Embedded system engineering as a solution to face future automotive industry challenges

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Abstract: Zero emission, zero accident, connected car, automotive industry is facing several challenges in which embedded electronic systems play a huge role. This paper describes the growing functional interdependencies and the related necessary rework of the functional architectures. The paper then analyses the feasibility of turning this functional architecture into a physical architecture, detailing the compromises an automotive architect has to find.

Keywords: Automotive, system engineering, functional and physical architecture

1. Introduction

Automotive world is today facing different, self opposing challenges. On one hand, society trends are driving the car to become a functional object in which embedded electronics systems play a huge role. But on the other hand, pressure for cost efficiency and quality tends to limit introduction of new components. The job of the architect is to identify the right compromise and match these two tendencies. Structured as a system engineering study, this paper will give keys in order to understand impact of society challenges on feature contents of the car, possible answers to these challenges at the functional level, and difficulties and trade-offs an automotive embedded system architect is facing when implementing in a real vehicle.

2. System Features: To face automotive industry challenges car has to become functional

Embedded electronics functions were limited twenty years ago to very few functions like ignition management. Today Society trends and pressure on car industry are turning car into a functional object in which electronic embedded systems are playing a major role. This reflects in the feature content of the car.

First objective is to increase road safety. This results not only in increased passive safety but also in increased active safety, with improved car stability trough coupling of systems acting on the different dynamic axis, creating new functional flows.
Another axis for road safety improvement is to increase driver perception with support of a set of environment sensors. Advanced driver assistance systems are emerging in the car, with a large spectrum of feature, from simple lane departure warning, though adaptive cruise control, to active collision avoidance.
These assistance functions are creating new functional interdependencies. On one hand, the more active the assistance is, the stronger the link to chassis and drivetrain function will be. On the other hand driver workload needs to be carefully managed, in order to ensure efficiency of the assistance.

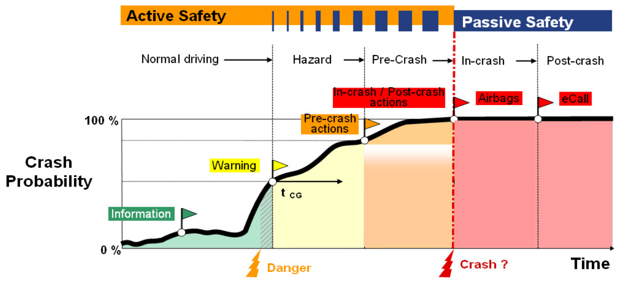

Figure 1 : Active and Passive Safety functions around crash

A second target of automotive industry is to fight emission of pollutant and greenhouse effect gas.
For more than 20 years, this fight has been residing in continuous improvement of internal combustion engines, with an intensive support of real time electronics. Functional granularity of control laws necessary to manage the complex phenomenon of combustion is increasing at each new pollution norm issue, introducing new sensors and actuators. This increased granularity is leading to resources problems when implementing. Consequently the internal combustion engine management could become more distributed than it was in the past.

But what is making torque production function even more distributed is introduction of electric drive, which introduces new functional challenges in the car.
Torque sources arbitration is needed in case of hybrid drives, in order to define the most energy efficient strategy for coupling electrical and thermal torque creation.
Regenerative braking is as well introducing functional impacts. For the first time, braking becomes a distributed function and mechanical link between pedal and caliper is broken. This feature

will introduces a strong coupling between drive chain and braking function that wasn't required before.
This coupling becomes even stronger when considering fully distributed torque production systems like wheel hub motors. Stability control, formerly in the sole perimeter of braking, is now distributed and partly realize by electric drives.

Electrical energy management is as well becoming critical in case of electric vehicle, with or without range extender, in order to ensure continuity of service of the vehicle and maximize the range. This energy management will require as well a new human machine interface, in order to inform driver about drive chain and battery status.

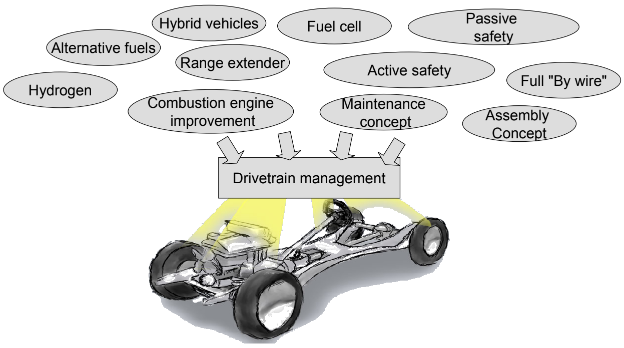

Figure 2: Drivetrain architecture functional drivers

Driver education and assistance with the objective to reach a more ecologically friendly driving style is as well foreseen as one way to reduce energy consumption in car usage. Ecological guidance becomes even mandatory in usage of electrical vehicle, which range is limited. One application could be to define the most energy efficient way considering an updated context, for example traffic conditions or charge station availability. It introduces a close link between energy management, drive train, navigation and telematics functions. Once more, introduction of new functional dependencies in the car !

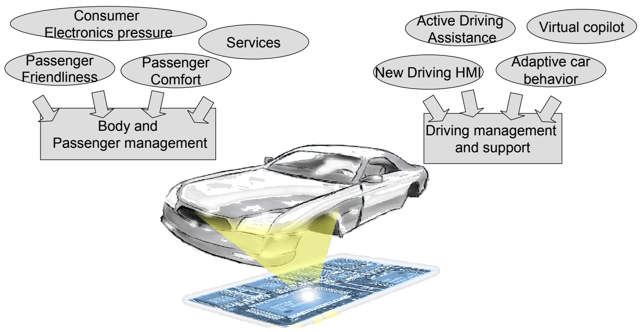

Figure 3: Interior architecture functional drivers

This drives us into another problematic: connected car.
For ten years, car industry has been struggling with providing access to services identical to the services provided by nomadic devices. As the consumer electronics world is evolving at a pace automotive can't industrially follow, solution seems reside in connectivity to these nomadic devices. That means making smart phones enabled services available in the car, audio streaming or internet for example, with the same man machine adaptation problem as for driver assistance function, in order to consider driving context.
The car's being connected to outside world is as well bringing a huge opportunity of new car dedicated services. Not only from infrastructure to car downward information, like updated traffic information or fuel prices, but as well upward services or remote car control : Information once limited inside the car could be made accessible for outside usage. Preventive maintenance or fleet management are the first applications that one can think of when dealing with a connected car. But in context of electrical vehicle or car sharing, Phone activated thermal pre conditioning or access control could become mandatory. Main difficulty is that the functional architecture has to be flexible enough in order to adapt to services that may arise during ten years after it has been designed.

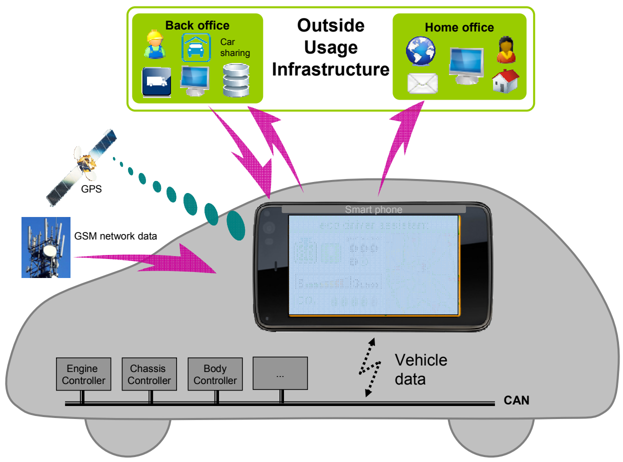

Figure 4: Connected car

But that spectacular explosion of new function should not lead us into forgetting that not all cars will be equipped with all options. Feature content definition is still today one differentiating aspect in car manufacturer's marketing policy.
Seeing the above depicted one can't deny that car manufacturers would require a single comprehensive functional architecture for their cars. Without it configuration management becomes difficult, and cross carline reuse policy becomes difficult.
But a huge constraint is that this functional architecture needs to be modular enough in order to

cover a very wide feature list spectrum, from affordable cars, with only basic functions like information display and engine management to high end cars containing the full spectrum of driver assistances.
In parallel level of hybridizing propulsion, from basic stop and start to full electrical vehicle with wheel hub motors, is adding another layer of complexity on functional architecture. Functional architecture of the rest of the vehicle must not be impacted by a change in the management of the traction chain.

What could then be the main lines of such a functional architecture?

3. What functional architecture for the car in the future?

Today, car functional architecture of embedded electrical and electronic system is divided in clusters called domains. Number of domain may vary from one car manufacturer to the other, but a common acceptation can be found around 4 clusters: powertrain, chassis & safety, infotainment and comfort.

This split is mostly driven from history of automotive electronics.

Electronic ignition and later electronically controlled injection necessary to fulfill first pollution norms are the basis of the powertrain domain. Centered on the engine management electronic control unit, it now clusters all functions around positive torque management from thermal engine down to wheel, including transmission management.

Originated with first ABS systems, Chassis and safety domain is now containing much more than pure braking functions. It is now clustering all vehicle stability related function from basis Electronic stability control, to coupling between differential braking and steering actuation.
With their strong potential interaction with chassis actuator, ADAS like lane keeping are uselly associated to chassis and safety domain.
Passive safety, that is most of time considered to be as independent as possible, has functional interaction with ADAS and braking for pre crash management and therefore is considered as a sub domain of chassis and safety.

Infotainment was originally clustered around instrument cluster and radio. It deals with driver and passenger information and entertainment. Rather limited in entry vehicles, functional complexity of infotainment explodes with high end vehicles. Infotainment will have to deal with management and broadcasting of numerous audio and video sources, while in parallel taking care of man machine interface not only for entertainment and comfort but as well for critical driving information and feedback. Historically embedded navigation is included as well in that domain.

Finally comfort domain is gathering passenger comfort related function. From single zone to multiple zone Climate system, from simple electrical windows to global closing, from central door locking to keyless access and start, functional complexity is quite high in comfort domain.
Comfort domain includes as well all servitude function like electrical board net state management and multiplexing network management. Indeed, comfort domain is originally clustered around body controller control unit, kernel of the electrical and multiplexing networks. Despite its name comfort domain is critical for the car to operate properly.

Problem is that this classical domain structuring, that is so well accepted that it reflects in the organization structures of the automotive companies, will have difficulties to deal with the functional interaction brought by evolutions of the feature content described in our first part.
Regenerative braking and distributed torque creation structure like in wheel electrical motors are creating a clear overlap between chassis and power train while ecological guidance is creating a clear relation between infotainment and powertrain.

Let's try to figure out what could our functional architecture look like when considering challenges described in part one, with the objective of minimizing the interactions between the obtained domains.

For complexity management reasons, hierarchical approach is mandatory to consider complete vehicle scope.
Some rules can be defined for this analysis:

- All function in level N-1 contribute to realization of function N
- Information generated in level N-1 are sent out to level N only if they are used at level ≥N
- Functions at level N-1 are not slower than level N. (rapid loops should be included in slower ones)
- If possible, Process and control loop are placed at the same level.

Primary function of a car is "to move a load over a controlled trajectory". It can be decomposed into two sub functions : "Interface driver" and "realize driver demand". Would 2 domains, driver interfacing and execution/drivetrain be sufficient to structure the functional architecture? let's use a hierarchical approach !

Interface driver can itself be decomposed into 3 basic function : "Acquire driver demand", "feedback to driver" and "assist driver".

"Acquire driver demand" deals with pedals, steering wheel acquisition and interpreting in a vector execution/drive train can use. Impacts being clustered in a sub function, it would be easier to replace standard driving HMI with an Innovative Hmi close to what can be found in airplanes, like a Throttle and braking hand lever.

"Feedback to driver" would deal with all usable medium to inform driver of a situation, visual feedback via cluster and display, but as well audio and haptic feedback, through an arbitration function. In such structure, feedback arbitration can be frozen like in conventional car, tuned to driver wishes or activated mode if a vehicle moding function is implemented. It can even become context sensitive if driver monitoring and workload management are used.

"Assist driver" can be divided in two : "assist driver in navigating" and "assist driver in driving".
Those two functions are relying on creating a model of the vehicle environment, analyze the vehicle behavior in such environment, identify driving situation and determine driver feedback strategy.
For "assist driver in navigating", infrastructure model is created, based on embedded map, but as well on telematics updated information, like maps, traffic, fuel price or availability of charge stations. Then an optimum route is computed based on criteria that could be context depending, for example on driver's chosen mode or batteries state of charge. Driver's feedback is most of time the sole output of this route analysis, but one can think also of a drive envelop limitation, for example when energy saving becomes critical in order to reach a given goal.
In order to establish eco guidance, "assist driver in navigating" requires a clear knowledge of energy storages management, required as well for driver information. To which domain does this new "manage energy storages" function belong ? let's finish our analysis before answering !
In case of "assist driver in driving", environment model is related to immediate vehicle surroundings, driving situation recognition relies on vehicle dynamics information generated in the execution/drive train domain, and actions can spread from driver feedback to generation of a new driving vector trough limitation of the "driving envelop".
In order to avoid conflicts, the different assistances' output, feedback and driving vector for instance, need to be prioritized. As well in case of active assistance it is mandatory to consider arbitration function between driver requested driving vector and assistance proposed driving vector.

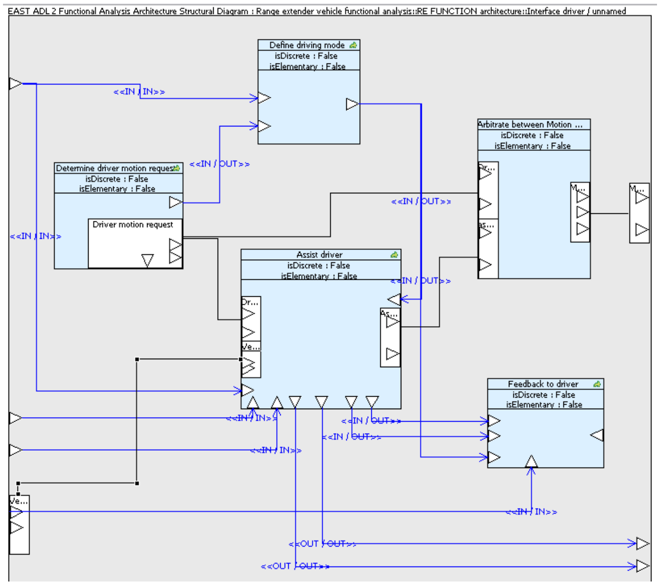

Figure 5: "Interface driver" function structure

What about scalability in such a functional architecture?
Limit "acquire driver demand" to throttle pedal acquisition and interpreting in torque, limit assistance to torque regulation and limitation versus speed, embed the whole in engine management and you'll get a conventional car with cruise control.

Now we will try to decompose "realize driver demand".
Input would be a driving request vector. Realization strategy definition should be split from actuation level.
Let's first speak about actuation function: "drive internal combustion engine", "drive transmission", "drive electrical drive(s)", "drive suspensions", "drive steering" and "drive braking".
Paradoxically, though those functions are managing very complex system, they can be considered from the vehicle perspective as smart actuators: component designed in order to realize an applicative command, for example torque at crankshaft for thermal engine.
These functions are as well responsible for the low level strategy in order to enssure efficiency and protect the actuator: Combustion management in thermal engine, power inverters control depending on electrical motor technology, and even ABS, that can be considered as a low level control loop of the braking system.
This example of ABS gives us a good opportunity to discuss information management in such a functional architecture. ABS is the function that requires the wheel speed sensor information with the

faster recurrence. Then it makes completely sense to acquire these sensors at the same level as the ABS function. As all other functions are using wheel speed info with a slower recurrence, only a downgraded is sent to the higher levels. Would another function require the same information with a quicker pace, this status would be reconsidered.

These "smart actuators" can't in all cases be controlled directly from the driving request vector.
An arbitration and strategy definition level is required in order to determine the best actuation strategy.
First example: Regenerative braking. Regenerative braking through the electro mechanical chain will depend on the maximum power the electrical storages can accept. For instance, this power will depend on the battery technology and state of charge. Based on the maximum recoverable defined by energy storages management, arbitration function will have to determine which amount of braking torque will be created using electrical motors in generator modes, and what is the necessary addition created from friction brakes.
We see there that management of energy storages have as well interaction with execution/drivetrain domain.
On this example we can see as well that we only deal with actuation strategy, in a decoupled manner from chosen HMI. No matter whether regenerative braking is triggered by pressing a switch, releasing gas pedal or by pressing brake pedal, this strategy is clustered in the "interface driver" domain.

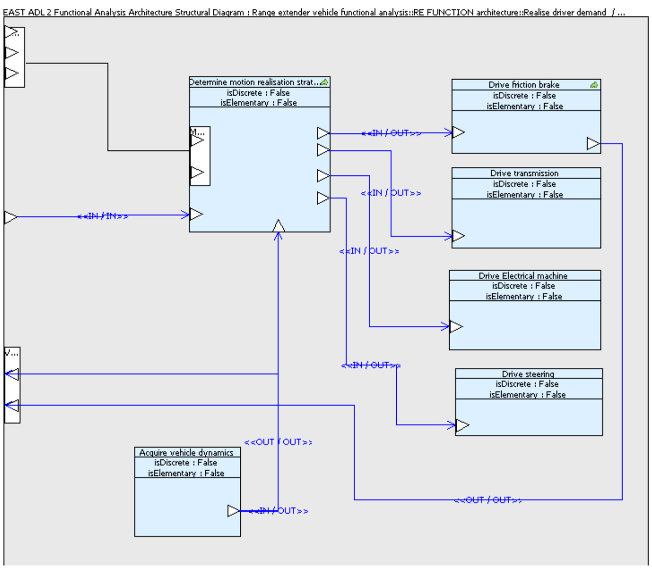

Figure 6: "Realise driver demand" function structure

In order to illustrate another aspect of the execution arbitration function, we will use the example of distributed torque production through wheel hub motors.

In such a structure, positive torque creation at each corner of the car can contribute to stability of the car, or impair it. This drives us into considering stability filtering as a control loop that should be added to the actuation arbitration function.
As for wheel speed information, Acquisition of vehicle dynamics information should be done in the same perimeter and sent to driver assistance function with a lower recurrence.

One must not forget that car should as well ensure access, comfort, entertainment and protection of passengers and payload.
So an additional domain is required in our big picture: "welcome passengers", that would be composed of the functions mentioned above.
Before giving hints on the content of each function, let's make a small precision: "passengers" here includes as well the driver, when not acting in his driving role.
Passenger entertainment will principally deal with acquisition and broadcasting of entertainment sources. Connectivity to nomadic devices can be place in that function. It is to be noted that functionally, this connectivity is split from the one necessary for telematics..
"Protect passenger" will deal with conventional passive safety function. It requires a link to driver interfacing, for pre-crash and emergency braking situations identification.
"Ensure passengers access" clusters all access control and accessibility functions. It may be impacted by car sharing in the future.
As well, "Ensure passenger Comfort" will be impacted. It will have to adapt to specificities of electrical vehicle. Basically this domain deals with thermal and acoustic management of passenger compartment. In electrical vehicles, a thermal comfort vs range tradeoff establishes. Thus thermal management will have to be context dependent. It will have to adapt to number of passenger, to level of energy in the storages. Once more a link to energy storage management!

Staring at the picture described above, we can now figure that a specific domain for energy storage management may be required. Formerly hidden in the comfort domain in conventional car, it takes clear importance when considering electrical and hybrid vehicle management. As already mentioned information about battery state of charge or acceptable power is becoming a central information used for function spreading from thermal comfort management to arbitration of driving strategies.
What about range extender in such a frame? Functionally, control of this internal combustion engine driven generator is integrally part of the power management domain. Internal combustion engine in range extended electrical vehicle is not

taking part in the driver demand realization; crankshaft torque is not transferred to wheels. So in that case Internal Combustion engine management is functionally transferred from execution/drive train domain to energy storage management. Anyhow content of the engine management will differ and may be simplified due to the operation of engine in nearly steady states.

As a conclusion to this part, we can see that through hierarchical functional analysis, starting from vehicle level, we could come to restructuring the car functional architecture into four domains: "interface driver", "realize driver demand", "welcome passengers" and "manage energy storages"

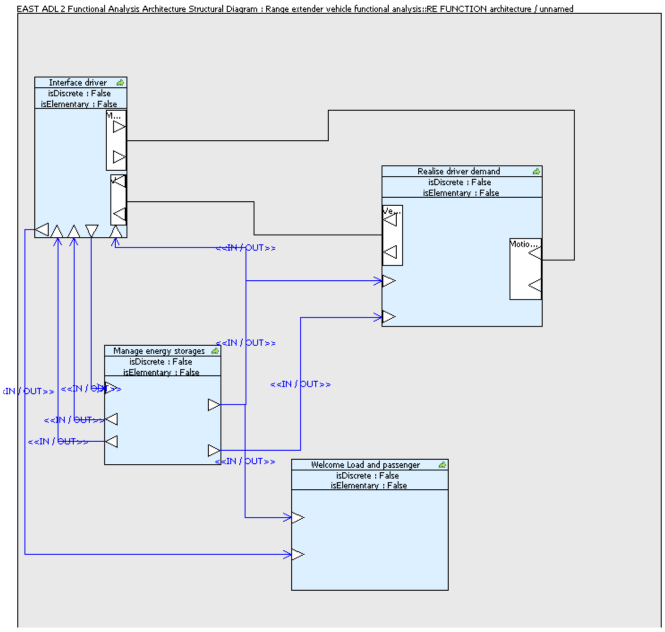

Figure 7: Overview of the functional architecture

With this approach, a satisfying level of genericity and scalability can be obtained. Let's now have a look at the constraints when implementing it into a physical architecture.

4. Getting physical: difficulties of implementing a functional architecture into a real car

Electronic embedded system architect have to define physical architecture according to two axis : electronic architecture and electrical architecture.

For electronic architecture definition, meaning mapping of software functions on electronic control units (ECUs) and definition of communication channels between these ECUs, Autosar based methodology and tool chain represents a real support for system architect.
Indeed, virtual functional bus based integration phase will be a real support to migrate from the functional architecture to the software architecture, enabling debugging and consistency check, prior to implementation. More over more test during RTE generation could support validation of communication concepts.

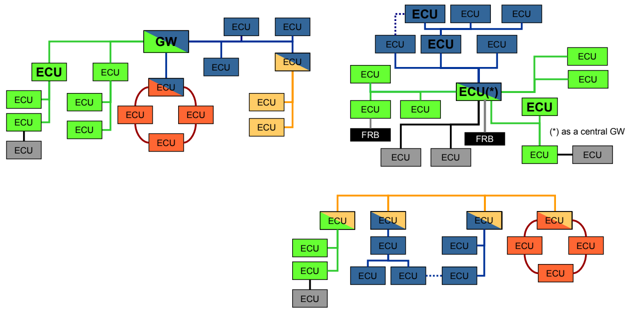

Figure 8: Typical electronic architetcure

But things become difficult when considering the electrical architecture definition. There need to be defined: Wiring harness routing and physical split, Electronic Control Units (ECU) pining and packaging, servitudes management, for instance multiplexed life phases and terminal management, and related power distribution.
Major difficulty with passenger car is that it represents a very constrained physical target; Packaging spaces for control units are limited and have shapes that are deformed by structural design or by styling constraints.
Car has also to be produced in very large series, with production of several hundreds of thousand units per year, sometimes up to one million on one platform.
As a consequence quite commonly known, cost hunting is the priority of the architect, as a few euro savings on a car turn into millions at the end of the year. One must not forget than costs are hiding not only in material price but also in the complete design, logistics and assembly process.

Number of part and number of reference for each of these parts must be limited, therefore complexity management is critical and it is directly impacted by electrical architecture. Complexity is measured through the number of reference of each product necessary in order to realize the complete marketing definition of the car, when taking into consideration take rates. This criterion is particularly important for wiring harness. Indeed complexity management represents a non negligible fraction of the wiring harness cost. Architecture can contribute to reduction of this wiring harness complexity and sometimes to its increase. In multiple piece harness it is important to decouple the complexity of each harness.
For example connector of an high-speed CAN node connector can't be left in the car when the car is not equipped with the related ECU. So there are reference with or without this connector, it creates a

combinatory in the references calculation for the wiring harness. Let's assume this node is connected to roof harness. If this sensor is supplied with power from a fuse attached to a body harness and passing through an inline connector, combinatory will impact both harnesses. If it is powered from a fuse directly connected to the roof harness, complexity will only impact roof harness.
Sometimes a change in the marketing definition of the car, for example options grouping, is necessary in order to ensure industrial feasibility of wiring harness.

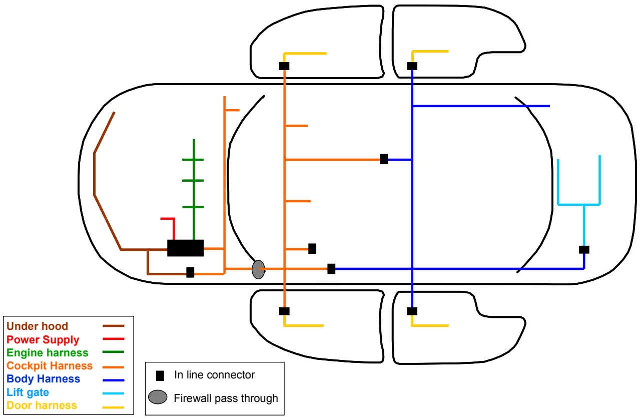

Figure 9: Example of multipiece loom harness

Possibility to assemble parts of the architecture in the car in an efficient manner is essential and must be kept in mind all along the architecture definition process.
Let's take an example, to illustrate danger of not considering those aspects. Imagine an architecture aiming at simplifying the body controller, with a single board concept where two boards were necessary before. Complete design is done, architecture is functionally viable. But, in the body controller, single board constraint led electronics designer into pushing one of the connectors closer to side of the product. This slight change in the connector position was making access very difficult to that connector when dashboard was mounted, connecting the related wiring harness being then very difficult for the operator on the assembly line. As no economically viable solution was found to contain that technical risk, the complete electrical architecture scenario was abandoned.
In addition, as investment are very high, any technical choices in electrical architecture definition that leads to a change of the assembly line needs to prove high economical efficiency, with the danger of being rejected otherwise. This slows also the pace of technical changes in architecture.

These constraints represent some primary architecture selection and comparison criteria. Let's study some other criteria and how they impact functional architecture implementation.

Performances as response time, multiplexed network load, but as well capacity to withstand electrical demand need to be verified. Part of it can be checked trough simulation versus requirement defined in the functional architecture. We reach there another trade off for the architect : for cost reasons some functions that are independent in the functional architecture will have to share common resources, like processors, network, or even antennas or displays. When proposing such integration, architect should ensure that resources can support the need of the integrated functions in order to avoid costly material upgrades. This applies not only to concerns like processing power, but as well to a lot of other limitation like for example limits in the pining of the ECU for connector packaging reasons.

Reliability, Availability, Maintainability and Safety (RAMS) criteria are also to be considered when designing the architecture. Safety concepts of safety critical function is primarily defined at the architecture level and choices in that domain can drive over costs quite rapidly. Lets take the example of electrical steering column lock management. Used in keyless start this device brings the risk of locking while the vehicle is rolling. Some architects are pushing the strategy to distribute the safety concept over several already existing ECUs, while other prefer to have it centralized. The second solution results in a huge over cost in the ECU design, while cost impact of first solution is only limited to the lock itself.
Safety concerns represent also a difficulty in heterogeneous function integration. For example should display of MP3 ID3 tag in instrument cluster endanger display of vehicle speed? Defining such architecture requires good understanding of available technologies and their cost impact.
Very difficult to evaluate during architecture design phase, quality and reliability of the overall system must nevertheless be considered due to impact on the brands image. Return on experience from the field must be considered in the design of the architecture.

We will finish this list with two criteria of quite an high importance: downward compatibility and scalability.

Downward compatibility constraint is highly impacting implementation of the functional architecture. For investment reasons most of component that are used across several carlines are not redesigned. This has impacts on the complete architecture: impacts on electrical architecture, impacts on electronic architecture, even our functional architecture may be impacted. Electrically, compatibility of connectors, power supply and terminal management for these loads must be ensured. Electronically, multiplexing compatibility must be ensured, limiting evolutions and optimizations that can be made on message matrix. Functionally, as the functional content of such component is frozen, it may not be consistent with a reworked functional architecture; it limits then the implementation of innovative functional architecture. In the future, this last problem should be partly solved by the flexibility brought by Autosar once it will be more widely implemented.

Last but not least, Scalability. Scalability represents the ability of the architecture to realize content of each equipment level at an optimized cost. It represents a real challenge for generalist OEM, the marketing definition of car spreading from very low end with almost no features, to high end with full features, with several levels of equipment and their options combinatory. In particular, scalability concerns are driving decision on the functional integration we can do in the several electronic control units of the architecture.

Then what integration scenario should we promote for our functional integration?
One function-one box isn't acceptable. Considering electrical architecture it is a nightmare: number of ECUs to package and mount in the car would be definitely too high, number of fuses required for power distribution would be huge.
In terms of flexibility, it could seems perfect, only what is needed is mounted in the car, but when having a closer look we come to realize that it is not optimized for any of the equipment levels.

In parallel, with processing power increase, one could think of one functional domain, one ECU.
This is quite unlikely as well. Sensors and actuators related wiring harnesses and connectors will make this ECU difficult to assemble in the car. One could think of smart sensors and actuators to solve this issue, but this would be pushing the cost issue to these components. Safety concepts in such architecture would be difficult to analyze, with costly functional independence management structures to be implemented in the hardware and software design.
As scalability is concerned, this solution is quite cost optimized for high end, but it will represent by far a too high infrastructure cost for the low end to bear.

So integration solution stands somewhere in the middle, depending on the marketing mix of the vehicle. Integration should be favored for function with significant take rate, and located in the same area of the marketing mix. This theory is of course once more limited by the physical and safety feasibility of the integration concepts.

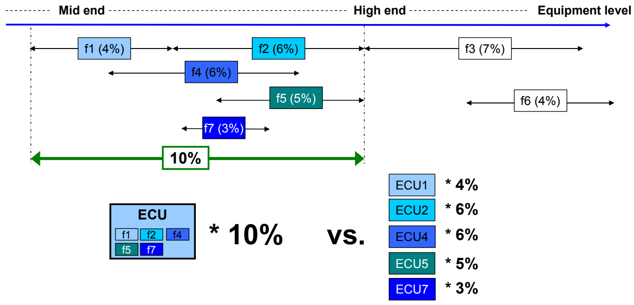

Figure 10: illustration of a possible integration strategy

As a conclusion we can see that the physical implementation of a functional architecture is subject to so much car and OEM dependant constraints that no genericity can be found at the complete vehicle level. Architecture design remains a matter of compromise finding, in which the architect is playing a huge arbitration role. Functional architecture studies have nevertheless an impact on the physical level. They help a lot in structuring the bricks of an electronic design platform, bricks that could be made generic even if the assembly in a complete ECU is application dependant.

4. Conclusion

Next ten years' automotive challenges are bringing so much the functional impacts in the standard car feature, that a complete rework of the car functional architecture may be necessary. Domain oriented, this architecture could be subject to a certain level of standardization.
But in parallel, mass-production, styling, reuse and marketing constraints prevent us from finding a generic answer at the physical level.
The reworked functional architecture can then be seen as an asymptote, migration pace to new functional architectures will be highly depending on the car manufacturer strategies.