

A Comparative Case Study of Distributed Network Architectures for Different Automotive Applications

Jakob Axelsson¹, Joakim Fröberg^{2,3}, Hans Hansson³, Christer Norström³, Kristian Sandström³, and Björn Villing⁴

¹Volvo Car Corporation AB, ²Volvo Construction Equipment Components AB, ³Mälardalen Real-time research Centre, Mälardalen University, ⁴Volvo Truck Corporation AB

Contact: kristian.sandstrom@mdh.se

Abstract

In recent years, networking issues have become more and more important in the design of vehicle control systems. In the beginning of the 1990s a vehicle control system was built up by ‘simple’ computer nodes exchanging ‘simple’ and relatively non-critical data. Today we have moved into distributed vehicle control systems with functions spanning several nodes from different vendors. These systems are running on communication architectures consisting of different types of communication busses providing different functionality, from advanced control to entertainment. The challenge is cost efficient development of these systems, with respect to business, functionality, architecture, standards and quality for the automotive industry.

In this article we present three different architectures – used in passenger cars, trucks, and construction equipment. Based on these case studies with different business and functionality demands, we will provide an analysis identifying commonalities, differences, and discussing how the different demands are reflected in the network architectures.

1 Introduction

One of the initial driving forces for introduction of communication networks in automotive vehicles was to replace the numerous cables and harnesses and thereby reduce the number of connection points, cost and weight. Moreover, *multiplexing*, as vehicle networking is traditionally referred to in the automotive industry, is an important enabler of new and increasingly complex functions. Using software and networking it is today possible to create new functionality, such as an anti-skid system, that was considered unfeasible, both with respect to cost and functionality, some ten years ago.

The vehicle industry strives to enable cost effective implementation of new functionality. A network enables reuse of sensor data and other calculated values. Moreover distributed functions can be facilitated for truly distributed problems like coordination and synchronization of brakes.

Another driving force is the demand for increasingly efficient diagnostics, service, and production functionality. The network in a vehicle should provide functionality not only during normal operation of the vehicle, but also in the after market and during production. It should also provide communication for diagnostic functions in control units, and provide a single point interface to service tools to meet goals on more efficient service.

There is a wide span of requirements on the communication infrastructure in today’s vehicles. The vehicle industry works with demands on functionality, reliability, and safety, but also with demands related to product variation, extendability and maintenance of delivered products, and integration of sub supplier components. This implies high requirements on network flexibility in terms of adding or removing nodes or other components. Moreover, part of the functionality has stringent requirements on real-time performance and safety, e.g., safety critical control applications; whereas other parts of the functionality, such as the infotainment applications, have high demands on network throughput. Yet, other parts require only lightweight networks, as for example locally interconnected lights and switches. All of these varying requirements in vehicle networks are reflected in the architecture, implementation, and operation of a modern in-vehicle network.

In this paper, we try to describe the context in which today’s vehicle industry work and develop distributed systems. This is uncovered in three case studies covering passenger cars, trucks, and construction equipment. Although the three different vehicle domains have very much in common there are also distinct differences, e.g., in production volume and the number of different models. In fact, these differences are so important that they result in three quite different network architectures.

The contributions of this article are (1) the presentation of three case studies and (2) an analysis of the relation between business needs and architectural design issues of networking in automotive vehicles. The three case studies cover much of automotive industry and describe the business context and demands for automotive networking.

The rest of this article is organized as follows: Section 2 provides a structuring and presentation of important issues and challenges in automotive networking. An introduction to automotive network technologies is provided in Section 3. Section 4 presents the three case studies and in Section 5 we analyze the architectures with respect to the different business needs. Finally, in Section 6 we draw some conclusion and in Section 7 links to relevant web sites are provided.

2 Challenges

In this section we present some current trends in vehicle networking, together with descriptions of some of the context in which vehicle networks are developed today. The presentation is structured into sections on the main aspects of vehicle networks, namely functionality, cost, standards, and architecture.

2.1 Functionality

Functionality in a vehicle is not limited to end-user functions, but includes also functions to support, for instance, production and service. In this section we will outline some important groups of functionality, both supportive and end-user functions that is often addressed in vehicle development.

Feedback control includes functions that control the mechanics of the vehicle, for example engine control and anti-lock-brake-systems. Feedback control systems can be combined to achieve advanced control functions for vehicle dynamics. Examples are electronic stabilizer programs, ESP, and other chassis control systems like anti-roll systems. Furthermore, the vehicle manufacturers strive to achieve cheaper and more flexible functionality by going towards x-by-wire solutions. X-by-wire solutions, such as steer-by-wire, are achieved by replacing e.g., mechanical or hydraulic solutions by computer control systems.

Discrete control, in this context, includes simple functions to switch on or off devices, e.g., control of lamps or wipers. The challenges for this group of functions often relates to the sheer number of such simple devices and thereby the amount of traffic on the network.

Diagnostics and service. Functions in this group are used in vehicles to support maintenance of delivered products. Diagnostic functions provide means to diagnose physical components, such as sensors, as well as software properties, such as version number and network load. Service functions provide means for updating the electronic system by downloading new software and to test vehicle operation. Because of the large amount of retrievable information, solutions are needed for automatic, or at least tool supported, diagnoses and service.

Infotainment refers to in-vehicle systems not related to driving the vehicle, but more related to information and entertainment. Examples are Internet connection and video consoles. This leads to requirements on high bandwidth for vehicle networks. Components like network controllers and software are often purchased off-the-shelf, and must be integrated in a harsh physical environment. Components must also be integrated without impacting safety critical functionality in the vehicle

Telematics [1] is a name of the set of functions that uses communication networks outside the vehicle to perform their task. This includes functions in the vehicle and outside the vehicle. There is a strong trend in the vehicle industry to increase the use of telematics. Examples include fleet management systems, maintenance systems, and anti-theft systems.

2.2 Cost

Providing cost efficient network architectures is a challenge in several respects. The architecture should exhibit properties that support a variety of business needs. Business needs in the context of vehicle network systems often include life-cycle aspects of development, production, maintenance, and service.

Fixed and variable cost. Building a vehicle is a process of finding the best compromise between conflicting aspects, and one of the most important trade-offs is to find the balance between cost, performance, and functionality that provides the best business case. The cost can be divided into variable cost (the cost of purchasing the physical components that go into the vehicle and the resources consumed during production) and fixed cost (the investments made in development, production facilities, tooling, after market support, etc.). There is always a trade-off to be made between the two, which depends heavily on the production volumes, and the relations between various cost factors [2].

Maintenance and service. To reduce the life cycle cost of the product it is often important to consider various aspects of maintenance. To facilitate maintenance it is desirable to develop architectures that allow future upgrades and extensions to the delivered product. Servicing delivered products require the ability to upgrade both software and physical components. Configuration management and distribution is then a crucial issue, e.g., to determine compatibility of new components in an existing configuration.

2.3 Standards

The use of standards is motivated by the need to meet goals related to:

- Cost reduction
- Integration of supplier components
- Increased reliability of components
- Commonality in tools used in e.g., development, diagnostics, and service.

One example is the Controller Area Network (CAN) standard that has provided the vehicle industry with cheap network controllers. Due to the large volumes of these controllers, they are tested to a great extent (in the field) under diverse conditions, which increases reliability.

A challenge with respect to standards is to standardize properties of software to accommodate reuse of software components and to allow for common development tools.

Although there are great benefits in using standards, they should also allow for proprietary solutions in key areas of a domain in order not to hinder competitive and brand specific solutions.

2.4 Architecture

The IEEE has the following definition of architecture [3]:

"Architecture: the fundamental organization of a system embodied in its components, their relationships to each other and to the environment and the principles guiding its design and evolution."

For automotive electronic architectures, the components are mainly the electronic control units (ECU), and the relationships between them are the communication networks. The environment is the vehicle itself, as well as the life-cycle processes that must support it. An important aspect when designing the architecture is the physical packing of the ECUs. A guideline is to put them as close as possible to their inputs and outputs, to reduce the wiring length (and thereby the cost and weight). At the same time, the architecture must be easy to assemble on the manufacturing line, and the overall architecture of the car puts restrictions on the possible locations, since space is generally very limited. Aspects of maintenance must also be considered when designing the architecture in order to facilitate aftermarket service of ECUs and software. Also, environmental factors like temperature and EMC influence the location of the ECUs. As the product development is increasingly focused on platforms and commonality, the ability to create many variants from the same overall structure is important.

3 Network Technologies

In this section we will introduce present and emergent network technologies in the automotive industry. The network technologies in focus are different types of field buses that meet the requirements of automotive applications and communication software and high-level protocols. Throughout the section we will give an overview of automotive network technologies in general and provide more detail about technologies covered in the case studies of Section 4.

3.1 Automotive field busses

3.1.1 Control busses

The dominant bus technology for power train and body electronics in vehicles is the Controller Area Network (CAN) standard [4]. The CAN standard is divided into standard CAN (CAN 2.0A) and extended CAN (CAN 2.0B) where the length of the message frame differs. The wide use has made processors available with integrated CAN controllers. CAN is a broadcast bus designed to operate at speeds of up to 1 Mbps. Data is transmitted in messages (frames) containing between 0 and 8 bytes of data. An identifier is associated with each message. The identifier serves two purposes: (1) assigning a priority to the message, and (2) enabling receivers to filter messages.

CAN is a collision-detect broadcast bus, which uses deterministic collision resolution to control access to the bus. During arbitration, competing stations are simultaneously putting their identifiers, one bit at the time, on the bus. By monitoring the resulting bus value, a station detects if there is a competing higher priority message and stops transmission if this is the case. Because identifiers are unique within the system, a station transmitting the last bit of the identifier without detecting a higher priority message must be transmitting the highest priority queued message, and hence can start transmitting the body of the message.

3.1.2 Low cost busses

Low cost busses have been introduced in automotive applications in order to facilitate cost effective integration of components such as smart sensors and actuators into the vehicle network. Smart sensors and actuators, have some ability to process (typically filter, or translate) measurements and send signals on the network whereas non-intelligent ones are wired to the I/O of an ECU that handles processing. The introduction of low cost controllers and single-wire networks is made at the expense of bandwidth, which is relatively low for these busses. Besides being a low cost alternative to adding a full featured ECU, the low cost busses present a way of reducing complexity of the master node and also facilitates variants without numerous configurations of the master node.

One bus in this category is the Local Interconnect Network (LIN) [5] that is a serial bus based on the Universal Asynchronous Receiver Transmitter (UART) present in most micro-controllers. Based on UART, LIN implements a time-triggered protocol, where a master node handles synchronization on the bus. LIN provides low bandwidth (up to about 20 kbit/s), but controller circuits are considerably cheaper than for CAN. The LIN standard provides not only the protocol specification but also an *application interface* and a *network configuration description* that conforms to the LIN *configuration language description*. The application interface provides a software level abstraction for interfacing the network whereas the configuration description holds information on the composition of the complete LIN network.

Other busses included in this category are the TTP/A bus [6] which is also a time-triggered bus based on UART, and the SAE 1850 [7], an asynchronous serial protocol.

3.1.3 Infotainment busses

Since vehicles are becoming equipped with more and more multimedia and telematics applications, the need for dedicated infotainment busses have arisen. A bus system in this category is MOST (Media Oriented Systems Transport) [8], which is based on optical fibre technology, and provides bandwidth up to about 20 Mbit/s. MOST has services optimized for infotainment applications. The topology supported is ring, star, and daisy chain. The network is synchronous with a common clock so that devices can synchronize their operation; this is suitable for streaming of audio and video. MOST also has defined mechanisms for asynchronous, packet based data, which can be found in e.g internet traffic.

Other infotainment busses relevant to automotive applications are the IEEE1394 [9] and the wireless Bluetooth [10] and IEEE 802.11b [11] protocols. (Bluetooth and IEEE 802.11b are used mainly to connect external devices)

3.1.4 Time-triggered safety critical busses

Emergent safety critical functions, such as x-by-wire applications, where x may be e.g. steer or brake, have forced the development of bus technologies for use in automotive vehicles that meet demands on very high reliability and timeliness. A group of busses that meet this demand are evaluated by the automotive industry. These busses are all based on the time-triggered paradigm where the progression of time initiates data transfers rather than asynchronous events. The time-triggered busses provide synchronous communication without the need for arbitration. Moreover they offer mechanisms for redundant networks and have built in support for a global time base. Therefore the time-triggered protocols are suitable for implementing safety critical control functions with stringent demands on low latency and low jitter. Three time-triggered protocols developed for automotive use are FlexRay, TTP/C, and TTCAN. All these protocols offer services, such as global time and time-triggered communication enabling pre-run-time scheduling of communication. Moreover, all three protocols also make it possible for event-triggered traffic to co-exist with time-triggered.

The FlexRay communication protocol [12] supports bandwidth up to 10 Mbit/s with the possible topologies bus, star, and multiple star. Available communication controllers for the TTP/C [13] protocol support 25 Mbit/s for time-triggered transmission and 5 Mbit/s for event-triggered transmission. TTP networks can contain up to 64 nodes and the cabling topology can be bus, star, or any combination of the two. Finally, TTCAN [14] is a further development of Extended CAN (version 2.0B), which like Extended CAN is limited to 1 Mbit/s.

3.1.5 Summary

	Feedback control	Discrete control	Diagnostics & Service	Infotainment & Telematics	Maximum Speed
CAN	primary use	primary use	primary use		1 Mbit/s
LIN		primary use			20 kbit/s
MOST				primary use	20 Mbit/s
FLEXRAY	primary use				10 Mbit/s
TTP/C	primary use				25 Mbit/s
TTCAN	primary use				1 Mbit/s

Table 1. Primary use of different busses in automotive applications

Table 1 shows the typical use of some different busses in automotive industry. As indicated, CAN is used in many different application areas. However, for safety critical control, CAN does not have the same abilities as Flexray, TTP/C, and TTCAN which offers of global time base and redundant networks. Furthermore, for simple nodes the CAN solution is more expensive than LIN.

3.2 High level protocols and communication software

High-level protocols and communication software have been introduced in automotive industry to address problems concerned with integration, configuration, and timing properties. The high level protocols span from proprietary representation of a given type of engineering data by a specific CAN identifier to powerful methods and tool sets automating large parts of the network configuration. Depending on application area, both proprietary and standardized protocols are in use.

In this section we will describe three different high-level protocols, Volcano, SAE J1939, and MOST. These protocols are intended for different areas of application within the automotive domain.

Volcano [15] is a communication concept used throughout the Volvo Car Corporation for managing network traffic. Currently Volcano supports the CAN and LIN busses. The basic concept in Volcano for communication between software components is signals, where a signal typically represents some engineering data. Through the Volcano API the underlying network technology is hidden from the application engineer. Moreover the engineer is not concerned with issues regarding assignment of signals to network frames. Instead this is done automatically ensuring signal timing requirements.

The Volcano concept also addresses vehicle manufacturer controlled integration of components developed by sub suppliers. This is done through the use of the Volcano API and by separate specification of the signals used by a component and the network configuration. The network configurator is provided by the integrator and specifies how signals are to be transferred over the network.

In the domain of heavy vehicles, the J1939 standard [16] for communication between components has been created by a number of vehicle manufacturers and sub suppliers. SAE J1939 uses standard CAN 2.0B for communication and communicates with 250 kbit/s. J1939 defines a transport service in the network layer. In the application layer the protocol defines data (signals e.g. vehicle speed) and the packaging of signals in frames. Moreover, J1939 also define the interaction between components, e.g. the interaction between engine and transmission during gear shifting. To provide for vehicle manufacturer specific functionality the protocol also allows some proprietary messages.

Both Volcano and J1939 addresses integration of sub supplier components, but the approaches differ. Volcano does not, as J1939, explicitly define assignment of specific signals to given frames. Instead, the assignment is resolved in the implementation phase. This makes it possible to do application specific network configurations that are optimal with respect to e.g., timing and bandwidth usage.

For vehicle infotainment systems, MOST, in addition to defining the low-level communication protocol, also defines architecture at the application level of a component connected to a MOST network. At the application level a MOST application such as e.g., an audio system is represented by a *device*. Devices are supported by the *system services*, which provide a standard interface to network management functions and services for sending and receiving data. A MOST device can on the top level logically be described by a set of function blocks, where a function block represents an application in the device e.g., a CD player or tuner. Moreover, each function block contains a set of functions, e.g., play and stop, which are visible to the rest of the MOST system. Function blocks interface other function blocks on the same device or devices connected to the network through services constructed from the system services.

By the definition of the application architecture devices connected to a MOST system are logically constructed in the same manner and can be interfaced in a consistent way.

4 Case Studies

4.1 Volvo Car Corporation

4.1.1 The car industry

Volvo Car Corporation (VCC) is a subsidiary of the Ford Motor Company, where it is one of the premium brands aiming at the upper end of the car market. The European premium car brands are driving the development of vehicle electronics, having both the demand for advanced functionality and the production volumes to support the costs associated with the introduction of new technology. The components developed for cars are often later used in other parts of the automotive industry. Cars are consumer products, and the customers tend to be sensitive not only to the functionality of the car, but also to how it feels and its visual appearance.

Cars are typically manufactured in volumes in the order of millions per year. To achieve these volumes, and still offer the customer a wide range of choices, the products are built on platforms that contain common technology that has the flexibility to adapt to different kinds of cars. As an example, the Volvo XC90, which appeared in 2002, is based on the same platform as four previous Volvos launched since 1998. This reduces the development cost, but also makes it possible to reuse the same manufacturing facilities and strengthens the brand image through an increased similarity between the models.

The component technology is to a large extent provided by external suppliers, who work with many different car companies (or OEMs, original equipment manufacturers), providing similar parts. The role of the OEM is thus to provide specifications for the suppliers, so that the component will fit a particular car, and to integrate the components into a product. Traditionally, suppliers have developed physical parts, but in modern cars they also provide software. As the computational power of the electronic control units (ECUs) increase, it will be more common to include software from several suppliers in the same nodes, which increases the complexity of integration.

4.1.2 Functionality

The driving factor behind the development is increasing demands on functionality. There are several classes of functionality, and in the following paragraphs we provide examples in each of them, that represent some of the largest future challenges for VCC.

Feedback control systems were one of the earliest uses for electronics in cars, and the early applications were engine control, ABS brakes, and vehicle dynamics. These areas are still developing, and one of the main challenges is to cope with new environmental constraints, in particular related to the reduction of the level of CO₂ emissions. The systems are refined in the sense that more and more sensors are added, and new modes of interaction are included, thereby increasing the overall complexity of the functionality.

Discrete control systems are also common in current cars, in particular in body electronics. Applications include driver information, security (locks and alarms), and lights. Due to the fact that the overall functionality increases, as well as the abilities of the owner to configure the car through various parameter settings, the complexity of the driver interface becomes a bottleneck. This is caused both by the physical space around the driver seat, and the ability of the driver to process information while driving the car. Novel ways of interaction is thus needed, but also more intelligent systems that in most cases can make correct decisions without driver intervention.

Safety critical control systems become more common as traditional mechanical solutions are replaced by electronics. For the functions currently implemented, there is always a natural fall-back solution if the electronics fail, but future by-wire systems may not have that possibility, which increases the need for fault-tolerance in the electronics and communication. The first such application is likely to be brake-by-wire, and later steer-by-wire will follow. The driving factors behind this development are that the cost and weight could be reduced, but also that it enables new control systems to support the driver, e.g. to enhance safety. Again, this means a considerable increase in system complexity.

Diagnostic systems provide information about the status of the vehicle. Initially, this was driven by legal requirements that mandated monitoring of emission related components, but it is also an important factor in increasing the perceived quality of the system. The diagnostic system consists of an in-car part and a workshop tool. The former is usually distributed to all the nodes of the on-board network, and consists of fault detection

routines and diagnostic kernels that interact with the workshop tool. As the number of sensors increase, so does the need for diagnostics, and there is also a wish to increase the intelligence of the on-board system, to e.g. detect the need for preventive maintenance so that the customer never experiences critical problems, and thereby gets a perception of high quality.

Infotainment systems implement entertainment functionality, extending from traditional radios to multimedia applications such as TV, video, and gaming, and also contains information functions such as navigation systems. As the number of devices for audio and video data increase in cars, sharing of input and output is essential to bring down cost and conserve space, and this means that complexity moves from hardware to software and communication.

Telematic systems are used in cars for wireless data communication with the world outside via a built-in mobile phone. The applications range from automatic emergency calls in case of an accident to Internet access, and many ideas exist for services that the car owner could be interested in. The area is still in its infancy, and the business cases are currently unclear, but the underlying technology is being developed rapidly.

As can be seen above, complexity is a keyword that must be handled in the development. (For an introduction to the nature of complexity in technical systems, see [17].)

4.1.3 Cost

In the car industry, the development cost is huge in absolute numbers, but still comparatively small in relation to the total variable cost of the production, or the investment in tooling. This means that it is usually profitable to invest in development cost to optimize the components, or to increase commonality between car models on the same platform. Since the cost of development is closely related to the complexity (i.e., the information that needs to be processed to describe the product), it is thus profitable to increase complexity to obtain more flexible components that can be used in many different cars.

For software, the cost relations are somewhat different. There is an indirect variable cost, in that the characteristics of the software influences the resource needs in terms of memory size and processing capability. This cost can to some extent be manipulated by optimizing the performance, but this makes the software more complex and thus the development more expensive. In the long term, Moore's law will make hardware increasingly cheap and thereby making it more profitable to optimize software development cost rather than hardware resource needs.

One way to decrease software development cost is to raise the level of abstraction when describing the functionality. At VCC, model based system development is being introduced [18], where the system is described using a tool chain based on UML, Statecharts, and data flow models. Code generation is then employed to reduce the cost of producing the final software. In a way, the complexity is moved from the specific applications to general tools that can be used over and over again. Another example is in network communication over the CAN buses. The Volcano system [15] provides tools for packing data into network frames, and for verifying the end-to-end communication timing to ensure the control performance.

4.1.4 Standards

As indicated above, the OEM's role is to integrate systems from suppliers into a product. This means that it is important to have well-defined interfaces so that the various systems fit together. Also, standards are important as a means to reduce cost of components by sharing development, and allow competition between suppliers. One area where standardization has been particularly vivid is in communication protocols. The following protocols are now used or planned by VCC:

- **CAN** is used for backbone control-oriented peer-to-peer communication.
- **LIN** is a low cost alternative for control-oriented master-slave communication. Originally developed at VCC, it is now an international standard.
- **MOST** is used for multimedia communication in the infotainment system.
- **Flexray** is expected to be used instead of CAN for safety-critical applications where fault-tolerance is needed.

Selecting a bus protocol is thus a trade-off mainly between cost, bandwidth, predictability, and fault-tolerance. Another area where standards are important is in diagnostics, where authorities mandate it so that they may check that a vehicle fulfils emission regulations, using a single tool.

The current development trends in automotive software also calls for increasing standardization of the software structure in the nodes. In particular, the use of code generation requires a clear interface between the support

software and the application, and the need to integrate software from different suppliers in the same node also calls for a well-defined structure. The node architecture (see Figure 1) includes several important components:

- **Operating systems** (RTOS) provide services for task scheduling and synchronization. Traditional real-time operating systems are usually too resource consuming to be suitable for automotive applications, and do not provide the predictable timing that is needed. Therefore the new standard OSEK has been developed. There are several suppliers of OSEK compliant operating systems.
- **Communication software** (Network Communication) provides a layer between the hardware and the application software, so that communication can be described at a high level of abstraction in the application, regardless of the low-level mechanisms employed to send data between the nodes. At VCC, the Volcano concept [15] is used for both CAN and LIN communication.
- **Diagnostic kernels** provide an implementation of the diagnostic services that each node must implement to act as a client towards the off-board diagnostic tool. It relies on the communication software to access the networks and on the operating system to schedule diagnostic activities so that it does not interfere with the application functionality.

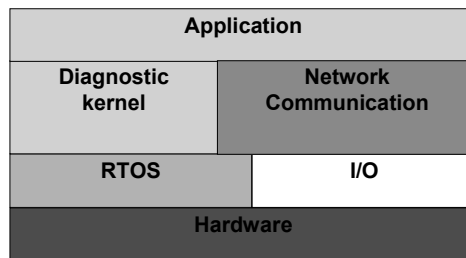


Figure 1. The node architecture.

All these components interact with each other and with the application, and must therefore have standardized interfaces, and at the same time provide the required flexibility. To conserve hardware resources, the components are configurable to only include the parts that are really necessary in each particular instantiation.

4.1.5 Architecture

An example of a contemporary car electronic architecture is that of the Volvo XC90 (see Figure 2). The maximum configuration contains about 40 ECUs. They are connected mainly by two CAN networks, one for powertrain and one for body functionality. From some of the nodes, LIN sub networks are used to connect slave nodes into a subsystem. The other main structure is the MOST ring, connecting the infotainment nodes together, with a gateway to the CAN network for limited data exchange. Through this separation, the critical powertrain functions on the CAN network are protected from possible disturbances from the infotainment system. The diagnostics access to the entire car is via a single connection to one ECU. The figure shows approximately how the ECUs are placed in various locations in the car. The partitioning of functionality is decided by the location of the sensors and actuators used, but also by the combinations of optional variants that are possible. If a car is sold with only a subset of the full functionality, the amount of physical hardware installed should be limited to the minimum necessary.

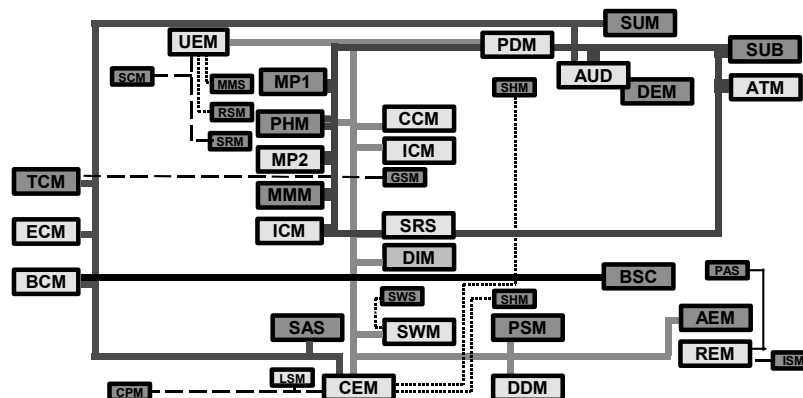


Figure 2. The electronic architecture of Volvo XC90.

In the future, when safety-critical functionality is introduced, the architecture will be extended with a Flexray based network, and this will again be isolated from the less critical parts using a gateway. Another important aspect is to create a more flexible partitioning. The main use for this is probably not to find the optimal partitioning for each car on a given platform, since that would create too much work on the verification side, but to allow parts of the software to be reused from one platform to the next. This puts even higher demands on the node architecture, since the application must be totally independent from the hardware, through a standardized interface that is stable over time. Therefore, further standardization work is needed, in particular for sensor and actuator interfaces.

4.2 Volvo Trucks

4.2.1 The trucking industry

The functionality in trucks has grown dramatically during the past 10 years. Earlier a separate stand-alone system for handling each function; today all these sub-systems are integrated into a single complete system. The development time has decreased and the vehicles are much more complex.

There are different demands depending on market in the truck industry. One example is the system voltage, which is 12V in the North American market and 24V in the rest of the world. Moreover, it is very common for the customers to choose their own driveline in the U.S., which puts special demands on OEMs to integrate engines and transmissions from various suppliers.

One way to obtain cost-effective solutions is to use a common platform covering both mechanical, electrical and software systems. The challenge is to have a shared platform and yet maintain the unique truck brands.

The market has changed from delivering vehicles, to providing a complete transport solution, which may include several different types of services, e.g. ‘around the clock’ support and online fleet management, etc. A complete transport solution could mean providing the full logistic routing system for a town.

4.2.2 Functionality

Trucks have many areas of use. The requirement on functionality can be split in three different segments.

- Goods transportation and logistics
- Building and construction
- City distribution and waste handling

‘Goods transportation and logistics’ means transportation of goods over long distances, e.g., food from southern Europe to Sweden. ‘Building and construction’ e.g. concrete trucks, crane trucks or gravel trucks operate under rougher conditions such as on a construction site, in mines or in roadworks. ‘City distribution and waste’ refers to local transport, for instance a garbage truck.

Feedback control systems were among the first electronic systems introduced in the beginning of the 80ies (e.g. electronic motor control and anti-lock braking system, ABS). These systems were complete stand-alone systems. Over time the systems became more complex and integrated. For example, the ABS system can command the engine not to apply the exhaust brake when ABS is activated. Furthermore, some sensors are shared between the systems and data can be exchanged through the vehicle network.

Discrete control systems include functions such as driver information, but also systems like climate control, exterior light, central locking, tachograph etc. With increasing amount of functionality and information on the network, the requirements on the Human Machine Interface (HMI) are getting increasingly complex. It becomes a challenge to support the driver in deploying the functionality the right way.

Superstructures. Trucks can be supplemented with superstructures, such as concrete aggregates, tipping devices, refrigerator units etc. One way to decrease the total cost of the vehicle is to have a well-defined interface between the electrical system and the superstructure, to allow, e.g., the crane equipment to control the engine speed to facilitate the right flow in the hydraulic pump.

Safety Critical control systems. The increase in safety critical systems has been striking in the last few years. One driving factor for this is to prevent personal and property damage in case of accident Earlier mechanical systems are being replaced/supplemented. Many systems are common with the car industry, for instance ABS and airbags. One difference is that the gross combination weight (weight of vehicle and trailer) is greater. VTC also have many variants and it is common that trucks have more than 4 wheels.

Recently the EBS (Electronically-controlled Brake System) and ESP (Electronic Stability Program) were introduced. In the EBS, an electronically controlled valve located close to each wheel applies individual braking force to each wheel. There is also a centrally positioned ECU that controls the vehicle's braking effect, both in the disc brakes and the engine brake. There is a back-up system using pressurized air.

The ESP system is a supplement to EBS. By means of a YAW rate sensor, a lateral accelerator sensor and a steering wheel sensor the new functionality can be added. ESP is an active safety-enhancement system whose task is to stabilize the vehicle, e.g., prevent jack-knifing when the driver makes a rapid avoidance maneuver.

Diagnostic system. An increasing part of the vehicle electronics has demands on efficient built-in diagnostics. Not only for the aftermarket, but also to check the mounting of components in production. The goal is to be able to check all components, not only ECU's but also very simple components like switches and bulbs¹.

There is an aftermarket tool that communicates with the control units. Through this tool it is possible to read out fault codes, sensor values etc. The tool is also able to run tests in the control units and download new software and parameters. Since the North American market requires support for 3rd part components, it must also be possible for the suppliers' aftermarket tools to co-exist.

Infotainment has not been very common in trucks, but because many drivers that are transporting goods far away are living in their trucks, the need has increased. Because of the low product volumes compared to the car industry it is likely that the truck industry for cost reasons will inherit from the car industry.

Telematics in trucks is mainly used for traffic information and tracking of goods. Volvo has its own telematics system called Dynafleet. Tracking of goods gives the possibility to enhance logistics. This type of system becomes more and more common due to the demand for just in time transports. Because of the growth of the Internet, the telematics systems will become more integrated in all business systems. By using the information on the truck location and data about the goods (e.g. the temperature in a cold transport) the transports can be planned with a positive effect both on economy and the environment.

4.2.3 Cost

Reducing costs is becoming more and more important. The vehicles offer more and more functionality but the cost per function is decreasing. Because the truck industry has lower volumes compared to passenger cars it is important to get the right trade-off between development cost and product cost. Systems that are fitted in all truck models, like the VECU (Vehicle Control Unit), must have a low product cost. But the systems that are only available in some variants produced in a couple of 1000s/year are less sensitive for product cost. Here is instead a gain to be made by using "general purpose" components that realizes more than one variant.

To get the best trade-off between development cost and product cost the architecture design is crucial. The architecture should identify which components are convenient to share with respect to cost. During the life cycle of a platform the development cost for software is higher than the development cost for hardware, but hardware costs have a more direct effect on the product cost.

4.2.4 Standards

A truck is essentially built by integrating system from many suppliers. Volvo Trucks has some in-house development of core control units that is important to give the truck the characteristic "feeling". Still there are a lot of systems that are not profitable to develop in-house. One such system is the ABS brakes. In this area there are a few big suppliers that have key-knowledge and their own development of systems. But still, Volvo Trucks is deeply involved in formulating requirements on the system and adding unique Volvo functionality. It is however important to use as much standard as possible to make the integration in different brands as simple as possible.

For heavy vehicle there are two standard protocols that are used in today's production:

- SAE J1939 [16]
- SAE J1708/J1587 [19], an older protocol. It uses RS485 as base and communicates with 9600 bit/s, and is mainly used in the vehicles for diagnostics and for some fall-back for J1939.

Other protocols that will be used or are under investigation at Volvo trucks include:

- LIN [5] will be used for sensor networks but also for sub-busses.
- MOST [8] is the optical ring bus that is used for infotainment by some manufacturers in the car industry
- Flexray [12] is under evaluation for safety critical systems.

¹ Compare to the semiconductor industry where diagnostics is included on the chips for production tests only.

- TTCAN [14]. Because TTCAN is built on the well used CAN protocol, TTCAN might be very interesting for control intensive vehicle systems.

4.2.5 Architecture

The market pull in the US for selecting truck components from different vendors introduces additional complexity, when more and more electronics is integrated in the trucks. To handle the electrical integration, Volvo Trucks uses the standardized protocol J1939. Since J1939 not only defines network and application layer services but also the interaction between vehicle components it partly acts as architecture, see Figure 3. Volvo trucks have also added some in-house strategies and guidelines to J1939 and for other electrical installations. Together with the standard this defines the architecture.

The advantage of using a standard is the relatively straightforward integration of components from different vendor suppliers. On the other hand there are some disadvantages, e.g. development or changes to the protocol can only be done through standardization work.

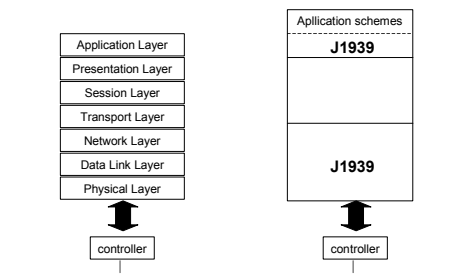


Figure 3. SAE J1939

J1708/J1587 is also used. It is used in parallel with J1939 for diagnostic, information sharing, and as a backup for J1939.

These standards, strategies and guidelines have been a good support when all stand-alone systems have been integrated to a distributed system. With software and communication it is now possible to create functionality that was not possible 20 years ago. Nonetheless, it also introduces some new problems. One example is start up and shut down of the systems, where all systems must synchronize through the network.

Despite the added complexity, the demand for reduced product development time has increased, and at the same time has the demands on decreased product cost also increased. To be able to reduce the development time it is important to find new solutions. One way is to use a reference architecture that covers all products and include both SW/HW. This will also set demand on new tools that can handle complex system models in real time. Real time because there will be a lot of persons working in parallel with the model. Because Volvo Trucks is a global organization with product development on four sites, it is also important that the tools support this way to work. A common misunderstanding is that the high product development cost is related to HW. This is usually wrong. It is therefore very important to have an architecture that supports both hardware and software. This gives the possibility to have a high degree of re-use between the products. This saves both product development time and cost. Of course, this will also give a profit in higher quality.

To increase the possibility to reduce the number of physical control units, it is important to look at the total system instead of the physical control units. The boundaries between the systems will be erased and functions can be deployed into the control unit that is closest to the sensor/actuator.

The superstructure interface must also be included into the architecture. A well-defined interface is believed to decrease the cost and time for adding superstructures. This is believed to increase customer satisfaction and thereby profit for the company.

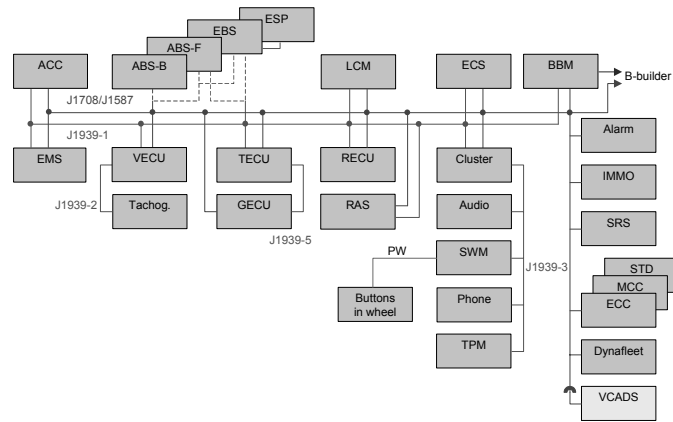


Figure 4. Volvo FH electronic architecture.

4.2.6 Conclusion

The progress in the last ten years has moved VTC vehicles from centralized computer systems to distributed systems, and much functionality has been added. This has of course increased the complexity and together with demands on a shortened product development time and increased quality, there is a need not to re-invent the wheel. One way to handle this situation is to use reference architectures supported by tools and better methods for product development.

4.3 Volvo Construction Equipment

Volvo Construction Equipment, VCE, develops and manufactures a wide variety of construction equipment vehicles, such as articulated haulers, excavators, graders, backhoe loaders, and wheel loaders. The products range from relatively small compact equipment (1.4 tons), to large construction equipment (52 tons). VCE is divided into product companies with focus on one type of equipment, and which typically manufactures product lines of similar products e.g. excavators, or wheel loaders.

Compared with passenger cars and trucks, construction equipment vehicles are equipped with less complex electronic systems and networks. Also, the focus in product development is somewhat different. The products are to be used in construction sites, and the most important aspect of the vehicle is to provide a reliable machine to increase production. A customer of passenger cars, on the other hand may be interested in a number of styling attributes related to the look and feel of the car, whereas the dominant requirements for customers of construction equipment are relate to production goals. The requirements for reliability and robustness are equally high in both cases, but styling requirements are typically low for construction site machinery.

In-vehicle electronic systems and networks are an important part of the construction equipment product and are crucial to provide end-user functionality, such as automatic gearbox, as well as providing diagnostic and service functions. Using a distributed electronic system also accommodates functions that reduce the cost of the vehicle e.g. reuse of sensors and displays, and adaptive solutions to accommodate cheaper mechanical parts.

4.3.1 Functionality

Here we describe today's situation in functionality requirements for construction equipment at VCE. To each class of functionality we present some major drivers and examples.

Feedback Control. The main feedback control functionality in VCE products includes control of engine, gearbox, retarder brake, differential lock, and engine cooling fan. Besides engine control, the automatic gearbox is a complex feedback control system that can include control of clutches and brakes for the gear pinions as well as converter, lockup, and drop box. The functionality for an automatic gearbox includes logics for when to shift gears, minimization of slip, avoidance of hunting, various efficiency optimizations, and self-adapting solutions to accommodate a variance of mechanical properties. There are also distributed control functions that synchronize engine speed for good comfort in shifting gears. Feedback control systems also include the cooperation of brakes to minimize wear e.g. the cut in of a retarder brake, or exhaust brake.

Discrete Control. Like in the truck case, discrete control systems include control of driver information, wipers, lamps, and other on-off type devices. The challenges arise due to configuration issues rather than constructing a functional system.

Diagnostics and service. Diagnostic functions are used to determine status and operational history of electronic components. Some diagnostic functions reside in the on-board software and some in service tools. On-board diagnostic functions implement criteria for faults, and can send fault codes via the network. Diagnostic functions also include logging functions to store operational data e.g. fault history or general operation statistics on buffers, network load, or sensor input. A service tool (a PC with service applications) can be connected to the vehicle network via a service connector. The service tool can run tests to diagnose faults either by invoking on-board functions, or by running test programs to verify functionality.

The service tool can, thus, extract diagnostic data for a service technician, but also download new software or parameters into the vehicle control units. The tool can be connected to a central configuration database that holds information on compatibility between versions and configurations. When downloading software or parameters, the central system is updated to reflect the current configuration. Also, the operational data can give valuable feedback to the development department.

Infotainment. As mentioned, customers of construction equipment purchase products with the intent of increasing production at construction sites. There is little incentive to pay for entertainment systems and therefore VCE does not provide any such systems today. There are demands for information systems, but this does not usually include general systems such as Internet connection and video. Instead, tailored applications to increase production are requested.

Telematics. In the field of construction equipment, telematics can be used to achieve the increased production in several ways. The challenge is to accommodate telematic functions in a cost efficient way. Construction sites could be located in remote regions and wireless technology like satellite or radio communication must be considered as opposed to the car industry where mobile phone communication seems to be sufficient. Fitted equipment and cost for communicating over commercial networks is expensive and may not be crucial to every customer.

Applications running on an office desktop computer can be developed to access information in a fleet of vehicles and to present and analyze data far away from the actual vehicles. Examples are fleet management systems, maintenance systems, and anti-theft systems. A fleet management system can provide information to increase efficiency of a fleet of vehicles. A maintenance system could, for instance, report on status of mechanically worn components like brakes and thereby reduce maintenance cost.

The trend towards telematic systems is very strong and a variety of systems are expected to be available in a few years.

4.3.2 Cost

The electronic systems in VCE products are, in total, less complex and are sold in smaller volumes compared to cars or trucks. The final products are also much more expensive than passenger cars, but the electronic content is a much lower percentage of the total product cost. Therefore, the cost for developing electronic systems in VCE is relatively large compared to the variable costs for production, at least compared to VCC and VTC. This implies that it is usually not profitable to optimize hardware to a large extent since it would generate increased complexity of the system and increased development cost e.g. need for configuration handling.

Accommodating commonality is considered very beneficial because VCE has a large number of products (although sold in smaller volumes). Reuse is beneficial for both hardware and software as it directly affects development cost. This results in VCE focusing heavily on commonality, even though it may mean that a lower-end product is produced with some spare resources in terms of electronics.

Compared to both cars and trucks, VCE builds on-board electronic systems that have a lower development cost, smaller volumes, and lower overall complexity.

Trends indicate that the electronic content (and complexity) will increase quite rapidly in construction equipment over the coming years. The situation for construction equipment is likely to resemble the situation of trucks today and later maybe the situation for cars. However, the volumes will not equal those of trucks or cars. VCE have fewer products with higher price and will thereby not focus as much on optimizations, but rather at handling complexity and commonality. Commonality can also help reducing development time

To customers of construction equipment, providing efficient maintenance and service is probably as important as providing a functional product. This is because of the long term service contracts where 80% of the vehicles are in use after 20 years.

VCE, like VCC and VTC, also anticipate a trend of increasingly cheap hardware and will focus on optimizing software development cost rather than optimizing hardware content in products i.e. designing electronic systems for a minimum slack of hardware such as memory and processing power.

4.3.3 Standards

VCE uses the same standards for communication protocols as VTC, i.e. SAE J1939 / CAN and SAE J1587 / J1708 (see Section 3.2 and 4.2.4 for details).

4.3.4 Architecture

The focus of VCE's electronic architecture effort is mainly concerned with assuring system properties that are judged essential to provide the "right" product (a good business case) and to have an architecture that supports working with platforms. System properties include scalability to support product variation, reusability and partitioning of SW components to lower development cost, as well as safety and reliability issues.

This means that methods for designing SW in control units and handling communication is also considered architectural issues. The goal is to have an architecture that helps designing on-board electronic systems with respect to the wanted system properties that are identified as the most important for the VCE business case.

As temporal behavior is considered very important, VCE uses a design process [20] that focuses on high-level design and temporal attributes of the system. VCE use the operating system Rubus, which provides a configuration tool allowing specification of temporal constraints, communication and synchronization. This method separates the design of timing characteristics from the design of functionality, and enables early verification of temporal behavior.

Partitioning, scalability, and commonality. VCE has a different setting than VCC and VTC in that there is almost no use of externally developed vendor control units. This leads to the possibility to use the same software component model, operating system, and reusing software components. By doing this, the partitioning of functionality is likely easier than in the case of a network with many differently developed control units. Easy partitioning gives the possibility to scale the system with respect to hardware and optimize hardware content in a specific product. For instance, a low-end product with fewer features requires less hardware resources, and can be realized by placing software components on other nodes and thereby reduce the number of control units. This means that the number of control units can be chosen according to resource needs for a given configuration of a product. Thus, the architecture is reused, but the numbers of ECUs differ between products (see Figure 5).

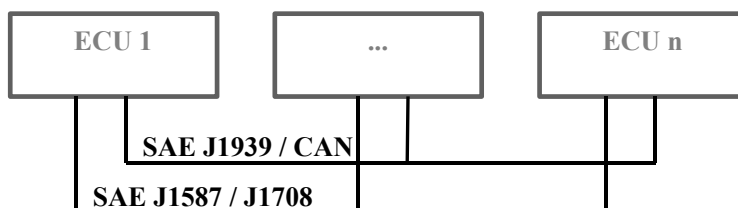


Figure 5. VCE Network Architecture

To have a situation with a large degree of in-house developed control units also give benefits in terms of commonality. The use of common design methods for control units gives in itself reduced cost, but also helps in decreasing the complexity of the system. (The overall information that must be processed during development is decreased). Reusing infrastructure like drivers, communication components and other software components is a goal in commonality that can be met as long as common design methods are used.

On the other hand, VCE platforms are used in a wider variety of different products. Facilitating commonality in very different products, such as an excavator and an articulated hauler presents a different situation compared to VTC or VCC.

The different situation in VCE is caused by lower demands for many variants. While trucks are delivered in numerous configurations, construction equipment often provides quite few. Examples are an optional tachograph, or an optional enhanced suspension system.

In the car and truck industry, there are several vendors that specialize in certain systems, deliver in large numbers, and can provide competitive prices. VCE is likely to move towards the VTC situation with products

including external vendor nodes. This will likely generate a need for new methods for accommodating scalability partitioning commonality.

Furthermore, the trend towards supplying services rather than vehicles could be relevant to VCE. Currently the trend of increasing rental products could be seen as a step towards providing services, as VCE accepts responsibility for up time of products.

5 Analysis

The different business demands on cars, trucks, and construction equipment lead to different focus in the design effort of the respective vehicles. In this section we present analysis of the correlation between different business and product characteristics and key properties of the resulting network architectures. In Table 2 below, the business and product characteristics are given for the three different organizations.

Organization	VCC Volvo Car Corporation	VTC Volvo Truck Corporation	VCE Volvo Construction Equipment
Annual production volume (Order of magnitude)	10 ⁶	10 ⁵	10 ⁴
Products	~8 products	~8 products	>50 products
Platforms	3	3	8
Number of physical configurations per product	Many	Very many	Few
Amount of information	Huge	Very large	Moderate
Standards application level	Proprietary (Volcano)	J1587 – J1939	J1587 – J1939
Number of network technologies	~4	2	2
Hardware optimization	High	Medium	Low
Openness	None	High	Some
Safety critical	Yes	Yes	Yes
Advanced control	Yes	Yes	Yes
Infotainment	Much	Some	None

Table 2. Business characteristics for each organization.

The case study has shown that the product volumes are different for the three organizations, and thereby also the focus on fixed cost and hardware optimization. The willingness to reduce fixed cost at the expense of variable cost increases with the product volume. One way of achieving a reduced fixed cost is to optimize vehicle hardware content to include a minimum of resources. Software components are not subject to the optimization profit, due to increase in variable cost but almost no gain in fixed cost. VCC that produces vehicles in the range of 10⁶, can benefit to a larger extent by reducing fixed cost and therefore an increased cost for design of optimal hardware is more profitable than for VCE that has volumes in the range of 10⁴.

The number of vehicle models sold for the respective organizations is indicated in the table by ‘Number of products’. The number of products and the product volume directly affects the profitability of reusing components i.e. commonality, and this also includes software components. VCE has a high number of products, but smaller volumes, while VCC and VTC have high volumes. Thus, the effort to achieve commonality is emphasized in all the three organizations.

The ‘Number of physical configurations’ means the different options of network topologies that can be fitted in a certain product. VTC products, which may be configured in many ways, achieve a high extendability and can facilitate change of configuration in the aftermarket or adding superstructures by other vehicle developing organizations. The large amount of data and the many configurations put high requirements on management of different components, e.g., ECUs, connected to the network in different variants.

The large amount of information together with the requirements for optimization in the VCC case, imply that using several tailored networks for specific needs can be profitable. The use of LIN networks provide a cost effective network for handling locally interconnected lights and switches, and a high bandwidth MOST network serves the needs of infotainment applications. Especially for VCE, the increase in development cost for designing tailored networks for a certain purpose is deemed unprofitable and this is reflected in the small number of network technologies.

The use of in-vehicle networks open up the possibility for efficient diagnostics and service, by the ability to extract information via the bus. Although the amount of information varies in the three cases, the needs for diagnose and service are emphasized in all three organizations. The reason is that there is enough information in all systems to substantially ease analysis of the distributed system.

As mentioned, VTC needs to facilitate superstructures, and this is reflected in the large number of physical configurations. In order to support extensions to the network by other parties, standardized communication interfaces like SAE J1939 and J1708/J1587 are used. VCE uses the same standards, since both VTC and VCE belong to the Volvo group and there is commonality in service tools.

Safety aspects on networking include that messages are transferred with correct timing and without being corrupted. One step towards guaranteeing the real-time properties and integrity of messages related to safety critical functionality is to use communication protocols with support for deterministic and analyzable timing behavior. Examples are CAN and LIN and the coming protocols Flexray and TTCAN, which are all used or evaluated by the three considered organizations. Another step is to use several networks that are interconnected through gateways. Safety critical communication can thereby be separated from communication that is not trusted to the same degree.

6 Conclusion

In recent years, networking issues have become more and more important in the design of vehicle control systems. One of the initial driving forces for introduction of communication networks in automotive vehicles was to replace the numerous cables and harnesses and thereby reduce cost and weight. Today it is possible using software and networking to create new functionality that was considered unfeasible some ten years ago.

We have presented case studies of the context, use, and requirements of networking in construction equipments, trucks, and passenger cars. Furthermore we have identified challenges with respect to functionality, cost, standards, and architecture for development of vehicles. Based on these case studies with different business and functionality demands, we have provided analysis of the design principles used for the communication architectures in these domains. Despite a common base of similar vehicle functionality the resulting network architectures used by the three organizations are quite different. The reason for this becomes apparent when looking at different business and product characteristics and their affect on the network architecture. An important lesson from this is that one should be very careful to uncritically apply technical solutions from one industry in another, even when they are as closely related as the applications described in this paper.

7 Further information

Listed below are links to sites where detailed information about the presented technologies can be found:

OSEK (www.osek-vdx.org)

CAN (www.can-cia.org)

LIN (www.lin-subbus.org)

MOST (www.mostnet.de)

Flexray (www.flexray-group.com)

Rubus (www.arcticus.se)

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