree to which the supplier's inherent component or subsystem design implements the recommended IVHM functionality and identifying the degree to which the supplier wishes to implement the discretionary aspects of IVHM or to provide the design data to allow these functions to be implemented by another organization (e.g., integrator, third party).
2. Defining the **Message Semantics**: This includes identifying and specifying the health state data parameters, message content and format as well as meaning (i.e., semantics) that must be provided by the component or subsystem to support the critical IVHM interfaces at run-time.
3. Developing **Run-time Interfaces**: This encompasses determining the baseline recommendations for the vehicle run-time interfaces and developing the corresponding interfaces to the IVHM system.
4. Developing the **Design-time Data**: This involves determining the baseline recommendations for exchanging design-time data (message semantics and run-time interfaces) and developing the recommended submittals for the particular program implementation.

In addition, component suppliers must also develop the maintenance actions for the information sent from the component for a faulted black box or component. The vehicle OEM may not know what to do when a message is sent from the component supplier's box indicating a faulted box or component. The component supplier must provide the recommended maintenance action for his specific box or component indicating a fault and the recommended practice to fix it. Component information may not be useful unless the developer divulges to the end user what the information means in terms of operation and maintenance.

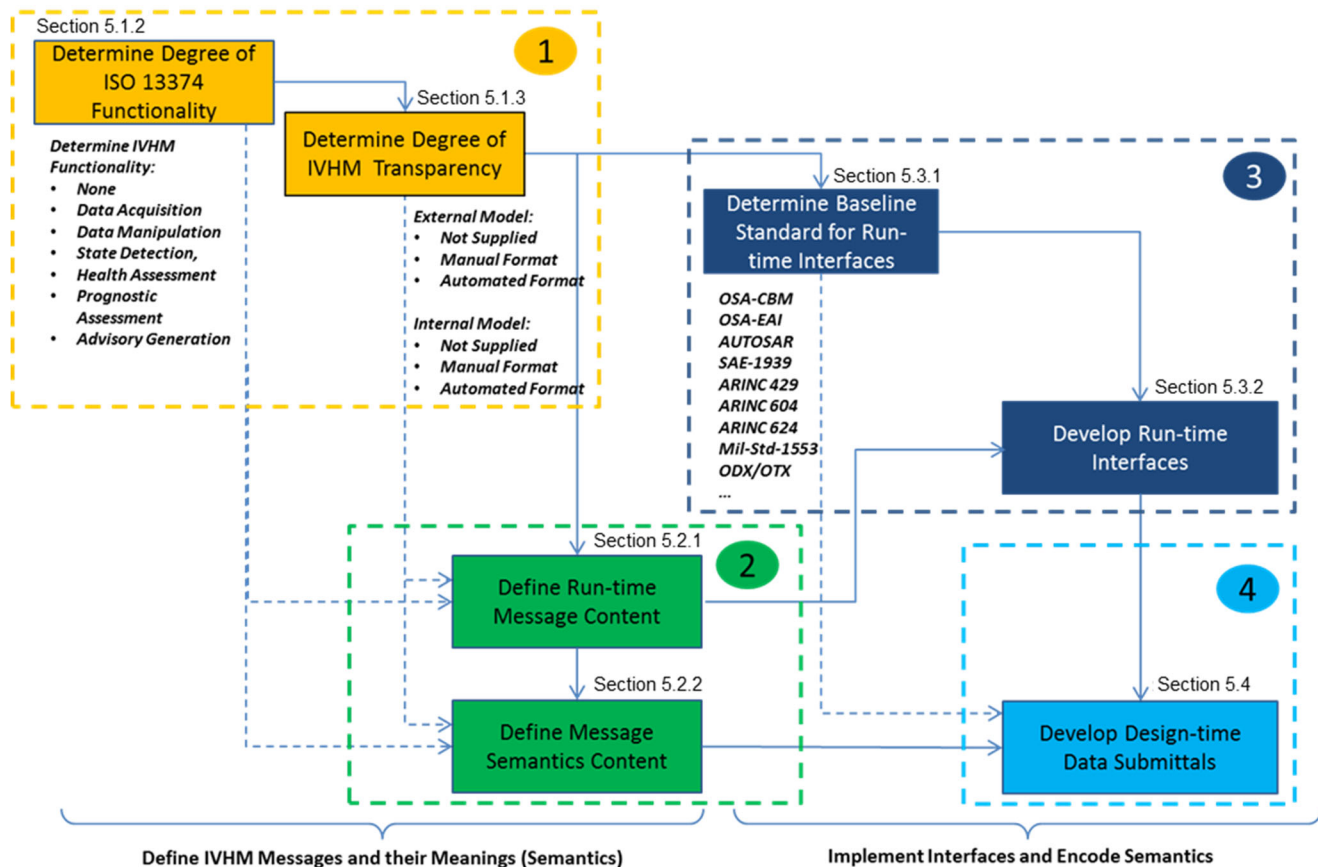


Figure 5 - Health-ready component development methodology

The remainder of this section describes the recommended practice for each of the four major methodology elements highlighted in Figure 5. While the figure contains more detail, there are four principal components represented.

5.1 Inherent IVHM Functionality

The first task that a supplier must undertake is to determine the degree to which its component or subsystem implements the recommended IVHM functionality and to make a decision for providing additional data that allows the integrator or other party to implement the functionality. Using a common IVHM Functional Reference Model (Figure 6), the supplier should determine (in general) the IVHM functionality supported by its component or subsystem (as is). The underlying objective of this process is to expose and specify the specific design functions, methods and interfaces used by component or subsystem suppliers to better enable IVHM.

Over time, suppliers who offer the most comprehensive and integration friendly, health-ready components are anticipated to enjoy a competitive advantage in the marketplace. Suppliers who do not do this will be less successful.

5.1.1 IVHM Functional Reference Model

This document incorporates the design principles within ISO 13374 and the Open Systems Architecture for Condition-Based Maintenance (OSA-CBM) specification to provide a functional reference model (Figure 6) for characterizing the inherent design functions in a component or subsystem to enable IVHM. In this context, the idea is to provide practitioners a common IVHM functional reference model for characterizing and exposing the inherent component, subsystem or system health monitoring functions and the existence, lack thereof or constraints with respect to the recommended functional elements. These include data acquisition (DA), data manipulation (DM), state detection (SD), health assessment (HA), prognostic assessment (PA), and advisory generation (AG). This layering provides an insightful framework for understanding the overall functionality and is well adapted for communications. In practice, some implementation shortcuts will be taken to achieve efficiencies. For example, the strict layering process might be sacrificed in some cases in the name of performance, but the model should still be useful conceptually.

IVHM Functional Block	Description	IVHM Process Stage
Advisory Generation (AG)	This function provides actionable information to operational and maintenance personnel or external systems.	Act
Prognostics Assessment (PA)	This function provides future state of health, performance life remaining, or remaining useful life (usage) indicators.	Analyze
Health Assessment (HA)	This function provides information to determine the current state of health of equipment.	
State Detection (SD)	This function evaluates equipment state conditions against normal operating profiles and generates normal or abnormal condition indicators.	
Data Manipulation (DM)	This function processes and transforms the sensor data and health state information collected by the DA.	Transfer
Data Acquisition (DA)	This function collects the sensor data and health state information from the equipment internal monitors, the system data bus or data recorder.	Acquire
		Sense

Figure 6 - IVHM functional reference model

In the above model, DA is the lowest level block and acquires sensor output data. The next level, DM implements low-level signal processing of raw measurements from the DA block. The SD level supports modeling of normal operation and detection of operational abnormalities and creates a CI. A subsystem can generate multiple CIs depending on the number of sensors. The CIs are communicated to the next level, HA where the health of the system is established by creating a HI. Depending on the type of subsystem and the complexity of interaction with other subsystems, HA might be performed at the subsystem or vehicle level.

The upper three functional blocks of the model provide decision support to operations and maintenance personnel based on the health of the target system. Within this group, the HA function provides fault diagnostics and health condition assessment. The PA level is aimed at enabling the forecasting of future health conditions based on current state, projected usage and the operational envelope. Prognostics can be health-based using sensor data and degradation models of components or can be usage-based which is typically simpler but less accurate. The health-based model approach can be pushed to whatever level of detail is necessary to support the accuracy required. The life usage-based models typically rely on stress factors such as loads on mechanical systems and are employed to capture actual use from which an estimation of Remaining Useful Life can be made. Both approaches should be considered, and the final choice should be based upon the criticality of the systems under discussion. PA typically crosses the boundaries of subsystems and could be implemented on-vehicle and/or off-vehicle.

Finally, the AG level provides actionable information related to the health of the target system which is correlated to the system level maintenance specifications. This information can be used by the operator and maintainer without the necessity of engineering interpretation for maintenance activities. This document discusses how the supplier should support development of these various levels with respect to health-ready components both on the vehicle and off the vehicle. In cases where these functions are to be implemented by another organization, it is again recommended that the supplier provide the design data needed to implement these functions in a machine interpretable format.

The figure also illustrates the mapping of IVHM functional blocks (ISO 13374 Layers) to the SAE IVHM Stages (see ARP6803 for an explanation) to further clarify the functions performed at each level.

5.1.2 Common IVHM Functions and Processes

Health-ready components will be required to support a wide variety of real-time IVHM-related functions and processes, including but not limited to those identified in Table 1. In addition to the required real-time functions and processes, the equipment must support the implementation of non-real-time functions associated with the upper 3 layers of the reference model stack. A representative summary of these functions and processes is listed in Table 1.

Any of the non-real-time functions can still be hosted on the vehicle and can be executed in a real-time operating system. The key point is that the functions identified as real-time in Table 1 must be hosted on the vehicle in a real-time operating system. Non-real-time functions have the option of being hosted off the vehicle and being performed later relative to when their input data is produced. Of course, Table 1 is just representative of what might need to be in real-time vs. non-real-time. The ultimate decision as to what functions and processes need to be real-time depends on a number of factors including the rate at which a component might degrade, the ability to precisely assess RUL, the criticality of the component, etc. In addition, some aspects of a particular function such as prognosis might need to be performed in real-time where post processing of those results might be deferred for off-board on non-real-time.

Table 1 - Real-time and non-real-time IVHM functions and processes

Real-time IVHM Functions & Processes	Non-Real-time IVHM Functions & Processes
• Analog I/O and digitization • Serial I/O and parameter extraction • Signal processing, filtering and state detection • Fault detection and reporting • Support for Initiated Test functionality and protocols • Performance or degradation reporting • Intermittent fault data capture • Functional availability reporting • On-platform screen and user message generation • Usage monitoring and reporting of usage related data • System mode or state reporting • System configuration reporting • Data recording/logging management	• Feature Extraction • Diagnostics & Fault isolation: - Nuisance suppression (events which can safely be ignored) - Cascade removal (additional symptoms triggered by one symptom that don't add diagnostic value) - Correlation of loss of function to root cause - Guided troubleshooting and repair • Prognostics • Maintenance planning • Logistics or material planning • Supplemental analytics • Anomaly Detection • Engineering Analysis: - Root Cause Analysis - Precursor Analysis - Fleet Performance Analysis - Design Improvement Analysis • Bench Testing

There are several functions and processes common to the design and implementation of IVHM capabilities, whether at the system, subsystem or component level—and whether the system implementation involves a new or legacy platform. Table 2 provides a general definition of the common functions and processes mapped to the IVHM functional blocks in the reference model (see Figure 6). The extent to which a component provides [inherent in the design] the functions described in the table determines the component's level of "health-readiness". As a rule, with respect to components, health-readiness is tied for the most part to the functions associated with the DA, DM and SD functional blocks. The specific methods of how these common functions and processes are implemented depend on the specific (inherent) design of the components, subsystems, the vehicle and off-board elements. The purpose of the engineering analysis, using the reference model described in this section, is simply to expose and specify the specific design functions, methods and interfaces used by component or subsystem suppliers to enable IVHM.

Table 2 - Common functions and processes within the IVHM functional blocks

Common IVHM Function or Process	General Description	IVHM Functional Block					
		DA	DM	SD	HA	PA	AG
Decision Support Analysis	System function and process for the transformation and analysis of health state data and information to produce prescriptive actions for the user community.						X
Health Reporting	System function to monitor, record and report health state data and information for consumption by downstream systems.						X
Caution Warning Indicators	System function to monitor, record, assess and report safety critical equipment failures and produce caution and warning indications for operators.						X
Time-to-fail Assessment	System function to monitor, record, assess and report equipment degradation parameter data and produce predicted performance life remaining estimates.					X	
Usage Monitoring & Assessment	System function to monitor, record, assess and report equipment life usage parameter data and produce predicted remaining useful life estimates.					X	
BIT Filtering & Correlation	System function and process to manage false alarms, fault persistence and correlate primary and secondary diagnostic trouble (BIT) codes to operational capabilities.				X		
Fault Isolation Analysis	System function and process to resolve reported failure ambiguities using model-based diagnostics or multiple data observations.				X		
Parametric Data Analysis	System function to process degradation parameter data streams captured in a predefined event, anomaly condition or using external equipment.			X			
Onboard Diagnostics	A dedicated system function for self-diagnostics and reporting of system failures.			X			
Built-in-test (BIT)	The integrated system function that monitors and controls system self-tests to detect and report system failures to downstream systems.			X			
Feature Extraction	System function to manipulate data and compute certain statistical indicators from degradation (predictor) parameters.		X				
Data Normalization	System function to manipulate data and compute a limited range of values within a norm.		X				
Data Processing	System function to manipulate data to compute health state indicator(s) or extract information for downstream systems.		X				
Data Management	System function and process to control, protect, manage, deliver and enhance the value of health state data and information for the user community.	X					
Data Transfer Interface	System function or system to download or communicate raw data, health state indicators and information for consumption by downstream systems.	X					
Data Capture	System function may be a specialized data acquisition module that has analog feeds from sensors, collects processed data from a data bus or provides the software interface to a smart sensor.	X					

5.1.3 Degree of ISO-13374 Implementation Assessment

This step involves determining the degree of ISO-13374 functionality inherent in the component or subsystem and the level of existing design transparency. Using the functional blocks described in Figure 6 above as a reference model for IVHM, a practitioner should perform systems engineering analysis at the system, subsystem or component level to characterize their inherent IVHM capabilities. For existing components, these will typically consist of functions addressing the foundational layers of the model (DA, DM and SD) but in some cases, will also include the higher-level functions (HA, PA and AG). All areas where the existing implementation does not provide the required functions should be identified.

For areas that the existing implementation does provide the required functions, an additional assessment should be performed to determine if sufficient Design-time data has been produced to allow the use of the associated Run-time messages by the integrator. Areas where Run-time functionality exists but is not adequately documented should also be identified.

5.1.4 Assessment of Degree of IVHM Transparency

Another element important in determining the health-ready status of a component is assessing the degree to which the supplier is willing or required to provide the semantic data for its component/subsystem. The methodology uses an enumeration of three values (Not Supplied, Manual Format and Automated Format) to reflect the way the supplier is willing to provide semantic data for the component/subsystem.

- Not Supplied (N) – The supplier **will not** provide additional data.
- Manual Format (M) – The supplier **will** provide additional semantic data but **not in** a format supporting automated reasoning. (This is the current default for most aerospace programs).
- Automated Format (A) – The supplier **will** provide additional semantic data **in** a format supporting automated reasoning. (A small number of aerospace programs are at this level).

This assessment must be performed twice – once for the external model (or interface message syntax) and again for the internal semantic model. The external model concerns data related to failures that affect external interfaces (and the impact of loss for each input) and is primarily useful for making the interface definition clear. This data is critical to allow interactions between systems to be correctly interpreted by the IVHM system. Traditionally, this is the extent of the supplier-provided information. The internal model concerns failure modes and effects internal to the component/subsystem boundary. This information “inside the black box” traditionally has not been shared. Some of this internal information is needed to enable IVHM functionality for the component/subsystem to be performed by the higher-level IVHM system or possibly a third party. Application of the assessment criteria is summarized below (Figure 7):

		Internal Semantic Model		
		Not Supplied	Manual Format	Automated Format
Interface Message Syntax	Not Supplied	Not Health Ready	Not Health Ready	Not Health Ready
	Manual Format	Not Health Ready	Not Health Ready	Not Health Ready
	Automated Format	Health Ready *	Health Ready *	Health Ready

* Provided that the supplier implements all required IVHM functionality inside their boundary

Figure 7 - IVHM transparency assessment summary

To be “health-ready”, suppliers should provide the external or interface message syntax in a machine-readable format. As highlighted in the figure, the ideal “health-ready status” is achieved when the assessment shows the recommended Interface message syntax and internal semantic model are both provided in an automated format (lower right-hand corner). There is no requirement *per se* for health-ready components to have their own embedded processor, but the more sophisticated components will have one.

5.1.5 Combining Inherent Functionality and Degree of IVHM Transparency

The characterization of inherent functionality enables the initial design of an IVHM system integration strategy. For example, propulsion, avionics, payload sensors and digital communications systems normally have some inherent health monitoring capabilities (DA, DM, SD). The supplier may wish to augment these capabilities to provide a more complete IVHM solution or they may choose to provide additional Design-time data to address the gaps.

Design transparency supports the specification of enabling system functions for any missing foundational layers. For the examples above, addition of HA, PA, and AG functional layers is required for a fully functional IVHM system. As always, the impact on integration and cost must be assessed. This analysis may result in using a different component with different “health ready” capabilities.

Based on the gaps identified by these analyses, the supplier will develop a strategy to either develop additional IVHM Run-time capabilities intrinsic to their device (internal functions or web-based services) and to provide additional Design-time data to enable integration of these capabilities into the larger IVHM system.

5.1.6 Optimizing the Cost Benefit Ratio

The functionality prescribed for a health-ready component should not necessarily require substantial new development and may be limited in wide scale deployment due to cost. These costs may be driven by some combination of (1) the need for computing Cloud Services; (2) communication to the Cloud Services; (3) complex algorithms; (4) deep knowledge pertaining to the failure and degradation modes, symptoms and corrective actions of the specific equipment; and/or (5) integration into the vehicle and associated verification and validation of IVHM communications and computing hardware and software. Dramatic advancement in the capabilities of computer hardware, software, and communication systems has largely mitigated the costs associated with the first three. The cost of obtaining knowledge pertaining to the health-ready design characteristics of the specific equipment and integration into the vehicle are the major cost drivers. Size, weight and power concerns as well as verification, validation, and certification remain the dominant cost drivers and barriers for the aerospace domain. As a rule, automotive tends to be somewhat less weight constrained than aerospace but more cost sensitive due to the much higher volumes.

5.2 Message Semantics

Once the scope of the IVHM functionality and the level of design transparency to be implemented by the component or subsystem is determined, the next step is to define the types of messages which the component or subsystem will exchange with the higher level IVHM system, the variety of message instances to be exchanged, and the semantic data for each message instance. The decision to implement a subset of the semantic data exchange at run-time will not affect the scope of data being exchanged but will affect how the data is exchanged—again including the types of messages the component or subsystem will exchange with the higher level IVHM system, the variety of message instances that will be exchanged, and the semantic data for each message instance. Sufficient semantic data is required from the equipment supplier to mechanize the following functions:

- **Report detected fault conditions** and related symptoms to allow [normally] higher-level systems to better determine the appropriate corrective action and any related loss of system function.
- **Report equipment performance characteristics**, usage characteristics and usage events to allow accurate assessment of the rate of consumption of life-limited components and/or materials and to assess overall equipment performance.
- **Report equipment degradation** and estimated remaining useful life (RUL) or performance life remaining (PLR) for all faults for which the precursor is detected at least one operational cycle in advance of the occurrence of the fault (or more operationally, in time to be actionable).
- **Implement protocols** to allow higher-level systems to request the equipment perform initiated functions (e.g., BIT, calibrations, special functions, etc.) to gather information not accessible during normal operation and to report the results.
- **Report the part numbers** and serial numbers of all hardware components connected to a serial data bus and all software components (version numbers) installed on those devices.

5.2.1 Run-Time Message Content

Table 3 should be used as guidance to identify the types of run-time messages being supported. As shown in the table, the types of messages that will need to be supported are largely determined by the degree of ISO 13374 functionality to be implemented by the component or subsystem. For example, a component that is implementing all the ISO 13374 functions will need to implement all of the run-time messages, while one implementing only certain functions will need to implement a smaller number. While this document defines a set of run-time interfaces that must be supported, it does not specify an implementation for these interfaces. This allows an IVHM implementation to continue to use existing message protocols and standards and allows the document to avoid unnecessary updates as new standards become available.

Table 3 - Run-time interfaces

ISO 13374 (OSA-CBM) Implementation Level / 6268 Interface Name		None	Data Acquisition (DA)	Data Manipulation (DM)	State Detection (SD)	Health Assessment (HA)	Prognostic Assessment (PA)	Advisory Generation (AG)
Run-Time Interfaces	Report Parametric Values		X					
	Report Modes and States		X	X	X	X	X	
	Report Condition Indicators			X	X	X	X	
	Report Health Indicators				X	X	X	
	Report Predictive Indicators				X	X	X	
	Report Diagnostic Conclusions					X	X	X
	Provide Requested Data Recording					X	X	X
	Report Asset Configuration					X	X	X
	Run Requested Action					X	X	X
	Report Prognostic Conclusions						X	X
	Report Maintenance Workplan							X

A further consideration in this area is to determine whether or not the component will be required to provide some of the semantic data within run-time messages. If so, the specific set of message types that need to be supported will be extended and the set of design-time submittals will be correspondingly reduced. Once the set of types of messages has been identified, the supplier should identify the specific instances of each message to be supported based on the list of corrective actions, failure modes, condition indicators, configuration items and maintenance work plan entry points developed from the detailed analysis of the component or subsystem.

5.2.2 Message Semantics Content

Using the same scope of IVHM functionality and degree of transparency as discussed above, the next task is to identify the set of design-time semantic descriptions which need to be supported. The following table should be used to identify the types of design-time data to be provided by the supplier, based on the IVHM functional blocks supported by the component or subsystem.

Table 4 - Design-time interfaces

ISO 13374 (OSA-CBM) Implementation Level / 6268 Interface Name		None	Data Acquisition (DA)	Data Manipulation (DM)	State Detection (SD)	Health Assessment (HA)	Prognostic Assessment (PA)	Advisory Generation (AG)
Design-Time Interfaces	Table of Corrective Actions	X	X	X	X	X	X	X
	Table of Interfaces	X	X	X	X	X		
	Table of Parameters	X	X					
	Table of Failure Modes	X	X	X	X			
	Table of Condition Indicators			X	X			
	Table of Health Indicators				X	X	X	
	Table of Predictive Indicators					X	X	
	Table of Reported State/Mode Indicators		X	X	X	X	X	
	Table of Loadable Software and Data Files	X	X	X	X	X	X	X
	Table of Automatically Reported Configuration Indicators				X	X	X	X
	Table of Internally Managed Data Recordings				X	X	X	X
	Table of Suggested, Externally Managed, Data Recordings	X	X	X				
	Table of Suggested, Externally Executed Algorithms	X	X	X				
	Table of Corrective Actions to Health Indicator Relationships	X	X	X	X	X	X	
	Table of Corrective Actions to Interface Anomaly Relationships	X	X	X	X			

ISO 13374 (OSA-CBM) Implementation Level / 6268 Interface Name		None	Data Acquisition (DA)	Data Manipulation (DM)	State Detection (SD)	Health Assessment (HA)	Prognostic Assessment (PA)	Advisory Generation (AG)
	Table of Indicator to State/Mode Validity Relationships	X	X	X	X			

5.3 Run-Time Interface

Once the sets of run-time and design-time messages have been determined and agreed upon with the integrator, the next steps are to implement the run-time messages and develop the design-time data.

5.3.1 Baseline Recommendations for Run-Time Interfaces

The integrator of the IVHM system will specify the baseline recommendations to be used for the run-time interface protocols. Typical examples of recommended protocols for run-time interfaces include:

- **OSA-CBM:** Open System Architecture for Condition-Based Maintenance based on ISO 13374 (OSA-CBM, 2010)
- **OSA-EAI:** Open System Architecture for Enterprise Application Integration (OSA-EAI, 2014)
- **AUTOSAR:** AUTomotive Open System Architecture (AUTOSAR, 2003)
- **SAE-1939:** Recommended Practice for a Serial Control and Communications Vehicle Network (SAE J1939, 2013)
- **ARINC 429/604/624/629:** *Digital Information Transfer System, Guidance for Design and Use of Built-In Test Equipment, & Design Guidance for Onboard Maintenance Systems* (ARINC429, 2014) (ARINC604, 1988) (ARINC624, 1993) (ARINC629, 1995)
- **Mil-Std-1553:** Aircraft Internal Time Division Command/Response Data Bus (Mil-Std-1553, 1978)

Each standard provides guidelines for how each type of message is encoded for interaction with higher level and lower-level systems.

5.3.2 Develop Run-Time Interfaces

The supplier of the component or subsystem will be responsible for implementation of the mechanism through which each of the message instances are transmitted in response to events and conditions where that message instance is appropriate. The data communicated by the equipment should be in a format which maximizes the degree of automated interoperability between the equipment and the higher-level platform systems and systems employed to support the equipment operators.

5.4 Design-Time Data

The supplier of the component or subsystem is responsible for delivery of the design-time data required based on the assessment performed in sections 5.1 through 5.3. Again, the component or subsystem supplier should create the design-time data in a format that maximizes the degree of automated interoperability between the equipment or higher-level platform systems, as appropriate, and any systems that might be employed to support the equipment operators. This might include supplemental data beyond what is required for the baseline standards in order to support automation of higher-level IVHM functions. The integrator may choose to have design-time data created in a different communication format. Again, good design practice is to provide an interface for an automated translator function."

5.4.1 Baseline Recommendations for Design-Time Data

The integrator of the IVHM system will specify the baseline standards to be used for the submittal of design-time data. Typical examples of standard data formats for design-time submittals include:

- **OSA-CBM:** Open System Architecture for Condition-Based Maintenance based on ISO 13374 (OSA-CBM, 2010)
- **OSA-EAI:** Open System Architecture for Enterprise Application Integration (OSA-EAI, 2014)
- **S1000D:** International Specification for Technical Publications (S1000D, 2017)
- **AUTOSAR:** AUTomotive Open System Architecture (AUTOSAR, 2003)
- **ODX/OTX:** Open Diagnostic Data Exchange/Open Test Sequence Exchange (ODX.OTX, 2010)

Each standard provides guidelines for how each entity is encoded for submittal to the next higher-level integrator.

5.4.2 Develop Design-Time Data

A health-ready component supplier chooses the degree to which it wishes to directly implement the required IVHM functionality and the degree to which it wants to provide data to allow for someone else to implement the functionality. For a component/subsystem that implements a larger degree of ISO 13374 functionality, the amount of required design-time data should be decreased. This is due to the fact that the primary use of design-time data is to allow the higher-level system or a third-party system to implement IVHM functions not provided by the component/subsystem itself. The exception to this principle is that all components and subsystems must provide design-time data to allow the higher-level functions to interpret the content of the messages from the equipment and to correctly interpret interactions between the supplied equipment and the higher-level systems and platform. That is, some amount of semantic data will always be required in order to use the indications generated by the equipment through its interfaces. Good design practice is to implement processes to be able to easily adjust the shared data content depending on the specific implementation

One of the more important sources of data to be used to develop IVHM capability are the “run to failure” qualification tests performed on aerospace subsystems to demonstrate robustness in specified environments (e.g., temperature, vibration, chemical, etc.) These tests are frequently conducted in the supplier’s laboratory and can be expensive, but in addition to demonstrating Line Replaceable Unit (LRU) or subsystem robustness, data should be collected from these tests to capture the signature of LRU/component degradations as well as degradation progression. These results are extremely valuable as a basis for IVHM algorithm development and parameter tuning. They are something to be used by the supplier or provided to the OEM/third party developers for appropriate consideration. Such data would include knowledge of sampling rate and data resolution.

In addition, consideration should be given to design-time data for potential IVHM HA or PA algorithms to be developed, or at least matured, after the vehicle becomes operational. This analysis should include processes to analyze and implement data collected during vehicle operation to support IVHM development. The agreement between the OEM/third parties/LRU supplier should consider this situation, which is very likely given the complexity and shortage of data on LRU degradations. The development path shown in Figure 14 below includes “integrate and verify IVHM functionality” as part of First Article Inspection (FAI). This is extended into vehicle operational phase through exchange of actual performance and degradation data of the component in the field, since this will be a likely source of actual data on failure/degradation signatures and progression.

Ultimately, the cost of developing and exchanging equipment-specific IVHM design characteristics will be greatly reduced when suppliers of the equipment provide more of their design data in a machine-readable form. This reduces the chances of making an error when interpreting what was intended. Section 7 provides examples of an IVHM design-time data model (in XML) for a hypothetical fuel management system implementation. The objective is for the supplier to provide the content required to support the IVHM functions with the model data supplied in a format that allows automated processing by the platform model integration process.

6. DESIGN-TIME DATA EXCHANGE PROCESS

To best understand the data exchange process, it is necessary to consider the component data model needed to support an IVHM system. The information provided by the design-time data submittals is used to build an IVHM Integrated Reference Model (IRM), which consists of a Fault Model, a Processing Model and an Advisory Model. Each of these models is described below using an oil pump as an example.

The Fault Model specifies the characteristics of the functional failure modes of the component, the inputs and their effects on the outputs and symptoms of the component. The primary relationships include:

- Symptoms Affected by Abnormal Values of Inputs
- Outputs Affected by Abnormal Values of Inputs
- Symptoms Affected by Internal Failure Modes
- Outputs Affected by Internal Failure Modes

The model also contains a set of secondary relationships between items. These relationships are secondary because they model interactions flow in the opposite direction of material and energy in the system:

- Inputs Affected by Abnormal Values of Other Inputs
- Inputs Affected by Failure Modes
- Inputs Affected by Abnormal Value of Output
- Outputs Affected by Failure Mode
- Outputs Affected by Abnormal Value of Other Output

A simplified fault model for the oil pump example encodes these relationships is shown below. Note: This figure uses a “P” to represent a primary relationship between the item on the left column and the item on the top row and an “S” to represent a secondary relationship.