24

Information and Communication Support for Automotive Testing and Validation

Mathias Johanson
Alkit Communications AB
Sweden

1. Introduction

The need for automotive testing and validation is growing due to the increasing complexity of electronic control systems in modern vehicles. Since testing and validation is expensive in terms of prototypes and personnel, simply increasing the volume of the testing can be prohibitively costly. Moreover, since product development cycles must be shortened in order to reduce the time-to-market for new products, there is less time available for testing and validation. Consequently, more testing and validation work will have to be performed in less time in future automotive development projects. To some extent this challenge can be met through virtual product development techniques and simulation, but there will still be an increasing need for testing and validation of physical prototypes. This can only be accomplished by improving the efficiency of automotive testing and validation procedures, and the key to realizing this, we will argue in this chapter, is by introducing novel information and communication support tools that fundamentally transform the way automotive testing and validation is conducted.

With the explosive proliferation of wireless communication technology over the last few years, new opportunities have emerged for accessing data from vehicles remotely, without requiring physical access to the vehicles. Special purpose wireless communication equipment can be installed in designated test vehicles, acting as gateways to the internal communication buses and to on-board test equipment such as flight recorders. With a fleet of test vehicles thus configured, sophisticated telematics services can be implemented that enable communication of virtually any kind of data to and from any vehicle, providing the bandwidth of the wireless connection is sufficient. This has an enormous potential of making automotive testing and validation more efficient, since much of a test engineer's time is spent finding the right data to analyse.

By eliminating the need for the engineer to have physical access to the test vehicle, scarce vehicle prototypes can be made available for multiple simultaneous tests, reducing the overall need for physical prototypes. Moreover, the test vehicles can be accessed by the engineers irrespective of their geographical location, which makes a much broader range of test objects available for tests and frees up time for the engineers in scheduling a prototype for a test. The data resulting from the test can be uploaded from the vehicles to a server from where it can be accessed by any number of interested (and duly authorized) engineers. By having measurement data automatically collected into a central database, as opposed to being stored on the hard drive of each engineer's computer, the opportunities for reuse of data is greatly improved. One can also imagine (semi-)automated analysis mechanisms being executed on the data being uploaded to a server, assisting the engineer in interpreting the data.

A specific kind of data of paramount importance in automotive testing and validation is diagnostic data generated by designated diagnostic functions built into the vehicle's Electronic Control Units (ECU). By collecting and analysing Diagnostic Trouble Codes (DTC) for test vehicles, faults can be detected and corrected before the vehicle goes into production. Statistical analysis of DTCs is also important in order to find correlations between faults and to prioritise different development efforts. With the advent of wireless telematics services, diagnostic data can be collected more systematically in different development phases. This means that there will be fewer faults in production vehicles, preventing costly recalls.

Since many faults that are detected in the testing and validation phases of automotive development are software related, having wireless access to fleets of test vehicles means that the software in the ECUs can be remotely updated with a bug-fixed software release over the wireless connection. Reprogramming an ECU in the traditional way is a time consuming procedure that requires test equipment to be connected physically to each vehicle. Through remote software download, many vehicles can be updated simultaneously without requiring physical access.

Automotive testing facilities are commonly located in remote rural areas, due to the need for extreme climate conditions and privacy. A side-effect of this is that a significant part of the budget for automotive testing expeditions is the travel costs for the engineers. By utilizing tools to remotely access data, complemented with tools for distributed collaborative work between the test site and the automotive company's development sites, engineers can take part in testing expeditions remotely, without having to travel.

The tremendous impact on automotive testing and validation processes that will result from large scale introduction of the technology and concepts described here has the potential of affecting the whole automotive development process. Referring to the established V-model of product development that is often used to elucidate automotive development processes, the testing and validation phases are at the same level as the design and simulation phases (see Fig. 1). This captures the fact that there is a considerable interplay of creative and

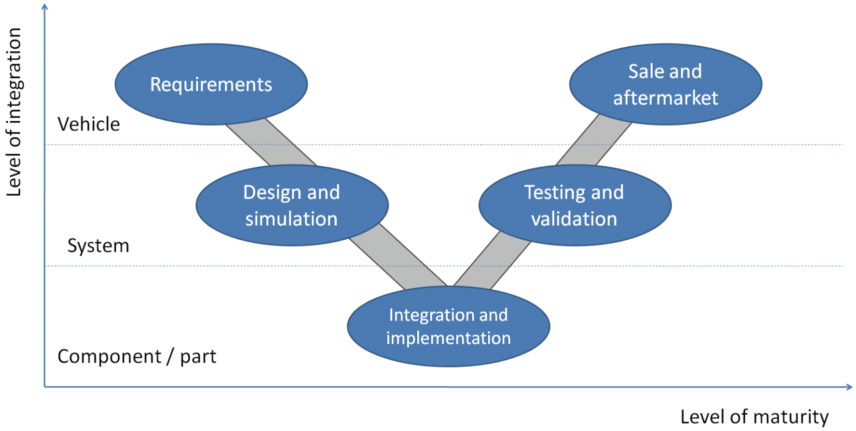

Fig. 1. V-model of automotive product development

analytical processes between these stages of the automotive development (Weber, 2009). Hence, it is easy to see that when the testing and validation phases are changed, this will heavily influence the design and simulation stages. Specifically, with an improved testing and validation process, whereby performance measurements and diagnostic data can be efficiently collected, analysed and fed back into the design process, the opportunities for component and system re-design is greatly facilitated. Moreover, validation of simulation models by measurement data improves the possibilities of more extensive simulations and virtual prototyping.

Since the innovations in automotive engineering made possible by telematics services and related information and communication systems go way beyond the testing and validation stages, automotive management processes will have to be adapted to maximize the benefits. From an innovation management standpoint, Lenfle and Midler (2003) argue that the introduction of telematics services constitutes a definitive turning point for the automotive industry, which will require the adoption of management tools specifically adapted to the collective learning process involved in this field of innovation.

In the remainder of this chapter we will explore the opportunities of improving automotive testing and validation by means of sophisticated information and communication support tools. Specifically, the following classes of applications will be studied:

- automotive metrology and data collection,
- remote vehicle diagnostics,
- remote software download,
- distributed collaborative automotive engineering.

The focus is primarily on consumer grade vehicle development (i.e. passenger cars), although most of the technology and applications are equally relevant (and in some cases even more relevant) for trucks, buses, construction equipment, and other special purpose vehicles. Furthermore, the focus is on the later stages of the automotive development process, where testing and validation of physical prototypes and pre-series vehicles is of vital importance.

The rest of this chapter is organized as follows: Section 2 gives a short introduction to automotive testing and validation; section 3 contains an overview of vehicular communication infrastructure; section 4 discusses information and communication support for automotive metrology and data collection; section 5 deals with automotive diagnostics and prognostics applications, in particular concerning telematics services and statistical analysis of diagnostic data; section 6 treats telematics services for remote ECU software updates; section 7 discusses distributed collaborative automotive engineering, and section 8 provides conclusions and a future outlook.

2. Automotive testing and validation

The development of complex products in the exceedingly competitive automotive industry is a demanding undertaking that requires a very sophisticated quality assurance process. Quality assurance in the automotive industry is complicated by the high level of integration of components from many different suppliers and the fact that many of the subsystems are safety-critical. Specifically, for the embedded electronic systems that constitute a substantial part of the total development cost, the design process is based on a close cooperation between car manufacturers and suppliers, whereby the carmakers provide the specifications of the subsystems to the suppliers, who design and deliver the systems. The resulting components are integrated into the vehicle platform by the carmaker, which performs the necessary testing and validation (Navet & Simonot-Lion, 2009).

The automotive testing and validation processes have undergone dramatic developments following the exponential increase in the number and complexity of electronic control systems in vehicles. With as much as 23 percent of the total manufacturing cost of a high-end vehicle being related to electronics, and an estimate that more than 80 percent of all automotive innovation stem from electronics (Leen & Heffernan, 2002), the importance of testing and validation methods for electronic components, including software, becomes evident. This situation has spurred the development of on-board diagnostics functions being designed in parallel with the electronics components. Increasingly sophisticated external test equipment connected to the vehicles' internal communication buses has also been developed and the ability to measure physical properties through built-in sensors has been greatly improved. This has led to the current situation where automotive testing and validation is largely a practice of data capture (metrology), communication and processing. Sophisticated data analysis software has been developed to meet the need for high volume data processing, which includes filtering, transformations, visualization and various statistical methods.

2.1 Validation and verification

In many situations a distinction is made between verification and validation. Verification refers to a process to determine whether a system or service complies with its specification, whereas validation is a quality assurance process for determining if a system or service fulfils its requirements and lives up to customer expectations. In this chapter we will use the term validation informally in both meanings, leaving to the reader to discern the subtle distinction from the context.

3. Vehicular communication infrastructure

The tremendous development of digital communication technologies over the last few decades has fundamentally transformed automotive testing and validation, making it possible to access and distribute vehicle data efficiently and reliably. We will briefly outline the state of the art in communication infrastructure for automotive applications.

3.1 In-vehicle communication networks

Modern automobiles typically contain between 20 and 50 ECUs, controlling different subsystems of the vehicle. The ECUs are interconnected by an in-vehicle communication bus. In many cases there is more than one such bus, interconnecting different subsets of ECUs. The original motivation for in-vehicle networks was to reduce weight by replacing discrete wiring, but the additional benefit of improved means of communication between electronic subsystems can now be seen as one of the major facilitators of technological innovation in automotive engineering.

The most common in-vehicle bus technology currently in use is the Controller Area Network (CAN) developed by Bosch in the mid 1980s. CAN is a broadcast serial bus technology with a prioritization scheme based on arbitration. More recently the FlexRay bus technology which is based on time-division multiplexing for multiple access has been developed. FlexRay provides higher data rates than CAN, while being a deterministic protocol suitable for time critical applications. For in-vehicle applications requiring very high data rates, such as infotainment services, the fiber-optic-based Media-Oriented Systems Transport (MOST) has been introduced. MOST is a bus technology usually based on a ring topology with a Timing Master controlling access to the bus. Although not originally designed for automotive applications, the prolific Ethernet technology is now also making its way into vehicle architectures. Due to its unquestionable success as the foremost Local Area Network (LAN) technology, it will be increasingly important also as an in-vehicle network technology complementing FlexRay and MOST.

In emerging vehicle architectures, CAN, FlexRay, MOST and Ethernet are combined to form a network topology with a backbone bus (typically based on FlexRay) interconnecting multiple subnetworks based on CAN and MOST. Other network technologies such as LIN (Local Interconnect Network, a time-triggered master-slave protocol) can also be interconnected. With this evolution, automobiles become distributed systems of ECUs interconnected in sophisticated network topologies. The next natural step is to interconnect the in-vehicle networks to the outside world using telematics systems.

3.2 Automotive telematics

Grymek et al. (2002) define automotive telematics as the convergence of telecommunications and information processing for automation in vehicles. This encompasses systems to enhance the experience of the end-users of a vehicle, such as navigation aids based on GPS positioning and various infotainment services, but what mainly interests us here is the capability of such systems to communicate data between in-vehicle networks and the outside world for use in the testing and validation phases of automotive development. However, the opportunity of leveraging the technology investments in telematics systems designed for aftermarket services for development benefits is particularly compelling. By implementing remote diagnostics and remote software download functions into telematics units that are installed in production vehicles the need for dedicated systems for testing and validation, installed in test vehicles only, is reduced. It must be noted though, that testing and validation will most likely always require some amount of external equipment connected to test vehicles.

3.3 Wireless networking for automotive applications

The explosive proliferation of digital mobile telephony and wireless data communication networks is one of the foremost catalysts of automotive telematics. The almost ubiquitous wireless communication infrastructure provided by cellular networks, together with the availability of inexpensive microelectronic communication devices make it possible to design powerful automotive telematics systems for many different applications. A differentiating feature of telematics services for automotive testing and development, compared to many other mobile communication services, is that the data upload capacity is usually more interesting than the download capacity. Somewhat unfortunately, many of the wireless communication technologies targeting mobile computing are by design asymmetrical, with higher downstream capacities. Nevertheless, the evolution of wireless communication technology with higher bandwidths and better coverage will continue to benefit the automotive telematics industry.

One of the most important wireless communication technologies for automotive telematics is the General Packet Radio Service (GPRS), which is a packet-switched data service available in second generation (2G) cellular telephony systems. GPRS provides data rates of 56-114 kilobits per second, which is good enough for many automotive applications. By using multiple time slots of the underlying GSM network, Enhanced GPRS (EGPRS), also known as EDGE (Enhanced Data Rates for GSM Evolution), up to four times the bandwidth of a traditional GPRS connection can be achieved.

Third and fourth generation (3G, 4G) mobile telecommunication technologies based on UMTS (Universal Mobile Telecommunications System) and HSPA (High Speed Packet Access) are now gaining momentum in automotive telematics. The higher bandwidths, up to several megabits per second in ideal situations, will enable improved services and novel applications.

In addition to mobile telephony technologies, automotive telematics systems frequently also utilize wireless LAN technologies, mainly based on the IEEE 802.11 standards, and short range personal area radio networks such as Bluetooth or ZigBee. Special versions of short range wireless communication technologies customized for vehicular communication are sometimes labelled Dedicated Short-Range Communication (DSRC) technologies. The main target for DSRC is vehicle to roadside equipment communication for Intelligent Transportation Systems (ITS), to improve safety and reduce traffic congestion.

Multiple short range wireless communication devices can be organized into a self-configuring network known as a Mobile Ad hoc Network (MANET). For vehicular applications, Vehicular Ad hoc Networks (VANET) have attracted a lot of research interest lately. An overview of VANET technology is given by Jakubiak and Koucheryavy (2008).

3.4 Secure vehicular communication

Due to the safety-critical nature of many applications of vehicular communication, the need for security and privacy mechanisms to protect sensitive data and prevent malicious behaviour is well understood (Papadimitratos et al., 2008, Schaub et al., 2009). When interconnecting in-vehicle networks with public network infrastructures through telematics services for remote diagnostics and remote software download, the safety of the users of the vehicles may be compromised. Although this difficulty is somewhat lesser for automotive development applications (i.e. testing and validation vehicles), compared to aftermarket applications, appropriate security mechanisms nevertheless need to be carefully designed.

Traditionally, the automotive industry is very security minded and secretive about its engineering and design data. As expected, this also applies to data communication in testing and validation and hence security measures to protect all kinds of data from illicit eavesdropping are necessary. Fortunately, this is a mature field of information technology and a multitude of data encryption techniques and products are readily available.

4. Automotive metrology and data collection

Metrology, the science of measurement, can be defined as the application of one or more well-defined measurement methods in an effort to obtain quantifiable information about an object or phenomena (Bucher, 2004). In the automotive industry, the process of measuring various physical properties of a vehicle in operation, and collecting the measurement data for analysis of the behaviour of components or subsystems, is a crucial part of the testing and validation stages of development. Automotive metrology encompasses a vast array of different measurement techniques, measurement systems, data formats and analysis software for different applications.

A specific application of metrology that is of fundamental importance in automotive engineering is diagnostics. Because of its significance, we will devote section 5 entirely to diagnostic data management and confine this section to the study of collection and analysis of measurement data not specifically for diagnostics. This involves collection of a broad range of data resulting from various sensors built into in the vehicle and from specialized measurement systems installed in dedicated test vehicles. The data collected is typically used for troubleshooting faults appearing during testing or to collect performance data on different subsystems for validation.

One of the most common kinds of data collection is the recording of signals from sensors connected to ECUs and communicated over the in-vehicle network (e.g. the CAN bus). In modern automobiles, a large number of such signals (several thousand), are available for monitoring and recording on special purpose devices known as *flight recorders*[1]. A flight recorder is a versatile piece of equipment that can be configured to monitor and record a number of signals that later can be analysed using a plethora of analysis tools. The conditions for when to start and stop recording the signals is typically controlled using some sort of triggering method, which can be for instance a change of the vehicle's power mode, the push of a button, or the appearance of a certain CAN frame on the CAN bus. Usually, there is a configurable time period before and after the event during which the signals will be recorded (known as pre-trigger and post-trigger times). The specification of which signals to record, along with capture parameters such as the trigger conditions, sample rates and precision for each signal, is typically defined in a configuration file on the flight recorder. We will call this configuration file a *measurement assignment*. The measurement assignment is created by the test engineer using a dedicated software tool, and compiled into a format readable by the flight recorder. The assignment is then downloaded to the flight recorders in the test vehicles designated for the specific tests. As the test vehicles are operated, measurement data is generated, which can subsequently be offloaded from the flight recorders for analysis. Based on the results of the analysis, the measurement assignment may need to be re-designed and the process reiterated to capture additional data. In this fashion, specific malfunctions or operational anomalies can be provoked during testing and the relevant sensor data for fault tracing can be captured and analysed. The process is illustrated in Fig. 2, highlighting the cyclical nature of the work.

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[1] The name reflects the origin of the technology in the aerospace industry. For automotive applications, the terms 'data recorder' or 'data logger' are sometimes used synonymously.

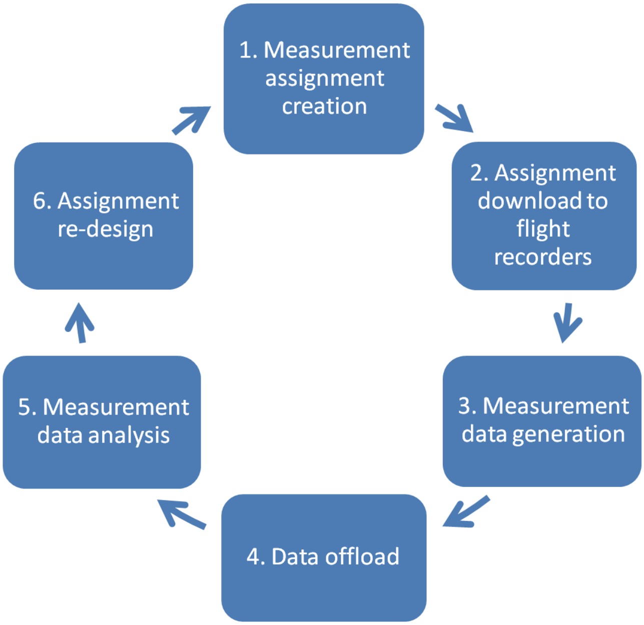

Fig. 2. Measurement data capture and analysis cycle

4.1 Wireless communication in automotive metrology

To improve the efficiency of fault tracing in automotive development, a key concern is to reduce the time of the data capture and analysis cycle, shown in Fig. 2. With the advent of more or less ubiquitous wireless data communication networks, as discussed in section 3.3, the measurement assignment download and the measurement data upload can be realized over a wireless connection using a telematics service. This means that the engineer does not need physical access to the test vehicle to reconfigure the flight recorder or to access the measurement data for analysis. Since prototype vehicles are often physically inaccessible to the engineers for extended periods of time while away on testing expeditions this is a significant benefit.

A telematics service for remote metrology and data collection is generally based on an architecture with a web server acting as a gateway between the wirelessly accessible flight recorders and the users. Measurement assignments are uploaded to the server by the users, and the identities of the test vehicles that the assignment is intended for are specified. The assignment is then automatically downloaded to the flight recorders of the specified vehicles, by means of the telematics service. Once the flight recorders are configured by the assignment, measurement data can be generated and continually uploaded to the server, where it is stored in a database. The user can then download the data from the server and perform the desired analysis.

4.2 Measurement data storage and management

Telematics based metrology systems not only increase the availability of prototype vehicles for tests and reduce the time needed for the data collection; they also open up many new opportunities to further improve the automotive testing process. For instance, the aggregation of data into a centralized database with a common (web-based) interface improves the possibilities of reuse of data compared to the situation where the engineers manage their or own data. Hitherto, the typical situation has been that the measurement data generated by a particular test is offloaded from the flight recorder onto the hard drive of the responsible engineer's computer, and once the analysis is finished the data is discarded. With proper metadata tagging, appropriate database schemas and a consistent signal naming scheme (e.g. as standardized by ASAM, the Association for Standardisation of Automation and Measuring Systems), measurement data can instead be stored in a central repository, and be made available for search, retrieval and reuse for other purposes than what it was originally intended for. Preservation and reuse of data throughout the product lifecycle is an increasingly important factor for competitiveness, not only in the automotive industry but in design and engineering in general (Wilkes et al., 2009). With the advent of telematics based metrology systems that automatically upload measurement data to a centralized database, a more systematic preservation and reuse of data can be achieved as an additional benefit.

4.3 Automated analysis of measurement data

Another possibility arising with the introduction of telematics based automotive data collection systems is that certain processing of the data can be performed automatically when the data is uploaded to the server. The data collected by the flight recorder is typically stored on a solid state drive, in some well-known measurement data file format (such as MDF developed by Vector and Bosch), before being uploaded to the server. The upload is typically triggered by some event such as the ignition going off, indicating that a measurement session is complete. At the arrival of the measurement data files at the server, a software component is launched that extracts the measurement data and applies some preconfigured processing, storing the results into a database. Ideally, different kinds of processing can be applied as defined by the user, from simple preprocessing operations (such as filtering out invalid or uninteresting data) to sophisticated signal processing algorithms. An automated data analysis system of this kind is described by Isernhagen et al. (2007), although no telematics service is included in their concept. The system supports user-defined data analysis through a descriptive language and parametrisation files and includes many different signal processing modules for different analyses. As an alternative to temporary storage of data on the flight recorder, the data can be transmitted in real time as a measurement data stream. The processing of the data stream at the server can then be performed by a Data Stream Management System (DSMS). Such an approach for online analysis of streaming CAN data is outlined by Johanson et al. (2009).

4.4 Geographical positioning of data

Since telematics systems are commonly equipped with GPS receivers, measurement data that is collected through a telematics service can easily be tagged with metadata about the geographical location of the measurement. This provides provenance of the data, which is important for preservation and reuse. Knowing where a measurement was conducted can also be valuable contextual information in the analysis of the data.

5. Remote vehicle diagnostics and prognostics

Collection and analysis of diagnostic data from electronic control units in vehicles is of vital importance in the automotive industry, both from a life cycle support perspective and during product development, providing performance data and statistics as input to decision making. Moreover, through vehicle diagnostics services, prognostics to anticipate vehicle failures and improve operational availability can be realized, lowering support costs through anticipatory maintenance. For pre-series test vehicles, access to diagnostic data is crucial in order to be able to track problems as early as possible in the development process, preventing serious faults to pass undetected into production vehicles. However, systematic collection of diagnostic data from test vehicles is complicated by the fact that pre-series vehicles are frequently unavailable for diagnostic read-outs, while away on testing expeditions in remote rural areas or being otherwise inaccessible. In response, a multitude of systems and services for wireless read-out of diagnostic data have been suggested (Campos et al., 2002, Johanson & Karlsson, 2007, Vilela & Valenzuela, 2005, Zhang et al., 2008).

5.1 Integrated vehicle diagnostics

In the automotive industry, the need for verification of the functionality and quality of products does not end when the product is sold; on the contrary, this is an important part of the service and maintenance agreement. For this purpose, diagnostic functions are built into the electronic control units, making it possible to access diagnostic data when vehicles are brought in for service. The diagnostic data can be uploaded to the car manufacturer's database over the Internet or using dial-up connections. Statistical analysis of collected diagnostic trouble codes is important in order to monitor the quality of components and subsystems, to prioritise in which order problems should be addressed, and to find correlations between different faults, or correlations between faults and the operating environment. To track problems earlier in the development phase of a new car model, it has been suggested that collection of diagnostic data from test vehicles and pre-series vehicles, in different stages of the development cycle, can be utilized in a more systematic way (Johanson & Karlsson, 2007). However, as previously mentioned, systematic diagnostic read-outs from test vehicles are cumbersome to administer, since the vehicles are often inaccessible. By making test vehicles available for remote wireless diagnostic read-outs, faults can be detected and corrected before the vehicle goes into production and is sold. This prevents costly recalls and warranty obligations. Wireless remote diagnostic read-outs from production vehicles in the aftermarket can also be envisioned; indeed for special purpose vehicles like construction equipment and trucks, such systems are already in commercial use. Commercial services are also emerging for premium cars (Hiraoka, 2009).

Since diagnostics systems are important both for aftermarket services and during product development, an integrated framework for collection, analysis and management of diagnostic data is highly desirable. Campos et al. (2002) argue that previous generations of diagnostics systems have not been well integrated, resulting in unnecessary duplication of effort in developing different diagnostics applications, each with its own infrastructure and software components. This leads to inefficient use of resources and high costs for developing and maintaining the diagnostics applications. Luo et al. (2007) further stress the need for integrated diagnostics and propose a new model-based diagnostic development process for automotive engine control systems, which seamlessly employs a graph-based dependency model and mathematical models for both online and offline diagnosis. Johanson and Karlsson (2007) present an integrated diagnostics system, that can accommodate both aftermarket and product development needs. With this approach, the infrastructure and workflow for diagnostics and prognostics can be streamlined and optimized for high productivity.

5.2 Information and communication support systems for diagnostics

The main information and communication support components of a diagnostics system can be categorized as follows:

- diagnostic read-out systems,
- diagnostic databases,
- diagnostic analysis toolsets,
- diagnostic authoring tools.

Below we will discuss each of these classes of tools and systems and explore the interdependencies between them.

5.2.1 Diagnostic read-out (DRO)

A diagnostic read-out system connects to the in-vehicle communication network, typically through the OBD-II connector, and queries the ECUs for diagnostic data. This is generally performed using a collection of standardised protocols for automotive diagnostics (ISO 14229, ISO 15765) transported over the Controller Area Network (CAN) communication bus, which interconnects the vehicle's ECUs.

As discussed above, diagnostic read-out system can be implemented as telematics services, which precludes the need for physical access to the vehicles. For such systems, sometimes referred to as remote or wireless DRO services, there are two main modes of operation: synchronous (online) read-out or asynchronous (offline) read-out. In a synchronous remote DRO application, the diagnostics tool establishes a direct network connection to a gateway unit in a vehicle, which relays diagnostic queries and answers between the DRO tool and the ECUs on the in-vehicle network. This can be realized using a tunnelling protocol, such as the CAN-over-IP protocol described by Johanson et al. (2009), or using a dedicated online diagnostics protocol such as the emerging ISO standard Diagnostics-over-IP (DoIP, ISO 13400). In an asynchronous remote DRO application, the diagnostic queries are assembled into a diagnostic script file, which is downloaded to the telematics unit for execution at a suitable time. The actual read-out of diagnostic data is performed by the telematics unit (or some other on-board equipment), and the resultant diagnostic data is encoded in a suitable representation (typically an XML file) and uploaded to the server infrastructure supporting the asynchronous read-out service.

The distinction between the two modes of operation reflects two different kinds of diagnostic applications. The synchronous case is preferable for applications like remote troubleshooting of specific (test) vehicles, whereas the asynchronous case is more appropriate for automated diagnostic read-outs from fleets of vehicles for state-of-health or prognostics applications. The distinction is not clear-cut however.

5.2.2 Diagnostic databases

The diagnostic database is a crucial component wherein all diagnostic data of all vehicles produced by a specific manufacturer is stored. This requires a substantial amount of storage capacity, typically realized using data warehousing solutions, for managing the large volume of data accumulated over the lifetime of the vehicles. The database must be easily searchable and data must be efficiently retrievable. Moreover, to support provenance of diagnostic data, the data must be tagged with metadata describing the origin and capture parameters of the data. This includes vehicle identification data, read-out time, geographical position of read-out (if available), various troubleshooting data and other metadata.

5.2.3 Diagnostic analysis toolsets

The diagnostic analysis toolset is a collection of software tools for performing various kinds of processing and analysis of the diagnostic data. This includes tools for data visualization, case-based reasoning, data mining, statistical analysis and various prognostics tools. A variety of generic data processing systems such as Microsoft Excel and MATLAB are heavily used for realizing the specific analysis tools.

A simple form of diagnostic data analysis is the troubleshooting assistance support built into diagnostics tools used at authorized repair shops. These tools are based on a knowledge database mapping specific fault conditions, indexed by DTC, into suggested troubleshooting and repair actions. A more sophisticated data analysis takes place at the automotive company after the DTCs have been uploaded to the diagnostic database, either from aftermarket (i.e. production) vehicles or from test vehicles during product development. This processing, consisting primarily of data mining and statistical analysis, will be described in more detail in section 5.3.

5.2.4 Diagnostic authoring tools

Diagnostic authoring tools are used by diagnostics engineers to develop new diagnostic functions in the ECUs, in the DRO tools, and in the analysis toolsets. Based on requirements from the product development, and novel needs identified in the analysis phase, new diagnostics functions are developed in tandem with new analysis tools in a constantly ongoing development process. A diagnosis script editor is typically used to design new read-out functions in DRO systems, based on new or updated diagnostic functions in the ECUs. Preprocessing and interpretation of the results of the new DRO functions then need to be implemented, before the data can be stored in the diagnostic database. The analysis tools may also need to be updated for processing the new diagnostic data.

The information flow between the different stages of the automotive diagnostics process is illustrated in Fig. 3.

5.3 Statistical analysis of DTCs

A DTC is a compact representation (typically five digits encoded in two bytes) of specific component malfunctions. A number of DTCs are standardised through the OBD-II (on-board diagnostics) initiative (SAE J2012/ISO 15031-6), but each vehicle manufacturer typically also defines a large number of additional codes. The conversion from the compactly encoded form into a humanly legible text format is performed through a table

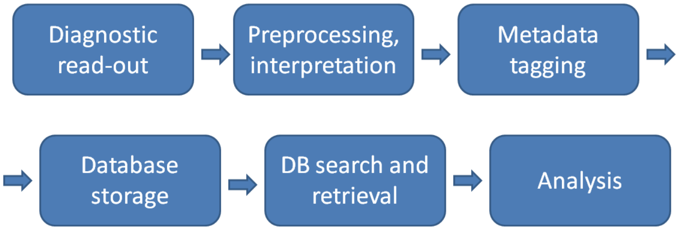

Fig. 3. Typical information flow in automotive diagnostics

look-up by the diagnostics tool. After a DTC has been read out from an ECU, it is generally erased from the ECU's memory bank. To enable statistical analysis, the DTCs must be uploaded to the diagnostics database for persistent storage.

Let's consider an illuminating example of how statistical analysis of DTCs can be performed. When a large number of DTCs have been collected, we can query the database for a specific DTC set during a specified time interval in a fleet of vehicles defined by a number of characteristics such as car model, engine type, transmission type, etc. The frequency of DTCs over time can be plotted in a histogram (see Fig. 4). Here, mileage is used instead of time as independent variable, as is common practice in automotive reliability engineering.

In order to perform statistical analysis, we can design a function *f(t)* that approximates the histogram. Such a function is called a probability density function (PDF). The probability of a failure (resulting in a DTC) in a time interval [*t1*, *t2*] is then the area under the curve *f(t)* between *t*=*t1* and *t*=*t2*, i.e.

$$P(t_1 \le t \le t_2) = \int_{t_1}^{t_2} f(t)dt\,. \quad (1)$$

The probability of failure before a given time t_1, $F(t_1) = P(t \le t_1)$, is called the cumulative distribution function (CDF). Conversely, the probability of survival beyond a given time t_2 is given by the reliability function $R(t_2) = P(t > t_2) = 1 - F(t_2)$.

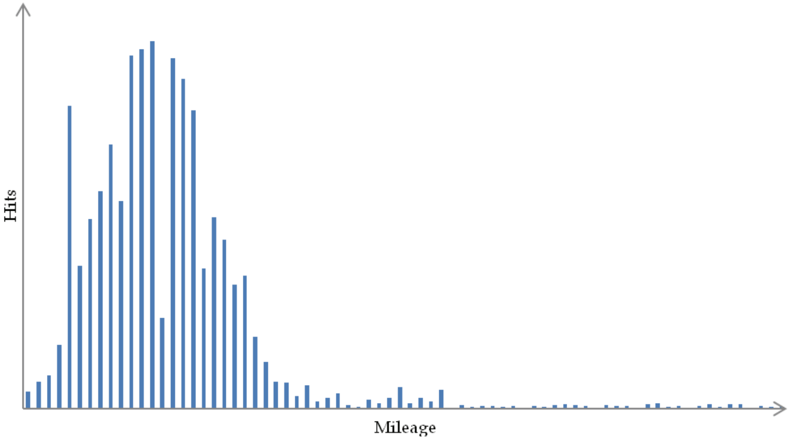

Fig. 4. Histogram showing the frequency of failures in discrete intervals of mileage

The hazard function *h(t)* gives the probability of instant failure in the next small time interval Δt, given survival until time *t*. The hazard function is better known as the failure rate, and is simply the number of failures at time *t* divided by the numbers at risk at *t*, i.e.

$$h(t) = f(t) / R(t). \tag{2}$$

To visualize a trend of failures, we can study the integral of the hazard function, called the cumulative hazard, which is calculated as

$$H(t) = \int_0^t h(t)dt = \int_0^t \frac{f(t)}{R(t)}dt = \int_0^t \frac{f(t)}{1-F(t)}dt = -\ln(1-F(t)) \tag{3}$$

The cumulative hazard can be interpreted as the probability of failure at time *t* given survival until time *t*.

Now, to be able to calculate all of the abovementioned useful statistics of a collected data set, we need to find a PDF that approximates the histogram of collected DTCs in a good way. One very well known PDF that has proven highly useful for statistical modelling in reliability engineering and failure analysis is the Weibull distribution, given by

$$f(t;k,\lambda) = \frac{k}{\lambda}\left(\frac{t}{\lambda}\right)^{k-1} e^{-(t/\lambda)^k}, \tag{4}$$

where $k>0$ is the shape parameter and $\lambda>0$ is the scale parameter of the distribution.

Using regression analysis, the parameters k and λ can be easily calculated from the histogram data. For instance, looking at our histogram in Fig. 4 we can calculate the values $k=3.1$ and $\lambda=1.5$ from the histogram data by a simple curve-fitting algorithm. This gives the Weibull density function for our hypothetic DTC shown in Fig. 5.

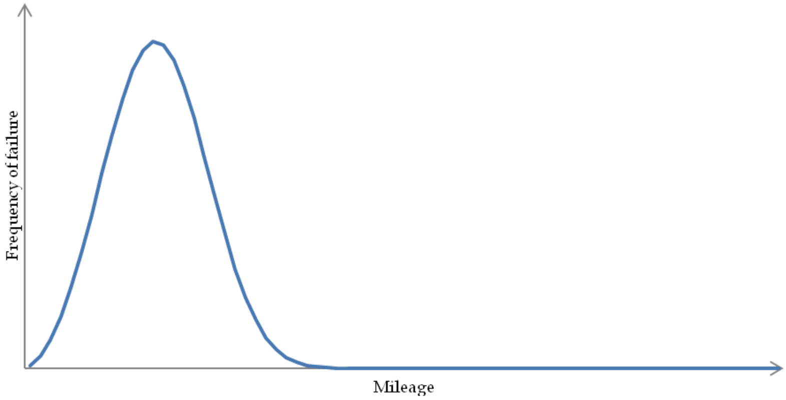

Fig. 5. Weibull density function

From the Weibull function we can now calculate the hazard function using formula (2) and the cumulative hazard, shown in Fig. 6, using formula (3). This gives a good visualization of the trend of failures of the component or subsystem from which the DTC originates, and can be used for instance to optimise service intervals or as input to the development of the next generation of the component or subsystem.

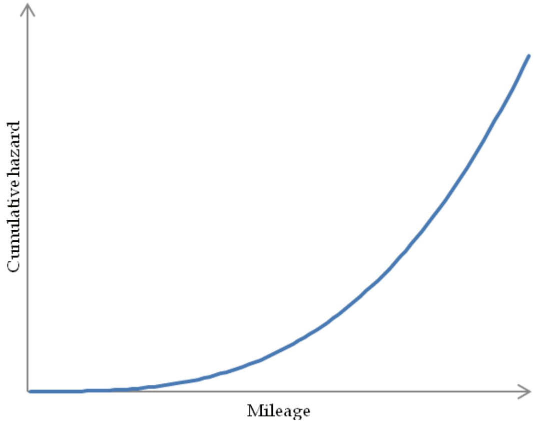

Fig. 6. Cumulative hazard function

The statistical analysis shown above is just one example out of a wide variety of computational methods for diagnostics and prognostics. When the volume of the diagnostic data collected grows due to improved means of collecting data through telematics services, it will be increasingly important to have sophisticated computer-based tools for processing the data.

6. Remote software download

With the explosive growth of software in vehicles, development and maintenance of ECU software (firmware) are increasingly important tasks in automotive engineering. From a testing and validation perspective, tracking down and documenting ECU software bugs have become major issues. When a software bug has been found and fixed, the new version of the software needs to be installed, followed by new testing to verify that the problem is solved and that no new problems have been introduced. The cycle of finding software related problems, upgrading the software and repeating the tests can quickly become very time-consuming and needs to be streamlined as much as possible to optimise efficiency. In this context it is of great value to be able to upgrade ECU software as quickly and effortlessly as possible. Unfortunately, ECU reprogramming is typically a rather tricky and time-consuming procedure, often requiring the vehicle to be taken to a workshop. With test vehicles frequently being inaccessible, as previously discussed, software updates are commonly delayed. Once again, telematics services seem to be the answer. With the ability to remotely update the ECU software over a wireless network connection, test vehicles can get the latest software versions installed with little or no manual intervention. Moreover, with version management systems keeping track of all vehicles' software status, the burden of keeping track of which software version is currently installed on a particular test vehicle is lifted from the engineer.

Remote software download has also been suggested as an aftermarket service, giving the customers the opportunity to get the latest ECU software versions installed without having to take the car to an authorized repair shop.

6.1 Telematics services for remote software download

A telematics service for remote software download can be developed by implementing an ECU upgrade component in the telematics unit and making new ECU software releases available on a server for download over a wireless network connection. A revision control system keeps a centralized record of the versions of all ECUs in all vehicles managed by the system. When the telematics service detects a new version of the software for one or more of its ECUs, it downloads the software packages, sets the vehicle in programming mode, and replaces the software in the ECUs via the in-vehicle network (e.g. the CAN bus).

Automated software update mechanisms are well-known in the computer and telecommunications industry. For upgrades of mobile phone firmware over a wireless network, the term FOTA (Firmware update Over the Air) is commonly used. It has been suggested that the principles of FOTA in the telecommunications industry can be applicable also in the automotive industry (Shavit et al., 2007).

A generic mechanism for remote ECU software update is presented by de Boer et al. (2005). Their approach is based on a generic OSGi (Open Service Gateway initiative) service platform installed on a telematics unit and a remote administration server, which keeps a repository of ECU flash-bundles. A key feature of their solution is that the ECU reprogramming controller is downloaded from the server together with the flash-bundles, which alleviates problems with different reprogramming procedures for different ECUs.

Although the prospects of remote ECU software upgrades seem very promising, many practical obstacles related to safety and security need to be overcome before large-scale deployment of telematics based services can be realized. Specifically, remote access to vehicles must be restricted based on authorization mechanisms and the integrity of ECU software updates must be guaranteed. To this end, Nilsson and Larson (2008) suggest a protocol for secure remote ECU software updates based on symmetric key encryption and digital signatures. In a similar vein, Mahmud et al. (2005) present an architecture for secure ECU software updates through a combination of one-time authentication keys and symmetric key encryption.

7. Distributed collaborative automotive engineering

Automotive proving grounds are commonly located in remote rural areas, due to the need for extreme climate conditions and privacy. As a consequence, test engineers must travel to remote locations for extended periods of time, which is time consuming and expensive. By making heavy use of broadband communication infrastructure and by developing new work procedures based on distributed collaborative work, automotive testing can be performed with less need to send highly qualified personnel to remote regions. The specialists on a subsystem of a car can stay at the car manufacturer's development site, where they can be more productive in their work, while still having immediate access to the measurement data of the tests being performed elsewhere. Less qualified test engineers can be hired for conducting the tests, with data being analysed and the tests being coordinated from a remote location. Furthermore, the opportunity of conveying test results in real time over a network to the development site means that people traditionally not involved in testing until a much later stage can be engaged earlier, shortening development cycles.

To realize such a distributed collaborative work environment requires a number of sophisticated software tools for remote interactions and data sharing between the engineers.

Traditionally, tools for collaborative engineering and design have focused on supporting distributed group meetings using synchronous communication tools, like videoconferencing and application sharing. Sophisticated collaboration studios have been built for the purpose of group-to-group communication. Although useful, these collaboration studios do not explore the full potential of distributed collaborative work, and in particular they fail to support the day-to-day communication between engineers. Arranging a distributed meeting using a collaboration studio is of course less troublesome compared to travelling to face-to-face meetings, but it still requires the involved engineers to get out of their ordinary workplaces, book a studio, and so on. Instead, software tools supporting distributed collaborative work directly from the engineers' workstations are needed. This way synchronous collaboration sessions can be initiated effortlessly, supporting impromptu interactions and a much tighter collaboration between the members of a distributed team.

A technological framework supporting distributed collaborative automotive testing is presented by Johanson and Karlsson (2007), along with a pilot study demonstrating the use in distributed winter testing of climate control systems. This system supports audiovisual communication, synchronous sharing of measurement data and shared visualization of data. Validation of climate control systems is an interesting application, since it involves a considerable amount of subjective testing, complementing the measurement data collection and analysis. In this context it was found useful to have direct voice (and even video) communication with the engineers riding in the test vehicles, to communicate subjective impressions.

Nybacka et al. (2006) describe a system for feeding real time measurement data from a car into a simulator, for computation of dynamical properties that cannot be measured directly. With this system, measurement data about a car's current position, velocity and acceleration can be used as input to a simulation model, to calculate the normal forces acting on the tires of the car. The result is visualized collaboratively in real time using a 3D model of the car, giving the distributed engineers an improved understanding of the behaviour of the car during handling tests. This kind of hardware-in-the-loop simulations, combining real time measurement data acquisition, simulation techniques and collaborative visualization has a strong potential of improving automotive multi-body dynamics testing and validation in the future.

8. Conclusions and future outlook

In this chapter we have explored the information and communication needs of the testing and validation stages of automotive development. As we have seen, the growing complexity of electronic control systems in modern vehicles increases the need for testing and validation. The challenge of achieving this extended testing in less time, due to shortened development cycles, must be met with improved testing and validation processes based on sophisticated information and communication systems for data capture and processing.

The interconnection of in-vehicle communication networks with wireless internetworks through telematics services enables communication of measurement data, diagnostics data and other vehicle data almost ubiquitously. This has a tremendous impact on the way automotive testing and validation is conducted. Instead of devoting much of their time to hunting down prototype vehicles for the purpose of reading out diagnostic data or reconfiguring flight recorders, the engineers can focus on designing test procedures and analyzing the data made available through telematics services. When software-related problems are found through remote metrology and diagnostics services, the ECUs can be remotely updated with new versions of the software. With computer-based tools for distributed collaborative work, engineers at remote test sites can seamlessly collaborate with colleagues at the automotive company's development sites, without need for excessive travel.

When fleets of test vehicles are interconnected with server-side infrastructure through sophisticated telematics services they are in a sense being transformed into a giant distributed system of data producing units. Probing into the future, we can envision a situation when all vehicles (not just test vehicles) are constantly online, monitored by sophisticated management systems operated by the automotive manufacturers or third party service providers. This poses many challenges of scalability, maintainability, safety and security, but at the same time promises great opportunities for meeting the challenge of delivering superior products to future customers in the automotive sector.

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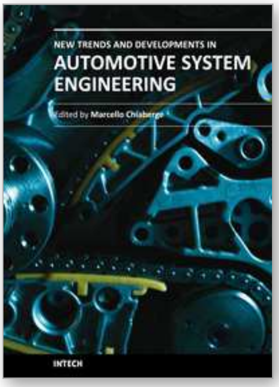

New Trends and Developments in Automotive System Engineering
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In the last few years the automobile design process is required to become more responsible and responsibly related to environmental needs. Basing the automotive design not only on the appearance, the visual appearance of the vehicle needs to be thought together and deeply integrated with the â€œpowerâ€ developed by the engine. The purpose of this book is to try to present the new technologies development scenario, and not to give any indication about the direction that should be given to the research in this complex and multi-disciplinary challenging field.

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InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821