Correlating Bussines Needs and Network Architectures in Automotive Applications – a Comparative Case Study

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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 buses 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 equipments. Based on these case studies with different business and functionality demands, we will provide an analysis identifying commonalities, differences, and 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 the in-vehicle networking is commonly 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 some ten years ago, both with respect to cost and functionality.

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 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 product variation, branding, super structures, and extendability in aftermarket. This leads to 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; 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 the presentation of three case studies covering much of automotive industry and describing the business context and demands for automotive networking, together with an analysis of the relation between businesses needs and architectural design issues of networking in automotive vehicles.

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

2 Challenges

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. Several 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. 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 as well as software properties, such as version number and bus load. Service functions provide means for updating the electronic system by downloading new software and to provide feedback of vehicle operation. Because of the large amount of retrievable information, solutions are needed for automatic, or at least tool supported, diagnoses and service.

Infotainment. Information and entertainment systems are sometimes requested in today's vehicles. 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] refers to 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 develope 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) [3] standard that has provided the vehicle industry with cheap CAN 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.

2.4 Architecture

The IEEE has the following definition of architecture [4]: *"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.

Aspects of maintenance must 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 Case Studies

3.1 Volvo Car Corporation

3.1.1 The car industry

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. 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.

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.

3.1.2 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 the industry.

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 CO_2 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, 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, 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 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 [5].)

3.1.3 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 influence the resource needs in terms of memory size and processing capability.

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 [6], 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 [7] provides tools for packing data into network frames, and for verifying the end-to-end communication timing to ensure the control performance.

3.1.4 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. One area where standardization has been particularly vivid is in communication protocols. The following protocols are now used or planned by VCC:

CAN [3] is used for backbone control-oriented peer-to-peer communication. It provides predictable timing and moderate bandwidth (up to about 500 kbit/s), and many microprocessors are available with built-in support circuits.

LIN [8] is a low cost alternative for control-oriented master-slave communication. Originally developed at VCC, it is now an international standard. The bandwidth is low (up to about 20 kbit/s), but controller circuits are considerably cheaper than for CAN.

MOST [9] is used for multimedia communication in the infotainment system. It is based on optical fibre technology, and provides bandwidth up to about 20 Mbit/s, with timing characteristics and services optimized for infotainment applications. However, the cost for circuits is substantially higher than for CAN or LIN.

Flexray [10] is expected to come in use instead of CAN for safety-critical applications where fault-tolerance is needed. The protocol is time-triggered, which makes it suitable for implementing control functions with high demands on jitter, and for redundancy.

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 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 exist.

Communication software 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 [7] 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.

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.

3.1.5 Architecture

An example of a contemporary car electronic architecture is that of the Volvo XC90 (see Figure 1). 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.

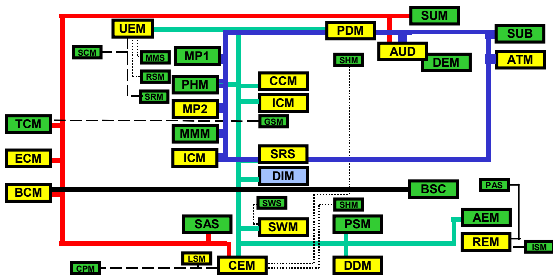

Figure 1. The electronic architecture of Volvo XC90.

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.

3.2 Volvo Trucks

3.2.1 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.

3.2.2 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 etc. 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 functionally 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 manoeuvre.

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 bulbs[1].

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 supplier’s 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

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

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 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.

3.2.3 Cost

Cutting costs is becoming more important. The vehicles offer 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 must have a low product cost. On the other hand, systems that are only available in some variants produced in a couple of 1000s/year are less sensitive for product cost. Here instead, is a gain to be made by using "general purpose" components that realizes more than one variant.

3.2.4 Standards

A truck is essentially built by integrating systems from many suppliers. Volvo Trucks develops core control units, but there are a lot of systems that are considered unprofitable 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.

It is important to agree on standards to make the integration in different brands as simple as possible. For heavy vehicle there are two standard protocols that Volvo Trucks is using in today's production:

SAE J1939 [11] use standard CAN 2.0B for communication and communicate with 250 kbit/s. J1939 also define data (signals e.g. vehicle speed) and the packaging in frames. J1939 also define how some control functions, e.g. the interaction between engine and transmission under gear shifting. J1939 also allows for some proprietary messages.

SAE J1708/J1587 [12] is an older protocol that has been available for a long time. It uses RS485 as base and communicates with 9600 bit/s, and is used in the vehicles for mainly diagnostics and for some fallback for J1939.

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

LIN [8] will be used for sensor networks but also for sub-busses.

MOST [9] is the optical ring bus that is used for infotainment by some manufacturers in the car industry

Flexray [10] is under evaluation for safety critical systems.

TTCAN [13] is a further development of CAN 2.0B. TTCAN offers services, such as global time and scheduling of communication. Because TTCAN is built on the well used CAN protocol, TTCAN might be very interesting for control intensive systems.

3.2.5 Architecture

The market pull in the US for the option to select truck components from different vendors introduces additional complexity, when deciding on a feasible architecture. To handle the electrical integration, a couple of OEMs and vendor suppliers have created a standard for communication between components in vehicles; the J1939 that is based on CAN.

Since J1939 defines how the interaction between some components should be performed e.g. controlling the engine speed, it acts partly as architecture. 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 is the proportionately simple way to integrate components from different vendor suppliers.

To be able to meet requirements on reduced 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.

The superstructure interface must also be included into the architecture. A well-defined interface decreases the cost and time for adding superstructures.

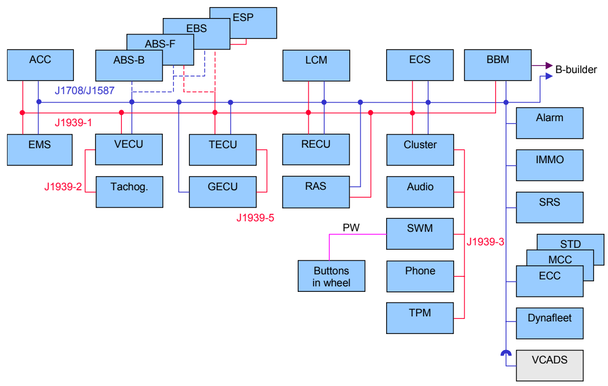

Figure 2. Volvo FH electronic architecture.

3.2.6 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. The complexity of the systems is increasing at the same time as demands on shortened product development time and higher quality is increasing. One way to handle this situation is to use reference architectures supported by tools and better methods for product development.

3.3 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 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 related 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.

3.3.1 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 typically includes control of engine, gearbox, retarder brake, and differential lock. 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. 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 criterions 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. The service tool can run tests to diagnoze faults either by invoking on-board functions, or by running test programs to verify functionality, but also download new software or parameters into the ECUs. 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.

Infotainment. As mentioned, customers of construction equipment purchase products with the intent of increasing production at construction sites. There is currently 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. 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 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.

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

3.3.2 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 generally 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

3.3.3 Standards

VCE uses the same standards for communication protocols as VTC, i.e. SAE J1939 / CAN and SAE J1587 / J1708 (see Section 3.2.4 for details).

3.3.4 Architecture

The focus of VCE's electronic architecture effort is mainly concerned with assuring system properties that are judged essential to provide a good business case. 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 [14] 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 control units. This leads to the possibility to use the same software component model, operating system, and to reuse software components. By doing this, the partitioning of functionality is likely easier than in the case of a network with control units from many vendors. 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. Thus, the architecture is reused, but the numbers of ECUs differ between products. (see Figure 3)

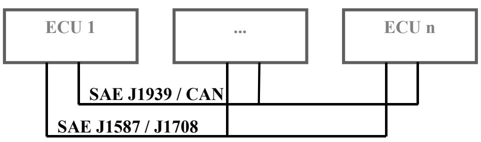

Figure 3. VCE Network Architecture

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.

For the future, VCE is likely to move towards the VTC situation with products including external vendor nodes. A new approach to accommodate scalability, partitioning and commonality will be required. Furthermore, the trend towards supplying services rather than vehicles is relevant to VCE. Currently the trend of rental products can be seen as a step in this direction, as VCE accepts responsibility for up time of products.

4 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 1 below, the business and product characteristics are given for the three different organizations.

	VCC	VTC	VCE
Annual production volume, order of magnitude	10^6	10^5	10^4
Products	~8	~8	>50
Platforms	3	3	8
Number of physical configurations per product	Many	Very many	Few
Amount of Information	Huge	Very large	Moderate
Standards - Application level	Propriet. Volcano	J1587 J1939	J1587 J1939
Number of network technologies	~4	2	2
Hardware optimization	High	Medium	Low
Openess	None	High	Some
Safety critical	Yes	Yes	Yes
Advanced Control	Yes	Yes	Yes
Infotainment	Much	Some	None

Table 1. 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 10^6, 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 10^4.

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.

5 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 passenger cars, trucks, and construction equipment. 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.

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