Business Situation Reflected in Automotive Electronic Architectures: Analysis of Four Commercial Cases

Joakim Fröberg
Volvo CE Components AB
SE 631 85, Eskilstuna, Sweden
+46 16 152404
joakim.froberg@volvo.com

Kristian Sandström
Mälardalen University, IDE
SE 721 23, Västerås, Sweden
+46 21 101518
kristian.sandstrom@mdh.se

Christer Norström
Mälardalen University, IDE
SE 721 23, Västerås, Sweden
+46 21 101464
christer.norstrom@mdh.se

ABSTRACT
Automotive vehicle electronic systems are developed facing a complex and large set of inter-related requirements from numerous stakeholders, many of which are internal to the Original Equipment Manufacturer, OEM. The electronic architecture, of the product, or its structure and design principles, form an equally complex construct; including technology and methods, which ultimately should be chosen to optimally support the organization's own business situation.

In this paper, we have analyzed the relationship of four automotive electronic architectures to their respective business requirements and business context. The study shows four functionally rather similar products with computer controlled power train, body functions, and instrument. In the light of the business situation, we explain the solutions and why design principles are pursued. The analysis shows that despite a common base of similar vehicle functionality the resulting electronic architectures used by the four organizations are quite different. The reason for this becomes apparent when looking at different business context and business requirements and their affect on the architecture. Differences in business situation drive the use of different methods for integration, different standards, different number of configurations, and different focus in the development effort. Some key parameters in business situation affecting architectural design decisions are shown to be product volume, size of market, and business requirements on openness and customer adaptation.

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 work. Understanding the requirements from the business case is the key to choosing architectural solutions.

Keywords
Automotive, Electronic Architecture, Case-Study, Requirements

1. INTRODUCTION
Designing a complex computer system such as an in-vehicle electronic system is a process of choosing solutions that best meets the huge set of, often conflicting, requirements. Modern in-vehicle electronic systems must provide functions and exhibit properties to support several of the OEMs business processes. In fact, the main part of the requirements does originate from the OEM business processes such as production, aftermarket support, variant handling, verification, and commonality efforts. The desired functions can be very different in nature, and the desired properties can be conflicting. Functional solutions span from web- to control applications and the desired properties call for radically different architectures and technologies.

Thus, the automotive industry seeks an improved way of synthesizing all the requirements into an electronic architecture that meets the diverse requirements from the business case as closely as possible.

In this paper, we present key findings from four case studies with the intention of describing the situation for commercial vehicle electronics developers; both the diverse requirements and the solutions in terms of architecture; as well as analyzing the relation between requirements and solutions. The inspected electronic architectures are all Volvo brand vehicles; Volvo Construction Equipment (VCE), Volvo Trucks (VTC), Volvo Busses (VBC), and Volvo cars (VCC). The three first are companies within the Volvo Group, and Volvo Cars is a subsidiary of Ford Motor Company.

Out of the complete result of the study, we have listed the key figures into tables and attempted analyzing the relations. Further, with the driving requirements in mind, we have commented on how several of today's trends address the studied OEM challenges.

The first contribution of this paper is the analysis of how key parameters in business situation affect OEM choices in architecture. The second contribution is the analysis of the relation between OEM business requirements and some of today's trends in automotive industry.

Section 2 contains the key figures of the study (2.1), the analysis of relations between architectural solutions and key figures (2.2), analysis of other findings (2.3), and summary of analysis (2.4). Section 3 presents comments to some of today's trends in automotive electronics development with respect to the requirements outlined in this study. Section 4 concludes the paper.

2. THE FOUR CASES ANALYSED
The four cases were investigated with respect to background, functionality, cost, standards, integration, and architecture. Informants from the four organizations were interviewed in a series interviews and common workshops where all informants participated. The complete data from the study is presented in [1]. Here, we outline the characteristic findings from each case.

2.1 Key Figures from Study

In order to compare the cases and analyze the result we have extracted a number of key parameters in business context, business requirements, and resulting architecture from the case studies and listed them in the following tables. Using this data, we present analysis of the correlation between key parameters in business context, business requirements and electronic architecture solutions.

Table 1. Business context for each organization

Organization **Business context**	**VCE** **Constr. machines**	**VTC** **Trucks**	**VBC** **Buses**	**VCC** **Cars**
Production volume	~15000	~80000	~9000	~400000
Products	~35	~8	7	~8
Vehicle platforms	4	3	2	3
Organization size electronics	~45	~140	~30	~400
Market share	~5%	~15%	(~15%)	~1%

VTC product volume includes only the Volvo brand trucks. 'Products' is the number of models that have an own model name. 'Vehicle platforms' is the number of physical platforms used to achieve all the products. The 'organization size' includes the number of people who are working with development of electronic systems. The 'Market share' measure is an estimate of the percentage of the market that the OEM is in; the whole markets of construction equipment, trucks, busses, and cars respectively. The Volvo bus figure of 15% is related to only the European market, which is VBCs strongest market, and the percentage of the world market should thus be considerably lower.

Table 2. Business requirements for each organization

Organization **Business Requirements**	**VCE**	**VTC**	**VBC**	**VCC**
Product variants	Few	Very many	More than very many	Many
Commonality	High	High	High	High
Hardware optimization	Low	Medium	Medium/ Low	High
Openness	Some	High	High	None
Customer adaptation	None	Much	Very much	None
Safety critical	Yes	Yes	Yes	Yes
Advanced control	Yes	Yes	Yes	Yes
Infotainment	None	Some	Some	Much
Telematics	Little	Much	Much	Some

Table 2 constitutes the key business requirements for the different organizations as elicited from the case studies. 'Product variants' indicate the diversity of vehicles requested by customers. 'Commonality' is the focus of the own organization to commonalize components between products. The requirements for 'Hardware optimization' are an estimate of the level of optimization that the organization desires for target products. 'Openness' reflects the requirements on ability to be open and integrate vendor components such as an engine Electronic Control Unit (ECU). 'Customer adaptation' refers to the whishes of customers to add or change functionality (often by adding ECUs) to the existing system. 'Safety critical', 'Advanced control', 'Infotainment', and 'Telematics' measures represent relative estimates on the requirements for the respective functionality.

Table 3. Architecture solutions for each organization

Electronic Architecture	**VCE**	**VTC**	**VBC**	**VCC**
Physical configurations per product	Few	Very many	More than very many	Many
Network information	Moderate	Very large	Very large	Huge
Standards – network application level	J1587 – J1939	J1587 – J1939	J1587 – J1939 Proprietary (Volcano)	Proprietary (Volcano)
Network technologies	2	2	2	~4
Internally developed nodes	All – 2-5	Few - 4-5	Few - 2-3	Very few – 1-3 (partly)
Ext node suppliers	0	~6-8	~6-8	>10

Table 3 presents the architecture solutions used by the different organizations. The 'Physical configurations per product' is the number of possible variants in ECU, sensor, and actuator configuration. The 'Network information' is the amount of information on the vehicle network. 'Standards – network application level' denotes the standard used for specifying syntax and semantics of network messages on the application level. The number of 'internally developed nodes' refers to nodes whose functionality is implemented internally and not necessarily the hardware. In the VBC case, the number of internal nodes is what is developed for the chassis, and the number gets higher if VBC also develops the bus body.

2.2 Analysis of Architectural Solutions

Here we analyze the parameters presented in the architecture table (Table 3) in relation to the business context and business requirements.

Physical configurations per product - A high number of vanriants in physical products is not something that an OEM desires. The aim is always to keep the configurations as few as possible to ease operations and thereby lower cost.

The VTC high number of physical configurations is likely in correspondence to requirements on openness and customer adaptation. VTC customers require very high openness of system with a configurable drive train that can include non-Volvo engines and gearboxes with non-Volvo electronics. Further VTC delivers to body builders as indicated by the high measure on customer adaptation.

VBC has a similar situation as VTC, but with even higher demands from customers that are body builders and add chassis and superstructures to the vehicle. The superstructures include much electronics and this drives a need for numerous interfaces to the system delivered by VBC. Thus, VBC shows an even higher measure than VTC in the number of physical configurations.

VCC that does not have high requirements on openness and customer adaptation, show a smaller number of configurations, but still VCC has many configurations. This high measure has more to do with the requirement for hardware optimization as many configurations can provide just that. The high VCC product volume is the underlying factor producing the high requirements for hardware optimization.

VCE who has neither the volume to drive requirements for high hardware optimization or the direct requests from customers to provide an open system, shows no variants in ECU configuration and only few sensor/actuator configurations. Instead VCE has a relatively high number of vehicle platforms and products, which suffices to provide a sufficient number of configurations to meet customer requirements.

Network information - VCC show the highest amount of network information. VCC also shows requirements for much infotainment functions and some telematic functions, which partly explains the high amount of network information. Even so, the stringent requirement on hardware optimization is likely to affect this measure. Physical components can, to some extent, be replaced or reduced by the use of computer functionality and, thus, reducing product cost and weight of the car. The product volume and the requirements for hardware optimization amplify the arguments for introducing these functions as they become available and, thus, yield an increase in network information.

The amount of functionality can be expected to be in relation to the amount of network information. Thus, supposedly the requirements for functionality, including safety critical control, advanced control, infotainment, and telematics, drive the amount of network information. The requirements for hardware optimization are, in this sense, requirements for functionality that removes or reduces physical components.

This reasoning corresponds well to the situation of VCE, and VTC, which have moderate and vary large amounts of network information respectively. VBC, however, shows a low volume and correspondingly low requirement on hardware optimization, at the same time as having equal requirements on functionality as VTC otherwise. The explanation for this seems to be the tight relation between to VTC with many systems reused.

Standards – Network application level - VTC customers require freedom of choice in use of non-Volvo engines and gearboxes that come with ECUs and network interfaces. SAE J1587 was the used standard for diagnostics in the US market and is therefore required to be supported [4]. Because of the situation with vendor ECUs and body builders, the distributed applications cannot be governed by a VTC specific method. SAE J1939 is a standard that addresses problems in integrating ECUs from different vendors in that it defines syntax and semantics of signals.

VCC is a passenger car company and that segment of the vehicle industry does not have standards that cover OEMs and suppliers, because car customers do not require the ability to integrate a certain vendor engine. Instead, VCC is free to choose tools and methods to accommodate a network application level interface as seem fit. VCC uses the Volcano concept for two reasons: (1) Volcano supports integrating vendor ECUs while allowing VCC to manage the network traffic. (2) Volcano also facilitates automated optimization of network usage by packing signals into frames to save bandwidth with guaranteed timing. (1) is desired because of the high number of external node suppliers. Having a communication component that provides communication services as specified by VCC, provide management of a network with many different ECUs. (2) is desired because it provides VCC with good control of bandwidth and timing which, in turn, provides benefits. Firstly, high network efficiency addresses goals in hardware optimization which is high in the VCC case. Predictable timing is beneficial for developing and assuring safe and reliable functionality.

Network technologies - 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 worth the added development effort. The use of LIN networks [2] provide a cost effective network for handling locally interconnected lights and switches, and a high bandwidth MOST [3] network serves the needs of infotainment applications.

VTC with a relatively high product volume has not chosen to introduce low cost or infotainment networks. Evidently, the benefits have not been deemed large enough for these specialized networks compared to the development cost and increased complexity of the system. Also for VBC and VCE, the increase in development cost for designing tailored networks is deemed unprofitable and this is reflected in the small number of network technologies.

Although additional network technologies mean added complexity, LIN for example can lower complexity due to its ability to achieve variants without the need for ECU I/O variants or software variants. Also, as is the case with VTC, VCE, and VBC there are commonality goals within the organization that strongly affect the choices in network technologies.

Internally developed nodes - The number of internally developed nodes differs in the four cases. VCC shows very few internally developed nodes, while VCE develops all nodes internally. The reason for this difference is mainly the differently sized markets. The market share of each organization together with the product volume shows an indication of the total size of the market. VCC stands out as operating in a very large market (~1% with ~400000 units). The size of market creates a situation where suppliers can accommodate many OEMs and get a huge market. This, in turn, yields prices that are, in many cases, considerably cheaper compared to OEM internal components.

For VCC, this means that developing components is sometimes not an option as it would be a considerably more expensive alternative. Also, the fact that VCC shows business requirements on infotainment e.g. video, games and communication makes

VCC prone to purchase these systems as they are often produced for the large mass market of consumer electronics.

VBC, on the other end, shows the smallest market (~24% with ~9000 units), and the potential for suppliers to gain large markets within the bus segment would therefore be limited, if the bus segment of the market was isolated. Busses however, have numerous components that are similar to the truck market. This and the fact that VBC and VTC are so tightly related makes the VBC measure of few internally developed nodes, difficult to interpret.

VTC, shows a relatively large market (~15% with ~80000 units), but still orders of magnitude smaller than VCC, develops a minor part of the ECUs internally. Apparently, the price benefits of purchasing supplier ECUs are not as great as for VCC, due to the smaller market. However, in terms of electronic systems, the truck market is also closely related to other markets e.g. busses, and this makes the potential market bigger for suppliers.

VCE, who shows the second smallest market (~5% with ~15000 units), develops all ECUs internally. The size of the market for similar components is too small for suppliers to produce at a considerably lower price. Even though the VCE market is not magnitudes smaller than that of VTC, the similarity between products in this market is questionable. The needed electronic functionality of a wheel loader is not necessarily related to that of an excavator for instance, and thus, a supplier does not easily target all products in this market. This fact is likely to affect VCE in the direction of choosing internal development.

The fact that cars have the by far largest market yields a situation where OEMs of other vehicles very well might consider using car components as their price is attractive, even though, they may not be perfectly suited to the intended application.

The key to explaining the differences in internal development between the four organizations is, thus, the size of the market of similar components. A supplier that can target many OEMs with similar needs in electronic functionality can achieve a market far larger than the OEM alone.

This general reasoning does not apply to all types of electronic functionality and all ECUs. Some components might address the whole vehicle market, while other may serve only a small fraction of the market. There are even areas where suppliers of electronic functionality can be target markets outside the vehicle segment such as machinery, consumer electronics etc. But, the size of market does have the influence of creating cheap components and thereby making OEMs purchase rather than develop components.

2.3 Analysis of Other Key Mechanisms

The analysis of the resulting architectures against a background of business context and business requirements has shown a number of central mechanisms that are crucial to the reasoning of the OEMs. These key notions deserve some explanation.

Annual production volume - The case study has shown that the product volumes are different in the four organizations, and thereby also the focus on fixed cost and hardware optimization. The willingness to reduce variable cost at the expense of fixed cost increases with the product volume. One way of reducing variable cost is to optimize vehicle hardware content to include a minimum of resources. This way, development effort is spent to reduce the cost of each product. This is also reflected in table 1 by the organization size; VCC having the highest number of engineers in electronic development. Software components are not subject to the optimization profit in that they represent almost only a fixed cost. VCC that produces vehicles in the range of 400000, can benefit to a larger extent by reducing variable cost, and therefore an increased cost for design of optimal hardware is more profitable than for VBC that has volumes in the range of 9000.

The focus on commonality - The desire for 'Commonality' is the desire to commonalize and coordinate use of components in many product lines. All four organizations emphasize the desire for commonality, which shows that commonality is not solely related to the product volume. All OEMs desire commonality because of the benefits in purchasing large volumes of components, but also has to balance these goals with benefits of optimization to reduce cost. The reason for the shared emphasis, although volumes are different, is related to the fact that production and service is costly with worldwide distribution as well as factories and service shops keeping physical components in store. Hence, the number of physical components must be kept low. Software on the other hand, should not present a high cost for distribution and storage. Instead, the use of numerous variants of software puts strain on working process and configuration management, but not on the cost of operations.

Commonality also indirectly affects the use of technology, process and tools which should affect development cost, knowledge transfer and supposedly product quality.

Methods for integration - VCC, VTC, and VBC uses the communication busses as interfaces in the process of integrating subsystems while VCE is not yet integrating vendor ECUs at all. The method to perform integration differs between the organizations. The method of specifying bandwidth and signals with Volcano together with statecharts, and power consumption, is suitable if the vendors can agree to follow OEM specifications. VCC specifies in this way to vendors, while VTC and VBC both have requirements on high openness in that specific components should be possible to integrate. Some crucial components such as a vendor engine can be manufactured by a large company that does not easily conform to VTC or VBC specific requests. Instead the interfaces are defined in standards. This is, in short, how the different organizations use different methods for integration.

2.4 Summary of Analysis

The bottom line of the provided analysis is that, even though the four electronic architectures are used for vehicles with many similarities in functionality, the resulting architectures show differences in key architectural solutions. These differences stem from the fact that business context and business requirements differ in the four organizations.

Analyzing the relation between key parameters in business context, business requirements, and resulting architectural solutions has shown that the four organizations are choosing different architectural solutions. The key parameters that affect these choices are product volume, market size, and requirements for openness and customer adaptation.

These results are valid for the four organizations and for organizations with similar business situations. An automotive organization with some business parameters way outside the scope of these cases might not be included by the explanations provided. On the other hand, none of the lines of reasoning are specific to these four cases, except the commonality relation that exists within the Volvo group. Also, the line of reasoning is presented so that deviations from the assumptions in this work should be identifiable. The reasoning on basic parameters such as product volume, and market size should be applicable in a more general setting than just the automotive industry since these business settings has no dependency to automotive products.

3. TRENDS IN PERSPECTIVE OF STUDY

Against the background of this study, we use this chapter to reflect on some contemporary trends in automotive electronics development today. This constitutes discussion topics and speculation on why certain solutions are in focus today and presenting solutions in the light of some of the key challenges.

3.1 Summary of Requirements

In order to summarize some of the challenges faced by OEMs with respect to computer systems, we note that the following areas are recognized by the four organizations in this study.

Integration - The OEM situation puts integration in focus. The OEM must purchase components from suppliers in order to keep costs down, while at the same time leveraging reliability and safety. Methods and tools for specifying and verifying compositions are strongly in focus. Today, integration is largely done using a communication bus as an interface between vendor ECUs.

Cost, Safety, and Functionality - Drives the exchange of physical components to computer systems. Cost can be severely reduced by removing or reducing mechanical components e.g. the removal of steering column or reducing dimensions of a shaft. As more and more control is done by computers, optimizing or coordinating functions gets feasible. For instance; fuel consumption can be reduced by considering many temperature and load sensors, or brake coordination. Also, safety functions are made feasible by computers and software. While allowing functions such as ESP and active collision avoidance, computer controlled systems can also impose a challenge with respect to safety. Assuring computer system function is recognized as more difficult than assuring the replaced mechanical system.

Aftermarket - As the computer system become more complex, the handling of configurations gets more difficult. Functions to accommodate e.g. emission reduction or reduced wear, may require unique software or parameters for each individual vehicle. Moreover, keeping track of compatibility among the subsystems is a challenge since products live for a relatively long time with many versions released. Distribution and storage of software is not burdened with the high costs of physical components, but complex processes introduce cost and some risk as failures affect customer relations just as a failed physical component. Finally, the manufacturing of processors and memory chips may be discontinued during the vehicle life-time. This can force redesigns of hardware, causing costly re-verifications or costly stock piling of components.

Variants, Brand and Commonality - Requirements on providing computer systems in many variants yielding different look and feel of the product are recognized as important means to satisfy different customers. Achieving this by using variants of the same design is desired due to goals in commonality.

3.2 Addressing Requirements

Currently, some solutions are proposed as means to address these problems in developing vehicle electronic systems. Here, we describe them in the light of these requirements.

Model-based development tools - Using a model to construct a system is always preferred to prototyping and testing due to cost and development time. The aim with using a model is to predict aspects of the system before constructed. Models of computer systems are currently not as mature as models of mechanical systems and the potential of achieving mature models is considered huge. Thus, the desired models should offer a high level view of the system allowing predictions on properties such as reliability, overview of system functionality and implementation. All with the aim at leveraging complexity – increasing quality and reducing cost.

Current model based tools include code generators in such tools as Rational Rose [5] and Rhapsody [6], where graphical representations of a software system automatically generates implementation.

The unified modeling language, UML [7], is intended to provide such a high level model where the system can be described using object oriented graphical notations. UML also include use case diagrams which can be used for specifying system functionality.

The goal of modeling clearly addresses requirements on cost, reliability, and integration. As models become more mature, OEMs of automotive vehicles can reduce the number of prototypes during development.

Software architecture - As computer hardware is getting cheaper while housings, connectors, and cables are not, we will get more processing power and reduce product cost mainly by reducing the number of control units. Fewer control units implies more software in each one. OEMs that come up with methods to integrate software components from different vendors in the same ECU will, thus, be able to reduce product cost. Challenges in achieving this goal include problems with specification, intellectual property (IP) issues, safety, and verification.

To make this feasible, software architectures are investigated that provide the necessary mechanisms for automotive applications and at the same time can be agreed upon by many OEMs and suppliers making it a standard.

The EAST-EEA project [8] involved some of the European OEMs and first tier suppliers, and investigates unifying the run-time environment (and also development process) for on-board software. One goal of this project is to define a software middleware based on OSEK specifications in order to allow integration and partitioning of software components. The AUTOSAR partnership [9] of European OEMs and tier 1 suppliers, have a similar objective and will develop and try to establish an open standard for automotive software architecture.

Network technologies - In order to meet requirements on safety, network technologies such as Flexray [11], TTP/C [12], and TTCAN [13] are proposed. These technologies include bounded message delay, global clock, and fault tolerance. These mechanisms all aim at assuring function and providing a more reliable communication link that provides means to ensure safety related transmissions. These busses are all based on the time-triggered paradigm where the progression of time initiates data transfers rater than asynchronous events. The time-triggered busses provide synchronous communication without the need for arbitration. Therefore the time-triggered protocols are suitable for implementing safety critical control functions with stringent demands on low latency and low jitter.

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. The low cost busses also present a way of reducing complexity of the master node and facilitate variants in differently equipped products with only one ECU configuration.

Since vehicles are becoming equipped with more and more multimedia and telematics applications, the need for dedicated infotainment busses has arisen. A network in this category is MOST (Media Oriented Systems Transport) [3], which is based on optical fibre technology, and provides high bandwidth and services optimized for infotainment applications.

By wire solutions - Inside the computer system, everything can be considered to be a “by-wire” solution, but generally exchanging crucial functions like steering and braking is considered when using the term by-wire. As reported in this study, many functions are already implemented using the computer system. However, computer control of all the crucial functions to do with maneuvering the vehicle is considered as a shift in paradigm. In order to do so, the OEM must be confident that the computer system is at least as safe as a passive system and this is shown to be more difficult in computer systems as the failure modes increase [14]. The systems that are considered to have a safe state, e.g. the throttle, are easier to change into by-wire and all the vehicles investigated in this study have by-wire accelerator.

The trend towards by wire solutions is strong because of the envisioned benefits. Decreased product cost and numerous new types of functions can be offered. The product cost would become reduced because of removed hydraulic and mechanical links. Also many new functions would be facilitated, many of which are safety enhancing functions, such as emergency braking and collision avoidance. The overall layout of the vehicle would also become more flexible as fixed mechanical solutions are removed.

4. CONCLUSION

We have presented four case studies of vehicle electronic architectures in their business situation; in this describing the business context, business requirements, and resulting electronic architectures.

We have shown that challenges in cost, integration, variants, brands, and commonality as well as challenges in functionality, aftermarket, and safety are important to OEMs design decisions. Further, there are parameters in the business context of an OEM that strongly affects design decisions such as product volume and size of the market. The analysis shows that despite a common base of similar vehicle functionality the resulting electronic architectures used by the four organizations are quite different. The reason for this becomes apparent when looking at different business context and business requirements and their affect on the architecture. Differences in business situation drive the use of different methods for integration, different standards, different number of configurations, and different focus in the development effort. Some key parameters in business situation affecting architectural design decisions are shown to be product volume, size of market, and business requirements on openness and customer adaptation.

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 work. Understanding the requirements from the business case is the key to choosing architectural solutions.

Against the background of this study, we have also reflected on some contemporary trends in automotive electronics today and provided discussion topics and speculation on why certain solutions are in focus today. These speculative sections include the topics; model based development tools, software architecture, network technologies, and by-wire solutions.

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