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'Intelligent Automotive Systems'

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Van de Technische Universiteit Delft

Door

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Cover design by Eva Holweg, age 6, representing her view on a vehicle, which is truly intelligent and friendly to the occupants and the environment.

Cover artwork by Victor Haans.
Mijnheer de Rector Magnificus, leden van het College van Bestuur, Collegae hoogleraren en andere leden van de universitaire gemeenschap. Zeer gewaardeerde toehoorders.

Dames en heren,

The modern car of today is no longer a truly mechanical system. Electronics, mechatronic systems and sophisticated control algorithms have been incorporated in the car at a rapid pace and will continue to do so in the future. The question now is: does this make the car more intelligent? If we search for the definition of intelligence in a dictionary, we find "possessing intelligence", which can be defined as "the ability to learn or understand or to deal with new or trying situations" [1]. This is perhaps not what we associate with the automobiles of today, albeit in the future there may be cars that are intelligent from a human behaviour point of view. However, today we are developing the foundations, in other words the ability to make the vehicle understand how to deal with driver commands and to judge the environment in a way that significantly increase its overall performance and safety.

In this speech I would like to give a short overview of the history of the development of the automobile, with a focus on active safety systems that interact with the vehicle's dynamic behaviour, and the main industry trends. This will be followed by an outlook on the future research in sensing, vehicle control and actuation mechanisms, including the opportunity to re-position the vehicle control architecture from the current motion-based into the force-based domain.

A short history
It is already more than one century since the first mass-produced automotive vehicles saw the light of day; the famous T-Model Ford appeared in 1908 (figure 1). It is remarkable that this vehicle, being one of the first really affordable automobiles, already resembled today's vehicles in many aspects. It had a modern looking steering wheel and a 2.9 litre inline four cylinder internal combustion engine running a four-stroke

Figure 1. A T-Model Ford from 1910 [2].
cycle. Furthermore, the driver had three foot pedals and two levers to operate the vehicle. Here the resemblance with the modern vehicle stops, however, since the throttle was operated using a lever on the steering wheel. The left foot pedal was used to engage gear, the middle pedal to select reverse gear and the right pedal to engage the engine brake, which was integrated in the transmission rather than connected to a drum or disc brake. A floor lever controlled the parking brake, which could also be used as an emergency brake. It connected to the rear wheel brake drums.

Before the T-Model Ford, other motorized vehicles had been developed, based on the four-stroke combustion engine principle (1861, Alphonse Beau de Rochas), but these were never produced or developed for mass production. One of the earliest well-known developers in engine technology is regarded to be Nikolaus August Otto who developed the four-stroke engine. Engines using the four-stroke cycle are still today often referred to as Otto Engines. Henry Ford had already started his development 1896 with the Quadricycle. Some of the early examples include Karl Benz three-wheeled vehicle (1885, see figure 2), the Daimler-Maybach automobile (1889), Renault Voiturette (1898), Panhard-Levassor (1890) and many others.

It must be noted that, however, that these vehicles can at best be regarded as a carriage which has been retrofitted with an internal combustion engine, and not really resembling the automotive vehicle introduced by Ford [2].

Figure 3 depicts a time-line of the evolution of automotive vehicles and the development of various sub-systems, such as, steering and safety systems. In the early days, the introduction of new vehicle models progressed rapidly. However, it was only in 1922 that hydraulic technology was introduced in the service brakes and 1938 that, for example, the last T-Fords were produced with full mechanical brakes. About 30 years later, in the early fifties, the hydraulic technology advanced into power steering systems, assisting the driver in steering the vehicle, which was particularly required for steering heavy vehicles at low speeds.
It was in the mid-seventies of the previous century that a new major new technology entered the automotive industry, namely the use of digital electronics. This opened up the possibility to read sensors, implement digital control loops and to control various systems in the vehicle. After the successful implementation of digital car electronics in engine management control, a real acceleration took place in the development of many other applications, such as ABS, Traction Control, ESP, Electric Power Steering, to mention just a few.

**Main Trends**

If we look more closely at the developments described in the previous section, we can observe that the implementation of many automotive systems first occurred in the mechanical domain and then migrated via hydraulic, electro-hydraulic into the electro-mechanical domain. The main driving force behind these developments is the constant need for improved controllability and functionality of the various systems in the vehicle, providing increased safety, performance and comfort to the driver. However, it must be noted that some developments do skip the intermediate steps and migrate directly into the electro-mechanical domain. Supported by the general availability of advanced digital electronics in today's vehicles, the latest developments are frequently positioned directly in the electro-mechanical domain. Some examples of major developments are discussed in the following sections.
From the mechanical to the hydraulic domain

In the first mass-produced vehicle the service brake was implemented in a mechanical fashion and operated, for example, on the vehicle's transmission, instead of the drum or disc brakes. The driver operated the brake by means of a lever. Not much later, in 1919, a real brake foot pedal, as we still know it today, replaced the lever. Soon after this, in 1922, a fully hydraulic brake system was introduced, giving better controllability and operation of the service brake.

In power steering applications, hydraulic technology is used to offer the driver improved comfort and ease in steering, especially at low vehicle speeds, to overcome the high lateral tire forces.
From the hydraulic to the electro-hydraulic domain
As described in the previous section, steering migrated into the hydraulic domain to offer the driver more steering comfort. Although this increased driver comfort, the main disadvantage of this solution lay in the power consumption of the hydraulic solution. At all times hydraulic pressure needs to be available in order to deliver a torque assist request. The hydraulic pump, being directly connected to the engine, is constantly rotating with the engine speed. By doing so a significant amount of energy is lost, because the pump is always rotating, even if no torque assist is required and because of the loss of pump efficiency due to the varying engine speed.

One way to solve this is to replace the combustion engine with an electric motor. By doing so, the pump can rotate at the most efficient speed and it also enables the system to switch off the pump if no hydraulic pressure needs to build up. Due to the low dynamic steering cycle a significant amount of energy can be saved. These systems are often referred to as Electro-Hydraulic Power Assisted Steering or EHPAS.

![Figure 6. Electro-Hydraulic Power Assisted Steering System set-up [8].](image)

1. Electronic speedometer in the vehicle
2. Electronic control unit (ECU)
3. Electro-hydraulic transducer
4. Rack and pinion power steering gear
5. Steering pump
6. Oil reservoir with fine filter
7. Anti-vibration expansible hose
8. Manually adjustable steering column

From the hydraulic to the electro-mechanical domain
In order to further enable fuel savings and to increase the driver’s comfort, full electric power steering has been developed. Here, hydraulic technology is replaced by electro-mechanical actuation to provide the required assisted torque to the driver.

In the electro-mechanical domain, various architectures can be identified. Column top mounted actuation is, due to the packaging space requirements, especially suited for small passenger cars, but has the downside that electric motor noise travels into the passenger compartment. A rack-based solution is able to deliver more power than top mounted solutions and is therefore a more
suitable support for power steering larger vehicles. In rack based solutions unitized actuation mechanisms are developed, delivering high power and control performance. These systems can be regarded as the frontrunners of full drive-by-wire steering architecture, in which the actual mechanical steering column is eliminated. This enables a complete re-design of the steering function and layout inside the vehicle and provides additional functionality such as variable gearing ratio as a function of the vehicle speed and augmented steering feedback. A similar trend can be seen in service brake development, replacing the hydraulic actuation by an on-calliper mounted electro-mechanical actuation device.

It is paramount that by replacing the mechanical or hydraulic links with electro-mechanical actuation and the reliance on software control loops, great attention must be given to the reliability of these drive-by-wire systems. Fail-safe and fault-tolerant system architectures must be developed to remain at least at a similar reliability level, but which do fit the current cost level of automobiles.

From the mechanical to the electro-mechanical domain
A conventional throttle system is fully mechanical and consists of an accelerator pedal and wires to connect the pedal to the throttle body valve. By pressing the pedal, the throttle valve will open and more air is allowed into the combustion chamber, which in effect accelerates the vehicle. Throttle systems of today are
fully by-wire, which means that the pedal has integrated sensors measuring the pedal travel, which in turn is used to control the integrated throttle body electric motor, which is connected to the actual throttle valve. By doing so, the system is capable of filtering out pedal vibrations, which will save fuel. It is also a key enabler in cruise control applications.

A similar trend can be seen in the development of the lever operated parking brake. The electro-mechanical solution replaces the lever with a push/pull button, which activates a cable puller or an electro-mechanical actuator integrated in the service brake to activate the parking or emergency brake function. By doing so, for example, an automatic hill-hold function can be implemented, greatly improving driver’s comfort.

![Figure 9. Examples of an electro-mechanical throttle body and parking brake [7].](image)

**Safety Systems**
From the beginning, safety systems have always been present, such as the service and parking, or emergency brake systems. However, after the introduction of vehicle electronics, the development in active or dynamic safety related systems increased rapidly. Car electronics made it possible to read sensors, implement advanced control algorithms, and close the control loop making use of various actuation mechanisms available. Table 1 lists various dynamic safety systems developed for passenger cars in the premium vehicle segment. These systems can be categorized into longitudinal, lateral and vertical domain, assisting the driver in comfort, safety & stability and vehicle agility.
<table>
<thead>
<tr>
<th>System</th>
<th>Description</th>
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<tbody>
<tr>
<td>EDC</td>
<td>Electronic Damper Control</td>
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<tr>
<td>LF</td>
<td>Active Airsprings</td>
</tr>
<tr>
<td>ARS</td>
<td>Active Roll Stabilization</td>
</tr>
<tr>
<td>TPC</td>
<td>Tire Pressure Control</td>
</tr>
<tr>
<td>CBS</td>
<td>Condition Based Service</td>
</tr>
<tr>
<td>ADB</td>
<td>Automatic Differential Brake</td>
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<tr>
<td>HDC</td>
<td>Hill Descent Control</td>
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<tr>
<td>ASL</td>
<td>Automatic Speed Limiter</td>
</tr>
<tr>
<td>GMR</td>
<td>Yaw Torque Control</td>
</tr>
<tr>
<td>DTC</td>
<td>Dynamic Traction Control</td>
</tr>
<tr>
<td>MSR</td>
<td>Engine Drag Torque Control</td>
</tr>
<tr>
<td>EMF</td>
<td>Electro-Mechanical Parking Brake</td>
</tr>
<tr>
<td>ASC</td>
<td>Automatic Stability Control</td>
</tr>
<tr>
<td>EBV</td>
<td>Electronic Brake Distribution</td>
</tr>
<tr>
<td>CBC</td>
<td>Cornering Brake Control</td>
</tr>
<tr>
<td>DBC</td>
<td>Dynamic Brake Control</td>
</tr>
<tr>
<td>ABS</td>
<td>Anti-lock Braking System</td>
</tr>
<tr>
<td>HSR</td>
<td>Active Rear Steering</td>
</tr>
<tr>
<td>AFS</td>
<td>Active Front Steering</td>
</tr>
<tr>
<td>EPS</td>
<td>Electronic Stability Program</td>
</tr>
<tr>
<td>HPS</td>
<td>Hydraulic Power Steering</td>
</tr>
<tr>
<td>LDW</td>
<td>Lane Departure Warning</td>
</tr>
<tr>
<td>PMA</td>
<td>Park Assist</td>
</tr>
<tr>
<td>DCC</td>
<td>Dynamic Cruise Control</td>
</tr>
<tr>
<td>ACC</td>
<td>Active Cruise Control</td>
</tr>
</tbody>
</table>
Table 1. Overview of various dynamic safety systems developed for passenger cars grouped by lateral, longitudinal and vertical dynamics [3].

It is important to understand that the dynamic safety systems listed in table 1 are to a large extent independently operated systems. Each of these safety systems has its own sensors, possibly added with standard available data, such as vehicle speed, etc., and an interface with actuators, such as brakes, steering or suspension. A limited interaction between these systems is present and as a consequence of this a possible conflict between these systems may very well occur, especially if the number of the dynamic safety systems available in the vehicle is increasing.

The main reason for these conflicts lies in the fact that the required vehicle states are derived using different sensors. Due to inaccuracies in the measured signals, different sensor locations and software algorithms, the output and hence the vehicle state may be different. It is paramount that this scenario must be avoided at all times, since we must ensure the safe and reliable operation of the vehicle under all circumstances from a vehicle dynamics performance perspective.

Global Automotive Trends & Challenges

Main Challenges
One would expect developments in technology to go hand-in-hand with the trends in the automotive world and that this would provide answers to the problem statements defined by the market. However there are several factors that can offset this logic, which can be categorized as follows:

- The Society that sets barriers (general interest)
- The Customer that has its own requirements (personal interest)
- The Technology that is available or that has to be developed

If we take the introduction of hybrid vehicles as an example, one can argue that the environmental performance of the latest diesel engine technology is actually better, particularly if the total life cycle of the vehicle, including the manufacturing, actual usage and recycling phase are taken into account. Yet public opinion can be so strong (customers), in conjunction with government policy (society), that a decision is forced upon the industry (technology) to supply the market with hybrid solutions. It must be noted that from a wider perspective the development of electric traction and battery technology has the opportunity
to make a significant contribution to the total environmental performance with respect to future electric vehicles.

**Sustainability**

Today it is estimated that road transportation contributes to about 20% of CO₂ emissions in Europe alone. This should be set against the global view that car ownership is still growing in all parts of the world, especially in the BRIC markets (Brazil, Russia, India and China). In order to counterbalance this negative impact, legislation has been defined in all major markets targeting a 15% to 25% CO₂ reduction in 5 years and another 15% to 20% in 10 years for automotive vehicles.

Europe has announced regulations for lower CO₂ emissions (EU target 130 gr/km CO₂/car in 2012-2015). It is expected that this target will be further strengthened to 95 gr/km CO₂ around 2020. While the EU focuses on CO₂ reduction, North America is regulating the fuel economy of vehicles, which of course has a strong correlation with CO₂ emission. In 2009 North America set the fuel economy average per fleet to 35 mpg, with further improvements to follow. Exceeding the CO₂ emission targets in Europe and North America will imply a penalty fee. Japan has also focused on fuel economy, and has set similar fuel economy targets for 2010. Although lagging behind, the emerging markets (e.g., India and China) are also following these three leading regions on fuel reduction and CO₂ emissions.

One of the major challenges in the automotive industry is the ability of the technology development to meet the requirements of the legislation. The current efficiency of a vehicle is estimated to be around 15%, which indicates that 85% of the energy, hence fuel put into the gas tank, is converted to heat. This is mainly due to engine and driveline losses, vehicle idling and the usage of car accessories, such as air conditioning and power steering.

Some of the industry’s major technological developments, addressing the improvement of the overall efficiency of the powertrain, are:

- Combustion efficiency and after treatment
- Emission reduction using alternative fuels
- Engine downsizing
- Reduction of mechanical losses
- New powertrain concepts for hybrid and battery operated electric vehicles
- Lightweight solutions to address the vehicles inertia
Safety
The data on road accidents in Europe, according to eSafety Working Group (November 2002), are very striking:

- About 40,000 fatal accidents on Europe’s roads each year
- Most accidents (about 75%) are caused by human errors alone
- In 95% of the accidents human error was involved

Taking this data into consideration, one must conclude that the driver is the weakest link when it comes to lethal accidents. To counter these facts, the European Union has set the ambition to decrease this by half in 2010. Modern control systems react and master system usage faster, more precisely and more reliably than any human. Technology advancements are key in addressing this ambition, such as tire pressure monitoring, which as a side-effect also addresses the CO₂ legislation requirements, improved vehicle dynamic controllers, such as ABS and ESP and the use of integrated sensors and actuators.

At this particular moment, it is my strong belief that there is no technology available that can reduce the number of road accident fatalities by half in 2010.

Comfort
The average consumer in the developed countries will, on average, grow much older than in previous generations and it is usually older people who have the greatest purchasing power. This means that there is more money in the hands of the seniors, as well as more seniors around. This development will in general drive developments in the comfort of vehicles. Comfort incorporates, for example, the ease of entering a vehicle, which will increase the number of suicide doors and sliding doors in vehicles. Another development in comfort can be seen in the ease of navigating the vehicle whilst parking, and in both city and
highway driving, supported by developments in parking cameras, adaptive cruise control, night vision, collision warning and active suspension, to mention just a few.

Besides the aforementioned trend in the differentiation of the population, consumers in general appreciate comfort, including factors such as noise reduction in the vehicle, development of infotainment systems, connectivity and navigation systems.

**A look into the future**

As easy as it seems for my child to look into the future and design an intelligent vehicle, for the industry itself it is extremely difficult to foresee the future. As illustrated in the short history and trends in the automotive industry, it is clear that cars are becoming more and more complex. The car of today is no longer the mechanical device it used to be, but is evolving into a true mechatronic system, incorporating the system design of its components covering many domains including mechanics, electronics, computer science, chemistry, and others. As an illustration of this, in today’s vehicles more than forty percent of its value is based on electronics and this is expected to grow significantly with the fast-growing share of hybrid and battery electric vehicles.

A simple view would be to extrapolate the current developments and predict that complexity will increase over time. On the other hand increasing complexity is simply not a sustainable direction to follow and one might rather expect a paradigm shift to master the complexity of the vehicles of the future. Complexity in itself does not automatically go hand in hand with reliability. As an illustration it seems that the number of vehicle recalls is increasing.

My view is therefore focused on simplifying the current vehicle architecture in order to counter the increasing complexity and to improve the cost of the total system, the reliability and the functionality of vehicles for the driver. This has already been initiated by the implementation of the Global Chassis Control principle by some of the leading automotive vehicle manufacturers, but it can and should be pushed even further. One important challenge is to move the vehicle control architectures from the current motion-based into the force-based domain.

To support this view, research must focus on:

- The development of force sensors and integration in key vehicle
components, to enable a more accurate estimation of the vehicle state, which in turn provides better input for the vehicle controller.

- The development of improved electro-mechanical actuation systems, primarily focussing on power density and efficiency to reduce weight and to provide a stronger integration within the current design limits.
- Providing optimization methodologies to improve the total vehicle control architecture with respect to sensor inputs and actuation mechanisms, in line with the Global Chassis Control methodology, including the new challenges in hybrid and battery electric vehicles.

In the next chapters I will discuss my view on this research.

**Challenges in new sensing mechanisms**

The challenge is to simplify the overall sensor set required by the vehicle control architecture, to increase the overall robustness and at the same time to retrieve more information to determine more accurately the vehicle states, such as, for example, lateral velocity and acceleration, body yaw rate and slip angles. To tackle this challenge, the measured data should contain more rich information than today’s implementations.

Today’s sensor architecture is predominantly positioned in the motion domain, such as wheel speeds, vehicle speed, steering angle, etc. To complement this, additional acceleration signals are used, such as the vehicle yaw rate. Focussing on the performance of the vehicle dynamics, one can see that it is greatly determined by the forces acting on the tire and road contact patch. As an example, the understanding of the actual road friction coefficient and the acting forces on the tires in real-time would significantly improve the performance of the vehicle dynamics controllers. The objective of the research is to replace the current motion-based vehicle control systems with force-based vehicle control systems. As a consequence of this approach a significant reduction in the sensor set and reliability of the vehicle
can be achieved as will be shown later on in the chapter. First, however, the question remains as to how we implement load sensing in the vehicle?

In recent years, developments have taken place to integrate force sensors into the tires, which is an ideal location, close to the tire-road contact patch. The difficulty here is that tires are wear-components, making reliable force measurements more difficult. Tires are replacement parts, which, if force-sensing devices are to be included, will make them more expensive. The fact that tires rotate adds additional complexity and demands the integration of special data transmission from the tire to the chassis.

Other developments focus on the integration of load sensing in the wheel bearings or Hub Bearing Units (HBU). Although more distant from the tire road contact patch, wheel-bearing are high precision, non-wear mechanical devices, with the additional advantage that the sensors can be integrated into the non-rotating part, removing the need for complex data transmission. It is the objective in the Intelligent Automotive Systems research to focus on the integration of force sensing in wheel-bearing, see figure 11 as developed by SKF.

**HUB load sensing**

If a bearing is subject to a loaded condition, it will deform, as illustrated in figure 12. The method to reconstruct the load vector using the deformation can be described as follows. The deformation of the bearing and housing can be described using the mode shape approach. The actual bearing deformation is measured by placing strain sensors strategically on the bearing and housing. Using the measured strains, and the understanding of the mode shapes of the bearing enables the reconstruction of the actual load vector acting on the bearing.

The wheel-bearing unit is a central element in the corner of the vehicle, being very close to the forces acting on the tire-road contact patch. However the reconstructed load vector needs to be matched with the load vector acting on the tire road contact patch. This can be easily calculated by using suspension kinematics. More relevant information can be achieved using vehicle state estimator techniques. This enables the estimation of key vehicle state parameters, such as vehicle mass, vehicle inertia, location of the centre of gravity and tyre proper-
ties. Although the described solution has been put in practice, giving promising results, as can be seen in figure 13, there are still significant improvements to be made to this specific force sensing solution. Research is foreseen in the areas of modelling and simulation of the wheel bearings, load vector reconstruction and integration of the electronics and sensors in the wheel bearing.

The force vector reconstruction is a critical element in wheel bearing force sensing, due to the non-linear system behaviour of the wheel bearing. The challenge is to combine the understanding of the behaviour of the bearing under all loaded conditions with the actual vehicle manoeuvres in critical dynamic situations and the requirements of the measurements as defined by the vehicle dynamics controller. Detailed modelling of the wheel bearings in such situations is key to understanding, for example, which locations are best suited to mount the sensors.
In this analysis, several factors need to be addressed and optimized, such as the total amount of required sensors, a proper signal to noise ratio of the measured data and does a transfer function exist which is able to reconstruct the load vector within the required specifications? With respect to the transfer function, further developments are seen in the support of artificial neural networks or genetic algorithms to improve the performance of analytical based transfer functions. A hybrid model in which these approaches are joined is foreseen as an appropriate solution. Influences from the external environment, such as, for example, knuckle deformation, brake disc attachment, temperature gradients in the bearing, have an additional influence on the bearing behaviour and must be taken into account as well.

The force sensing measurements will be used in safety critical applications, such as Anti-lock Braking Systems (ABS) and Electronic Stability Programs (ESP). It is therefore paramount that the reliability and robustness of the transfer function is safeguarded. One proposal is to add a confidence level to the reconstructed load vector by implementing a plausibility check.

**Challenges in Control**

![Diagram](image)

Figure 14. Illustration of a Global Chassis Control architecture [9][10].
From a control perspective two main challenges can be identified. The first challenge concerns the increasing amount of dynamic safety systems present, especially in the field of the lateral vehicle dynamics domain as discussed in the section on Safety Systems on page 12. These safety systems operate largely independently and as a consequence may actually interfere which one another, reducing the overall vehicle performance and safety level. The solution proposed is to replace the individual system controllers with one overall vehicle controller, referred to as the Global Chassis Control (GCC) principle. The second challenge is to make a significant contribution to the improvement of the vehicle dynamics controller in vehicle performance and safety by moving the Global Chassis Controller into the force domain. An example of the architecture of such a Global Chassis Controller is illustrated in figure 14.

Vehicle State Estimator
Sensors integrated in the vehicle provide measurements for, for example, vehicle speed, yaw rate, driver steering input and wheel-bearing forces as input for the Vehicle State Estimator. The Vehicle State Estimator, which, for example, can be based on the extended Kalman filtering principle, is able to estimate the actual vehicle states required by the Global Chassis Controller. By adding load-sensing information, the vehicle state parameter estimation, input to the Global Chassis Controller, becomes more straightforward. In general one can state that feeding the Vehicle State Estimator with load sensing information improves the output of the state estimator with respect to the quality and robustness of the data and at the same time gives the opportunity to add even more vehicle dynamics related data. Typical parameters which can be estimated are the vehicles mass and mass distribution, vehicle inertia, location of the centre of gravity, body slip angle and tyre properties. The concept provides an ultimate source of real-time information for future vehicle dynamics control systems. Future research is required to further exploit the use of load sensing in order to fully replace existing inertial & motion sensors with load sensing technology. Further development of state estimator components is also necessary to deal with inputs from the force sensing bearings, influence of the tyre characteristics, robustness, reliability and fail-safe behaviour.

Global Chassis Control
The Global Chassis Controller influences the state or behaviour of the vehicle by means of the actuation systems. In figure 14, as an example, vehicle brake, steering and suspension actuators are present. Various configurations can be chosen, each with a unique impact on the overall performance of the Global
Chassis Controller. The challenge is to determine the optimized vehicle architecture, including sensors and actuators, able to improve the overall vehicle performance, robustness, fail-safe and fault tolerant behaviour.

**Longitudinal Stability and Hybrid and Battery Electric Vehicles**

In the introduction of hybrid vehicles, additional components are added to the vehicle powertrain to improve fuel efficiency. One or more electric traction motors are added to the driveline, either in parallel or in series with the internal combustion engine. The electric motors assist the combustion engine where the combustion engine has a low efficiency, normally in low speeds and during acceleration and in general allow the combustion engine to operate in a more efficient regime. The traction motors are also used to generate the electric energy stored in the battery. Unlike a combustion engine, an electric traction motor has the ability to provide a negative torque to the driven wheels and to decelerate the vehicle. This enables the implementation of a regenerative brake cycle, transferring vehicle kinetic energy into electric energy. The amount of deceleration torque provided by the traction motor depends on the state of the battery. In order to maximise the regenerative performance, the traction motor has to be used for braking as frequently as possible and the battery should only be partially charged in order to consume the generated energy.

![Wheel-slip curve](image)

*Figure 15. Wheel-slip curve.*

In braking, the wheel slip curve as depicted in figure 15 plays an important role. During an emergency brake the ABS controller will cycle around the optimum slip ratio in order to achieve the best braking performance, and enable steerability during braking. A similar approach can be achieved using traction motors. However, in certain situations a transition is required from electric to conventional hydraulic braking, for example, if the battery is fully charged or more brake torque is required than achievable by the traction motor. It is also for this reason that legislation today requires a fully hydraulic service brake to also be available. This control architecture needs to be optimized such that the performance of braking is safeguarded, but still a maximum of regenerative performance is kept. Important aspects of the difference in dynamic behaviour of both electric motors and
hydraulic brakes must be taken into account, as well as a deep understanding of the battery behaviour. In addition the perception of the driver in the situation where electric braking is replaced or assisted by hydraulic braking plays a dominant role. In other words, the brake feel must remain as it does today, during the full braking cycle.

**HMI**

By moving the Global Chassis Controller in the force domain, the overall vehicle performance is increased significantly. Due to the additional sensor information, provided by the load sensing wheel-bearings, a better understanding of the actual limits of the vehicle is known. This enables the Global Chassis Controller to push the vehicle further towards its limit, providing the driver with more performance and a similar or better safety level. However, in a changing environment, the vehicle's limit might be reduced, as is experienced when driving, for example, from dry to wet or even icy tarmac. In this particular case the Global Chassis Controller is able to estimate in real-time a decreasing tire-road friction and depending on a driver manoeuvre request, adjust the vehicles behaviour. This might result in unexpected behaviour by the vehicle, perhaps even beyond the drivers expectations.

Driver expectations are related to the inputs received by the vehicle, such as the visuals, the steering wheel and pedal feedback, including the general movement of the vehicle itself. If we consider the possibility to augment a feedback on the steering wheel and pedals, we could create the required behaviour for the driver (shaping) in all driving situations, where predictable behaviour of the mechanical system is not required, since the control system has the ability to compensate using the feedback to the driver. In order to allow such a change in vehicle design, it is paramount that the driver is included in the loop and becomes an integral part of the Global Chassis Controller. The main question that remains is what type of overall behaviour, or shape, the vehicle should have to be predictable to the driver from a comfort, handling, and safety point of view.

**Challenges in Actuation Systems**

The actuation systems in the vehicle are able to close the loop in the Global Chassis Controller concept. These actuation mechanisms must be chosen such that the dynamic behaviour of the vehicle in the longitudinal, lateral and vertical domain can be influenced appropriately. The following figure illustrates the most dominant points in a passenger car to be considered, including traction, transmission, brake, steering and suspension systems.
Although the requirements of the various actuation mechanisms are very different, they do have functionalities and components in common. This makes a modular approach in the definition of such actuation systems possible. For now only electro-mechanical actuation mechanisms are considered, since it is believed that these fit best with the future vehicle architectures and the trends as described in the section on “Main Trends” on page 8. The main objective of the actuator is to convert electrical power into a position, speed, torque or force to drive a mechanical load. The power electronics connects the electric power to the electro-mechanical device, for example, a rotational or linear electric motor. The electric motor can be connected either directly, or by means of a mechanical transformer to the application. Furthermore the actuator can support power regeneration to improve the vehicle’s total energy consumption.

Sensors measure the position, speed, torque or forces of the application and input this information to the local controller. The actuation system is part of the total control architecture, as can be seen in figure 14, and is commanded
by the central vehicle dynamics controller and will receive the set points over a network, such as CAN or FlexRay. Furthermore it is expected that the actuation systems have sophisticated on-board diagnostics available and can be configured to operate in either a fail safe or fault tolerant mode. A schematic overview of an actuation system is illustrated in figure 17.

As mentioned in the previous section, the requirements and working conditions can be very different per actuator, as illustrated in figure 18 by mapping the actuator force versus stroke requirements. Other design parameters do need to be taken into consideration as well, such as actuator mass, power density, efficiency, controllability, ambient versus operating temperature, packaging and reliability with respect to fail-safe and fault tolerant operation.

Today’s implementation of electro-mechanical actuation mechanisms is rather limited. Current implementations are frequently based on hydraulic technology, which has developed over the last hundred years into a very reliable and cost effective technology, and can often be found in actuation mechanisms for service brakes, power steering, anti-roll bar and reconfigurable dampers. The main advantages of hydraulic solutions are considered to include a high force density, ease of control and design and reliability. However the disadvantages of hydraulic systems are the high power consumption, relatively low bandwidth and overall complexity of the system, which includes hoses, accumulators, etc. These limitations can be circumvented by the high bandwidth and high efficiency of electro-mechanical solutions.

Figure 18. Force over stroke demands for actuation systems in various applications.
Therefore developments on electro-mechanical actuation mechanisms should focus on increasing the force density, reducing the unsprung mass, and further improving the controllability of the solutions. One example, which deals with an electromagnetic solution for a suspension application, is considered to be an important step in that direction [4].

Reliability of the actuators is paramount; therefore research in fault tolerant and fail-safe actuator designs and system architectures is required to be continued. From a complexity and cost perspective, the fly-by-wire architectures from the aviation industry cannot just be copied to a passenger vehicle. A dedicated solution, fitting the needs of the automotive industry still needs to be developed.

**Electro-Mechanical Corner Module Example**

Several studies have been performed in the design of a complete electro-mechanical corner module; see for example [5][6]. These modular designs incorporate many advantages, such as freeing up a significant amount of space inside the vehicles body, enabling a rigorous re-thinking of the vehicles interior design. In addition, there is the possibility to have a four-wheel driven vehicle, front and rear-wheel steering capabilities, and active suspension, providing more than adequate actuation freedom to influence the vehicle state and to improve the vehicle dynamics behaviour.

A very challenging design on a full Autonomous Corner Module (ACM) has been presented by Zetterström [5]. The purpose of this study was to identify the advantages of applying electro-mechanical actuation systems for suspension, steering and propulsion in order to develop a modular corner module. See figure 19 for an overview of the proposed autonomous corner module.

![Figure 19. The Autonomous Corner Module. Sketch (left), cross section frontal view (middle) and top view (right) [5].](image-url)
Besides these improvements, this study also underlines the necessity, as discussed in the previous section, to continue the research into electro-mechanical actuation systems with respect to force density, power requirements and reliability and to address the unsprung mass.

**Summary**
The car of today is no longer the mechanical device it used to be, but is evolving into a true mechatronic system, incorporating the system design of its components covering many domains including mechanics, electronics, computer science, chemistry, and others. As an illustration of this, in today's vehicles more than forty percent of its value is based on electronics and this is expected to grow significantly with the fast-growing share of hybrid and battery electric vehicles.

After the introduction of vehicle electronics, the development in active or dynamic safety related systems increased rapidly. It is important to understand that the dynamic safety systems are to a large extent independently operated systems. Each of these safety systems has its own sensors, possibly added with standard available data, such as vehicle speed, etc., and an interface with actuators, such as brakes, steering or suspension. A limited interaction between these systems is present and as a consequence of this a possible conflict between these systems may very well occur, especially since the number of the dynamic safety systems available in the vehicle is increasing.

There is a need to simplify the current vehicle architecture in order to counter this increasing complexity and to improve the cost of the total system, the reliability and the functionality of vehicles for the driver. This has already been initiated by the implementation of the Global Chassis Control principle by some of the leading automotive vehicle manufacturers, but it can and should be pushed even further. One important challenge is to move the vehicle control architectures from the current motion-based into the force-based domain.

To address this challenge I propose that research must focus on the development of force sensors to enable a more accurate estimation of the vehicle state and to provide better input for the vehicle controller. In addition, the power density and weight reduction in electro-mechanical actuation systems, to provide a stronger integration within the current design limits, must be addressed. And finally, I propose to introduce optimization methodologies to improve the total vehicle control architecture with respect to sensor inputs and actuation
mechanisms, in line with the Global Chassis Control methodology and to include the new challenges in hybrid and battery electric vehicles.

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