Wheel Corner Modules
Technology and Concept Analysis

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Abstract

The wheel corner module represents a new technology for controlling the motion of a vehicle. It is based on a modular design around the geometric boundaries of a conventional wheel. The typical WCM consists of a wheel containing an electrical in-wheel propulsion motor, a friction brake, a steering system and a suspension system. Generally, the braking, steering and suspension systems are controlled by means of electrical actuators. The WCM is designed to easily, by means of bolted connections and a power connector, attach to a vehicle platform constructed for the specific purpose. All functions are controlled via an electrical system, connecting the steering column to the module. A WCM vehicle can contain two or four wheel corner modules.

The purpose of this thesis is to serve as an introduction to wheel corner module technology. The technology itself, as well as advantages and disadvantages related to wheel corner modules are discussed. An analysis of a variety of wheel corner module concepts is carried out. In addition, simulations are conducted in order to estimate how an increased unsprung mass affects the ride comfort and handling performance of a vehicle.

Longitudinal translation over two types of road disturbance profiles, a curb and a bump, is simulated. A quarter car model as well as a full car model is utilized. The obtained results indicate that handling performance is deteriorated in connection to an increased unsprung mass. The RMS value of the tire force fluctuation increases with up to 18%, when 20 kg is added to each of the rear wheels of the full car model. Ride comfort is deteriorated or enhanced in connection to an increased unsprung mass, depending on the disturbance frequency of the road. When subjected to a road disturbance frequency below the eigenfrequency of the unsprung mass, ride comfort deterioration is indicated. The RMS vertical acceleration of the sprung mass increases with up to 6%, in terms of the full car model. When subjected to a road disturbance frequency above the eigenfrequency of the unsprung mass, decreased RMS vertical acceleration of up to 25% is noted, indicating a significantly enhanced ride comfort.

Implementation of wheel corner module technology enables improved handling performance, safety and ride comfort compared to conventional vehicle technology. Further development, e.g. in terms of in-wheel motors and alternative power sources, is however required. In addition, major investments related to manufacturing equipment and technology is regarded as a significant obstacle in terms of serial production.
Preface

This master thesis represents my last step towards graduation from the Master of Science programme at the Vehicle Dynamics Department, Royal Institute of Technology. I would like to thank Daniel Wanner, who has greatly contributed to this thesis by providing me with continuous guidance and feedback. I would also like to thank my examiner Lars Drugge.

In addition, a thank you goes out to my fellow master students Mikael Sjöholm and Igor Kovacevic, for great company.

Eternal gratitude is dedicated to my father Börje, mother Monica, sister Susanne and brother Fredrik, for always supporting and strengthening me. Hilda and Edith, thank you for brightening my life!
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# Nomenclature

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<th>Description</th>
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<tbody>
<tr>
<td>ABS</td>
<td>Anti-lock braking system</td>
</tr>
<tr>
<td>ACM</td>
<td>Autonomous corner module</td>
</tr>
<tr>
<td>AFPM</td>
<td>Axial flux permanent magnet</td>
</tr>
<tr>
<td>BBW</td>
<td>Brake-by-wire</td>
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<tr>
<td>CAN</td>
<td>Controller area network</td>
</tr>
<tr>
<td>ECU</td>
<td>Electronic control unit</td>
</tr>
<tr>
<td>EHB</td>
<td>Electro-hydraulic brake</td>
</tr>
<tr>
<td>EMB</td>
<td>Electro-mechanical brake</td>
</tr>
<tr>
<td>EWB</td>
<td>Electronic wedge brake</td>
</tr>
<tr>
<td>FCM</td>
<td>Full car model</td>
</tr>
<tr>
<td>GM</td>
<td>General Motors</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal combustion engine</td>
</tr>
<tr>
<td>MR</td>
<td>Magnetorheological</td>
</tr>
<tr>
<td>PM</td>
<td>Permanent magnet</td>
</tr>
<tr>
<td>QCM</td>
<td>Quarter car model</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
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<tr>
<td>SBW</td>
<td>Steer-by-wire</td>
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<tr>
<td>TBW</td>
<td>Throttle-by-wire</td>
</tr>
<tr>
<td>TTCAN</td>
<td>Time-triggered controller area network</td>
</tr>
<tr>
<td>TTP</td>
<td>Time-triggered protocol</td>
</tr>
<tr>
<td>WCM</td>
<td>Wheel corner module</td>
</tr>
<tr>
<td>XBW</td>
<td>X-by-wire</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Lithium-ion</td>
</tr>
<tr>
<td>Ni-Cd</td>
<td>Nickel-cadmium</td>
</tr>
<tr>
<td>Ni-MH</td>
<td>Nickel-metal hydride</td>
</tr>
<tr>
<td>Pb-acid</td>
<td>Lead-acid</td>
</tr>
<tr>
<td>$\omega_s$</td>
<td>Eigenfrequency of sprung mass [rad/s]</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td>$\omega_u$</td>
<td>Eigenfrequency of unsprung mass</td>
</tr>
<tr>
<td>$c_s$</td>
<td>Damper coefficient</td>
</tr>
<tr>
<td>$c_t$</td>
<td>Tire damper coefficient</td>
</tr>
<tr>
<td>$k_s$</td>
<td>Spring stiffness coefficient</td>
</tr>
<tr>
<td>$k_t$</td>
<td>Tire spring stiffness coefficient</td>
</tr>
<tr>
<td>$m_s$</td>
<td>Sprung mass</td>
</tr>
<tr>
<td>$m_u$</td>
<td>Unsprung mass</td>
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1 Introduction

Ever since the Ford Model T was introduced in the beginning of the 20th century, road vehicles have gradually progressed in terms of technology. Safety, comfort and performance have gone through vast improvements, yet the basic vehicle layout is similar to what it was one hundred years ago.

A wheel corner module (WCM), also called an active wheel module, electric corner module or robot wheel, represents a new way of controlling the motion of a vehicle. It is based on a modular design around the geometric boundaries of a conventional wheel. The typical WCM consists of a wheel containing an electrical in-wheel propulsion motor, a friction brake, a steering system and a suspension system. Generally, the braking, steering and suspension systems are controlled by means of electrical actuators. The WCM is designed to easily, by means of bolted connections and a power connector, attach to a vehicle platform constructed for the specific purpose. All functions are controlled via an electrical system, connecting the steering column to the module. The steering column may comprise a conventional steering wheel and pedals, or any other feasible solution, such as e.g. a joystick.

WCMs represent a fairly new technology, currently being developed by several car manufacturers and subcontractors for future implementation in road vehicles. According to Frost & Sullivan WCMs are likely to be on rear wheels by 2015 and on all four wheels after 2020 [1].

The goal with this thesis is to provide an overview of WCM technology and to serve as an introduction to the subject. Advantages and disadvantages related to the technology shall be evaluated. In addition, this thesis shall provide a view of the present development stage.

The first part of the thesis treats the technology which WCMs are based on. A thorough literature study of technical reports and conference papers is the foundation of this part. The main focus is aimed at novel solutions, even though other more conventional solutions may also be utilized in terms of WCMs.

In the second part, the impact in terms of vehicular, environmental and economical aspects are discussed.

A concept analysis is presented in the third part of the thesis. Since detailed technical information is generally infrequent in terms of concept solutions, the descriptions aim towards principal function rather than details. Most of the information presented in this part has been attained from patents and journal papers.

One concern regarding the WCM is increased unsprung mass. In the fourth part, modeling and simulations are conducted in the dynamic modeling program Dymola, in order to estimate the impact on ride comfort and handing performance, due to this matter.
2 Wheel Corner Modules

A wheel corner module, see figure 1, is a novel type of electro-mechanical system related to vehicular motion control. As the name implies it is based on a modular design. Generally the module is held within the boundaries of a conventional wheel. The WCM contains subsystems responsible for longitudinal, lateral and vertical motion respectively. These systems comprise electro-mechanical actuators and linkages and are operated upon input from a control system. The corner module is designed to easily, by means of bolted connections and an electrical connector port, mount to a vehicle body. The vehicle body together with two or four WCMs form a WCM vehicle. All functions of the WCM are electrically controlled based upon input from an operational device, in connection with one or several control units. It represents a pure x-by-wire based vehicle maneuvering system. Mounted around the vehicle are several sensors that continuously supply the control units with information regarding the vehicle position and state. The sensors might include position sensors, velocity sensors, acceleration sensors, force and torque sensors, pressure sensors, flow meters, temperature sensors, etc. [2]. The information supplied by these sensors might be yaw rate, lateral acceleration, angular wheel velocity, steering angle and chassis velocity [2]. The operational device comprises a conventional steering wheel and pedals, or any other feasible solution such as e.g. a joystick.

WCMs represent a novel technology related to vehicular propulsion systems, not yet available in any serial-produced vehicle. However, some of the technical solutions utilized in WCMs are already available in subsystems of current conventional passenger vehicles. Hence, comparisons to conventional vehicles and conventional vehicle technology are continuously carried out in the context of this thesis. The following paragraph defines these two expressions according to how they are used within this thesis.

Conventional vehicle technology refers to standardized technical solutions as found in most passenger cars, manufactured and sold in large quantities during the last decade. The conventional technology discussed within this thesis is mainly connected to vehicular motion control and is of mechanical type. It generally involves an internal combustion engine (ICE) and friction brakes for means of longitudinal motion control, both connected to pedals in the cabin. Lateral motion is actuated by operation of a steering wheel connected to the front wheels through a “rack and pinion” construction. Vertical motion is passively controlled by means of a conventional suspension comprising springs and dampers. Conventional vehicles are referred to as vehicles which are constructed around conventional technology as the one described. A conventional vehicle may alternatively include one or several unconventional technical solutions, such as throttle-by-wire (TBW) or brake-by-wire (BBW), however the main part of the structure shall be of conventional type.

A WCM vehicle, as referred to throughout this thesis, is a vehicle containing two or four WCMs. WCM vehicles involve an increased number of actuators compared to conventional automotive constructions, enabling improved vehicular motion control, see section 3.1.1. The corner modules may have different setups according to the previous description, hence the number of actuators may vary. Generally however, the number of actuators contained in a WCM vehicle exceeds the degrees of freedom, thereby forming an overactuated system [3].
2.1 X-by-wire

Traditionally, vehicular motion control have been executed through operation of a steering wheel and pedals mechanically connected to the wheels and ICE. X-by-wire is a fairly novel technology which involves pure electronic control of longitudinal, lateral or vertical vehicular motion. It has been successfully utilized in the aviation industry for decades, in that sense called fly-by-wire [5]. There are a variety of terms for the technology in context of road vehicles, such as x-by-wire, drive-by-wire or simply by-wire.

The basic principle of an x-by-wire (XBW) system is replacement of all mechanical/hydraulic linkages with electric ones [5]. In turn, the connection between driver and subsystem is no longer direct. Instead, the mechanical input supplied by the driver through the operational device, is interpreted and processed by computer electronics prior to realization of the demanded action. In accordance with figure 2, the input device contains a mechanical operational component, including e.g. a mechanical pedal, sensors for registration of the pedal movement, microelectronics and a haptic feedback device. The latter applies a force to the pedal to recreate the feeling of a conventional operational device, by use of a spring and damper device or an electrical actuator. Depending on what subsystem is being operated, it might allow the driver to physically sense the activity occurring in connection to the controlled sub-system, i.e. transfer haptic information. If the operational device is a steering wheel, an electrical actuator mounted in connection to the steering wheel may transfer a torque to the steering wheel. This torque corresponds to the torque transferred from the front wheels onto the steering wheel via the steering rack and pinion, during operation of a conventional steering system. Connected to the operational device via a bus system is the actual control system containing a microcomputer, power electronics, electrical actuators, mechanical components and sensors [6]. The mechanical components include eg. steering linkages or friction brakes. The microcomputer is responsible for actuator control, function control, supervision and management such as fault handling and optimization [6]. Owing to the non-direct connection structure including computer power, beneficial new handling and safety solutions are enabled, further discussed in subsection 3.1.
2.1 Fault tolerant x-by-wire systems

A fault tolerant system behavior implies a system which can continue to operate properly even in the event of one or several malfunctions. Concerning vehicular x-by-wire systems, fault-tolerant behavior is of utmost importance, as failure might lead to hazardous complications including personal injury.

There are three main XBW subsystems which apply to conventional vehicles, throttle-by-wire, brake-by-wire and steer-by-wire (SBW). TBW is not part of WCM technology, however the applications made possible due to the use of TBW, are similar to the ones enabled by the by-wire controlled in-wheel motors of WCMs. Therefore it will be further discussed in this thesis, see section 2.2.1. The TBW system is available in passenger vehicles as of today, and in its present form a pure XBW solution. The other two systems are currently utilized in a few conventional vehicles, however coupled with mechanical back-up systems. This is done in order to achieve a more reliable system. Steering and braking are safety-critical functions, i.e. a failure in such might involve personal injury. Electronic components have a different fault behavior compared to mechanical components, therefore fault-tolerant systems have to be incorporated in order to meet the high safety demands [6]. Until this is achieved and proven safe, mechanical back-up systems admit use of the XBW systems and their advantages, by offering reliable, fault-tolerant back-up technology in case of malfunction. Electrical failure is often caused by shortcuts, loose connections, parameter changes, contact problems or electromagnetic compatibility problems [6]. However, the potential reliability of well-designed, well-manufactured electronic systems is extremely high [7]. Typically the proportions that are defective in any purchased quantity are in the order of less than ten per million in case of complex components, and even lower for simple components [7].

A design containing a mechanical backup system involves additional mass and manufacturing costs as well as an increased structural complexity, therefore fault-tolerant electrical back-up systems are preferable when possible [6, 8]. A way of improving the safety profile of an electrical system is to implement redundant electrical components. The redundancy can either be static or dynamic. Static redundancy means that multiple redundant modules govern the same function by operating in parallel. If one module fails, the system might be degraded but still function, since all modules except one still maintain proper functioning. Concerning dynamic redundancy, two or several modules are available, however merely one of them is in operation. The other modules are in standby mode, ready to be utilized in case of malfunction regarding the module currently in operation.

Sufficient fault detection performance is of utmost importance in order to maintain safe...
operating conditions [6]. The number of back-up components may vary according to the required fault tolerance of the function it governs, a higher number of redundant components generally imply a higher level of fault tolerance. An essential benefit associated to electrical back-up systems is the reduced weight compared to mechanical equivalents.

2.1.2 Communication network architecture

Each vehicle containing one or several XBW solutions requires a communication network. The objective of this network is to handle the data transfer and communication among components within a subsystem, as well as between different subsystems. The components might be e.g. maneuvering devices, sensors and actuators. The communication network is responsible for transmission of control signals managing all functions of the XBW subsystems. Such a function might be to set a specific steering angle of a wheel contained in a steer-by-wire system, or to decelerate a vehicle by properly distributing brake forces among the wheels via a brake-by-wire system. A failure concerning the communication network might lead to maneuvering malfunction, thus fault-tolerant behavior of the network is of utmost importance.

An important issue is to find a network protocol which provides fast data transfer as well as sufficient levels of safety and reliability. Lots of industrial and academic work have been directed to solve this matter, and resulted in several reliable communication technologies, such as Time-Triggered Protocol (TTP), Time-Triggered Controller Area Network (TTCAN) and FlexRay [9]. The latter was designed specifically for automotive applications [10]. TTP, TTCAN and FlexRay are all mainly time-triggered architectures. Common for these protocols is that significant events, such as tasks and messages, occur not randomly in time, such as with the traditional event-triggered Controller Area Network (CAN), but according to a pre-determined time-schedule. CAN is currently used in automotive systems.

There are several reasons why time-triggered protocols are more appropriate for use in XBW applications, compared to event-triggered protocols. In order to understand this, one should possess basic knowledge of the structural differences between these two communication architectures. An XBW system comprises several electronic control units (ECU), set up as nodes in a network. The nodes are connected via a medium, generally an assembly of isolated copperwires forming a so called bus-system. They communicate via the bus by sending messages containing information regarding either the state of the node or an event that have occurred in the node. A pure time-triggered protocol involves solely state messages, while an event-triggered protocol involves solely event messages. As an example, consider a change of the steering angle regarding a SBW system from $9^\circ$ to $10^\circ$. A state message from a wheel angle sensor would include information stating a steering angle of $10^\circ$, as would a corresponding event message state information concerning a change of the steering angle of $1^\circ$, i.e. an event is a change of state. Since event-messages may be sent at any time, problems arise when two or more event messages are simultaneously sent to the same node. Only one message can be received at each instant, therefore the messages might collide and merely the one with the highest priority reaches the recipient. All event messages contain priority information stating its priority in relation to other messages. Message collisions are possible to prevent by adding a queue function
to the system, but the architecture is still non-deterministic, there is no way to guarantee when a message will be successfully transmitted. A time-triggered state message on the other hand, can only be sent at specific moments, according to a time-schedule. Thus, provided that the system is properly designed, no collisions arise, and the time at which a message can be successfully transmitted is guaranteed. The behavior described makes time-triggered protocols appropriate for XBW applications, where a deterministic behavior is of utmost importance [10, 11].

One drawback with the time-triggered protocols is due to the time-scheduling. If a node does not need to send a message during one of its designated time-slots, that specific slot is left un-used. Thereby, the performance of the system is not fully taken advantage of. Another problem is that time-triggered systems have to be synchronized and are complicated to expand. All nodes have to be implemented to the time-schedule from the start or excessive reconfiguration might be necessary [10].

TTP is a pure time-triggered protocol, see table 1. Every time-slot is assigned to a specific node. It supports bitrates up to 2-25 Mbps depending on transfer medium. TTCAN and FlexRay differs from TTP by implementing the event-triggered function as a lower layer to the time-triggered structure. Certain time-slots are assigned exclusively to specific nodes, and others are assigned to several nodes simultaneously in priority order, according to the event-triggered architecture. TTCAN, in resemblance with CAN, supports bitrates of up to 1 Mbps. Flexray supports bitrates of up to 10 Mbps on two channels. They can either be used together to achieve bitrates of up to 20 Mbps, or work redundantly, thereby implementing fault-tolerance to the system [10].

<table>
<thead>
<tr>
<th>Protocol name</th>
<th>CAN</th>
<th>TTCAN</th>
<th>TTP</th>
<th>FlexRay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification</td>
<td>Event-triggered</td>
<td>Time-triggered</td>
<td>Time-triggered</td>
<td>Time-triggered</td>
</tr>
<tr>
<td>Message type</td>
<td>Event</td>
<td>Event/State</td>
<td>State</td>
<td>Event/State</td>
</tr>
<tr>
<td>Bitrate</td>
<td>1 Mbps</td>
<td>1 Mbps</td>
<td>2-25 Mbps</td>
<td>10-20 Mbps</td>
</tr>
</tbody>
</table>

### Table 1: Protocol properties.

### 2.2 Longitudinal motion

The longitudinal motion of a WCM vehicle is controlled through operation of in-wheel motors and friction brakes. The in-wheel motors are able to accelerate as well as decelerate the vehicle, whilst the friction brakes are utilized when additional brake force is required.

#### 2.2.1 Propulsion

**In-wheel motor properties** All of the considered WCM concepts, discussed in section 4, utilize electrical in-wheel motors for means of propulsion. One major advantage and key property related to in-wheel motors is the compact design. In-wheel motors are constructed to fit into the unexploited volume inside the rim of a conventional wheel, see figure 5, in terms of conventional vehicles generally housing no more than a wheelhub and
brake components. By replacing the traditional ICE with in-wheel motors coupled with batteries, more structural freedom is enabled concerning the layout of the vehicle body and interiors. Hence, important aspects concerning passive safety, manufacturing costs and interior design versatility can be improved.

A conventional ICE based driveline requires a gearbox mainly for two reasons. Firstly, it transforms the high angular velocity and low torque on the outgoing shaft of the ICE to a low angular velocity and high torque on the propelling wheels. Secondly, the gearbox provides the ability to compensate for the narrow power spectrum generally related to combustion engines, by shifting gear ratio depending on desired vehicular velocity, see figure 3a.

Electrical motors possess quite different output characteristics compared to ICES. An electrical motor power curve can be divided into two sections, the constant force region and the constant power region, referring to tractive force and motor power respectively. The specific rotational velocity in between these sections is called the base speed, often expressed in revolutions per minute. Below the base speed the tractive force is at its maximum rated level, $F_{\text{max}}$. At higher rotational velocity, the motor produces a constant power output, $P_m$, illustrated in figure 3b [12]. Since tractive force is available from standstill, no clutch is needed to initiate movement. Owing to the constant power delivery related to electrical drives, shifting the gear ratio is unnecessary. Depending on motor specifications a fixed gear might be necessary between motor and wheel. However, in-wheel motors are often constructed to produce a high torque at low angular velocity, thereby enabling direct drive operation. Considering the characteristics described, the presence of a “multi-speed gearbox” is generally unnecessary in combination with in-wheel motor drives.

The weight of transmission components are generally high, therefore removal of such might enable weight reduction. However, one shall have in mind that a WCM vehicle might include other components carrying significant mass, such as dense battery packages.

\[ \text{Engine power} = \frac{mg \cdot v \cdot F_{\text{max}}}{P_{\text{max}}} \]

\[ \text{Engine force} = \frac{mg \cdot v \cdot F_{\text{max}}}{P_{\text{max}} \cdot \rho} \]

\[ \text{Engine speed} = \frac{mvF_{\text{max}}}{P_{\text{max}} \cdot \rho} \]

\[ \text{Engine displacement} = \frac{2 \cdot \pi \cdot L \cdot \rho \cdot v \cdot F_{\text{max}}}{P_{\text{max}} \cdot \rho} \]

\[ \text{Engine efficiency} = \frac{mg \cdot v \cdot F_{\text{max}}}{P_{\text{max}} \cdot \rho} \]

\[ \text{Engine torque} = \frac{mg \cdot v \cdot F_{\text{max}}}{P_{\text{max}} \cdot \rho} \]

\[ \text{Engine force} = \frac{mg \cdot v \cdot F_{\text{max}}}{P_{\text{max}} \cdot \rho} \]

\[ \text{Engine displacement} = \frac{2 \cdot \pi \cdot L \cdot \rho \cdot v \cdot F_{\text{max}}}{P_{\text{max}} \cdot \rho} \]

\[ \text{Engine efficiency} = \frac{mg \cdot v \cdot F_{\text{max}}}{P_{\text{max}} \cdot \rho} \]

\[ \text{Engine torque} = \frac{mg \cdot v \cdot F_{\text{max}}}{P_{\text{max}} \cdot \rho} \]

(a) Conventional vehicle equipped with ICE attaining desired ideal force curve by use of a 5-speed gearbox. (b) Ideal force curve by use of an ideal electrical motor.

Figure 3: Ideal force curve illustrative comparison [12].
The degree of efficiency related to in-wheel motor operation is often very high. Theoretically, the efficiency can be as high as 96% [13]. In comparison to other electrical drives like e.g. a single electrical motor setup, in-wheel motor applications benefit from the fact that they generally do not contain any transmission. A concept vehicle called IZA, presented at an IEEE conference in 1997, had a maximum total drive system efficiency of 91%, including losses in the power electronics. This vehicle used four permanent magnet synchronous in-wheel motors with a maximum output of 25 kW and 417 Nm each [14].

In-wheel motors are presently not used in any serial-produced vehicle. Large amounts of time and effort are spent for development and evaluation of this technology. The exposed mounting position inside the wheel rim makes the motor subject for vast amounts of dirt and dust. As part of the unsprung mass, it is also compelled to withstand a large amount of vibrations. High voltage cables connected to the hub are exposed to constant friction challenges due to the wheel's movement in relation to the chassis [15]. Before in-wheel motor drives can be implemented into serial-produced vehicles, such issues need to be sorted out, since reliability is a key property related to modern vehicles.

In 2008, Frost & Sullivan estimated that around 150,000 vehicles in North America and 120,000 vehicles in the European Union will be equipped with in-wheel motor technology by 2015 [16].

**Accelerate-By-Wire** The first XBW solution to be introduced in passenger cars was the throttle-by-wire system. A TBW system admits the following function. In conventional vehicles the driver regulates the amount of air included in the combustion process by adjusting the accelerator pedal. A cable connects the accelerator pedal to the throttle-plate. The driver controls the amount of air passing through the inlet manifold in a direct manner, by setting the angular position of the throttle-plate. Contrarily, in terms of TBW, an electrical actuator sets the throttle-plate angular position based on electrical signals transmitted from a control unit. The latter is influenced by, but independent from, the driver input. Thereby, the control unit may set the throttle-plate angle not only according to pedal position, but also by taking into account surrounding factors, hence enabling optimized throttle-plate regulation. Driver assisting applications such as adaptive cruise control and collision avoidance functions are made possible, due to the fact that the control unit can override the driver input. TBW technology is already implemented in many modern vehicles.

Regarding the motor control of WCMs, throttle-by-wire would be a misleading expression, since it refers to the throttle which regulates air infusion of an ICE. WCMs are not powered by ICES, consequently they do not include any throttle components. In terms of WCMs, the corresponding function to TBW is the by-wire controlled angular velocity and acceleration of the propelling motors. Hence, a more suitable expression, would be accelerate-by-wire.

A four wheeled WCM vehicle can be equipped with either two or four in-wheel motors. Depending on which setup is chosen, various properties concerning handling, comfort and active safety can be achieved. The most versatile behavior may be accomplished by the adaption of four individually controlled tractive wheels, although such a setup also involves an increased structural complexity, particularly regarding the control system. Each motor
is controlled individually, but since the specific torque applied to each tractive wheel affects the motion of the vehicle, they have to be regulated as one system. Each wheel need to deliver the amount of torque momentarily optimal for the specific vehicle corner in relation to the other forces acting on the vehicle. The optimal torque distribution is continuously calculated by one or several control units based upon driver input and information from position sensors, velocity sensors, acceleration sensors, force and torque sensors and pressure sensors. This setup supports efficient traction control systems and therefore offers major improvements in terms of handling as well as safety, compared to conventional vehicles, see section 3.1.

**Electrical machines suitable for in-wheel operation** Regarding in-wheel motor applications, certain fulfillments associated to geometry and torque output are required by the electrical machines. Since the general idea of in-wheel motor drives includes that the rim shall be capable to hold the major part of the machine body inside the boundaries of its volume, certain geometrical properties need to be met. The diameter of the machine may preferably be large in comparison to the depth, and the overall size and weight shall be kept down, in order for the motor to fit inside the rim and keep the unsprung mass to a minimum. For direct drive to be feasible, the motor shall also be able to produce a continuous high torque at low angular velocity.

In addition to these in-wheel motor specific aspects, the following demands presented by Zeraouilia et al. [17], are general for electrical machines intended for vehicular tractive applications:

1. High instant power and power density,
2. high torque at low speed for starting and climbing, high power at high speed for cruising,
3. wide speed range, including constant-torque and constant-power regions,
4. fast torque response,
5. high efficiency over the wide speed and torque ranges,
6. high efficiency for regenerative braking,
7. high reliability and robustness for various vehicle operating conditions,
8. reasonable costs.

Permanent magnet (PM) brushless motors, also called synchronous motors, are particularly suitable for in-wheel motor direct drive applications. Characteristic for such a machine is that the rotor is equipped with permanent magnets instead of windings, see figure 5. There are various types of PM brushless motors. Generally, they are classified according to the mounting position of the permanent magnets, surface-mounted or buried. The surface-mounted type contains the magnets on the surface of the rotor, whilst the buried magnet motor keeps the magnets embedded in the rotor core, see figure 4. The former requires less magnet material compared to the latter, given an equal size of the
machines. It also benefits from a cheap and simple construction. However, the buried magnet type may achieve higher air-gap flux density, which in turn admits higher torque per rotor volume. Additionally, the risk of demagnetization is smaller. Buried magnet PM motors represent the more rugged solution [17, 18].

PM brushless motors have a limited field weakening capability, owing to the presence of a PM field. Thus, the constant power region is generally fairly short. In order to extend the constant power region, and consequently the speed range, of a PM brushless motor, the conduction angle of the power converter can be controlled while above the base speed. This way the speed range may be extended three to four times above the base-speed [17].

PM brushless motors benefit from high power density, high efficiency and efficient heat dissipation [17]. Low unsprung vehicular mass is desirable in aspect of comfort and handling, as discussed in subsection 3.1.4. Since in-wheel motor structures generally involve the motor as part of the unsprung mass, it is important that the mass of the machine is kept down. The high power density of PM brushless motors make them particularly suitable for such applications. In addition, the design of PM machines can easily be adapted to the boundary conditions related to the specific geometry and volume of a wheel rim, see figure 5.

Figure 4: Magnet mounting positions [19].

Figure 5: In-wheel PM brushless motor [17].
2.2 Longitudinal motion

Rahman et al. investigates the axial flux permanent magnet (AFPM) motor, which is a particular PM brushless motor, as part of a direct drive in-wheel setup. The axial flux permanent magnet motor have favorable characteristics for in-wheel motor drive applications in terms of efficiency and specific torque. The torque density can be improved by as much as two times compared to an induction motor, which is another motor type utilized in vehicular propulsion systems. The highest amount of torque output is achieved by designing the machine with a large diameter and high number of poles. Thus, the geometry of AFPM machines makes them suitable for in-wheel placement [12].

2.2.2 Brakes

In conventional vehicles, friction brakes such as hydraulic, pneumatic or non-hydraulic mechanical disc or drum brakes are the primarily utilized solutions for means of deceleration. In terms of WCMs, the conventional drums and discs are still being used, although in a different manner. Significant amounts of energy are dissipated in form of heat when conventional friction brakes are applied. Regenerative braking through in-wheel motors makes it possible to re-use parts of this energy. The in-wheel motors and friction brakes can be applied separately or together depending on required brake force and momentary vehicular velocity. During deceleration from low velocity the friction brakes are primarily used, since the in-wheel motors require a higher angular velocity to be able to supply enough brake torque. During light deceleration from high velocity the in-wheel motors are preferably used exclusively. When excessive brake force is required, friction brakes and regenerative brakes are applied together.

Regenerative braking through in-wheel motors

The primary function of in-wheel motors is to supply propulsive torque to the driven wheels of a vehicle. However, they also have the ability to work in a reversed manner, thereby decelerating the vehicle. The in-wheel motors then work as generators, transforming the kinetic energy bound in the vehicle movement into electricity. This electricity is either directly redistributed to other components, or supplied to a battery pack or power electronics comprising capacitors. A compact design and capability of fast charge and discharge makes the latter a favorable solution for this matter. By temporarily storing the energy, it can be reused at a later point of time, thereby reducing the overall energy consumption. A regenerative brake setup such as the one described, when combined with conventional disc or drum brakes, also profits in form of less brake pad/shoe wear. This advantageous side effect helps keep friction brake maintenance and environmental impact to a minimum.

The dead time between driver input and initiation of vehicular deceleration is shortened by use of regenerative brakes compared to conventional hydraulic brakes [20]. Hence, active safety solutions can be improved, see subsection 3.1.3.

Brake-By-Wire

There are two types of brake-by-wire solutions suitable for operation in WCM vehicles, the electro-hydraulic brake (EHB) and the electro-mechanical brake (EMB). Both types are friction brakes.
EHB is based on a conventional hydraulic brake system, implemented with BBW control. It is realized by combining a hydraulic circuit with an electrical circuit. The latter comprises a control unit, wiring and sensors, in accordance with figure 6, as well as electrically controlled valves [21]. The hydraulic circuit comprises a hydraulic pump connected to a brake caliper, of which the pump is merely controlled by means of by-wire technology. Alternatively it may, in excess of the system previously described, contain a complete conventional brake system representing a direct hydraulic connection between brake pedal and brake caliper, for means of backup. In case of electrical circuit malfunction, the electricity is cut, thereby opening a valve engaging the conventional hydraulic system [22]. This fault-tolerant function makes it suitable for use during the transition from conventional brake systems to BBW, as the safety of a conventional brake system remains. Since 2001, Mercedes Benz AG implemented an EHB system into some of their passenger car models [23], called the Sensotronic Brake System. It shall however be mentioned that a problem concerning the system resulted in a recall of more than 680 000 vehicles in 2004 [24]. This was a significant set-back for the customers’ confidence in both Mercedes and BBW systems in general.

![Electro-hydraulic brake system](image)

**Figure 6: Block diagram of a basic electro-hydraulic brake system.**

EMB is a pure BBW solution including an operational device coupled with a control unit in connection with an electro-mechanical brake actuator [21], see figure 7. Through the operational device, the driver communicates the vehicular deceleration rate that is desired, after which the control unit calculates the appropriate brake actuator force to be applied to each wheel. EMB involves faster response compared to EHB, owing to its fast motor dynamics [25].

A WCM can contain either one of these two described brake setups, however EMB might be the technology primarily used as the technology evolves, owing to easier adaption to the vehicle structure and the absence of fluids.
Electro-mechanical brake system

![Block diagram of a basic electro-mechanical brake system.](image)

**Electro-mechanical disc brakes**  As previously stated, WCMs usually comprise regenerative brakes in combination with friction brakes. The purpose of the latter is merely to assist the in-wheel motors decelerating function when required, such as during heavy or low velocity braking. It is quite possible to utilize EHBs for this application. However, since EHBs involve hydraulic liquids, they require more maintenance and possibly hydraulic connections between wheel module and vehicle body. EMB setups are more easily implemented into WCM structures, owing to its pure electro-mechanical function. It eliminates the need for hydraulic oil, thereby simplifying maintenance as well as the connection structure of the WCM. Owing to its electro-mechanical function, the EMB can easily be integrated into the structure of advanced active safety systems, see subsection 3.1.3. Although a hydraulic brake can be electrically controlled, as with EHB technology, the faster processing of a pure electro-mechanical brake makes it more suitable for the application.

There are however a couple of problems surrounding the electro-mechanical brakes. During heavy braking the brake pad needs to be applied towards the disc with high pressure. To find a linear actuator which can deliver sufficient force, yet meet the demands of low cost, compact design and low weight can be difficult. One solution is to use a rotary-to-linear converter such as e.g. a ball screw device, in connection with a rotary actuator. That way a low torque can be converted into a high force. However, such devices require frequent maintenance, thereby lowering the overall reliability of the system [8].

The VDO Electronic Wedge Brake, thoroughly presented in subsection 4.3, utilizes another solution which enables use of a simple linear actuator. The latter applies a force onto the side of a wedge formed element mounted in between the actuator and brakepad, see figure 22. The geometrical relations in between the length and width of the wedge element induce an amplifying effect, thereby increasing the low force created by the linear actuator into an adequate force applied onto the brakepad.

Another issue concerning electro-mechanical brake systems is the fact that most of them require a 42 V electrical system to function properly [5]. Such a demand might inhibit implementation into serial-produced vehicles, since 12 V is the standard voltage utilized in conventional vehicles. Siemens VDO’s Electronic Wedge Brake is however claimed to function properly in connection to 12 V systems [26].
2.3 Vertical motion

A WCM may contain either a passive, a semi-active or an active suspension system or any feasible combination. The main objective of this section is to discuss the active suspension system, which offers several advantageous properties compared to passive and semi-active systems. Referring to the WCM concepts presented in section 4, active suspension solutions are widely used in terms of WCM technology.

An automotive suspension system have several tasks to fulfill. It shall...

- ...support the static load of the vehicle with passengers,
- ...reduce the vehicle body vertical acceleration, in order to improve passenger comfort,
- ...minimize the dynamic tire load during cornering and braking, in order to improve handling,
- ...minimize roll and pitch motions during maneuvering [27].

To fully understand the function of an active suspension system, one should possess knowledge about the conventional passive equivalent. Hence, below follows a basic presentation of the latter.

2.3.1 Passive suspension

The vertical motion of a vehicle is, in terms of conventional vehicles, passively controlled by means of a suspension system, generally comprising springs such as leaf springs, coil springs or air springs and dampers, usually containing hydraulic oil. Additionally, roll motions can be inhibited by means of a torsion bar. The suspension links the wheels to the vehicle body and allows relative movement.

The springs support the load of the vehicle body at all times, and absorb the dynamic energy related to acceleration, cornering and braking. Hydraulic dampers dissipate the kinetic energy absorbed by the springs into heat, through application of a velocity dependent force, counteracting the induced spring deformation. This way, excessive suspension movement and oscillation is inhibited.

In accordance with the principle function described, the main objectives when designing a suspension system is to isolate the vehicle body from road disturbances while maintaining continuous contact between road and tire. These properties, if successfully implemented, admit optimized ride comfort and handling performance. However, when utilizing a passive suspension system, the result is always a compromise between these two conflicting characteristics. A softer suspension setup generally involves a more comfortable ride but degraded road holding properties, while a stiffer setup generally involves better road holding properties but degraded ride comfort. Since the setup is invariable, it is a result of expected operating conditions according to the developer.

Passive suspension systems are low cost and easy to manufacture [28]. Additionally, they combine fairly good suspension performance with reliability and ease of implementation.
2.3.2 Semi-active suspension

A semi-active suspension system is basically a passive suspension system, with the ability to vary the damping properties. The damping characteristics can be adjusted through application of a low-power signal. The two most common technologies involve either a solenoid-valve or an electro-magnetic field, for the purpose of damper adaption. Both solutions involve regulation of the hydraulic oil flow between the extension chamber and compression chamber of the damper, see figure 8.

The solenoid-valve solution, in its simplest form, is based upon opening and closure of an additional valve in the piston. The oil transition in between the two chambers during damper action thereby increases or decreases respectively.

The electro-magnetic solution instead varies the viscosity of the specific magnetorheological (MR) fluid utilized as hydraulic medium, by activating an electro-magnetic field. The MR-fluid contains iron particles, which during influence of a magnetic field form fibres, which in turn increase the viscosity of the fluid. By varying the viscosity, the damper coefficient is altered.

Owing to the adaptable characteristics, semi-active suspension extends the range of operation compared to passive suspension [28]. Considering an MR-damper, the dynamic range (the ratio between the peak damping force and the damping force without magnetic influence) is often in the range of 5-10. This means that the damper can be widely adjusted according to prevailing road conditions and desired comfort and handling properties.

![Figure 8: Mono-tube conventional damper][28].
2.3.3 Active suspension

The principal function of an active suspension system is similar to the passive and semi-active systems previously described. The main objectives are still optimal ride comfort and handling performance. However, in contrary to passive systems, the vertical motion can be actively controlled, actuated by means of one or several suspension actuators coupled to a power source. The actuators are connected to suspension linkages, admitting active control of the relative movement between vehicle body and wheels. Often, the suspension actuators are coupled with passive components such as dampers and springs. These can be mounted in series with, or parallel to, the electrical actuators. Depending on this setup, the system attains quite different properties. This is further discussed in the following sections.

An active suspension system can store and dissipate energy in the same manner as a passive system, but also adds the ability to introduce energy to the system when necessary [29]. Hence, the relative vertical movement between wheel and vehicle body can be more freely assigned, compared to passive systems. To exemplify the opportunities enabled by utilization of active suspension systems, consider the following. A vehicle is in motion along a road. A camera mounted in front of the vehicle detects upcoming disturbances in the road profile, and transmits this information to the suspension control unit. Based on the road profile information, the control unit continuously adjusts the vertical distance between the wheels and the vehicle body. The wheels follow the road profile, while the body is kept unaffected from the road irregularities. It shall be mentioned that this is an idealized example. In reality there are boundary conditions set by the finite suspension travel and invariant points in the suspension transfer function [27].

The active suspension components are dependent on input from a proper management system. A closed loop control system ensures the calculation of a correct reference actuator force. It involves actuators, power electronics converter, mechanical components and instrumentation feedback [30]. For each instance, the suspension properties are adjusted according to prevailing operating conditions. Hence, improved ride comfort and handling performance is attainable.

Active suspension systems may overcome the need for setup compromises related to passive suspension systems. However, they generally involve drawbacks including high energy consumption, high weight, high cost and non fail-safe operation [28]. Thus, commercial vehicle implementation has so far been limited.

Active suspension systems are generally separated into two main types, high bandwidth systems and low bandwidth systems. These two types may in turn be categorized according to the actuator technology used. This section treats two kinds of suspension actuators, hydraulic and electro-magnetic.
**High bandwidth systems** In terms of high bandwidth active suspension systems, the actuator is generally mounted in between the sprung mass and the unsprung mass, often in parallel with a spring, see figure 9. It aims to counteract both high disturbance frequencies, with a maximum amplitude around the frequency 12 Hz, and low disturbance frequencies, with a maximum amplitude around 3-4 Hz. Since the suspension can be actively controlled over a broad bandwidth, it admits very good road holding and comfort properties. A drawback with this particular type of suspension is that it generally consumes a significant amount of power. It also requires the use of broad bandwidth actuators, which are generally more expensive than narrow operating actuators. Vehicle height regulation is only possible by increasing the applied actuator force [27, 29, 31].

![Figure 9: Principal setup for a high/low bandwidth active suspension system [27].](image)

**Low bandwidth systems** In terms of low bandwidth active suspension systems, the actuator is generally, in common with high bandwidth systems, mounted in between the sprung mass and the unsprung mass. However, it is mounted in series with a passive part comprising a spring and damper device, see figure 9. The active part of the suspension counteracts disturbance frequencies in the lower range, while the passive part handles the higher frequencies. This construction admits easier vehicle height regulation and lower energy consumption compared to high bandwidth systems [27, 29, 31].

**Hydraulic active suspension** A hydraulic active suspension comprises hydraulic actuators for means of suspension. A hydraulic pump supplies the actuators with sufficient pressure. According to figure 10, the pump may be driven by an ICE if implemented in a conventional vehicle. In terms of WCM vehicles, the pump is electrically driven, powered by batteries or any other feasible power source. Regulation of the actuator pressure
is taken care of by utilizing a low-power electromagnetic actuator which connects to a hydraulic valve. A control system including sensors and instrumentation together with a power electronics converter completes the construction [30].

Hydraulic active suspension have drawbacks in form of a complex structure due to a high number of mechanical devices, and the hydraulic oil requirement.

![Hydraulic Single-Wheel Active Suspension System](image)

**Figure 10:** Hydraulic active suspension block diagram [30].

**Electro-magnetic active suspension** A hydraulic damper converts kinetic energy into heat, which in turn dissipates without being utilized. Segal and Xio-Poo [32], shows that roughly 200 W of power is dissipated in terms of an ordinary sedan passenger car travelling a poor road at 13.4 m/s. Hence, a regenerative suspension structure might be desirable.

Electromagnetic suspension admits such a regenerative function by converting the kinetic energy involved in the vehicle body vertical movement into electrical energy, which in turn can be stored for latter use [28]. This function somewhat improves the high energy consumption issue that is generally associated with active suspension systems. Owing to the fully electrical function of this suspension type, it simplifies implementation with WCM modules.

Figure 11 shows a block diagram of a basic electromagnetic active suspension structure. As previously stated, this construction requires less mechanical parts compared to the hydraulic equivalent. Hydraulic components such as pump and valves are needless. However, the electromagnetic actuator as well as the power electronics shown in figure 11 must obviously be larger than the ones shown in figure 10. The electromagnetic actuator may be of either rotary or linear type. Rotary actuators may require some kind of gearbox to translate the rotary movement into linear and amplify the applied force, hence increasing the structural complexity [30].
2.4 Lateral motion

The control of a vehicle’s lateral motion is a safety-critical function. Thus, it is of utmost importance that the steering system maintains a proper function during all possible operating conditions. A conventional “rack and pinion” steering system is regarded as safe, owing to its rigid mechanical structure. However, in terms of WCM vehicles, by-wire based electrical steering systems are generally considered, since the utilization of such adapts well to the modular design. It allows the mechanical steering connections, generally found in between the front wheels and the passenger cabin, to be removed. With an electrical steering system comes the possibility of improved handling performance and active safety, see subsection 3.1, since the driver input can be optimized by utilization of computational resources.

2.4.1 Steer-by-wire

Steer-by-wire is a lateral motion XBW system, controlled by the driver in co-operation with an electronic control unit, multiple sensors and one or several actuators. Regarding conventional vehicles, when changing direction, the driver by own means compensates for varying road conditions and wheel slip by correcting the steering wheel angle. In terms of SBW the procedure is quite different. The driver communicates an input signal through operation of the steering device, indicating which direction of motion is desired. The control unit gets information from multiple sensors regarding prevailing road conditions and vehicle position. It then compensates for these factors and sets the optimal wheel angles, suspension setup and throttle/brake torque, required for the vehicle to move in the direction indicated by the driver. This process is very rapid and repeats continuously. As described, the key difference regarding the maneuvering of a conventional vehicle com-
pared to a steer-by-wire equivalent, is that the driver communicates the desired directional change of the vehicle, rather than the steering angle of the wheels.

SBW systems can comprise individually steerable or pairwise steerable wheels, the former being the technology primarily used in terms of WCM vehicles.

2.4.2 Steering device

Conventional vehicles generally have a mechanical “rack and pinion” setup connecting the steering device with the front wheels. In terms of SBW, mechanical connections are excluded, thereby allowing alternative variants of feasible SBW steering devices.

The conventional steering wheel is a good solution for controlling the direction of a WCM vehicle, since drivers are already familiar with its function and operational feeling.

An alternative solution is to implement a joystick, see figure 12. Such a device can control not only the direction of the vehicle, but also propulsion and brake forces. Hence, the conventional foot pedals controlling acceleration and brakes can be excluded, allowing the lower area of the cabin to be more freely designed. The absence of foot pedals also improves safety, since there are less parts that may protrude the cabin during a collision.

![Figure 12: Joystick steering device implemented in Mercedes-Benz SCL600 concept car [33].](image)

Despite which type of steering device is utilized, lateral displacement is enabled, owing to the absence of mechanical connections between the device and the wheels. Thereby, the steering wheel or joystick can be easily adapted to either right or left side steering. Concerning conventional vehicles, left side steering vehicles are manufactured for right-hand traffic markets, and right side steering vehicles are manufactured for left-hand traffic markets. Such a differentiation is not required when utilizing side-to-side adjustable SBW steering devices. Another alternative to enable this feature is to have a joystick mounted
between the front seats, see figure 12, allowing access from both the left and the right seat.

A haptic feedback device, as described in subsection 2.1, may be required in order for the driver to be able to “feel the road”. Such a device functions as a feedback tool for the driver, hence allowing a safer and more enjoyable ride.

Haas and Kunze [34] performed a comparison on the effect on driving performance during operation of a joystick compared to a conventional steering wheel and foot pedals. Eight male civilian volunteers with normal visual acuity drove a simulated military tank along a simulated road with a speed of either 15 mph or 45 mph. The task was to keep the center of the vehicle on the road while maintaining speed. The test was first conducted operating a conventional steering wheel in combination with brake and accelerator foot pedals. Thereafter, the same test was conducted using a joystick as steering device. The results indicated that a steering wheel did not provide any significant advantages over a joystick when it came to driving performance. During the lower test speed of 15 mph there was no significant difference regarding the mean driving velocity. The higher test speed of 45 mph resulted in a small difference between the two different steering setups, however it was small enough to be discarded as of no practical significance. Additionally, there was no difference in the driver’s ability to keep the vehicle centered on the road among the two controller types. The report further implies that a joystick steering device has potential as an alternative control technology because it provides more control through curves, possibly because it admits greater use of the hand, wrist and fingers to improve the degree of driver control, compared to a conventional control setup.

2.5 Power source

Operation of a WCM vehicle is based upon electrical power. This power can be supplied from several types of on-board power sources such as an ICE equipped with a generator, hydrogen fuel cells or a pack of chemical batteries. In this section, focus is aimed at the latter alternative, chemical batteries, since it represents a frequently utilized power source in terms of electrical vehicles.

2.5.1 Chemical batteries

Batteries store energy electrochemically. They are built up by one or several low-voltage battery cells, connected in parallel and/or in series depending on desired properties. The battery can be charged by applying a voltage over the two terminals, after which an internal chemical process takes place [35].

There is currently a major demand for high capacity batteries. Even so, the battery technology evolves in a slow manner. The main reason for this is the lack of suitable electrode materials and electrolytes. Research in the area is very time consuming [36].

One major benefit when considering a battery package as primary vehicular power source is its capability to adapt to various designs. Battery packages generally comprise a number of cells, which can be placed in different locations of the vehicle, according to desired weight distribution and design related boundary conditions. One particular alternative to
consider is the “skateboard-design”, see figure 13. By placing the batteries inside the floor of the cabin, the chassis adapts a basic design similar to a skateboard, flat with one wheel mounted to each corner. Such a layout enables the cabin, including impact deformation zones, to be more freely assigned, while at the same time lowering the center of gravity.

![Skateboard-design chassis, GM AUTOonomy concept vehicle](image)

Figure 13: Skateboard-design chassis, GM AUTOonomy concept vehicle [37].

**Battery types** Many types of batteries exist, such as lead-acid (Pb-acid), nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH) and lithium-ion (Li-ion). As the names imply, they contain different chemical reactants, giving each battery type unique properties. There are several factors to consider in terms of the capability of a certain battery type. Energy density, energy capability, round trip efficiency, cycling capability, life span and initial cost are all important [35].

Ni-MH batteries, with a specific energy of 60 Wh kg\(^{-1}\), represent an interesting alternative for vehicle traction purposes. These batteries can be specifically designed for high power outputs, allow fast recharging and offer a high number of charge cycles. Ni-MH batteries can be found in several current hybrid-electrical vehicles, such as e.g. Toyota Prius [38, 35].

Energy-dense Li-ion batteries, such as being used in e.g. laptops, are currently being implemented into electrical vehicles. As an example, the battery package installed in the Tesla Roadster, a fully electrical vehicle currently on the market, comprises 6800 Li-ion cells with a total package mass of 450 kg. With a specific energy of about 180 Wh kg\(^{-1}\) and an efficiency of around 90%, Li-ion batteries have a very high capacity compared to other battery types. Although currently associated with a high manufacturing cost, it is one of the most promising candidates for on-board power supply [38, 39].

However, there are some issues concerning the Li-ion technology. The cathode generally contains cobalt, which can only be obtained from natural resources. It makes up 20 parts per million of the earth’s crust. With the large amount of Li-ion batteries currently being produced, this cathode material might not be sustainable. In addition, if all 800 million cars of the world would be replaced by electrical vehicles or plug-in hybrid vehicles powered by 15 kWh Li-ion battery packages, 30% of all known lithium reserves would be used. If such a large share of the lithium reserves is to be utilized, price increases are likely
to appear, since the extraction process is likely to become increasingly expensive as the reserves decrease. However, recycling could ease these problem. Both Toyota and Tesla Motors are currently developing recycling processes which are intended to enable reuse of recycled metals such as cobalt and lithium in new batteries [40, 41]. Until now the recycled lithium have been used solely for steel production, since the quality and purity of the metal have been fairly low [40]. Owing to more precise extraction- and assorting-processes, the lithium can now be reused for manufacturing new batteries [40]. According to Armand and Tarascon [36] there are also possibilities to extract lithium from sea water in practically unlimited quantities.

Another factor to consider in terms of Li-ion is related to safety. The presence of both a combustible material and an oxidizing agent involves risks of fire or explosion. This safety risk can be minimized with improved monitoring and management [36].

Table 2 lists basic properties for the battery types discussed above.

Table 2: Battery properties [38].

<table>
<thead>
<tr>
<th>Type</th>
<th>Specific energy (Wh·kg⁻¹)</th>
<th>Specific power (W·kg⁻¹)</th>
<th>Number of cycles</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb-acid</td>
<td>30-40</td>
<td>80-300</td>
<td>500</td>
<td>82.5</td>
</tr>
<tr>
<td>Ni-Cd</td>
<td>50-60</td>
<td>200-500</td>
<td>1350</td>
<td>72.5</td>
</tr>
<tr>
<td>Ni-MH</td>
<td>60-70</td>
<td>200-1500</td>
<td>1350</td>
<td>70.0</td>
</tr>
<tr>
<td>Li-ion</td>
<td>125-180</td>
<td>80-2000</td>
<td>1000</td>
<td>90.0</td>
</tr>
</tbody>
</table>

The specific energy of petrol, 10-12 kWh kg⁻¹, is vastly more than any current battery technology can offer. Therefore, regardless of the type, battery packages involve large amounts of additional weight and volume compared to ICE based power systems. This is valid even though electrical motors operate with a much higher efficiency than ICEs. For a fully electrical battery-powered vehicle to attain a range of operation comparable with a conventional ICE vehicle, without adding a large amount of weight, a remarkable progression in high-capacity battery technology is required. In addition, the battery life-time needs to be extended in order to avoid high costs related to battery change. These issues have to be resolved in order for chemical batteries to become a sustainable competitive alternative as a primary vehicular power source.
3 The effects of wheel corner module technology

There are major construction differences between WCM vehicles and conventional vehicles. This results in quite different properties regarding vehicle handling, comfort and safety as well as environmental and economical impact. The following sections discuss these areas, in order to enlighten the possibilities and drawbacks involved with WCM technology.

3.1 Vehicular aspects

The following sections describe the characteristics and possible issues related to handling, comfort and safety of a typical WCM vehicle. The impact of an increased unsprung mass affects all of these areas. It is therefore discussed separately in section 3.1.4.

3.1.1 Handling

Handling is defined as a vehicle's response to driver input [42]. Good handling performance generally implies that the vehicle responds accurately to driver input. It shall behave in a safe and controlled manner, even during aggressive driving. The sports car is a typically well handling vehicle.

There are several factors to take into account when estimating the handling performance of a vehicle. The driver’s subjective experience of how well the vehicle reacts according to operational inputs can be difficult to measure and may differ between drivers. As of today, there is no standard of how to objectively measure handling performance.

P.E Uys et al. [43] investigate different methods generally utilized in terms of handling performance estimation, in order to find the most suitable objective measure. Investigated methods include among others dynamic wheel load as a measure of driving safety, pitch motion and roll angle as measures of steering stability and RMS tire contact force as an indication of wheel hop and road holding capability. Lateral acceleration is generally considered as a good measure of handling performance.

One of the key features of WCM technology is the opportunity to control all four wheels individually, enabled by the absence of mechanical connections between the wheels. Propulsion, braking, steering and suspension properties can all be set individually. This ability can drastically enhance the handling capability, since it involves additional degrees of freedom. Owing to the XBW structure, the handling properties can be set according to driver characteristics and road conditions.

Individually controlled corner modules make it possible for the driver to change the handling characteristics of the vehicle between understeering, neutralsteering and oversteering. Regardless of the necessity of such a function, it highlights the versatility enabled by utilization of WCM technology.

Since all wheels have the ability to maintain individual steering angles, several opportunities are enabled. The turning radius can be significantly decreased [44], and steering characteristics can easily be adjusted according to the driver’s desire. Improved handling
is enabled since the steering properties, such as steering ratio and force feedback, may automatically be set according to current driver characteristics and road conditions.

Individually controlled active suspension admits a higher level of comfort as well as improved handling capability, through instant adaption to prevailing road conditions. With individual rideheight adjustment comes the possibility of active roll- and pitch-angle management systems, as seen in e.g. Volvo Autonomous Corner Module (ACM). It also enables the ground clearance of the vehicle to be altered according to driving style and road properties. An aggressive driving style might benefit from decreased ground clearance, while driving on a rough bumpy road might benefit from increased ground clearance [45].

In one of the WCM concepts further to be presented, Volvo’s ACM, the camber angles of all four wheels can be individually controlled. This feature improves the handling versatility even more, by enabling increased lateral acceleration during cornering.

A WCM vehicle can be either two- or four-wheel driven. The latter alternative enables more advanced handling properties, but also increases the complexity of the management architecture. See subsection 2.2.1 for more information on this topic.

3.1.2 Comfort

Comfort is related to a person’s subjective experience of well-being. When it comes to automotive comfort the affecting factors are e.g. temperature, noise, body roll, pitch and vibrations. A particular area in terms of automotive comfort is ride comfort. Ride refers to the vehicle’s vibrational response to road disturbances [42]. Hence, ride comfort corresponds to a passenger’s subjective experience of a vehicular journey in relation to the induced environment in terms of mechanical vibration [42]. The root mean square (RMS) of the vertical acceleration is generally used as an objective measure of ride comfort. Also angular motions such as pitch and roll affect the experienced comfort.

As stated in subsection 2.3.3, active suspension systems may decrease the need for setup compromises generally related to passive suspension systems. WCM vehicles equipped with such systems are capable of combining optimized ride comfort with optimized handling performance. Active suspension systems can instantly and continuously adapt to the ground contact preferences for each wheel, resulting in an increased level of comfort. Active roll and pitch management systems can effectively counteract angular motions, which would otherwise deteriorate the level of comfort.

One shall notice, that implementation of WCM technology may have varying impact on ride comfort. An increased unsprung mass, as discussed in subsection 3.1.4, can lead to increased vertical accelerations.

Noise is defined as unwanted sound. There are several sources of noise in a conventional vehicle. The internal combustion engine, aerodynamical vortices and tire-road friction all create unwanted sounds. To a great extent, these sounds can be excluded from the cabin by utilization of sound-isolating materials. However, sound isolation involves additional weight and should only reduce the sound level to a certain level, since some sounds are desirable from a safety aspect.

Consider a battery powered WCM vehicle equipped with in-wheel motors. Electrical motors with associated components involve a significantly lower noise level compared to an
ICE with corresponding performance. Hence, the noise level can be reduced, particularly at low velocities. As the velocity increases, other sources of noise related to the tire-road contact and aerodynamics have an increased effect. Since the body of a WCM vehicle can be more freely designed compared to a conventional vehicle, see subsection 2.2.1, aerodynamics can be improved and unwanted sound reduced. As for noise related to the tire-road contact, active camber variation allows for the rolling resistance to be minimized [45]. Decreased rolling resistance generally involves decreased noise generation.

3.1.3 Safety

Vehicular safety can be divided into two sections, passive safety and active safety. The former includes safety equipment such as air-bags, deformation zones and seat belts. This equipment aims to minimize injuries in event of an accident. Active safety on the other hand, aims to prevent accidents from occurring in the first place. Anti-lock braking systems (ABS), electronic stability programs and collision avoidance programs are examples of active safety.

The utilization of XBW systems, such as the WCM, enable new safety solutions, passive as well as active.

A major advantage concerning WCM vehicles compared to conventional vehicles, is the absence of steering rack and pinion. It eliminates the risk of such components intruding the driver compartment during a collision, with severe personal injury as a possible result [46]. Furthermore, owing to the absence of a mechanical steering, additional space is left for impact absorbing collapse zones, improving passive safety for the driver as well as passengers [46]. Removal of the traditionally used ICE enhances passive safety in the same manner.

Regarding active safety, the introduction of WCMs enables implementation of novel advanced collision avoidance programs. All maneuvering inputs of a WCM vehicle involve electronic control units. In event of a hazardous situation, these control units can operate without influence of the driver, based on information from sensors and cameras. For example, if an object is detected in the vehicular path, the control unit have the ability to automatically, without influence of the driver, brake the vehicle and if necessary steer to avoid collision. Such a system has the benefit of reacting much more agile than a human driver. In addition to that, it has the ability to, with much more accuracy, calculate the optimal path to avoid collision with both the obstacle in front, and any surrounding objects. Obviously, such a collision avoidance system must involve a major fault tolerance [46].

Regenerative brakes can improve active safety functions compared to conventional hydraulic disc brakes, due to faster excitation of brake torque. Sakai and Hori [20] investigates this possibility. In order to visualize the difference in process time between hydraulic brake systems and in-wheel motor regenerative brake systems, the conventional ABS function is regarded. In terms of hydraulic ABS systems, a solenoid valve engages or disengages the hydraulic pressure onto the brake caliper in order to keep the wheel movement unblocked. According to the report, the hydraulic system involves a process time of more than 60 ms, including solenoid dead time of at least 10 ms, and a response delay in
The hydraulic circuit (first order delay) of at least 50 ms. This may be compared to the stated regenerative brake process time of 1.1 ms, split into a dead time of 100 µs and first order delay of 1 ms. Through simulations, Sakai and Hori noted a 20% shorter braking distance when combining a conventional hydraulic brake system with a regenerative brake system, compared to the hydraulic brake system unaided.

The human factor is likely the primary cause of a majority of the traffic accidents occurring today. Table 3 highlights the usefulness of automated systems by listing some of the most common driver errors, and which automated solutions that can prohibit these errors. Not all of these errors are hazardous by themselves, however several such errors could potentially attract the driver’s attention from the road, resulting in an accident [47].

<table>
<thead>
<tr>
<th>Driver error</th>
<th>Automated solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Get into wrong lane</td>
<td>Navigation system</td>
</tr>
<tr>
<td>Forget which gear</td>
<td>Automatic gear shift</td>
</tr>
<tr>
<td>Only “half eye” on road</td>
<td>Fully automated drive system</td>
</tr>
<tr>
<td>Distracted, need to brake hard</td>
<td>Anti-lock braking system</td>
</tr>
<tr>
<td>Plan route badly</td>
<td>Navigation system</td>
</tr>
<tr>
<td>Fail to recollect recent road</td>
<td>Navigation system</td>
</tr>
<tr>
<td>Wrong exit from roundabout</td>
<td>Navigation system</td>
</tr>
<tr>
<td>Intended lights, switched wipers</td>
<td>Automated lighting</td>
</tr>
<tr>
<td>Forget light on main beam</td>
<td>Automated lighting</td>
</tr>
<tr>
<td>Usual route taken by mistake</td>
<td>Navigation system</td>
</tr>
<tr>
<td>Misjudge speed of oncoming vehicle</td>
<td>Collision avoidance system</td>
</tr>
<tr>
<td>Queuing, nearly hit car in front</td>
<td>Collision avoidance system</td>
</tr>
<tr>
<td>Miss motorway exit</td>
<td>Navigation system</td>
</tr>
<tr>
<td>Manoeuvre without checking mirror</td>
<td>Collision avoidance system</td>
</tr>
<tr>
<td>Fail to see pedestrian crossing</td>
<td>Collision avoidance system</td>
</tr>
<tr>
<td>Brake too quickly</td>
<td>Anti-lock braking system</td>
</tr>
<tr>
<td>Hit something when reversing</td>
<td>Collision avoidance system</td>
</tr>
<tr>
<td>Misjudge gap in car park</td>
<td>Collision avoidance system</td>
</tr>
<tr>
<td>Try to pass vehicle turning left</td>
<td>Collision avoidance system</td>
</tr>
<tr>
<td>Attempt to drive off in third gear</td>
<td>Automatic gear shift</td>
</tr>
</tbody>
</table>

With a complex technology like WCM being introduced, new safety issues arise. Proper function of critical backup systems have to be regarded and guaranteed. Proving the safety of a new technology obviously is very time consuming since no experience or documentation from prior work exists. Even though one of the particular advantages regarding WCM technology is improved safety, incredible amounts of time is required for testing and evaluation in order to treat possible problems related to the technology itself. Routines used for testing conventional vehicles might not be well suited and developing new ones take time. Fault tolerant behavior in terms of XBW systems is of utmost importance, particularly concerning the steering and brake systems, see subsection 2.1.1.
3.1.4 Unsprung mass

The unsprung mass of a WCM vehicle is generally higher compared to an equivalently powered conventional vehicle. A major part of this weight increase is caused by the implementation of electrical in-wheel motors. Generally, the in-wheel motors are part of the unsprung mass. Bridgestone’s Dynamic-Damping In-Wheel Motor Drive System however, separates the in-wheel motor from the unsprung mass by utilizing a separate motor suspension, see subsection 4.2.

The main reason for in-wheel motors being part of the unsprung mass rather than the sprung mass, is that such a construction is less complex. A permanent magnet electrical motor with an output of 10-15 kW approximately weighs 10-15 kg, if a specific power output of 1 kW/kg is assumed [48]. If such a motor is implemented into each wheel of a vehicle, the unsprung mass of that vehicle increases with approximately 40-60 kg.

One of the major concerns regarding WCMs, is to what extent this increased unsprung mass affects the handling and ride comfort of the vehicle. It is known that an increased unsprung mass tends to increase the vertical accelerations in the vehicle body, which in turn deteriorates comfort. In addition, the dynamic wheel load fluctuations are likely to increase which in turn involves handling performance degradation. However, novel active suspension technology involves the ability to significantly reduce such issues. If the result is beneficial compared to conventional vehicles may be highly dependent on the overall module setup.

Vos et al. [48] investigated the effect of increased unsprung mass on ride comfort and handling safety, by adding weights to the wheels of an ICE vehicle. According to this study, the ride comfort decreased with 10-25% depending on road surface, when a 15 kg weight was added to each of the front wheels. An equal experiment conducted with the same weights moved to the rear wheels resulted in a 1-8% ride comfort deterioration. Based on a validated computer model of the same ICE vehicle, they modified it to correspond to a battery electrical vehicle. This was done by adding a total mass of 160 kg and shifting the weight distribution. When equal tests were simulated with this latter model, the ride comfort was equal to, or slightly better, than the original ICE vehicle without added weights. However, the dynamic wheel load had increased with up to 40%, which would likely affect the handling safety. This experimental data indicates that there is indeed a connection between deteriorated comfort, handling and unsprung mass.

Anderson and Harty [49], investigated the effect of increased unsprung mass in a similar manner to the above. In addition to the objective experiments, subjective measurements were conducted by experts. Concluded in the report is that an increased unsprung mass does indeed affect both ride comfort and road holding capability. However, according to Anderson and Harty, the difference is not greater than what could be overcome by the application of normal engineering processes within a product development cycle. Furthermore, implementation of individual motor control offer such improved vehicle dynamics, that the overall improvements regarding both comfort and handling could be substantial, despite an increased unsprung mass.

Since the extent of this matter is unclear based on these two fairly contradicting reports, simulations have been conducted in an attempt to get an improved view of the reality. The results are presented and discussed in section 5.
3.2 Environmental aspects

WCM technology is based on electrical traction. The environmental advantages considering a WCM vehicle compared to a conventional or even hybrid vehicle can be substantial, provided the energy comes from environmentally friendly electrical power production. Consider the currently available fully electrical Tesla Roadster, a vehicle that utilizes a Li-ion battery package as power source. It has a total drive-train efficiency of 88% [50]. This number can be compared to the efficiency of a conventional ICE vehicle, which is generally around 35% at its best. In addition, WCM vehicles have an advantage compared to conventional electrical vehicles, such as the Tesla Roadster. The in-wheel motors are generally constructed for direct drive operation, hence it does not require an efficiency deteriorating gearbox.

Several environmentally hazardous liquids are related to motorized vehicles, such as oil, petrol and battery acid. Owing to the introduction of novel electrical functions for means of e.g. braking and steering, the need for systems containing hydraulic oil is eliminated. Considering a battery-powered WCM vehicle, motoroil, petrol and diesel can also be excluded. These factors improve the environmental impact of WCM vehicles. However, one shall have in mind, that introducing additional battery power to a vehicle adds a significant amount of battery chemicals into the system. In case of battery leakage, e.g. in connection to a vehicle collision, these chemicals are harmful to the environment. Additionally, depending on the battery life time, it may need to be replaced at some point during the vehicle life time. Since manufacturing a battery has a negative environmental impact, this aspect has to be taken into account when considering how environment-friendly a specific vehicle is.

By continuously optimizing the wheel angles to the demands, the rolling resistance can be kept to a minimum [45]. Hence, tire and road wear can be reduced, resulting in decreased air pollution and increased tire life time.

3.3 Economical aspects

Implementation of WCM technology may result in economical benefits in favor of both manufacturers and consumers. One major economical advantage concerns the development and production stages. Many automotive manufacturers offer similar sized vehicle models with quite diverse bodies and dynamic properties. In terms of conventional vehicles, all models require their unique development processes, since there are major differences in terms of desired handling characteristics and construction. WCM technology enables diverse models to be constructed around a common platform, according to “skateboard design”, see subsection 2.5. For example, a two-seated sports car and a small four-seated “city vehicle” can be built on the same platform. By utilizing differently specified WCMs and software the dynamic properties are individualized. The sports car’s WCMs can be equipped with more powerful in-wheel motors and wider tires, to enable improved handling performance compared to the city vehicle. The bodywork and interior is obviously also individualized. By standardizing the connection structure between the WCM and the vehicle body, one type of WCM will fit many different vehicle models. To manufacture vehicles based on modularization can lower costs significantly.
3.3 Economical aspects

THE EFFECTS OF WHEEL CORNER MODULE TECHNOLOGY

since it involves a decreased number of unique parts. In addition, improved opportunities for individualization is enabled. The customers can, according to personal preference, choose from a selection of bodywork, WCMs, and interiors, to create a unique vehicle at a relatively low cost.

Conventional vehicles generally require workshop service every 15000-30000 km or once per year. Since such workshop visits often involve high costs, consumer expenses can here be significantly reduced. A major reason for the frequent maintenance related to conventional vehicles is replacement of motor oil and other fluids like e.g. brake fluid. With WCM technology comes the ability of extended service intervals, since electrical equipment require less maintenance compared to e.g. hydraulic systems and ICEs [8].

If WCM technology reaches serial production, novel production technology and manufacturing equipment will be required, involving vast investments. This is a major reason why WCM implementation, in terms of serial produced vehicles, probably will not be possible for a number of years. In order for the automotive industry to stay profitable, the WCM technology will have to be introduced step by step. That is also likely what is currently taking place. Novel technical solutions such as hybrid vehicle technology, rear wheel steering and various XBW systems are each year being introduced from an increased number of automotive manufacturers.
4 Concept analysis

Several different WCM concepts are currently being developed by a number of car manufacturers, tire manufacturers and other research institutions. This section summarizes a selection of these concepts by providing information gathered from various patents and articles. Concerning most of the concepts, the major part of the available technical information is of general character rather than specific. Hence, the following descriptions are typically general, with the exception of certain technical solutions which are described more in detail.

4.1 Michelin Active Wheel

Michelin have been developing the Active Wheel, see figure 14, since 1996. In 2004 it was first showcased in the concept vehicle HY-Light, containing a hydrogen fuel cell as primary power source. The Active Wheel was later implemented into Heuliez Will, a concept vehicle based on Opel Agila, which was closer to production than the HY-Light. In this form the vehicle contained two water-cooled in-wheel motors, used for front wheel drive with a total rated power of 30 kW. Each wheel module weighed 43 kg [4, 51].

![Figure 14: Michelin Active Wheel [4].](image)

The in-wheel motor (97) contained in the Active Wheel, see figures 15 and 16, is unsprung [1]. Generally, in-wheel motors are constructed for direct drive applications. However, regarding the Active Wheel, torque is transferred from the traction motor to the hub (15) via a pinion (95) and gearwheel (18) [52]. Since the torque is transferred to the wheel via a fixed gear, the motor can be constructed for maximum torque output at a higher angular velocity compared to a direct drive motor. Thus, a more compact design is enabled.

For retardation means the in-wheel motors can be used, regenerating power back to the batteries. When excess brake power is required, a brake caliper (90) coupled with a conventional brake disc (17) is available. The former is stated to be of hydraulic or electro-mechanical type [52].

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1Numbers within brackets mark component numbers contained in one of the figures 16 and 15, or both.
For suspension purposes Michelin’s WCM houses a coil spring (80) to hold the static load of the car. In addition, a suspension actuator (87) is installed to actively handle fluctuations. The construction comprises a wheel-barrier connected bar (camber lever) (4) which contains a rack (45), engaging a pinion (85) which is connected to an electro-mechanical machine (87). Thus, the linear motion of the wheel is converted to a rotational motion, which is then transferred onto the electro-mechanical machine. The latter is composed by a rotor (86) and a stator (88), of which the stator is integral with the guide member (6) [52].

Steering of the wheel is realized using a conventional steering lever (61) and rod (62), which could be connected to either a conventional mechanical steering setup or an electrical actuator attached to the chassis [53].

Figure 15: Side view of patent drawing covering the Active Wheel, Michelin [52].
Figure 16: Front view of patent drawing covering the Active Wheel, Michelin [52].
Michelin also has a patent covering active camber variation. Figure 17 shows a patent drawing illustrating a solution for actively controlled camber angle variation, mounted to a simplified wheel structure. In this construction an arm (70) is mounted to the chassis of the vehicle (1). Via this arm the loads of the latter are transferred to the wheel integrated suspension. The upper connection point (52) of the wheel support (5) is connected to a camber lever through a parallelogram linkage. A jack (45) connected between the chassis and camber lever controls the desired camber angle. This construction admits a maximum camber variation in the order of $\pm 15^\circ$ to $20^\circ$, which is far more than seen in conventional vehicles [53].

Furthermore, the patent presents a solution as where the passenger compartment integral with the camber lever, making it comprise a variable roll angle in relation to the chassis. The passenger compartment is tilted synchronous with the camber angle. It is stated in the patent that this function improves comfort as well as handling safety. The latter is improved since tilting the passenger compartment in a bend, displaces the center of gravity toward the inside of the bend, thus minimizing the load transfer to the wheels located on the outside of the bend [53].
Figure 17: Patent drawings covering a solution for active camber adjustment, Michelin [53].
4.2 Bridgestone Dynamic-Damping In-Wheel Motor Drive System

Bridgestone have been developing their in-wheel motor systems since 2000 in cooperation with Kayaba Industry Co. and Akebono Brake Industry Co.. The Bridgestone Dynamic-Damping In-Wheel Motor Drive System, see figure 18, was first announced in September 2003 [54].

![Figure 18: Bridgestone Dynamic-Damping In-Wheel Motor Drive System [55].](image)

As described in subsection 3.1.4, increased unsprung mass may deteriorate handling performance and ride comfort. To address this problem, Bridgestone developed an alternative suspension structure. In this structure, the traction motor is individually suspended in order not to increase the unsprung mass. Figure 19 shows a patent drawing covering the key components of the construction. The non-rotational part (3a) of the in-wheel motor (3), is mounted to a knuckle (5) on the axle (6), via springs (22, 24) and dampers (23, 25). This suspension setup separates the in-wheel motor from the unsprung mass. A flexible coupling (10), consisting of three hollow disc-like plates (11A,B,C) and guides (12A,B), transfers the torque from the in-wheel motor to the wheel hub (4). This coupling admits relative vertical movement of up to 50 mm between rotor and wheel [56, 57].

Regenerative function of the in-wheel motors handles deceleration. When additional brake force is required, a disc-brake (8) is available. The brake-caliper type is not specified in the patent [56]. The suspension system comprises a coil-spring and damper (7).
4.2 Bridgestone Dynamic-Damping In-Wheel Motor Drive System

According to Bridgestone, the individually suspended design of their in-wheel motor enhances ride comfort as well as road-holding capability, by making the in-wheel motors own vertical movements offset the vibrations from road and tires [57]. Nagaya et al. [58] investigated this matter. Three test vehicles were driven on a road containing projections with a height of 10 mm and width of 20 mm in a line with intervals of 5 m. The following motor configurations were examined and compared:

1. A conventional electrical vehicle with an unsprung mass of 40 kg per wheel corner, and the motor as part of the sprung vehicle body. Abbreviated Conv-EV in figure 20a,

2. an in-wheel motor electrical vehicle with an unsprung mass of 70 kg per wheel corner, of which 30 kg was assigned to the in-wheel motor. Abbreviated IWD-EV in figure 20a,

3. a dynamic-damper motor electrical vehicle with an unsprung mass of 40 kg and an individually suspended 30 kg in-wheel motor per wheel corner. Abbreviated ADM-EV in figure 20a.

The results, see figure 20a, indicate that the ground-contact load fluctuation of the tire is reduced in terms of the dynamic-damper setup, compared to conventional electrical
vehicles as well as other electrical vehicles equipped with unsprung in-wheel motors. This implies improved handling performance. Improved ride comfort is also indicated, see figure 20b. According to this plot, the dynamic-damper solution involves decreased vertical accelerations in the vehicle body. The accelerations are significantly reduced around 10-15 Hz. The resonance frequencies of the unsprung mass, the “wheel hop” frequencies, are generally located in this frequency band. Since the individual motor suspension involves reduced unsprung mass, thus reduced vertical acceleration of the unsprung mass, the major improvements are found in this specific frequency band.

![Graph of Tire contact force fluctuation](image1)

(a) Tire force load fluctuations.

![Graph of Vertical Acceleration](image2)

(b) Vertical acceleration of vehicle body.

Figure 20: Bridgestone test results for electrical vehicle equipped with single motor mounted to vehicle body (Conv-EV), unsprung in-wheel motors (IWD-EV) and Bridgestone Dynamic Damping In-Wheel Motors (ADM-EV) [58].
4.3 Siemens VDO eCorner

The Siemens VDO eCorner represents an advanced WCM containing a direct drive in-wheel motor, an active suspension system and an electro-mechanical disc brake.

The eCorner, see figure 21, is propelled by a direct drive in-wheel motor (2). From figure 21, it is visible that the rotor is integral with the rim.

This machine also has the capability to decelerate the vehicle with a regenerative effect [13].

When excessive brake power is required, a friction brake device called the Electronic Wedge Brake (EWB), is available. Its function is based on a patent protected wedge element design, intended to simplify the brake actuator structure compared to other electro-mechanical brake solutions [60]. Figure 22a shows the principal function of the EWB.

Electro-mechanical brake constructions generally utilize rotational actuators. A complicating factor is that the rotational movement of the actuator needs to be transformed into linear movement, prior to application onto the brake pads. This can be achieved by utilization of e.g. a ball screw device, however such a solution increases the structural complexity. From this point of view, the use of a linear actuator would be favorable. However, during heavy braking, linear actuators generally lack the amount of power that is required.

Siemens VDO claim to have solved this issue, by implementing a wedge formed element (4) in connection to one of the brake pads (11), see figure 22a. A description of the
principal function follows. First, an actuator force $F$, see figure 22a, is applied onto the side of the wedge element (4). The latter is pushed against another wedge formed element (9), forcing the brake pad to move towards the brake disc (7). A friction force is generated between the brake pad and the rotating disc. Owing to this force, the brake pad is pulled further into the intermediate space between the wedge element (9) and the brake disc, as well as towards the brake disc. This results in an additionally increased friction force. As described, the function of the wedge brake is based on a self-amplifying process.

Owing to the self-amplifying function, the actuator requirements decrease. Less actuator power is required to produce a certain brake pad force compared to a design where the actuator moves perpendicular to the brake pad/disc. Hence, a linear actuator provides sufficient force even during heavy braking.

Figure 22b shows the actual design of the EWB. Here, several rolling bodies (21) make contact between two elements (19, 20). Each of these elements contains a number of spaces formed as v-shaped bearing halves, which each function according to the same principle as the wedge elements previously described. Rolling bodies are placed in between these spaces, in order to reduce friction between the wedge elements. This design makes the brake force more evenly distributed over the brake pad contact surface, and admits equal braking properties independent of brake disc rotational direction [60].

The linear actuators (16, 17) regulate the brake force by moving in a reciprocating manner. Wedge brakes are generally associated with self-locking, as a result of an uncontrolled self-amplifying effect. In order to avoid this problem, very precise control is required.

The EWB benefits from a more compact and simple design, reduced weight and less maintenance compared to a rotational brake actuator setup [60]. It is compatible with a 12 V electrical system in contrary to most of the other electrical brake systems in development [26]. It can also be used as an automated parking brake [61].

The eCorner suspension system comprises an active suspension system. A coil spring holds the static load of the vehicle, while an electrical actuator handles load fluctuations [13]. The steering angle of each eCorner module can be individually set.

![Figure 22: Drawings covering patent US0230330A1, Electronic Wedge Brake by Siemens VDO [60].](image)
4.4 Volvo Autonomous Corner Module

The Autonomous Corner Module, see figure 23, is Volvo’s WCM concept, invented 1998 [62]. It contains solutions for electro-mechanical propulsion and braking as well as active steering, suspension and camber variation [63].

Figure 23: ACM front view [45].

Figure 24 is a descriptive patent drawing, showing the different components of the invention. Propulsion is handled by means of an in-wheel motor (9). According to Zetterström [45], a power output of 10-15 kW per wheel, i.e. a total power output of 40-60 kW, is sufficient for giving a 1000 kg city-car a fair performance. An estimated weight for a 10 kW motor is about 10 kg, given aluminum or metal matrix lightweight materials are assumed to be used for the rotor and stator [45].

Regenerative braking is supported by the in-wheel motor. When excessive brake force is required, an integrated friction drum brake actuated by means of an electro-mechanical rotational actuator (21), is available. It is operated by means of by-wire technology and houses a recirculating ball screw actuator. During braking, the friction material coated brake shoe (23) is pushed against the inside of the rotor (24), reducing its angular velocity, see figure 24. A spring device locks the ball screw in any position when electrically unpowered. During braking, an electromagnet unlocks the ball screw, enabling it to operate. This locking mechanism can be used as a parking brake. Alternatively, the front and rear wheels respectively can be set to maximum toe in or toe out position, disabling movement of the car [45].

A planetary hub gear (7,12) is mounted between the in-wheel motor and the friction brake device and corresponding wheel, thus dimensioned to transfer the loads not only
from the traction motor, but also from the drum friction brake. The gear ratio of about 2:1 amplifies the traction and brake torque when distributed to the wheel [63, 45].

The suspension consists of a passive as well as an active part. The passive part comprises springs that handle the static load. They are either conventional coil springs or composite leaf springs running transversely between the left and right lower link arms. The active part levels the body height and handles anti pitch and roll systems, by use of a combined rotary damper and rubber torsion spring unit (27), with integrated pretensioning function. Such a system can be utilized e.g. for stiffening the suspension before entering a corner, thereby obtaining better cornering characteristics [63, 45].

Two linear recirculating ball actuators (16, 16') are, via separate rods (17, 17'), connected to attachment points (18, 18') in the armature (10). The structure enables these actuators to adjust not only steering and toe angles individually, but also the camber angle. The latter is set through parallel displacement of the two steering rods. Advanced algorithms are used in order to maintain optimal steering, toe and camber angles adapted to driving style, tire characteristics and prevailing road conditions. Steering angles of up to ±22° are admitted [63, 45].
Figure 24: Drawings covering patent EP1144212B1, Volvo [63].
4.5 MIT Media Lab’s Robot Wheel 5

Students, researchers and professionals at MIT Media Lab have developed several early stage WCM concepts, which are different iterations of an original model. They are all called Robot Wheels. This section treats the Robot Wheel 5, see figure 25, which is the fifth iteration of the Robot Wheel original concept. The main purpose with this WCM is to reduce the unsprung mass and structural complexity as much as possible, by keeping the number of components to a minimum. As the name implies, the Robot Wheel 5 has the potential of operating as an autonomous unit. The invention has been realized as a 1:2 scale concept model consisting of four corner modules attached to a simple structural frame, see figure 26 [64]. The components described in this section are related to the scaled version and are likely to be different in terms of a full sized model.

The Robot Wheel 5 comprises an in-wheel motor (145) for propulsion means, see figure 27. The scaled concept vehicle utilizes a permanent magnet, 3-phase, brushless outrunner motor comprising 12 poles [64].

Regenerative in-wheel motor brake torque is applied for retardation means, and is claimed to be sufficient for all situations [65]. In difference to other WCM concepts, no friction brake is comprised in the design.
Similar to other WCM concepts, individual steering angles can be set by means of steering actuators (130). The servo motor utilized in the 1:2 scaled model does however not provide enough torque to steer the wheel when subjected to the weight of the prototype vehicle. In the following iteration this motor is stated to be replaced by a more powerful alternative [64, 66].

The suspension comprises a double wishbone setup, with flexible connection arms (125), fabricated out of carbon fiber, reinforced with aluminum profiles. The double wishbone setup connects to the front axle (105), containing a battery package (110), via a connector. The connector comprises a wheel side component (120) and a vehicle side component (115), which establish a structural connection when linked to each other. In addition, a power connection and a data connection is established. This suspension structure is merely adequate for the downscaled model. A full-sized version is likely to comprise an alternative suspension setup [65].

The most significant benefit of the invention is its steering capabilities. The Robot Wheel 5 is able to work in a steering range of up to $150^\circ$, by the use of five different drive modes,
see figure 28. It comprises a traditional ±30° front-wheel-steering mode (a), a four-wheel-parallel-steering mode (b), a four-wheel-converse-steering mode (c), a spin-on-the-spot mode (d) and a 90° sideways-movement mode (e) [65, 66].

(a) Drive mode 1. (b) Drive mode 2. (c) Drive mode 3.

(d) Drive mode 4. (e) Drive mode 5.

Figure 28: MIT Media Lab’s Robot Wheel steering modes [44].

4.6 General Motors Wheel Module

During 2002 General Motors (GM) presented two concept vehicles based on XBW technology, the AUTOonomy and the Hy-Wire. Both these vehicles were powered by means of hydrogen fuel-cells.

The AUTOonomy concept vehicle is propelled by four in-wheel motors. It is built around a hydrogen fuel-cell stack contained inside a skateboard platform, see subsection 2.5. Acceleration, braking, steering and suspension are controlled by means of electrical signals.

GM Hy-Wire represents a drivable update of the AUTOonomy. It does not contain all components related to propulsion, brakes and steering within each corner module, hence it does not represent a pure WCM vehicle. However, owing to the skateboard-design and extensive XBW technology utilized, it will be further discussed.

The Hy-Wire was the first drivable vehicle to combine a hydrogen fuel-cell stack with XBW technology. As previously stated, it is based on a skateboard design, and utilizes XBW technology in terms of propulsion, braking and steering. Rather than in-wheel motors, one single electrical motor located in the skateboard platform propels both front wheels, leaving the rear wheels unpropelled. The skateboard platform, which also contains the 94 kW fuel-cell stack, is 279 mm thick. This structure enables a unique interior design of the vehicle, see figure 29. The Hy-Wire is controlled via an alternative steering device, called the X-drive. To accelerate, either the right or the left handgrip is twisted. Brake levers are located on the handgrips. The X-drive can be laterally adjusted between the right and left side of the vehicle by means of a sliding device. The total weight of the Hy-
Wire is 1898 kg. With a total length of 5 m, the weight is in the same order of magnitude as a corresponding conventional ICE vehicle [67].

A patent filed in 2002, covers a corner module developed by General Motors. It comprises a brake system (9), a steering system (not visible in the patent drawing), a suspension system (28) and an in-wheel traction motor (50), see figure 30. In terms of frame connections the wheel module houses a load-bearing mechanical coupling (32). A control signal receiver, including a vehicle attachment interface, is integrated with the corner module. Braking, steering, suspension and propulsion are controlled by means of a steering device connected to the control signal interface, i.e. the system is based purely on XBW technology.

The in-wheel motor comprises a rotor (12) which is rigidly mounted to the hub, and a stator (18) connected to the motor housing (26). The former contains two rotor discs (14, 16).

For means of retardation an electro-hydraulic friction brake system (9) is available, comprising a brake disc (8) and a caliper (6). A hydraulic line is operatively connected to a brake actuator (36) at one end, and the brake caliper (34) at the other. The actuator is operated according to input from a control signal receiver (38). An electrical signal transmitted from the brake control device via the control signal receiver, causes the actuator to apply a hydraulic force onto the caliper [68].

The suspension system contains an upper suspension arm (29) and a lower suspension arm (31). The upper arm is connected to a suspension actuator (48), which operates the suspension by application of a mechanical force, based on input from the control signal receiver (38). The suspension is actively controlled according to prevailing conditions.
4.7 Summary of concepts

Throughout the concept analysis, specific technical solutions regarding wheel corner modules have been pointed out. This section summarizes the most advantageous solutions.

The Bridgestone Dynamic-Damping In-Wheel Motor Drive System utilizes an individual motor suspension, which separates the motor from the unsprung mass. Comfort and handling deterioration related to an uncreased unsprung mass are thus minimized.

In terms of the Siemens VDO eCorner, a highly-developed electro-mechanical brake called the Electronic Wedge Brake have been discussed. It represents a cheap and energy-efficient friction brake alternative that eliminates the requirement of hydraulic brake circuits.
Volvo’s Autonomous Corner Module integrates active camber variation as part of the concept. Owing to this function, handling performance can be improved in order to enhance driving experience as well as safety.

The Wheel Robot 5 from MIT Media Lab is capable of working in a wide steering range, thus improving the handling versatility. This versatility can be beneficial during e.g. urban driving, where the space available for vehicular operation is often very limited.

General Motors’ Hy-Wire combines XBW technology with a hydrogen fuel-cell. The vehicle is constructed around a skateboard-design, which allows the interior and bodywork to be more freely designed, compared to conventional vehicle structures.
5 Modeling and simulation

A major concern regarding increased unsprung mass is deteriorated ride comfort and handling performance. Referring to subsection 3.1.4, there are varying conclusions regarding the extent of this matter. To clarify this uncertainty, simulations to assess the ride comfort and handling performance of a vehicle with different amounts of unsprung mass are conducted. Two different models are assembled, one quarter car model (QCM) and one full car model (FCM).

5.1 Quarter car model

Simulations are conducted based on a quarter car model, see figure 31. The model, as the name implies, represents a quarter of a car. It involves parameters for the sprung mass $m_s$, unsprung mass $m_u$, tire stiffness $k_t$, tire damper coefficient $c_t$, spring stiffness $k_s$ and damper coefficient $c_s$. The degrees of freedom, $u$, $z_u$ and $z_s$, are all vertically directed. Simulations based on a QCM represent a very simplified method to estimate the dynamics of a vehicle.

![Figure 31: QCM, block diagram.](image)

Equations 1 and 2 describe the dynamics of the QCM.

\[ m_s \ddot{z}_s + c_s \dot{z}_s + k_s z_s = c_s \dot{z}_u + k_s z_u \]  

\[ m_u \ddot{z}_u + (c_s + c_t) \dot{z}_u + (k_s + k_t) z_u = c_s \dot{z}_s + k_s z_s + c_t \dot{u} + k_t u \]  

A QCM is assembled in the dynamic modeling program Dymola, by utilization of basic modelica blocks representing tire, unsprung mass, spring, damper and sprung mass. The
tire, the spring and the damper are modeled by use of linear spring and damper blocks. The sprung and unsprung masses are modeled as punctual masses. The properties are set through definition of each modelica block according to the vehicle parameters presented in table 4. This data represents a mid-sized vehicle, with dimensions in the same order of magnitude as e.g. a Volkswagen Golf Mk 6. Since the QCM represents one corner of the vehicle, only one suspension setup is possible for each simulation. These simulations aim to estimate the influence of rear-wheel mounted motors, since in-wheel motor systems are likely to first be implemented onto the rear wheels once serial-production is possible [16]. Hence, the spring and damper constants are set according to the rear suspension of the vehicle.

<table>
<thead>
<tr>
<th>Vehicle parameter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprung mass (per corner) [kg]</td>
<td>325</td>
</tr>
<tr>
<td>Unsprung mass (per corner) [kg]</td>
<td>40</td>
</tr>
<tr>
<td>Spring constant [N/m]</td>
<td>56000</td>
</tr>
<tr>
<td>Damper constant [Ns/m]</td>
<td>1276</td>
</tr>
<tr>
<td>Tire spring constant [N/m]</td>
<td>200000</td>
</tr>
<tr>
<td>Tire damper constant [Ns/m]</td>
<td>100</td>
</tr>
</tbody>
</table>

### 5.1.1 Simulation

Simulations are performed, in order to estimate to what extent an increased unsprung mass influences ride comfort and handling performance of a vehicle. Hence, all simulations are conducted for two setups:

1. The original setup containing 40 kg unsprung mass,
2. an alternative setup containing 60 kg unsprung mass.

Two different road models are utilized. One contains a flat surface with a bump profile, intended to resemble a speed bump. The other one contains a flat surface with a ramp, intended to resemble a curb. As visualized in figure 32, the bump has an amplitude of 0.05 m and a length of 0.10 m. The curb has an amplitude of 0.05 m and a rise angle of 60°, i.e. a length of 0.02 m. For all simulations, the QCM hits the disturbance profile 5 s after the simulation start time.

![Bump and Curb Diagram](image)

Figure 32: Simulated road disturbances.
In the QCM simulations, the road input signal is the road amplitude as a function of time. The input signal for the bump profile consists of one half of a sine wave. By altering the sine wave frequency, different vehicle velocities are resembled. These velocities, including their disturbance frequencies, are listed in Table 5. Regarding the curb profile simulations, variation of the vehicle velocity is performed by variation of the ramp rise time. Simulated runs are performed for each of the two road profiles for a selection of velocities between 1 km/h and 90 km/h. The velocities are chosen to cover a wide spectrum, in order to enable a complete analysis of the output data.

Table 5: Simulated vehicle velocity and corresponding bump profile disturbance frequency.

<table>
<thead>
<tr>
<th>Velocity [km/h]</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>50</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disturbance frequency [Hz]</td>
<td>1.39</td>
<td>4.17</td>
<td>6.94</td>
<td>9.72</td>
<td>13.89</td>
<td>27.78</td>
<td>41.65</td>
<td>69.44</td>
<td>125</td>
</tr>
</tbody>
</table>

The eigenfrequencies of the system are calculated according to equations 3, 4 and 5. They are relevant for a proper analysis of the simulation output data.

Sprung mass:

\[ \omega_s = \sqrt{\frac{k_s}{m_s}} = \sqrt{\frac{56000}{325}} = 13.1 \text{ rad/s} = 2.1 \text{ Hz}, \]  

which corresponds to a vehicle velocity of 1.5 km/h.

Unsprung mass 40 kg:

\[ \omega_u_l = \sqrt{\frac{k_l + k_s}{m_u}} = \sqrt{\frac{200000 + 56000}{40}} = 80.0 \text{ rad/s} = 12.7 \text{ Hz}, \]  

which corresponds to a vehicle velocity of 9.1 km/h.

Unsprung mass 60 kg:

\[ \omega_u_h = \sqrt{\frac{k_l + k_s}{m_u}} = \sqrt{\frac{200000 + 56000}{60}} = 65.3 \text{ rad/s} = 10.4 \text{ Hz}, \]  

which corresponds to a vehicle velocity of 7.5 km/h.

5.1.2 Results and analysis

The simulation output contains the vertical acceleration of the sprung mass and the tire contact force, both as functions of time. These are plotted for each simulation setup. A representative set of plots are shown and described in the following subsection.

RMS calculations provide a single value for a certain time frame. Thus, it is an appropriate method to facilitate direct comparisons between different simulations. RMS values based on the simulation output data are calculated for the vertical acceleration of the sprung
mass (vehicle body), as a measure of ride comfort. Increased vertical acceleration indicates deteriorated comfort [48]. In order to estimate the handling performance, RMS values for the tire contact force fluctuations are calculated. Increased force fluctuation indicates deteriorated handling performance [48]. All the RMS calculations are based on a 3 s time frame starting from the instance where the vehicle hits the road disturbance. This time frame includes the major part of the vertical acceleration and tire force fluctuations.

In terms of a FCM, a measure called the ride comfort index, can be calculated as the RMS of the vertical, lateral and longitudinal acceleration of the sprung mass. The major accelerations of the sprung mass, during longitudinal translation over a road bump or a curb, are vertically directed. Hence, in terms of these simulations, the ride comfort index and the RMS vertical acceleration are comparable. A reduction of the ride comfort index of 5 - 10 % is generally regarded as a respectable ride comfort improvement [48].

Figure 33 shows the RMS of the vertical acceleration of the sprung mass as a function of the vehicle velocity, during longitudinal translation over the bump profile. The vertical acceleration of the sprung mass continuously decreases as the velocity increases.

Two lines connecting the RMS vertical acceleration values are implemented, see figure 33, accentuating the dynamic characteristics of the system. An offset of 0.5 m/s² is added, in order to separate the line diagram from the bar diagram to increase visibility. In addition, values for 1.5 km/h, 7.5 km/h and 9.1 km/h are added, marked with x in figure 33. These velocities correspond to the eigenfrequencies of the sprung and unsprung mass, according to equations 3, 4 and 5. When an object is subjected to a force acting with a frequency that is close to its eigenfrequency, even a small excitation force can induce a significant oscillation amplitude. The damping factor is low in connection to the eigenfrequency, due to a natural tendency to oscillate at this specific frequency. Due to this, the RMS vertical acceleration around these certain velocities are amplified. At 1.5 km/h, the RMS vertical acceleration is close to its peak value. Above 9.1 km/h, the RMS vertical acceleration decreases significantly.
For each simulated vehicle velocity, it can be seen that the vertical acceleration is dependent upon the amount of unsprung mass. Figure 34 shows the percentage increase of the RMS vertical acceleration caused by an increased unsprung mass. At velocities of 7 km/h and below, an increased unsprung mass causes increased RMS vertical acceleration of the sprung mass. At 10 km/h and higher, an increased unsprung mass results in decreased RMS vertical acceleration, during transition of this certain road disturbance profile. Since the bump profile inputs are based on sine waves with altered frequencies, these results indicate that the extent to which the unsprung mass influences ride comfort is dependent upon the disturbance frequency.

Figure 33: RMS vertical acceleration of the sprung mass, bump profile, QCM.

Figure 34: Percentage increase of the RMS vertical acceleration, bump profile, QCM.
Regarding the curb profile, the RMS vertical acceleration, see figure 35, increases in connection to increasing velocity from 1 km/h up to about 5 km/h, regardless of the amount of unsprung mass. Above 5 km/h, the RMS vertical acceleration remains fairly stable. It shall be noted, that the sprung mass will have a vertical displacement of 0.05 m, regardless of the velocity, since the amplitude of the disturbance profile remains at 0.05 m until the simulation end time.

According to figure 36, an increased unsprung mass is likely to cause deteriorated comfort during longitudinal translation over a curb, since the vertical acceleration is higher for all simulated velocities.

Figure 35: RMS vertical acceleration of the sprung mass, curb profile, QCM.

Figure 36: Percentage increase of the RMS vertical acceleration, curb profile, QCM.
The following characteristic description is valid for both the bump and the curb profile simulations, and all simulated vehicle velocities.

In figure 37, the vertical acceleration of the sprung mass during longitudinal translation over the bump profile at a velocity of 3 km/h can be seen. A low frequency fluctuation of around 2 Hz is visible, based on a period time of about 0.5 s (measured between second and third peak at about 5.5 and 6.0 s). In addition, a higher frequency fluctuation of around 10 - 15 Hz is present, explicitly visible at about 5.2 s. These fluctuations are connected to the eigenfrequencies of the sprung (2.1 Hz) and unsprung mass (40 kg: 12.7 Hz, 60 kg: 10.4 Hz) respectively. The 60 kg curve involves a phase delay compared to the 40 kg setup.

![Figure 37: Vertical acceleration of the sprung mass, bump profile, QCM.](image)

The RMS value of the tire-ground contact force fluctuation is a measure of the handling performance of a vehicle. Figure 38 shows this variable as a function of the simulated vehicle velocity, during longitudinal translation over the bump profile. The force fluctuation is higher in terms of the 60 kg setup compared to the 40 kg setup, for all simulated velocities. This indicates deteriorated handling performance.
The blue and red lines in figure 38 correspond to the RMS force fluctuation, added with an offset of 200 N in order to separate the line diagram from the bar diagram. Referring to the description of figure 33, amplified RMS force fluctuations are visible around the velocities corresponding to the eigenfrequencies of the sprung and unsprung mass.

The highest increase of the RMS tire force fluctuation, is found at a simulated vehicle velocity of 5 km/h, see figure 39. At this velocity, an increased unsprung mass has a maximum negative impact on handling performance.

Figure 38: RMS tire force fluctuation, bump profile, QCM.

Figure 39: Percentage increase of the RMS tire force fluctuation, bump profile, QCM.
At 1 km/h, corresponding to a disturbance frequency of 1.39 Hz, the RMS values of both the tire contact force fluctuation, see figure 38, and the vertical acceleration of the sprung mass, see figure 33, is significantly high. This is likely an impact from the eigenfrequency of the sprung mass, which is found at 2.1 Hz. It can be seen in figures 40 and 41, that the vertical acceleration and force fluctuation amplitude after the first period is significantly higher at 1 km/h compared to 10 km/h, despite a lower tire force in the first period. The flat spot that is visible at a time of 5.0 - 5.1 s in figure 41 is caused by the tire losing contact with the ground.

Figure 40: Vertical acceleration of the sprung mass as a function of time, bump profile, QCM.

Figure 41: Tire force fluctuation as a function of time, bump profile, QCM.
According to figure 42, the RMS value of the tire force fluctuation increases significantly as the velocity rises from 1 km/h up to about 7 km/h, for both setups. At velocities above 7 km/h, the RMS value is stabilized.

Figure 43 indicates that during longitudinal translation over a curb, the handling performance is significantly deteriorated for the 60 kg setup, compared to the 40 kg setup. This is valid for all simulated vehicle velocities. A peak RMS tire force fluctuation ratio value can be noted at 3 km/h. Above 3 km/h, the handling deterioration due to an increased unsprung mass decreases slightly in connection to increasing velocity.

Figure 42: RMS tire force fluctuation, curb profile, QCM.

Figure 43: Percentage increase of the RMS tire force fluctuation, curb profile, QCM.
5.1.3 Discussion

It is a common perception that an increased unsprung mass deteriorates the ride comfort as well as the handling performance of a vehicle. The presented results indicate that the impact of increased unsprung mass is highly dependent upon the disturbance frequency of the road surface. When subjected to a disturbance frequency above the eigenfrequency of the unsprung mass, the simulation output data shows a decreased RMS vertical acceleration, i.e. enhanced comfort, for a vehicle with an increased unsprung mass.

In section 3.1.4, a report by Vos et al. [48] is discussed. In that report, it is concluded that an increased unsprung mass on the rear wheels deteriorates ride comfort with 1 - 8 %. Vos et. al performs simulations with a real vehicle on highway, cobblestones and belgian blocks. The exact disturbance profiles of these roads are not presented, hence a direct comparison to the results attained in this thesis may be misleading. However, it is noted that for velocities below 10 km/h, the ride comfort deterioration noted in the performed simulations is in the same order of magnitude, 2 - 10 %.

The negative impact from an increased unsprung mass is generally higher in terms of handling performance, compared to ride comfort. A deterioration of the former is indicated for both road disturbance profiles and all velocities.

It shall be noted that all the conducted simulations are based on simplified models. For example, the influence of the geometry of the wheel is not taken into account. This might well affect the accuracy of the results.

A full car model is assembled in order to evaluate this matter to a further extent.
5.2 Full car model

A full car model is assembled in order to evaluate the results attained in subsection 5.1. The model is based on a template of a compact car, available in the dynamic modeling program Dymola. The vehicle parameters are set according to table 6, which are equivalent to the parameters utilized for the QCM in subsection 5.1.

**Table 6: Vehicle parameters for the FCM.**

<table>
<thead>
<tr>
<th>Vehicle parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass of vehicle [kg]</td>
<td>1460</td>
</tr>
<tr>
<td>Unsprung mass (per corner) [kg]</td>
<td>40</td>
</tr>
<tr>
<td>Moment of inertia around x-axis [kg-m$^2$]</td>
<td>542</td>
</tr>
<tr>
<td>Moment of inertia around y-axis [kg-m$^2$]</td>
<td>2480</td>
</tr>
<tr>
<td>Moment of inertia around z-axis [kg-m$^2$]</td>
<td>2656</td>
</tr>
<tr>
<td>Wheel base [m]</td>
<td>2.65</td>
</tr>
<tr>
<td>Track width front [m]</td>
<td>1.54</td>
</tr>
<tr>
<td>Track width rear [m]</td>
<td>1.53</td>
</tr>
<tr>
<td>Center of gravity (x,y,z from front center ground) [m]</td>
<td>1.08, 0, 0.54</td>
</tr>
<tr>
<td>Tire dimension</td>
<td></td>
</tr>
<tr>
<td>Tire spring constant [N/m]</td>
<td>200000</td>
</tr>
<tr>
<td>Tire damper constant [Ns/m]</td>
<td>100</td>
</tr>
<tr>
<td>SUSPENSION type front</td>
<td>McPherson</td>
</tr>
<tr>
<td>SUSPENSION type rear</td>
<td>Multilink</td>
</tr>
<tr>
<td>Spring constant front [N/m]</td>
<td>330000</td>
</tr>
<tr>
<td>Spring constant rear [N/m]</td>
<td>560000</td>
</tr>
<tr>
<td>Damper constant front [Ns/m]</td>
<td>1288</td>
</tr>
<tr>
<td>Damper constant rear [Ns/m]</td>
<td>1276</td>
</tr>
<tr>
<td>Stabilizer stiffness front [Nm/rad]</td>
<td>1897.8</td>
</tr>
<tr>
<td>Toe in front [rad]</td>
<td>0.0018</td>
</tr>
</tbody>
</table>

In terms of a QCM, the vertical movement of the road, the sprung and the unsprung mass are the only degrees of freedom. The vehicle body is represented by a point mass placed on top of the suspension. During simulation of the FCM, longitudinal and lateral translation as well as pitch, roll and yaw motions are introduced as additional degrees of freedom, see figure 44. The vehicle body is represented not only by a mass, but also involves geometric boundaries. Owing to these additional variables, the FCM is likely to better resemble a real vehicle, compared to the QCM. Hence, the influence on ride comfort and handling performance due to an increased unsprung mass can be further evaluated.
5.2 Full car model

5.2.1 Simulation

The FCM is simulated in a test rig, according to figure 45. Each wheel is placed on top of a cylinder, which can be vertically displaced. The input signals to each cylinder are equivalent to the QCM simulations, see subsection 5.1.2.

Consider a vehicle approaching a road disturbance. The front and rear axle reaches the road disturbance at different moments. Hence, a pitch motion is initiated. The time interval between the moments of impact depends on the velocity of the vehicle. To resemble a vehicle in longitudinal motion over a disturbance profile, this time interval is
implemented into the simulation model. The two cylinders that support the front wheels are displaced before the two cylinders that support the rear wheels, according to table 7.

Table 7: Time between the front and rear wheels reach the road disturbance.

<table>
<thead>
<tr>
<th>Velocity [km/h]</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>50</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time interval [s]</td>
<td>9.54</td>
<td>3.18</td>
<td>1.91</td>
<td>1.36</td>
<td>0.95</td>
<td>0.48</td>
<td>0.32</td>
<td>0.19</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Each simulation is conducted for two vehicle setups:

1. The original setup with an unsprung mass of 40 kg per vehicle corner,
2. an alternative setup with an unsprung mass of 40 kg per corner at the front and 60 kg per corner at the rear, intended to resemble a vehicle with rear mounted in-wheel motors.

All other vehicle parameters are kept constant.

In subsection 5.1.2, the vertical eigenfrequency of the rear unsprung mass was calculated. The vertical eigenfrequencies of the sprung mass and the front unsprung mass for the FCM are calculated in equations 6 and 7 respectively. All eigenfrequencies of the system are summarized in table 8.

\[
\omega_s = \sqrt{\frac{k_s}{m_s}} = \sqrt{\frac{2 \cdot 56000 + 2 \cdot 33000}{1300}} = 11.7 \text{ rad/s} = 1.9 \text{ Hz}, \quad (6)
\]

\[
\omega_{u_f} = \sqrt{\frac{k_t + k_s}{m_u}} = \sqrt{\frac{200000 + 33000}{40}} = 76.3 \text{ rad/s} = 12.1 \text{ Hz}, \quad (7)
\]

Table 8: Eigenfrequencies of the system.

<table>
<thead>
<tr>
<th>Mass</th>
<th>Eigenfrequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprung mass</td>
<td>1.9</td>
</tr>
<tr>
<td>Unsprung mass front 40 kg/corner</td>
<td>12.1</td>
</tr>
<tr>
<td>Unsprung mass rear 40 kg/corner</td>
<td>12.7</td>
</tr>
<tr>
<td>Unsprung mass rear 60 kg/corner</td>
<td>10.4</td>
</tr>
</tbody>
</table>

5.2.2 Results and analysis

The main objective in terms of the output data analysis is the vertical acceleration of the sprung mass, as a measure of ride comfort, and tire contact force fluctuation, as a measure of handling performance. The vertical acceleration of the sprung mass is measured at the center of gravity.
The unsprung mass at the front corners remains unchanged throughout all simulations. The increased unsprung mass at the rear corners mainly affects the contact forces on the rear tires. Hence, in order to evaluate the impact on handling performance, the contact force is measured at one of the rear wheels. The contact forces for the left and right rear tire are equivalent.

RMS values are calculated and analyzed for the vertical acceleration of the sprung mass and the rear tire contact force fluctuation, based on a 3 s time frame. Consider the two model setups in figure 46. When the front wheels reach the road disturbance, vertical acceleration of the sprung mass is initiated. Until the rear wheels are displaced at 5.95 s, the acceleration of the two setups is principally equivalent. Regarding the contact forces of the rear tires, the same pattern is noted, see figure 47. In order to simplify a direct comparison of the two different model setups, the RMS time frame is therefore initiated when the rear wheels reach the road disturbance. The described characteristics are valid for both disturbance profiles and all simulated velocities.

Figure 46: Vertical acceleration of sprung mass, rear wheels hit the road disturbance at 5.95 s.

Figure 47: Rear tire contact force, rear wheels hit the road disturbance at 5.95 s.
Figure 48 shows the RMS vertical acceleration of the sprung mass as a function of vehicle velocity, during longitudinal translation over a bump profile. For both setups the vertical acceleration remains fairly constant between 1 km/h and 10 km/h. At velocities above 10 km/h, it decreases significantly in connection to increasing vehicle velocity. This indicates that the overall ride comfort deterioration caused by the road disturbance decreases as the velocity increases.

The RMS vertical acceleration of the sprung mass depends on the amount of unsprung mass at the rear wheels. Figure 49 shows the percentage increase of the RMS vertical acceleration, caused by an increased unsprung mass. It can be seen that below 10 km/h the RMS vertical acceleration increases about 2 - 5%. This indicates deteriorated ride comfort. At higher velocities the RMS vertical acceleration is reduced with up to 25%, indicating significantly enhanced ride comfort.

![Figure 48: RMS vertical acceleration of the sprung mass, bump profile, FCM.](image)

![Figure 49: Percentage increase of the RMS vertical acceleration, bump profile, FCM.](image)
Figure 50 shows the RMS vertical acceleration of the sprung mass as a function of the vehicle velocity, during longitudinal translation over a curb profile. The RMS vertical acceleration varies between 0.58 and 1.13 m/s², depending on the vehicle velocity and the amount of unsprung mass. The highest value is noted at 90 km/h. Hence, at this velocity the ride comfort is likely to be significantly deteriorated.

Figure 51 shows the percentage increase of RMS vertical acceleration caused by an increased unsprung mass. Deteriorated comfort is indicated at all simulated vehicle velocities. It is noted that the impact of increasing the unsprung mass is significantly high at 1 km/h, compared to the other simulated velocities. At this specific velocity, the increased unsprung mass involves a 4% increase regarding the RMS vertical acceleration of the sprung mass. At other simulated velocities, the equivalent value is merely 0.1% - 0.7%.

Figure 50: RMS vertical acceleration of the sprung mass, curb profile, FCM.

Figure 51: Percentage increase of the RMS vertical acceleration, curb profile, FCM.
Figure 52 shows the RMS tire force fluctuation at one of the rear wheels as a function of the vehicle velocity, during longitudinal translation over a bump profile. It can be seen that the RMS force fluctuation increases with increasing velocity from 1 km/h to about 7 km/h, where it reaches a peak value. Above 10 km/h, it decreases with increasing velocity, indicating less deterioration of handling performance when passing the bump at velocities higher than 10 km/h.

According to figure 53, an increased unsprung mass deteriorates handling performance at all simulated vehicle velocities. At 5 km/h the handling performance deterioration is at its peak, with an RMS tire force fluctuation increase of 18%.

![Figure 52: RMS tire force fluctuation, bump profile, FCM.](image)

![Figure 53: Percentage increase of the RMS tire force fluctuation, bump profile, FCM.](image)
Figure 54 shows the RMS tire force fluctuation at one of the rear wheels as a function of the vehicle velocity, during longitudinal translation over a curb profile. The RMS force fluctuation increases with increasing velocity up to about 7 km/h. The diagram indicates that the handling performance deterioration caused by the road disturbance is fairly constant at velocities above 7 km/h.

An increased unsprung mass deteriorates handling performance at all simulated vehicle velocities, according to figure 55. It has the most negative impact at a vehicle velocity of 3 km/h, with an 18% increase of the RMS tire force fluctuation. The lowest value is noted at 1 km/h, where the RMS tire force fluctuation is increased by about 10%.
5.2.3 Discussion

The overall characteristics of the FCM simulation output data are in concurrence with the QCM simulations. The results from the QCM simulations indicate that the influence on ride comfort due to an increased unsprung mass, is dependent of the frequency of the road disturbance. The FCM simulations confirm this indication. At longitudinal translation over a bump profile, which is based on a sine wave input signal, ride comfort improvements are indicated in connection to a disturbance frequency above the eigenfrequency of the unsprung mass. All other simulations indicate deteriorated ride comfort in connection to an increased unsprung mass.

Figure 39 and 43 show the percentage increase of the RMS tire force fluctuation, attained from the QCM simulations, whilst figure 53 and 55 contain equivalent data for the FCM simulations. The characteristics of the QCM diagrams referred to, are very similar to corresponding FCM diagrams. Significant differences are however noted when comparing figure 36 with 51, which also contain results from the QCM and the FCM simulations respectively. Both figures show the percentage increase of the RMS vertical acceleration caused by an increased unsprung mass, regarding translation over the curb profile. Whereas the QCM simulations contain fairly constant acceleration values, regardless of vehicle velocity, the FCM values vary significantly.

It is noted that the overall values of the RMS vertical acceleration of the sprung mass are significantly lower in terms of the FCM, compared to the QCM. This is likely due to a different measurement point. The acceleration of the QCM is measured right on top of the suspension. In terms of the FCM, the measurement point is placed in the center of gravity, i.e. at a location between the front and rear axle. If the front wheels are fixed and the rear wheels are displaced 0.05 m vertically, the center of gravity is merely displaced 0.02 m. Hence, also the acceleration caused by this displacement is lower at the center of gravity, compared to right above the rear axle.
6 Conclusions

WCM vehicles enable significantly improved handling performance, safety and ride comfort compared to conventional vehicles, owing to the x-by-wire technology and an additional number of actuators related to motion control. Longitudinal, vertical and lateral motions can be individually set for each comprised corner module.

Several WCM concepts are currently being developed by automotive manufacturers and subcontractors. In order for serial production to be attainable, additional major investments in terms of research, testing and manufacturing equipment are required.

Implementation of in-wheel motors is likely to cause an increased unsprung mass in terms of the WCM vehicle, compared to a conventional equivalent. The simulation results are summarized in table 9. They indicate that an increased unsprung mass involves deteriorated handling performance, regardless of the vehicle velocity or road disturbance profile. In addition, a majority of the simulations indicates deteriorated ride comfort. At disturbance frequencies above the eigenfrequency of the unsprung mass, a significant ride comfort improvement is however indicated.

Table 9: Percentage increase of RMS values, caused by an increased unsprung mass.

<table>
<thead>
<tr>
<th>Simulation model</th>
<th>Road disturbance</th>
<th>RMS vertical acceleration min [%]</th>
<th>max [%]</th>
<th>RMS tire force fluctuation min [%]</th>
<th>max [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCM</td>
<td>Bump</td>
<td>-13</td>
<td>+10</td>
<td>+0.1</td>
<td>+21</td>
</tr>
<tr>
<td>FCM</td>
<td>Bump</td>
<td>-25</td>
<td>+6</td>
<td>+0.3</td>
<td>+18</td>
</tr>
<tr>
<td>QCM</td>
<td>Curb</td>
<td>+2</td>
<td>+2.7</td>
<td>+5.8</td>
<td>+12</td>
</tr>
<tr>
<td>FCM</td>
<td>Curb</td>
<td>+0.15</td>
<td>+4</td>
<td>+10</td>
<td>+17.2</td>
</tr>
</tbody>
</table>

A vehicle is continuously exposed to different disturbance frequencies during operation. Hence, the overall comfort experience is dependent not only of one single type of input, but upon a wide variety of disturbances. Regarding a majority of the conducted simulations, an increased unsprung mass causes deteriorated ride comfort. In addition, some of the simulations where enhanced comfort is indicated, represents uncommon driving situations. For example, speed bumps or curbs are rarely crossed at high velocities. Owing to these circumstances, it is likely that the overall ride experience is deteriorated in connection to an increased unsprung mass. Hence, the mass of in-wheel motors must be kept to a minimum, or an individual motor suspension may be required.
References


