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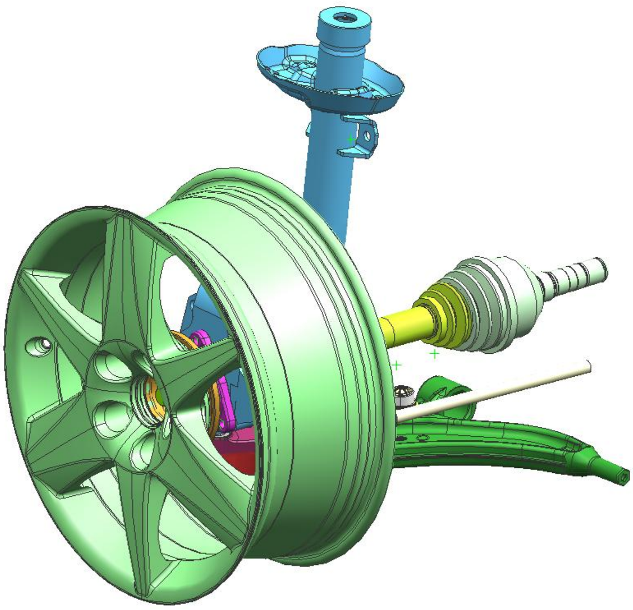

Development of a Hi-Per strut front suspension

Master's Thesis in Automotive Engineering

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Division of Vehicle Engineering and Autonomous Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
CAD assembly of a front Hi-Per suspension

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ABSTRACT

The aim of this master thesis has been to develop a front suspension of Hi-Per design suitable for a mid- or full size standard car. A Hi-Per suspension is a variant of the MacPherson strut suspension, with the difference of a steered knuckle and a rigid damper strut. In a MacPherson suspension the whole damper and knuckle assembly is steered, limiting the position of the steering axis by the body mounts of the strut.

The designed suspension should fit into the same interface as a suspension of MacPherson type and should be applicable for three different models with different ride heights. The vehicles featuring the new Hi-Per suspension shall have an increased track width making an unchanged MacPherson suspension unsuitable with respect to kingpin offset based phenomena such as torque steer or influence of road disturbances.

The base for the Hi-Per design was an available MacPherson vehicle and previous Saab vehicle models, of which one features a Hi-Per suspension design.

Within the thesis, solutions available on the market today has been investigated and benchmarked as well as previous solutions within Saab. This has together with the free thinking of the designers hopefully form the best solution possible for the new Hi-Per design.

The focus of the suspension has been to achieve a high level of commonality, at the same time as design requirements of packaging and kinematics are fulfilled together with maintenance and assembly improvements. Within the thesis a large effort has been used for packaging in CAD, at the same time as the geometry is verified by kinematic multi body simulations. This was done in order to fulfil wheel parameters and static design factors of the suspension.

Within this thesis a complete pre-study has been performed. This pre-study has resulted in a design proposal, based on the simulation results incorporating Saab vehicle- and suspension requirements. The CAD-models have been designed with regards to clearance during bump, rebound and steering. The models have been designed with similar wall thickness and geometries as the existing Saab Hi-Per solution.

The recommendations of this thesis are to continue working with the design proposal with regards to compliance calculations and more specific CAD-designs. There has not been any FE-analysis performed on the parts. Therefore there is a need to further investigate the CAD-models with regards to compliance calculations.

Key words: Vehicle suspensions, Hi-Per, MacPherson, Torque steer, Product development, Mechanical engineering, Automotive engineering

Utveckling av främre Hi-Per hjulupphängning

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SAMMANFATTNING

Målet med examensarbetet var att utveckla en hjulupphängning av typen Hi-Per anpassad för en mellan eller stor standardbil. Hi-Per är en variant av MacPherson upphängning men med ett styrt spindelhus och en fast dämparenhet. I en MacPherson upphängning är dämpare och spindelhus fast monterade i varandra och roterar under styrning, vilket begränsar positionen av styraxeln via karossinfästningen.

Upphängningen skulle passa samma gränssnitt som en upphängning av typen MacPherson och vara anpassad för tre bilmodeller med olika höjd. Bilarna som använder denna utvecklade Hi-Per upphängning kommer alla ha en utökad spårvidd. Detta gör en upphängning av MacPherson typ olämplig med tanke på fenomen beroende av kingpin offset, såsom torque steer och styrverkan från vägojämnheter.

Utgångspunkten för Hi-Per konstruktionen har varit en befintlig bil med MacPherson upphängning samt tidigare modeller från Saab, av vilken en var av Hi-Per konstruktion.

Inom ramarna för examensarbetet har befintliga lösningar tillgängliga på marknaden undersökts tillsammans med tidigare lösningar inom Saab. Detta har i kombination med konstruktörernas fria tänkande lett fram till den lösning som ansågs bäst lämpad för den nya Hi-Per konstruktionen.

Fokus för upphängningen har varit att ha ett högt antal gemensamma artiklar mellan modeller tillsammans med förbättringar inom underhåll och montering. Inom examensarbetet har mycket tid använts för paketering i CAD, samtidigt som geometrin kontrollerades genom multi body simulering. Detta genomfördes för att säkerställa och uppnå krav på hjulkinematik och design faktorer.

Arbetet innehåller en komplett förstudie. Denna förstudie har resulterat i ett designförslag vilket är baserat på de simuleringsresultat som är utfallet av simuleringar baserade på Saabs designkrav. CAD modeller har konstruerats med avseende på in- respektive utfjädring samt styrning. Modellerna har konstruerats med liknande godstjocklek och geometri som tillgängliga lösningar, såsom Saabs Hi-Per konstruktion av idag.

Rekommendationerna från arbetet är att fortsätta arbeta med den föreslagna designen med fokus på styvhetskrav och detaljkonstruktion. Det har inte genomförts några FE-beräkningar på de utvecklade komponenterna. Det finns därför ett behov att vidare undersöka utvecklade CAD geometrier med avsikt på styvhet och materialkrav.

Nyckelord: Hjulupphängning, Hi-Per, MacPherson, Torque steer, Produktutveckling, Maskinkonstruktion, Fordonskonstruktion

Contents

Preface

This study has been made at Saab Automobile in Trollhättan during January to June 2011. The aim of this study has been to propose a new front suspension design for upcoming models. The study has involved benchmarking of existing solutions followed by simulation and design work. The base for this work was a MacPherson front suspension which was further developed to move the king pin axis in a lateral direction in order to decrease road disturbance and torque steer.

The work has been carried out in cooperation with the Department of Applied Mechanics, vehicle engineering and autonomous systems, Chalmers University of Technology, Sweden. This part of the project has been carried out with Professor Gunnar Olsson at Chalmers as examiner. At Saab Automobile AB Anders Ånnhagen has been supervisor. The co-workers at Saab Automobile AB are highly appreciated. A lot of help has been given by the people at different institutions at Saab. Some of these are Henrik Hägglund, Dr. Matthijs Klomp and Pernilla Eden. Finally, it should be noted that this work would never have been possible without the professionalism and help from the various people involved at Saab Automobile AB.

Göteborg, June 2011

Notations

Abbreviations

CAD	Computer Aided Design
GM	General Motors Company
NVH	Noise, Vibration and Harshness
$SAAB$	Saab Automobile AB
SDF	Static design factors
SKF	Svenska Kullager Fabriken (Swedish Ballbearing Factory)
SLA	Short-Long arm suspension, a variant of double wishbone suspension
ZF	ZF Friedrichshafen AG

Tables and equation notation

d	Scrub radius
d_{KP}	Kingpin offset
F_X	Traction force
M_{KP}	Moment around kingpin axis
r	Tire rolling radius
T_d	Drive torque
ζ	Driveshaft inclination
λ	Kingpin inclination
ν	Caster angle

1 Background

Within Saab there has been a desire to investigate the use of a different kind of suspension suitable for different vehicle models of the same base platform. The suspension variant called Hi-Per using the same interface as the target platform has been studied. Within this thesis a first draft design of the Hi-Per suspension has been developed including an investigation of the potential to use this concept in the available platform.

1.1 Surroundings

1.1.1 Saab Automobile market

Saab Automobile is a passenger car manufacturer based in Trollhättan Sweden, where cars have been designed and built since 1949. Today (2011) three main vehicle models are produced and marketed worldwide; the D-segment sedan/wagon/convertible 9-3, the E-segment sedan/wagon 9-5 and the J-segment crossover 9-4x, see Table 1.1. Of interest for this thesis are their front suspension designs which are the base and starting point for this work. In detail mostly all of these models, that all are front wheel- or four wheel driven, uses a MacPherson type front independent suspension.

All the Saab models of today are designed in cooperation with General Motors (GM), of which Saab was a part until early 2010. As an independent car manufacturer, Saab designs its cars in house including front suspensions. The aim of this work is to design a variant of the former MacPherson suspension called Hi-Per and evaluate this concept as a suspension option for future vehicle applications. Today there are one Hi-Per suspension design in production for the Saab 9-5 model, mentioned as the Saab High Performance Strut in the analysis section.

Table 1.1 Saab model data

<table>
<tr><th>Vehicle Model</th><th>Saab 9-3</th><th colspan="2">Saab 9-5</th><th>Saab 9-4x</th></tr>
<tr><td>Body type</td><td>sedan/wagon/ convertible</td><td colspan="2">sedan/wagon</td><td>crossover</td></tr>
<tr><td>Year</td><td>2011</td><td colspan="2">2012</td><td>2012</td></tr>
<tr><td>Front suspension type</td><td>MacPherson strut</td><td>MacPherson strut</td><td>Hi-Per strut</td><td>MacPherson strut</td></tr>
<tr><td>Track width front/rear [mm]</td><td>1524/1506</td><td colspan="2">1585/1585</td><td>1622/1623</td></tr>
<tr><td>Wheelbase [mm]</td><td>2675</td><td colspan="2">2837</td><td>2807</td></tr>
<tr><td>Overall length/width [mm]</td><td>4646/1801</td><td colspan="2">5008/1868</td><td>4828/1909</td></tr>
</table>

1.1.2 Competitor analysis

Saab vehicles are marketed as premium cars, with German and Swedish car manufacturers as main competitors in its segment. Details of some of the competitor vehicles can be found in Table 1.2, as a reference to the Saab models produced. Suspension design varies from model to model, often using a multi-link version of a MacPherson or double wishbone suspension. Traditional MacPherson solutions are still common as it is cost effective and provides more space to a transverse front mounted engine.

Table 1.2 Market model data

Vehicle Model	Audi A4	Audi A6	BMW 3 series	BMW 5 series	Volvo S/V60
Body type	sedan/wagon	sedan/wagon	sedan/wagon	sedan/wagon	sedan/wagon
Year	2008	2008	2008	2008	2011
Front suspension type	Multilink SLA	Multilink SLA	Multilink strut	Multilink strut	MacPherson strut
Track width front/rear [mm]	1528/1512	1585/1586	1502/1507	1557/1555	1588/1585
Wheelbase [mm]	2805	2837	2762	2885	2776

Vehicle Model	Volvo S80	Audi Q7	BMW X5	Volvo XC60
Body type	sedan	crossover	crossover	crossover
Year	2011	2007	2007	2011
Front suspension type	MacPherson strut	Multilink SLA	Multilink SLA	MacPherson strut
Track width front/rear [mm]	1588/1585	1594/1659	1640/1645	1632/1586
Wheelbase [mm]	2835	3000	2925	2774

1.2 Objectives

The objectives of this thesis are to develop a first draft of a Hi-Per strut front suspension that could fit the body and wheel corners of a MacPherson suspension in a passenger car. The target vehicle will be available in three different ride heights and the suspension must be compliant with all these models. Track width of the front axle will be increased making the existing MacPherson solution unsuitable causing an increased offset between the kingpin axis and the plane of the wheel. This offset is a significant factor of torque steer and road disturbance felt by the driver at the steering wheel. A second objective is therefore to decrease the amount of torque steer by clever engineering and full utilization of the Hi-Per concept.

Desirable is to reach a high level of commonality to an existing MacPherson suspension as well as to accomplish symmetric components, mainly due to cost effectiveness. The finalized work should include a CAD assembly of a functioning first Hi-Per strut solution. A multi body simulation will be supplied, that verifies the solution to the design requirements provided by Saab for this kind of suspension.

1.3 Delimitations

As a first study of this suspension type, the design will not be ready for manufacturing and should be seen as a finalized concept that needs structural optimization to work in a vehicle. Material and strength calculations are therefore limited within this work and the focus is to have a first functioning concept.

Kinematic multi body simulations are based on simple geometry and rigid components apart from the type of rubber bushings used in the available MacPherson solution. No detailed specification of joints will be performed apart from the ones affecting the space of packaging within the suspension.

Other limiting factors are the interface of the subframe and vehicle body, which will be set by Saab and the existing MacPherson suspension. No further investigations in changing these points are therefore performed. Neither will any investigations be done regarding the target vehicle dimensions out of a market or performance point of view.

2 Theory

A suspension system of a vehicle connects the unsprung mass including wheels, brakes, knuckle and half the weight of control arms and dampers, with the sprung mass including the complete body. The suspension has primarily two functions; limit the transfer of road irregularities to the sprung mass and keep the tire in contact with the road at all times. All suspensions have a spring and a damper unit that transfer loads from the road to the sprung mass, or the other way around. Limited focus will be on the spring and dampers for this thesis apart from the actual mechanical design affecting the design of the suspension. Of more importance is the alignment of the wheel and tire with respect to static design factors, of which some are described in the next section.

Various types of suspensions are available on the market today all having different requirements of packaging and kinematics. The most common types are discussed in Section 2.2.

2.1 Suspension geometry

Some of the design factors that are of importance for the forces and the motions of a front vehicle suspension can be seen in Figure 2.1 for a double wishbone suspension. Most of these factors are determined by the position of the kingpin axis and must be set by the designer with the available packaging space in mind. Keeping track of the following design factors plays a major role for the loads acting on the suspension as well as various steering effects of the front suspension.

The two most important wheel angles are camber and toe. Camber is the angle between the wheel and a vertical plane seen from the front end of the car. Toe is the angle between the wheel plane and a vertical plane seen from the top of the car. Camber is noted negative as the top point of the tire is leaning towards the car. Toe however is negative as the front most point of the tire is leaning outwards from the car (for a front axle suspension). This means that the left wheel is steered to the left and the right wheel to the right when toe is negative.

Both camber and toe will change during bump travel, and the change of camber and toe with respect to travel is known as ride camber and ride steer. Some amount of increased camber is desirable to keep a negative camber during cornering, increasing the grip of the tire. The ride steer on the other hand should be low in order to keep induced steering low during wheel travel, still with negative sign to reduce driver induced disturbances.

Seen in a front view, left side of Figure 2.1, the inclination of the kingpin axis to a vertical plane parallel to the wheel is simply the kingpin inclination and sets the two distances kingpin offset at the hub and scrub radius at the ground. As discussed in Section 2.3, kingpin offset is of importance regarding torque steer as scrub radius is important for drivers feedback and brake torque steer. The caster angle is the kingpin angle from a side view and determines, together with the kingpin inclination, the camber gain as the wheel is steered. At the ground the caster angle sets the distance called caster trail, and will provide an aligning torque that steers the car in a straight line after turning (Gillespie, 1992).

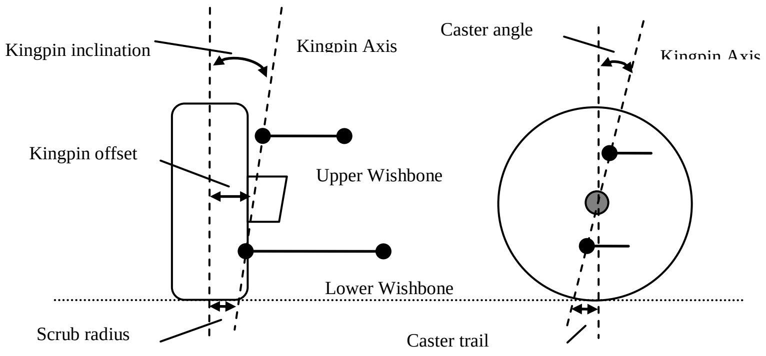

Figure 2.1 Suspension steer axis geometry

2.2 Suspension variants

2.2.1 MacPherson strut suspension

The perhaps most common independent front suspension of passenger vehicles today is the MacPherson strut. The reason of its popularity is that its compact design gives extra room for a transverse engine in the engine bay of a front wheel driven car. Its design is also relatively light and uses few components reducing the total cost of the suspension system.

First introduced by Earle S. MacPherson, the suspension is built by a load carrying damper unit fixed to the steering knuckle and a top mount in the bodywork where it is free to rotate. At the bottom of the knuckle a single control arm is mounted to support the strut laterally and longitudinally. As the damper strut is fixed to the knuckle, both knuckle and damper will rotate as the vehicle is steered and therefore sets the position of the kingpin axis, see Figure 2.2.

At the same time as packaging is one of the major advantages of this suspension design, it is also its largest disadvantage. The few mounting points used for this suspension will be limited by mainly the bodywork and tire size. Therefore the designer has little freedom to design the suspension in order to modify static design factors of the suspension; especially ride camber, kingpin and caster trail. Taking a closer look at the possibility of damper position it will be difficult to align the damper without an offset to the tire causing a bending moment in the damper inducing friction. The moment can be limited with a pretensioned coil over spring of a different inclination as the damper, something that is regularly used.

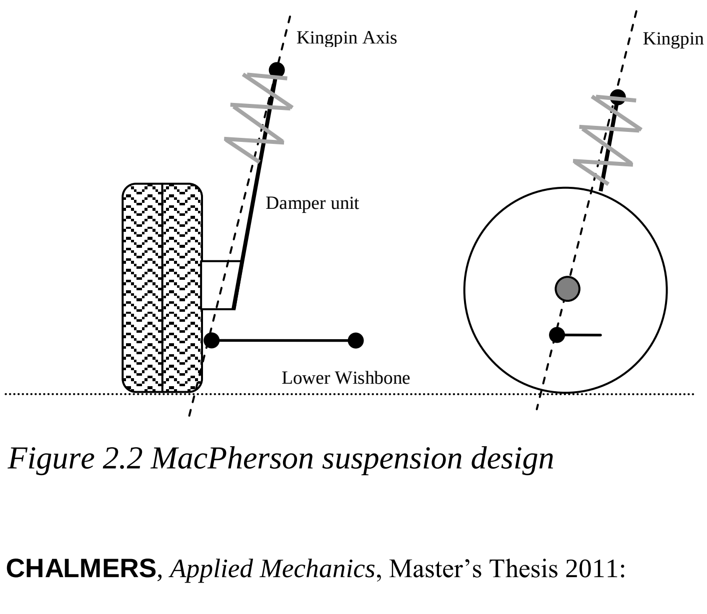

Figure 2.2 MacPherson suspension design

2.2.2 Hi-Per strut suspension

The Hi-Per strut suspension concept is an improvement of the MacPherson strut with the advantage of more freedom in design still keeping the interface with an existing MacPherson suspension. Main design changes compared to the MacPherson are the knuckle that is no longer rigidly connected to the damper strut and is free to rotate during steering without affecting the rotation of the damper strut, see Figure 2.3, which is locked in rotation. The kingpin axis is no longer locked to the damper mount or the outer control arm joint and will be determined by the joints for the knuckle solely. Instead of connecting directly to the knuckle, the damper strut connects to the control arm outer ball joint by a single supporting unit called a yoke. It is to the yoke the knuckle is attached and the yoke, together with the lower control arm and damper strut, is therefore the main structural members of the suspension. Noted is that the damper strut still will have an applied moment load causing friction in the strut due to the offset to the contact point of the tire.

One of the best advantages with the Hi-Per strut suspension is the commonality to an existing MacPherson strut suspension where little has to be changed between the two suspension types. Therefore the Hi-Per suspension has been popular in performance versions of existing standard cars with a MacPherson suspension as standard, of which some are mentioned as a benchmark in Chapter 4. Using a Hi-Per suspension in the packaging space of an existing strut suspension is anyhow not always straight forward. The Hi-Per concept adds components to the suspension making it hard to package as well as an increasing cost and unsprung mass, factors that must be considered in the suspension selection process.

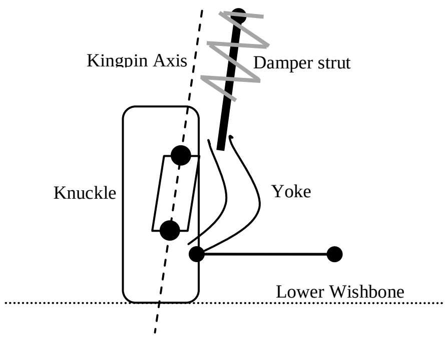

Figure 2.3 Hi-Per strut suspension design

2.2.3 Double Wishbone suspension

Double wishbone independent suspensions has for a long time been the natural choice in race cars as it is compact in height and provides good performance, mainly with respect to ride and roll camber. A passenger car on the other hand is quite different in the case of less packaging space, especially for transverse engine cars. Therefore variants of double wishbone suspensions are often found in RWD or 4WD trucks that have a longitudinal engine with more available space for the front suspension (A2mac1, 2011). Recently the double wishbone suspension has become more and more popular also in smaller passenger cars due to handling performance advantages.

As a designer the double wishbone offers the best handling performance, however with compromises in respect to noise and vibrations. It is built up by two separate control arms of unequal length and positioning where the designer can change the alignment of the wheel to meet the desired design factors and kingpin axis position, see Figure 2.4. A significant consideration to take into account is the mounts of the upper control arm that has to be relatively stiff compared to the top mount of a MacPherson strut. This may result in design changes to the front sub-frame or the bodywork where the space towards the engine is limited. The damper unit of a double wishbone suspension does not work as a load carrying member of the suspension as in the case of the MacPherson strut. Therefore, the damper piston rod can be reduced in size and thereby the friction losses lowered.

Today there are mainly two different variants of double wishbone suspensions, here mentioned as compact double wishbone suspension and Short-long arm suspension (SLA), respectively.

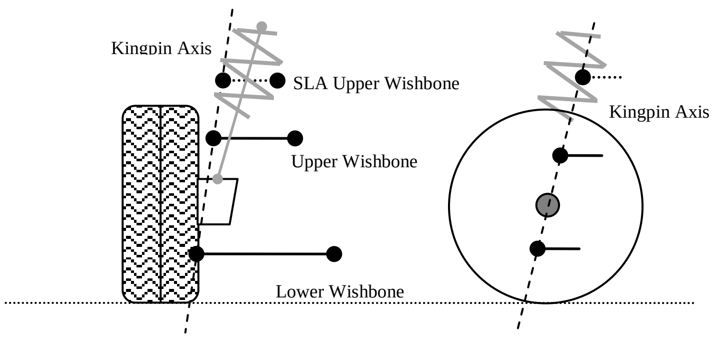

Figure 2.4 Double Wishbone suspension design

2.2.3.1 Compact double wishbone suspension

Significant for the compact double wishbone suspension is the short offset between both the control arms making it possible to package both the links inside the rim of the wheel. The height of such a suspension is therefore very low leaving extra room to body design and aerodynamics.

The disadvantage of long time use for this compact design is the high loads transferred to the control arms and the wear of joints and bushings. A narrow alignment of the control arms also makes this suspension sensitive to production tolerances, which is quite significant in the production of passenger cars.

2.2.3.2 Short-Long Arm suspension, SLA

A suspension variant that is used more and more in passenger cars is the SLA double wishbone suspension. Significant for the SLA is the high positioned and short upper control arm mounted over the tire. The inside wheel packaging demand for this suspension is improved from the compact double wishbone suspension at the same time as handling performance is improved from the Macpherson strut suspension. An SLA suspension will have an increased packaging demand above the tire and in level with the engine in order to save space for the upper control arm. As the base of the kingpin is larger than in the case of the compact suspension the loads in the top control arm is lowered, even if the mounts will take more space in the bodywork than the MacPherson suspension.

2.2.4 Multi-link front suspension

A multi-link front suspension is often a variant of a MacPherson or a double wishbone suspension where each control arm is split into two separate links mounted separately in the steering knuckle, see Figure 2.5. In this way a theoretical kingpin axis is created in the intersection of the paired control arm links, and the position of the kingpin axis can in fact be changed by the alignment of the links rather than the length of the control arms themselves. This gives the designer more freedom of kingpin selection by a cost of added components and joints as well as packaging space inside the rim.

As the wheels are steered the split control arm links are forced to move with respect to each other and the kingpin axis is therefore changed. This further adds complexity to the system and the determination of suspension design factors. Together with the increased cost of the system this is the main disadvantage with the multi-link design.

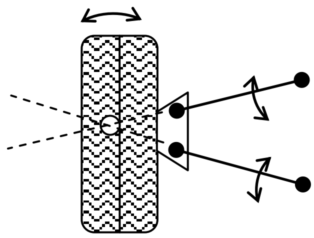

Figure 2.5 Multi-link suspension geometry

2.3 Torque steer

In a front wheel drive vehicle, with front steering, high amounts of drive torque tend to steer the wheels during acceleration. This induced steer torque is also known as torque steer. It is quite significant for high powered cars and will feel unpleasant for the driver who has to reply the steering torque by the steering wheel.

Simply the torque steer is induced as the traction force on the wheel is applied offset to the steering axis or kingpin axis causing an induced steering torque. As the same situation happens on the opposite side of the vehicle, the induced steering torque will cancel out as they are equal in magnitude. However, this is seldom the case during normal driving as (among other factors) vertical loads and surface friction may vary from side to side.

2.3.1 Torque steer mechanics

The mechanics behind torque steer is proven for one wheel studying the torques around the kingpin axis shown in Figure 2.6. To the system there is an applied drive shaft torque T_d of which a moment occurs around the kingpin axis. In detail the main expression can be seen as equation (2.1). By assuming small angles the expression is simplified. In straight forward driving and for front axle design load the driveshaft-angle is small and can therefore be neglected for the simple case below. For designs where the static driveshaft angle needs to be inclined this factor becomes significant. The magnitude of torque steer is simply the net torque difference from right to left side or ΔM_{KP}.

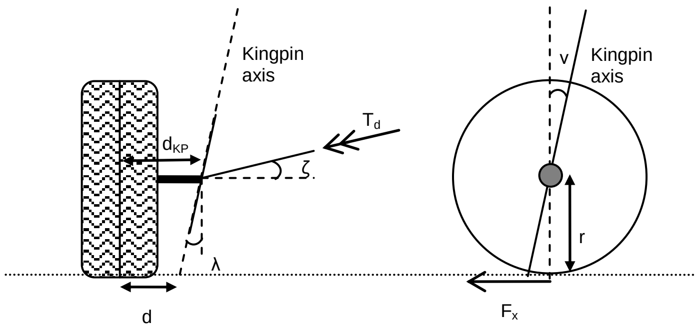

Figure 2.6 Torque steer

$$M_{KP} = \frac{T_d}{r} d_{KP} cos(\nu) \cos(\lambda) + T_d \sin(\lambda + \zeta) \approx \frac{T_d d_{KP}}{r}$$

(2.1)

From equation (2.1) it can be seen that the steering torque due to drive torque depends on drive torque, wheel radius and kingpin offset, d_{KP}. It is therefore desirable to keep the kingpin offset as low as possible for the design of the suspension system (Gillespie, 1992).

Other factors that effects torque steer is as mentioned; road conditions, vertical load, tire wear, differential design as it effects the traction force. Kingpin offset varies as the contact patch of the tire varies with primarily camber, tire conicity and road irregularities.

2.3.2 Differential effect on drive torque

Most standard cars of today use an open differential to allow a speed variation between right and left during cornering. This makes the car easy to drive but will also distribute the torque equally to the left and the right wheel limiting the traction force. For an ideal open differential the equal traction on each side could decrease the effect on torque steer significantly as the net steering torque is close to zero. As no differential is ideal and torque steer becomes significant in transient changes of drive torque, friction and moment of inertia in the drive train will cause a lock up effect and an unequal torque distribution. High performance front wheel drive vehicles are often designed for maximum traction and is often equipped with a limited slip differential where the torque distribution between left and right wheel is uneven. For a vehicle of this design a reduction of torque steer will be necessary.

2.4 Driving disturbance

Roads are seldom flat or the surface seldom smooth and the front wheels are disturbed from these irregularities at all time. Some examples could be minor bumps, pebbles but also wear paths of the road, tire conicity or camber. All irregularities apply a force to the tire contact patch, a patch that changes with the surface of the road and the wheel alignment. These applied forces can be seen similar to the case of torque steer in Section 2.3.1 where the disturbance force is applied to the wheel forming a resultant at the wheel centre resisted by the driveshaft. The kingpin offset between the application of the disturbance force and the kingpin axis at wheel centre is therefore kept to a minimum minimizing the steering torque. Where the disturbance force applies depend on the type of disturbance and where it affects the tire. Noticeable is that a wider tire is more sensitive to disturbances as the kingpin offset may vary over a wider range.

Similar to the case of torque steer the disturbance forces must be uneven from left to right side in order to apply a steering torque. Disturbances from bumps, pebbles or potholes are anyhow most often applied to one wheel separately making this phenomenon significant.

The discussion above applies to an unbraked hub only where the resultant force is formed at the driveshaft. For a braked hub it is a different scenario and the hub, wheel and knuckle can be seen as one fixed unit. Forces applied to the tire contact patch will therefore form a steering moment with respect to the scrub radius at ground level. Out of this reason it is desirable to keep the scrub radius low. A small scrub radius may be desirable for driver feedback and aligning torque.

3 Methodology

In this section the work process is described in more detail. The different stages of the development process can be seen in Section 3.1 and how the final design is reached. In Section 3.2 some of the evaluation criteria used for each concept can be seen in detail.

Finally the overall work method is described in detail in Section 3.3.

3.1 Process

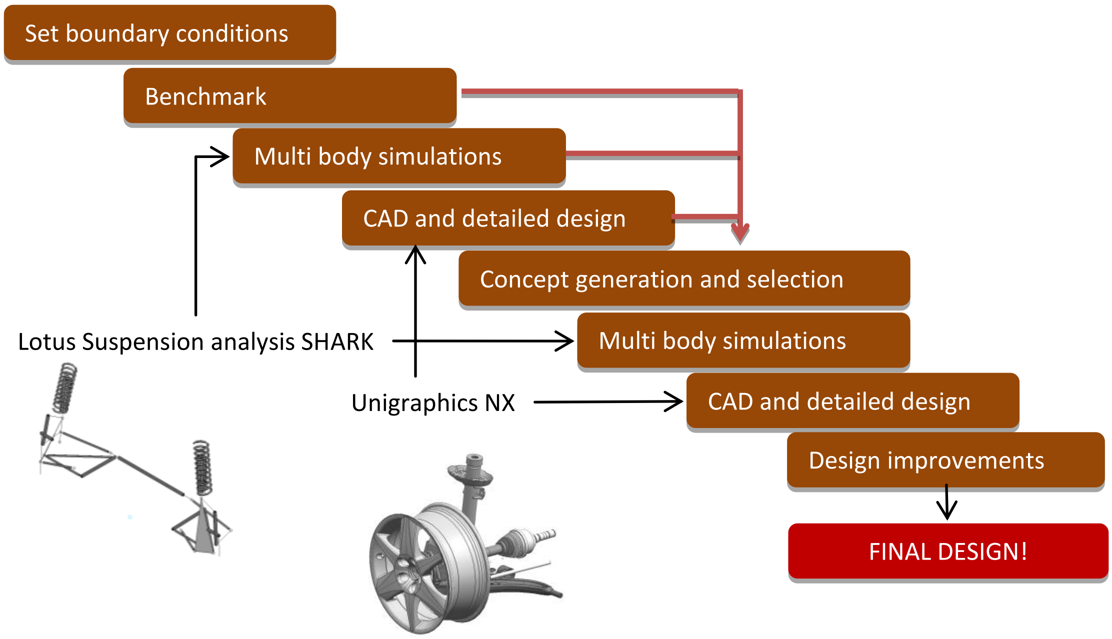

Figure 3.1 Process

The project process is split up by several minor steps in order to improve the final result of the project. First step has been to set boundary conditions and create the framework for the project. This decides what should be achieved with the final design and to where the process is aimed. Secondly large efforts is put in benchmarking and study similar designs on the market today, and try to learn what these solutions would do in the framework of this project. Together with benchmarked concepts new concepts are generated by the designers and the best suitable concept is chosen for the suspension design. This concept is studied in detail and a large effort is put in realizing the geometry in CAD as well as multi body simulations in order to fulfil requirements of packaging and kinematics.

3.2 Criterion analysis

During the project several factors are evaluated in order to give the best possible understanding of each concept. Some are considered more important than others, mostly due to the early project stage. The most important factors are the one determining the geometry of the suspension, such as packaging space and kinematics, validating the possibility to realize the suspension concept. Some factors are considered of less interest due to the accuracy of estimation in an early stage, for instance the cost of significant components. These factors are evaluated and compared to earlier designs and judged. Some of the evaluated factors are listed below together with a small explanation of the effort made in this early stage of development.

- Packaging - *Large effort to suit model variants*
- Kinematics – *Large effort to fulfil kinematic requirements*
- NVH – Noise and vibrations – *Small effort by comparing to previous suspension designs*
- Dimensioning – *Similar to previous designs, no detailed calculations*
- Production – *Large effort with input from assembly line*
- Maintenance – *Large effort with input from aftermarket and workshop personnel*
- Cost – *Certain components, others are estimated as better or worse*

3.3 Working method

In order to fulfil the requirements a comprehensive research has been performed at both internal and external resources. Experience from the existing Hi-Per solution has been taken into consideration from the mechanics in the chassis workshop, test drivers, engineers and the production plant at Saab.

In the beginning of the project a benchmarking process of competitor solutions was necessary in order to establish a view and knowledge of solutions on the market. Research was performed using benchmarking resources such as a2mac1.net, web search engines and real life investigation of vehicles equipped with the system of interest (A2mac1, 2011).

When the benchmarking process was finalized a concept phase was initialized. Two areas of the design were of particular interest, the connection between the strut and yoke and the connection between the control arm and yoke. Based on the knowledge from the benchmarking process several concepts were identified and evaluated. The two areas are independent of each other and were therefore evaluated separately.

The first area, the design of the connection between the strut and yoke, was developed and established early in the project.

More focus was put on the design of the connection between the yoke and control arm. This area was subject to packaging issues why certain solutions were rejected due to clearance issues. In the end only one solution met the requirements in packaging and boundary conditions. This concept became the final design.

In order to polish the final design an iterative approach was used. Joints were moved in Lotus Suspension Analysis to meet the static design factors. These joints where then placed in the actual design in Unigraphics. Components were designed with regards to these points and put in an assembly. This assembly was then motion simulated to check for clearance issues, both during bump, rebound and steering.

During the project several design changes in the overall platform were made causing slight adjustments and sometimes new comprehensive simulations of the kinematics.

4 Tools

4.1 Lotus suspension analysis (SHARK)

Lotus Suspension Analysis software SHARK is a multi body simulation software built especially for vehicle suspension modelling. With this software the user can create geometrical models of various suspension designs, also MacPherson struts and Hi-Per strut suspensions, that makes it suitable for this thesis. By simple changes in hardpoint positions the user can find a geometry that meets desired requirements, which is monitored by the software while being used. The software is also suitable for calculating the load distribution within the modelled suspension.

Within the scope of this thesis SHARK has been used to develop the first set of geometrical hardpoints and to verify that a Hi-Per strut suspension using these hardpoints complies with static design factors set by Saab. All aspects of ride, roll and steering motion, as well as compliance and deflections of certain joints has been monitored for the concept. The software has also been used to determine reaction loads within the suspension by applying external loads.

4.2 NX Unigraphics and Teamcenter

Unigraphics is a software used for computer aided design. Unigraphics is used as the standard software for CAD-work at Saab. This software has been used to model the components of the suspension. The models were put together in an assembly where a motion simulation has been performed in order to investigate clearances during bump, rebound and steering.

Teamcenter is the common sharing center used to connect several CAD users. With Teamcenter a user can open an assembly or part from another user. There are powerful tools to modify and prevent modification of different releases of a model. In Teamcenter the whole car assembly has been saved. This is also the software used to build assemblies out of existing components in the current base MacPherson vehicle.

5 Prerequisites

5.1 Boundary conditions

As mentioned in Section 1.2, the objective of this thesis is to develop a Hi-Per strut front suspension that can share the interface with an existing MacPherson suspension. The target vehicles differ from the base vehicle by numerous properties, (A Johansson & P Roubert, Saab Automobile, 2011). The three target vehicles noted as the standard, crossover and sport, differs primarily in ride height or wheel centre height without tires. The standard model will keep the wheel centre height of the base vehicle. The crossover will have an increased height by 30 mm while the sport version will have a lowered height by 10 mm. This is one of the most important factors when developing the suspension design as it primarily has a large impact on packaging space and roll centre height. The wheelbase will be changed for the standard and sport vehicle, but will be kept to the crossover model.

Another important design requirement is an increased track width. With respect to the base vehicle, the track width will be widened 25 mm in total. This makes the Hi-Per concept suitable as the design gives the possibility to increase the width and still decrease the kingpin offset. Target of kingpin offset in this study, is below 30 mm for all model variants.

The desired roll centre height of the standard vehicle is between 50-70 mm and 100-130 mm for the crossover vehicle.

5.2 Out of requisite targets and identified improvements

Studying the existing Saab Hi-Per solution mainly three different improvements becomes important for the new Hi-Per design.

Firstly there is a goal to reduce the time to dismantle for maintenance in a workshop. With information from aftermarket and workshop personnel it turns out that the Saab Hi-Per needs more than twice the time to perform a simple service, in this case a damper change, compared to a MacPherson suspension in the same car. The reason for this is that the yoke cannot be separated from the damper strut when mounted in the car. It is therefore necessary to dismantle most of the suspension to separate these parts. Desirable for the next generation of Hi-Per suspensions is therefore a simple way of separation between the damper and the yoke that can be performed on the car.

Secondly the objective is to increase the number of components that are equal for the left and right side in the new Hi-Per solution. This improves the cost both for manufacturing and aftermarket. Desirable is therefore to improve the level of commonality and to reduce the number of unique parts both between models and between suspensions.

At last, in the Saab Hi-Per design, the lower control arm is connected to the yoke by two rubber bushings. Torsion stiffness in the bushings contributes to the vertical spring stiffness of the suspension to a significant amount. As the tolerance of the torsional bushing stiffness is rather wide, the vertical spring stiffness will vary making the car difficult to calibrate. The bushings are also less convenient to assemble compared to conventional ball joints.

6 Analysis

There are mainly three different suspensions of Hi-Per design available on the market today, of which one is available within Saab. This section will analyse these three designs to get a better understanding of how the concept would work for the new Hi-Per design. This includes a general analysis of function, packaging and kinematics in the interface of the base MacPherson vehicle.

6.1 Saab High Performance Strut

Saab 9-5 of today, are available with two types of suspensions, of whom one is a Hi-Per design. This Hi-Per design is developed by the companies of GM and can be found in vehicle models by Saab, Opel and Buick. Significant for the Saab Hi-Per design is the connection between the yoke and the control arm, consisting of two paired rubber bushings. Of these bushings one is considerably stiffer than the other, acting as the point of rotation similar to the ball joint of an ordinary control arm. The other bushing acts as a third supporting point of the yoke and stops the yoke from rotating. There are two main disadvantages in the use of rubber bushings at this mounting point. One is the space needed for two bushings and this forces a large clearance between brake disc, rim and the rubber joints. This offset is primarily necessary to allow for steering motion of the wheel. The second issue is the amount of vertical stiffness added by the torsion of the rubber bushings. A pre-analysis shows that out of the total vertical stiffness 1/3 comes from the torsion of these bushings. Since the bushings has larger stiffness tolerances than the steel springs, this results in a considerable variation of vertical stiffness in finalized vehicles, leading to inaccurate calibration while testing[1].

Yoke, control arm and steering knuckle is made out of aluminium in the Saab Hi-Per solution as this reduces the overall weight of the suspension. The yoke is connected to the damper strut clamped around the damper tube. As the depth of the clamping is deeper than the by a workshop utilized compression of the damper and spring unit, it is hard to separate the yoke and damper mounted on the car. The serviceability of the Saab Hi-Per is worse compared to the McPhersson strut with increased service costs as a result. At the upper knuckle ball joint, there is a camber adjuster using an eccentric washer and screw moving the ball joint in lateral direction. This solution makes it possible to set the camber angle on a finalized car and cover production tolerances.

Implementing the current Saab Hi-Per geometry in the base MacPherson vehicle, results in a number of issues, of many are linked to the discussion above. Trying to work with commonality to the Saab Hi-Per in production today and carry over the control arm from the Saab 9-5, results in a relatively short control arm in comparison to the space available for the suspension. Multi body simulations of the suspension system with this control arm results in poor ride steer characteristics and a large roll centre height variation, both out of design tolerances. A possible change is to design a longer control arm that improves these characteristics, but unfortunately it cannot be extended enough as the package space of the two bushings is a limiting factor. Ride steer characteristics may be improved by changing the position of the track rod. Anyhow these changes are limited as the steering rack position is one of the shared geometrical interfaces with the base MacPherson vehicle hindering any vertical or longitudinal movements of the steering rack.

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[1] Calculations performed by Henrik Hägglund, Saab Chassis dep.

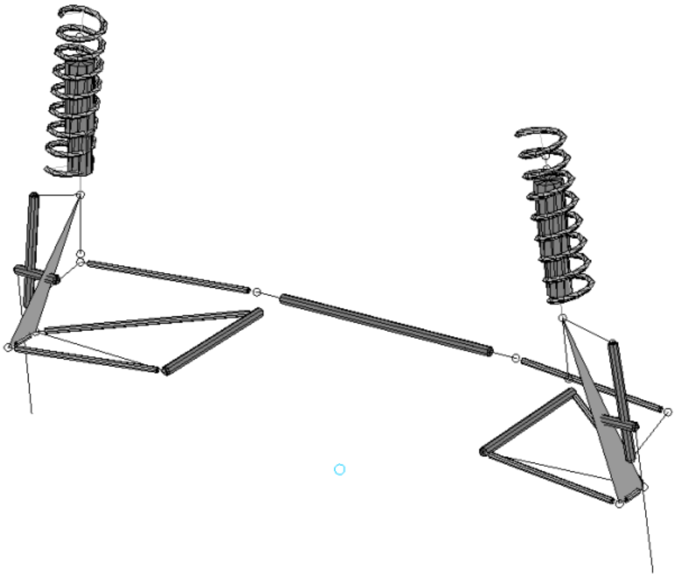

Figure 6.1 Saab Hi-Per Multi body model

The current Saab Hi-Per suspension suffers from several packaging issues if implemented in the new vehicle environment. The first occurs during steering when the brake shield approaches the bushings of the yoke to the control arm. The second area of concern is the lower knuckle joint. The joint consists of a plain spherical bearing with an additional socket in the shape of a tube mounted axially in the bearing. A spigot with splines is pressed into the lower bearing. This spigot is attached in both the upper and lower end to the knuckle. This solution requires relatively much space in vertical direction and aggravates the design of the control arm beneath the joint. The third issue is the yoke. Since this is a front wheel driven car there has to be space available for a drive shaft through the yoke. This space must allow for clearance during steering, bump and rebound. There must also be clearance on the outside of the yoke due to the brake calliper which demands space during steering.

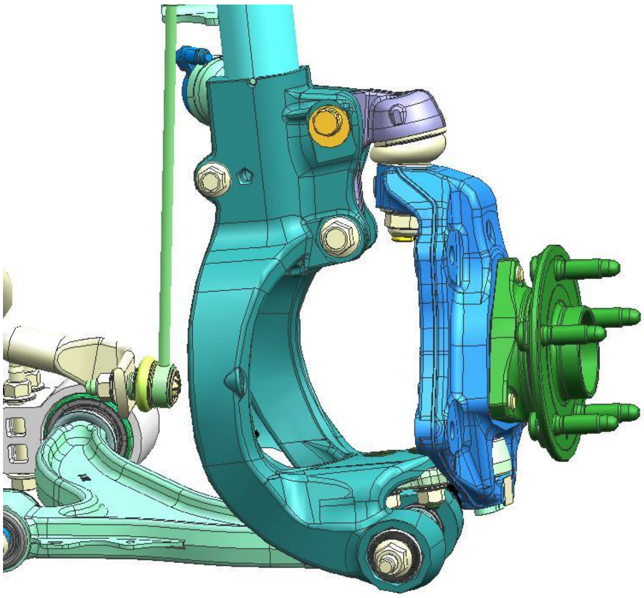

Figure 6.2 Saab Hi-Per assembly

6.2 Ford Revoknuckle

Ford Revoknuckle is another Hi-Per design available in performance versions of Ford Focus. Similar to the Saab 9-5, Ford Focus is also available in two suspension designs sharing the same interface. In the Revoknuckle design the same control arm as for a MacPherson suspension is used. This means that the yoke is connected to the control arm in a ball joint and needs an extra connection to prevent the yoke from turning. Specific for the Revoknuckle design is that this function is performed by the anti-roll bar and the anti-roll bar is therefore a load carrying member to the suspension instead of adding roll stiffness only. An anti-roll bar that operates under these conditions must be significantly redesigned to cope with the two different load curves. At the same time tuning the vehicle will be more complex.

As the anti-roll bar is mounted directly to the yoke, it will be the rotation of the anti-roll bar that determines the rotation of the yoke and damper strut. The anti-roll bar therefore effect ride steer of the wheel and suspension. Trying to fit this concept to the suspension of the base MacPherson vehicle, the connection to the yoke will be a design issue. Mounting the point on the rear most part of the yoke will result in an anti-roll bar lever arm of similar size as for the base vehicle reducing the loads applied by the yoke in the anti-roll bar. The torsion of the anti-roll bar increases and with the short lever arm the geometry becomes self-locking in the end of the vertical suspension deflection. This short anti-roll bar also adds a significant change of ride steer, and is by these reasons not possible to implement to the base MacPherson vehicle in order to meet the boundary conditions.

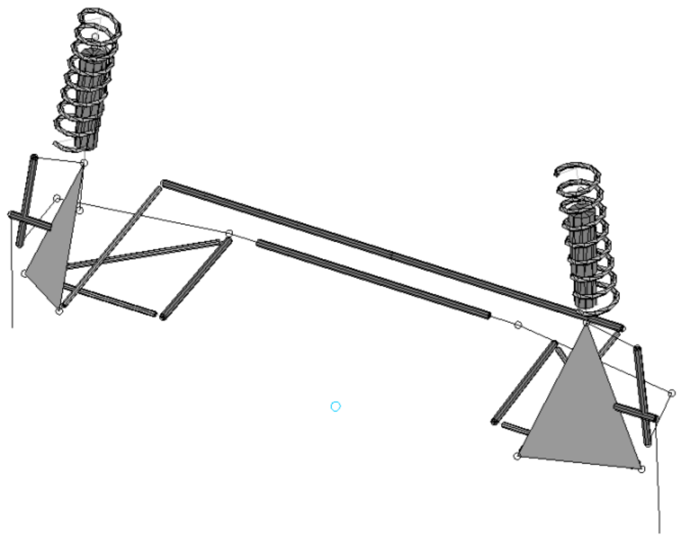

Figure 6.3 Ford Revoknuckle Multi body model

Mounting the point in the foremost part of the yoke, as it is done in the Revoknuckle design, reduces ride steer change due to a longer anti-roll bar lever arm. It will result in larger forces and torques in the anti-roll bar at the same time as the packaging space for an anti-roll bar crossing the driveshaft is limited. Choosing this concept for the base vehicle will result in mayor changes to the anti-roll bar, at the same time as ride steer requirements of the Hi-Per version are still not met, see Figure 6.4.

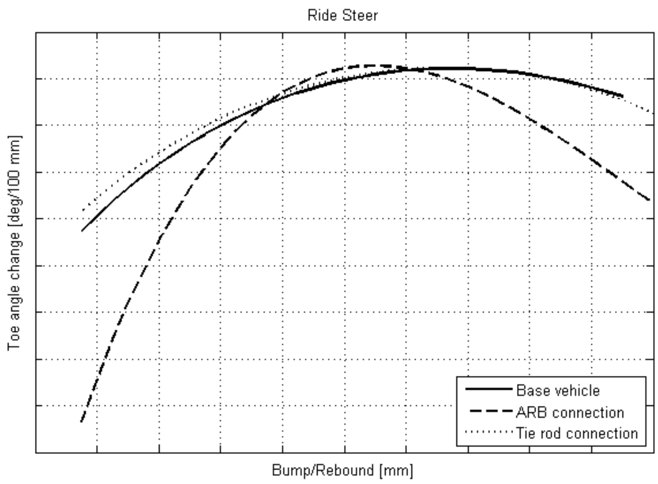

Figure 6.4 Ride steer characteristics

6.3 Renault Double Axis

A third Hi-Per concept is the Renault Double axis available in RS versions of Renault Megane and Clio. The Double axis system is similar to the Revoknuckle design, with the difference in yoke stabilization and the knuckle joints. The bearing of the Revoknuckle design is changed to a ball joint. The outer ball joint of the control arm is mounted horizontal rather than vertical. This gives additional space for packaging the yoke at the same time as lubrication is improved due to a rotation of the ball joint rather than an angular tilt.

Using a ball joint as the outer connection of the control arm, forces a stabilizing link to the yoke. In the Double axis solution this is performed by adding an extra link between the yoke and control arm, see Figure 6.5. This link is attached in the control arm rather than the frame, which will decrease ride steer effects at the same time as the link can be designed relatively short. A disadvantage is that the extra linkage including joints increases the cost of the suspension system. In order to mount the knuckle to the yoke, with its twin ball joints, the lower part is split in two pieces that is bolted together.

Multi body simulations of this concept adapted to the MacPherson base vehicle shows some advantages. By adjusting the added link and its attachment to the yoke it is possible to change the rotation of the yoke with more freedom. This also means that ride steer characteristics are improved compared to the Ford Revoknuckle concept, see Figure 6.4, at the same time as the effect on steering of the knuckle is smaller. The packaging of this concept is a bit tricky, as the added link needs clearance to the control arm at the same time as the space to attach the link in the yoke is limited. Both the Double axis and the Revoknuckle concept would use the same control arm as the available base MacPherson vehicle out of this scenario. This will limit the lower position of the roll centre height due to packaging space in the yoke and its connection to the knuckle.

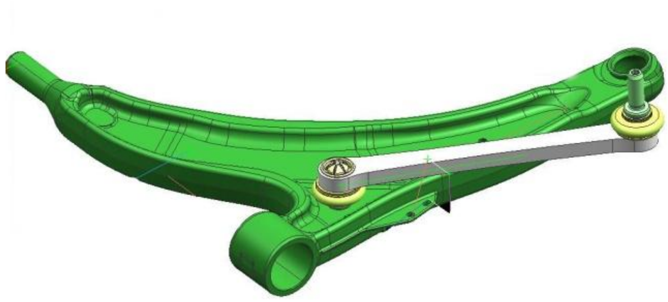

Figure 6.5 Double Axis control arm concept with added tie rod

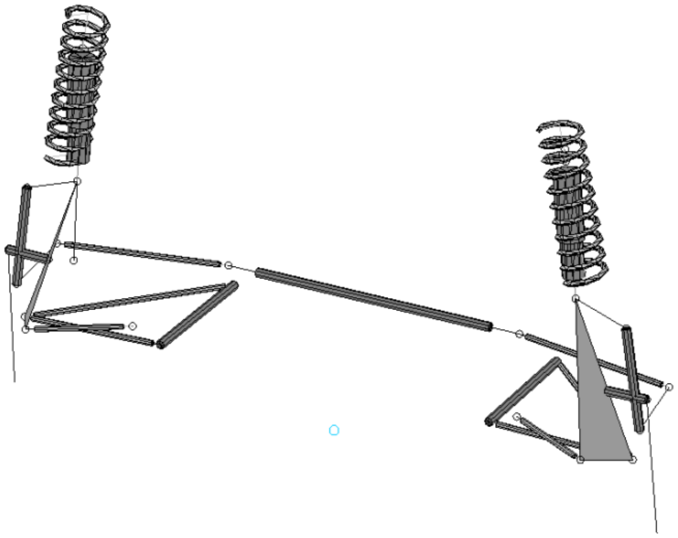

Figure 6.6 Renault Double Axis Multi body model

7 Design solutions

Design variants of the Hi-Per suspension will be split into two different areas; the damper to yoke connection and the control arm to yoke connection. In this way it is easier to combine various concepts and ideas from different designs in order to form the best solution possible for the target vehicles.

7.1 Strut to yoke connection

7.1.1 Clevis bracket connection

This solution uses the same strut connection as the knuckle of the base MacPherson vehicle. In a Hi-Per suspension it will be the yoke that is connected to the damper as the knuckle connects to the yoke, see Figure 7.1. It is therefore possible to carry over the damper strut from the base vehicle and save the cost of new tools and manufacturing. The main issue is the packaging of this solution. The yoke must implement the upper knuckle ball joint in the same packaging space as the damper is mounted, at the same time as the connection to the control arm will pass close to the knuckle and driveshaft. Especially the space between the damper and the driveshaft is limited and will result in a very thin volume where the risks of high material stresses are significant.

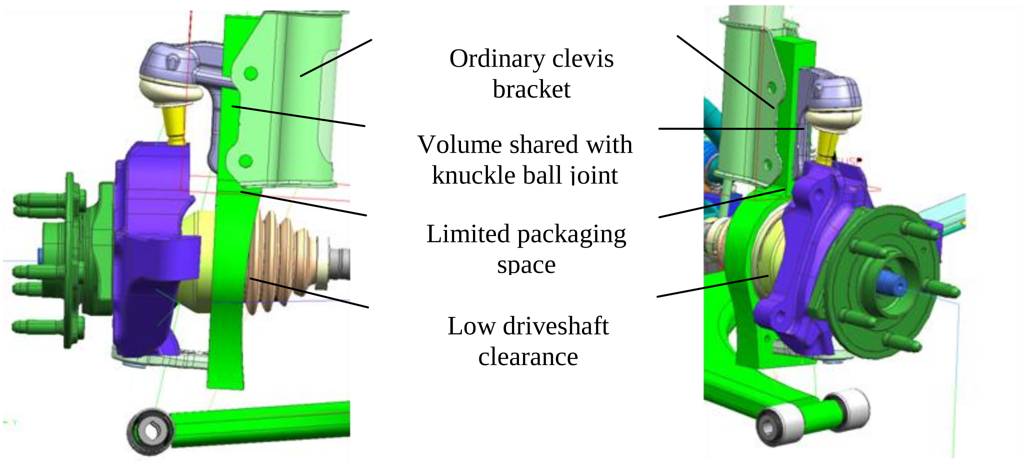

Figure 7.1 Clevis bracket connection

7.1.2 Double clevis bracket connection

A variant of the single clevis bracket connection is the double clevis bracket connection. This uses a similar damper strut attachment with the difference of one bolted joint on both inside and outside of the damper strut, se Figure 7.2. With this solution the yoke and knuckle upper ball joint will be using separate attachments to the strut and the packaging collision is avoided. This solution also offer sufficient packaging space of the yoke to the driveshaft as the yoke will cross the driveshaft on the inside of the CV-joint.

A downside of this concept is the inclination of the yoke due to the large offset between the bolted connection and the knuckle. This will increase bending moments in the yoke and the stresses will be high. Two bolted connections that rely on friction will increase the risk of slip unfavourable for the alignment of the suspension.

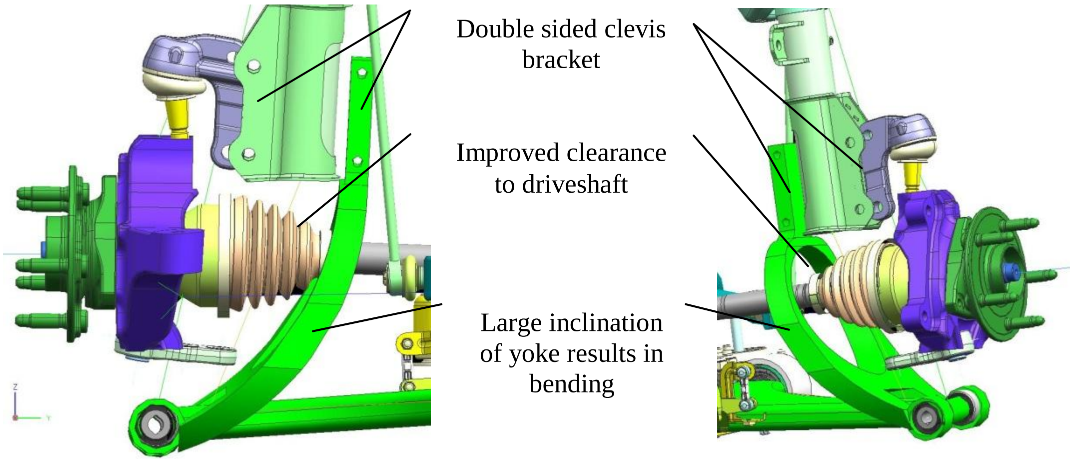

Figure 7.2 Double clevis bracket connection

7.1.3 Parallel bolted connection between yoke and damper

A final concept of the strut connection is named the parallel bolted connection and is a variant of a bolted joint described earlier.

For this concept the upper knuckle ball joint is mounted directly in the yoke with no interaction with the damper strut, improving packaging space and assembling.

A detailed description of the parallel bolted joint connection can be found in the internal report (A Johansson & P Roubert, Saab Automobile, 2011) due to confidentiality.

7.2 Control arm to yoke connection

7.2.1 Ball joint connection

Similar to the knuckle of a steered MacPherson suspension the yoke can be connected to the control arm via a single ball joint. This also gives the possibility to use the same control arm as for the base vehicle saving cost and improve the level of commonality. Using a single ball joint together with the strut mount, forces the need of a third support for the yoke. This support can be designed differently, see Section 6.2 and 6.3, but is necessary to control the motion of the yoke. An added linkage for the support increases the cost of the system and must be considered in this design. A ball joint provides no stiffness to the system for angular tilt, as the ball joint is free to rotate around all axes. It is on the other hand locked in translation and provides a stiff joint to applied loads in the ball centre. Ball joints in initial rotation provide an amount of stick slip friction damping to the system, seen in both MacPherson suspensions and Hi-Per variants.

Ball joints are more expensive than rubber bushings and will increase the cost of the system, but have some advantages in the function discussed above. Another problem with ball joints is the sensitivity to wear and vibrations due to the rigid design and no rubber isolators. This may increase the level of noise from frequent vibrations, but is at the same time similar to the design of the base MacPherson suspension of today.

7.2.2 Bushing connection

A second alternative for the connection is the use of rubber bushings, either as one wide bushing or two bushings mounted in pair as for the Saab Hi-Per design. In this way the need for a controlling link can be eliminated and the cost is thereby reduced. Rubber bushings are also cheaper than ball joints.

From a packaging and kinematic point of view rubber bushings are unfavourable. Paired bushings in the yoke or in the control arm leaves little clearance for the steered wheel rim and brake disc forcing the control arm to be considerably shorter. A short control arm has primarily a negative effect on ride steer and ride camber change as well as roll centre variation and change of track width. Especially roll centre variation will be an issue as the Hi-Per design is targeted for vehicles of various heights and the roll centre will therefore vary to a large extent between different models.

Bushings are not as easy to assemble as ball joints. The reason for this is the tolerances of the yoke and the bushings, designed by different suppliers, and the press fit varies for each part. Some bushings can therefore not be positioned correctly and the alignment towards the yoke might be wrong.

The main disadvantage of using bushings for the control arm connection is the torsion stiffness that adds to the vertical stiffness of the suspension. This contribution has proven to be a large part of the ride rate at the same time as the tolerance span of torsion in the bushings is wide. The ride rate from one car to another can therefore vary significantly making coil spring tuning difficult. Desirable is to focus the ride rate to the coil spring as this is easy to define and can be manufactured with high accuracy.

8 Selection of concept and design considerations

This chapter will focus on the selected sub concepts for the new Hi-Per design, as well as why the other concepts are not chosen. It is the selected sub concepts that together will be apparent in the new Hi-Per design and form the final solution. The selected concepts are chosen to work together and a large effort will be put in combining the concepts to the final Hi-Per design.

8.1 Strut to yoke connection

From the various types of damper connections available one is selected and used for the Hi-Per concept. The Saab Hi-Per with a clamped connection is considered as a reference. This solution can be studied in detail and is available within Saab today.

Alternative concepts are at first the single sided clevis bracket connection described in Section 7.1.1. This solution has some major packaging issues as it combines the connection of the damper with the upper knuckle ball joint, at the same time as it uses the space between the damper and driveshaft to connect further down the control arm. The double sided clevis bracket connection of Section 7.1.2 solves some of the packaging issues with the single sided clevis bracket connection. This is anyhow done by the cost of a double sided damper joint where the risk of slip is extensive and assembly more time consuming. A yoke of this design needs some extensive design work in order to fulfil strength and stiffness requirements.

The last concept is the parallel bolted damper connection described in Section 7.1.3. This concept solves the disassembly problem since it is easy to separate from the damper strut by releasing the screws of the joint.

Considering the advantages and disadvantages of each concept, the parallel bolted joint is chosen as the best choice for the new Hi-Per solution.

Table 8.1 Concept selection of damper connection

SAAB Automobile	*Pughmatrix:* HiPer Concept selection - Yoke to damper connection							
Anders Johansson & Peter Roubert								
		Concepts Grades -3 to 3						
Criteria	***Weight Factor 1-3***	Reference	A		B		C	
Packaging	3	0	-3	-9	1	3	0	0
Number of added parts	1	0	-1	-1	-1	-1	-1	-1
Modularity	2	0	-2	-4	0	0	0	0
Design for strength	2	0	-3	-6	-1	-2	0	0
Cost	3	0	1	3	0	0	1	3
Assembly	1	0	0	0	0	0	1	1
Weight	2	0	1	2	1	2	0	0
Maintenance, serviceability	3	0	2	6	2	6	3	9
Durability and reliability	3	0	-1	-3	-1	-3	0	0
End of lifecycle, material scrapped or reused	1	0	0	0	0	0	0	0
		0		0		0		0
Number of positives +		0	11		11		13	
Number of equals 0		11	3		5		7	
Number of negatives -		0	-23		-6		-1	
Sum of grades		0	-12		5		12	
Rank		3	4		2		1	
Further development for Pugh 2 (YES/NO)								
Decision	Solution C will be used as primary selected concept							

Concepts	*Name/Status*
SAAB 650 HiPer, clamped to damper	Reference
McPhers clevis bracket	A
Double sided clevis bracket connection	B
Parallel bolted connection	C

8.2 Outer control arm joint and yoke control

The considered ways of connecting the yoke to the control arm is either two paired bushings or one ball joint with an added stabilizer. Bushings are, as mentioned in Section 7.2.2, large in size and add a significant amount of parasitic stiffness to the system. The packaging space will make a redesigned control arm necessary and thus increasing the cost.

Using a ball joint as the connection to the control arm reduces the amount of parasitic stiffness as ball joints are free to move in rotation. As mentioned in Section 7.2.1 a single ball joint connection does need an extra linkage to control the rotation of the yoke, either as using the anti-roll bar or with an added link. A ball joint will also provide more clearance to the brake disc as the wheel is steered.

A third considered solution is the use of one single bushing instead of two as for the SAAB Hi-Per solution. This could improve the cost and packaging of the area.

The concept selection can be found in *Table* 8.2.

Table 8.2 Concept selection of control arm selection

SAAB Automobile	***Pughmatrix:*** **HiPer Concept selection - Yoke to wishbone connection**							
Anders Johansson & Peter Roubert								
Criteria	***Weight Factor 1-3***	***Concepts Grades -3 to 3***						
		Reference	A		B			
Packaging	2	0	2	4	-1	-2		
Parasitic spring stiffness	2	0	1	2	3	6		
Number of added parts	1	0	1	1	2	2		
Modularity	2	0	0	0	2	4		
Design for strength	2	0	-3	-6	-1	-2		
Cost	3	0	1	3	0	0		
Assembly	1	0	1	1	2	2		
Weight	2	0	0	0	0	0		
Maintenance, serviceability	3	0	1	3	2	6		
Durability and reliability	3	0	-2	-6	-2	-6		
End of lifecycle, material scrapped or reused	1	0	0	0	1	1		
		0		0		0		
Number of positives +		0	14		21			
Number of equals 0		12	4		3			
Number of negatives -		0	-12		-10			
Sum of grades		0	2		11			
Rank		3	2		1			
Further development for Pugh 2 (YES/NO)								
Decision	Ball joint							

Concepts	***Name/Status***
GM 650 HiPer, double bushes	Reference
Single Rubber bush in wishbone	A
Ball joint with yoke stabilizer	B

8.3 Bearing types and joints

A suspension design is built up by several components that all determines the motion of each part. Selecting these joints is crucial for the suspension to work as intended and to cope with suspension loads applied. The first focus is the control arm and the design choice for the yoke connection. By use of a ball joint, the control arm from the base MacPherson vehicle can be used. This means that the control arm is connected with the subframe by two rubber bushings isolating the vibrations.

The top mount of the damper in the MacPherson suspension is a ball bearing that rotates as the strut is steered. For the Hi-Per suspension on the other hand the strut is almost stationary and will only rotate due to the motion incorporated by the suspension links during bump travel. These rotations are small and can be taken as a deflection in a rubber bushing rather than the need of a ball bearing. Using a rubber bushing at the top mount will also reduce the cost compared to a bearing, at the same time as the reliability is improved.

Especially important for the Hi-Per design is the bearings for the knuckle and how it is mounted to the yoke. It is these two joints that decides the kingpin axis of the suspension and is therefore important for the steering geometry of the concept. The upper knuckle bearing will be of a similar design as in the case of the Saab Hi-Per concept. This means a ball joint bolted to the yoke with an added camber adjuster. The reason to use a ball joint is that it is free to rotate during steering motion while still being free for camber alignment. It will also take up a significant amount of vertical load from the wheel, as it is fixed in translation and supports high static loads. The camber adjuster will be used to compensate for misalignment during vehicle assembly to meet requirements of static camber. Using the existing ball joint of the Saab Hi-Per will also be in line with the requisite of using already available components from the production of today's vehicles, saving some cost.

For the lower knuckle bearing there are mainly two ways to go. Packaging space is limited, especially towards the outer ball joint of the control arm. Either design will be press fit from one direction only, in distinction to the Saab Hi-Per, for necessary clearance. The two bearing variants must support radial loads only, as axial loads (vertical loads in car) will be located to the upper ball joint only. At the same time the bearing must be insensitive to misalignment induced by camber adjustments or production tolerances.

The two designs considered is either a plain spherical bearing or a SKF CARB® toroidal roller bearing. Both are free with the respect to misalignment and axial play (for this application), but supports high radial loads. A plain spherical bearing is relatively simple but the mount will be designed especially for this application. Using the spherical bearing of the available Saab Hi-Per design does not fit in the packaging space of the new Hi-Per design. A disadvantage of the spherical bearing is the amount of added friction to the steering motion, which might have a negative effect on steering feel.

Using a toroidal roller bearing will reduce the friction of this joint significantly and will be easier to package due to its compact design. The toroidal bearing will be more expensive than the spherical bearing, but the reduced friction is a great advantage.

Competing solutions that use a toroidal roller bearing are proven to have significant wear problems and low reliability. The major reason to this problem is yet to be determined, and SKF works on a solution to the problem. Possible reasons are environmental factors and sealing problems, or brinelling due to the short rotational motion or vibrant loads. If the reasons for significant wear can be solved this will be the most suitable choice for the Hi-Per design. Until then a plain spherical bearing will be used. To make it suitable for the Hi-Per concept the bearing design from the current Saab Hi-Per must be changed in order to fit the available packaging space.

8.4 Changes for crossover and sport compared to the standard vehicle

As mentioned earlier the suspension design will be applicable to three different vehicles with different ride height. This means that the initial position of the suspension must be changed affecting the initial operating conditions of the suspension. At the same time the freedom of change is limited and no or few parts should be replaced between model variants according to the prerequisites of the design work. The sport chassis model is lowered 10 mm and the effect of the suspension is within the limits of the design parameters only requesting some minor changes of static camber and static toe. For the crossover vehicle the case is a little different. This vehicle will be raised 30 mm compared to the standard vehicle. This will do some major changes and a few compromises have to be done keeping the components unchanged.

Most apparent for this vehicle is the change of static camber and static toe, similar to the case of the sport vehicle but to a larger extent. It is also these parameters that are the most easy to adjust. The static camber can be changed by the built in camber adjuster at the upper knuckle ball joint meeting the same tolerances as for the standard vehicle. Static toe can be changed by the length of the track rod that is threaded and easy to tune.

The decreased wheelbase of the crossover compared to the standard vehicle also means some changes to the steering geometry of the vehicle. Most significantly is the percentage of Ackermann and the turning circle diameter. The Ackermann will be decreased slightly and is therefore a little less than the standard vehicle at the same time as the turning circle diameter is decreased. It can therefore be seen as give and take where the turning circle is improved to the cost of a small change in Ackermann.

As many other changes the ride steer and ride steer change are affected by the ride height of the crossover vehicle. It is therefore recommended to change the track rod with the inner ball joint moved further out the vehicle (laterally). This would improve the ride steer change and lower the ride steer at design load. Low ride steer is often most desirable (Milliken & Milliken, 1995).

Another change is the roll centre height of the crossover vehicle. This will be changed from 69 mm in the standard vehicle to 150 mm in the crossover vehicle being above the target of the prerequisites formed for this project. Anyhow compared to competitor vehicle this is still a reasonable height. What makes this height unsuitable is the rear roll centre height that adjusted for the crossover vehicle is in the same level as for the front. Desirable is therefore to have a decrease of roll centre height at the front for lateral load transfer and stable understeer while cornering (Gillespie, 1992). Roll centre height may be changed lowering the inner pivots of the control arm, changing the interface from the base MacPherson vehicle. Investigations of these changes are left out of this thesis as it does not comply with the prerequisite of equal interface, but will be recommended for further development.

9 Results and Discussion

9.1 Final design and geometry

The final design is the result of a comprehensive benchmarking and simulation process. The design was chosen since it was actually the only who fulfilled all of the prerequisites. The combination of components common with the previous platform, reduction of parasitic stiffness, clearance during steering and static design factors resulted in a solution which became a combination of several designs from the benchmark. The resulting concept is presented in Table 9.1 together with a comparison between the available MacPherson- and the Saab Hi-Per suspension. The concepts are valued with the base factors of commonality, sensitivity to disturbances and modularity known from the prerequisites of this thesis. Valued are also serviceability together with more general factors such as cost and weight of the suggested design.

Table 9.1 Final design comparison

	MacPherson	Saab Hi-Per (REF)	New Hi-Per concept	Comments
Commonality between models	+	0	+ +	Control arm is shared for the MacPherson suspension. New Hi-Per design shares components with both the available MacPherson suspension and the targeted models within this work.
Commonality between left and right side	0	0	+	Yoke and knuckle balljoints are shared in the new Hi-Per concept.
Sensitivity of disturbance including torque steer	- -	0	+	Kingpin offset is 50% larger for MacPherson and 25% less for the new Hi-Per concept.
Serviceability	+ +	0	+ +	All components are easy to separate mounted in the car, for both the MacPherson and the new Hi-Per concept.
Manufacturability	+	0	0	Fewer parts to assemble in the MacPherson suspension.
Cost	+ +	0	+	Fewer parts in the MacPherson suspension. Higher level of commonality in the new Hi-Per design.
Weight	+ +	0	0	Similar components for both the Saab Hi-Per and the new Hi-Per design.

The solution is connected to the strut using a parallel bolted connection described in Section 7.1.3.

The yoke is connected to the ball joint of the existing control arm with a clamping joint. This solution was the only that admits clearance during maximum steering angle. The ball joint of the control arm does not stop the yoke from rotating. Therefore there is a need to lock the yoke. The solution chosen is similar to Renaults Double Axis system which uses a toe link connected between the yoke and control arm. The design consists of two ball joints attached via a tube. This solution prevents the yoke from rotation. The combination of these solutions results in a yoke which is common to both right and left side. The symmetry between left and right side has been achieved by using an outer ball joint in the control arm. This allows for the angle of inclination between the strut and control arm to be cleared by the ball joint.

During the design phase two different control arms has been studied, here called A and B. Control arm A is equipped with a small pocket which is suitable for mounting the toe link. This solution has more clearance to the toe link during bump and rebound than control arm B. It is therefore preferable to use the control arm A. However, it is still possible to use the alternative even though it has decreased clearance between the toe link and control arm.

The upper knuckle bearing is the same ball joint as used in the existing Hi-Per solution. This ball joint is attached in a clamp joint with an asymmetric bolt to allow for camber adjustment.

The lower knuckle bearing was subject to severe design issues. The first design implemented a toroidal roller bearing from SKF. However, there were indications that this solution caused problems due to low life cycles in similar automotive applications. After further investigations the toroidal roller bearing was replaced with a regular spherical plain bearing. Since the lower knuckle bearing must allow some axial displacement the spherical plain bearing had to be mounted in a way which allowed for axial displacement.

In the design the existing control arm is reused but with a hole added. There are somehow a few parts which are new. The brake shield, the yoke, the lower knuckle mount, the knuckle and the tie rod are all new parts. The yoke, the lower knuckle mount and the tie rod are symmetrical and can be used on both right and left side. The brake shield and the knuckle can possibly be symmetrical but this needs further investigation and is not covered in this report.

9.2 Final kinematic results

The final geometry and the kinematics of the suspension are a mix of ideal geometry and packaging, as well as the requirements of similar interface as for the base MacPherson vehicle. The primary results of the suspension kinematics for the standard vehicle can be seen in Appendix A – Suspension kinematics, where the base MacPherson vehicle and the Saab Hi-Per design is plotted together with the new Hi-Per design. Many of the results are similar to the base MacPherson vehicle, as this suspension and the new Hi-Per design are built to the same requirements and design targets. Mayor changes can be seen in the kingpin alignment of the suspension and the by kingpin axis dependent offsets. Changes to the kingpin is one of the largest advantages of the Hi-Per concept and the kingpin offset has here been reduced by 50% compared to the MacPherson strut. Kingpin also effects the scrub radius that is less for both the Saab Hi-Per and the new Hi-Per concept, at the same time as it does not vary as much with bump and rebound travel.

Changes to the Saab Hi-Per is at first toe and ride steer. For the new Hi-Per design the variation of toe is decreased but not as linear as for the Saab Hi-Per. This is verified by the ride steer curve, where the ride steer at design load is lower. The ride steer varies more for the new Hi-Per and the base MacPherson design giving the characteristic toe curve, but as the ride steer values are all lower this is still considered an improvement decreasing the toe variation.

Roll centre height is another parameter changed for the new Hi-Per design, as this was one of the initial prerequisites of the thesis. Compared to the base MacPherson vehicle the roll centre height is increased and varies similar to the base vehicle. Compared to the Saab Hi-Per the roll centre change is decreased, much thanks to the implementation of the longer control arm.

Regarding the steering primarily the amount of Ackermann and minimum turning circle diameter is overseen. Ackermann is increased slightly as the turning circle diameter is decreased for better manoeuvrability in tight turns.

In total the new Hi-Per design does fulfil the requirements set for the base MacPherson vehicle, with a decrease of kingpin offset, as targeted from the beginning of the project.

9.3 Discussion

The prerequisites for this project can be divided in the following areas:

1. Symmetry between left and right side
2. High degree of commonality to existing platform
3. Reduction of parasitic stiffness
4. Maintenance friendly design
5. Static design factors from Saab

The final design has fulfilled all of these areas. All of the competing concepts missed on at least two prerequisites.

The lower knuckle bearing however is subject to severe packaging issues. The solution consists of a standard spherical plain bearing but with a new mount in order to fit the design. The mount however is an easy to fabricate solution which can be used on the different heights with slight adjustment of the hole pattern. This mount is symmetric and can be used on both left and right side.

There has been indications of some designs from the benchmarking process both knuckle bearings have taken axial loads. If this solution can be implemented the design can be simplified. This needs to be further investigated though.

In order to fulfil the static design factors the inner and outer steering joints had to be moved. This calls for a new steering rod since the inner steering ball joint is moved outwards, it might be possible to use an extension. Further investigations are necessary though. The outer ball joint is connected to a mount with a radius which coincides to the inner radius of the wheel. This radius is moved outwards since the steering arm on the knuckle is straightened. The mount does not have clearance issues with the wheel but needs to be reworked to decide whether the mount can be reused.

The parasitic stiffness is of great concern in the solution of today. A ball joint however, does not suffer from parasitic stiffness. The result is a suspension design where only the inner bushings of the control arm contribute with torsional stiffness. A ball joint however suffers from a stick slip effect. This effect causes the ball joint to resist the initiating movement. The effect is only initial and when the ball joint once has started to move the effect can be neglected. One subject that needs further investigation is how a ball joint performs when the rotational movement is less than it is designed for. The outer ball joint in the control arm will only rotate in one direction since the rotational movement normally initiated during steering is not present in this design. A comparison was done with the upper knuckle joint in the existing Saab Hi-Per design, as this ball joint move in a similar manner. Since this ball joint has performed well in fatigue tests, this effect is considered not being a problem. The suspension has been also designed to allow easy access and disassembly. There are two design solutions of big concern in the existing design, the use of spline bolts to prevent slip in joints and the clamping joint between the strut and yoke.

The spline bolts are hard to re-use in their existing hole since it cannot be fitted in exactly the same way from time to time. Therefore the bolt will cut new splines in the hole when reused. The result is a joint where the holes suffer significant wear with severe risk of slip. The new suspension has been designed to avoid this type of bolts. The only joint where these spline bolts might be used has been replaced by a joint with much larger contact surface to avoid slip.

The second area of concern is the clamping joint between the strut and yoke. The clamping length exceeds the total damping length. The strut is hard to remove due to this and therefore the yoke has to be removed before the strut can be removed. The choosen solution admits easy removal and increases the area of friction, thus reducing slip.

The geometry of the suspension has been verified according to a number of set static design factors (SDF). The design factors are all applicable to the base MacPherson vehicle and set the targets of the Hi-Per design as well. No effort has been done to verify or validate these design factors, and they are solely provided by Saab based on years of experience in house.

9.4 Recommendations and future work

The design is only meant to be a principal study of how to design a new Hi-Per strut suspension. Due to this, neither stiffness nor compliance calculations have been performed. The dimension of the existing yoke has been used in order to create a design which is as close to functional as possible. Compliance calculations are therefore left as a recommendation in order to complete the design.

The new Hi-Per design admits using a knuckle which is close to symmetrical. This design can also be stiffer compared to a traditional knuckle. A symmetrical knuckle also has the potential for reduced mass and cost. This design needs further investigation before it can be proven valid..

There is also a need for more specialized engineering work on the ball joints. The ball joints are provided by the German company ZF. During the design phase a ball joint of approximately 20 mm diameter has been used to model the space needed for the toe link.

Further investigations must be done regarding the lower knuckle bearing and the selection of bearing type. Using a toroidal roller bearing will improve packaging and reduce friction in the system. Finding a solution for excessive wear in this kind of bearing and for this kind of application is therefore desirable. The selection of bearing type will also affect the design of the knuckle and the spigot fitted to the inner ring of the bearing. Material selection, seals and packaging space will be crucial designing the lower bearing joint.

For the Hi-Per project the focus has been to validate the kinematic factors of steering geometry and wheel alignment during steer- and bump travel. This is due to the early development phase of the projects, and these can be considered the first steps. Next in line is to investigate elastokinematic behaviour with respect to deformation of components and bushing stiffness optimization. The Hi-Per design as presented in this thesis fulfils the static requirements of the base MacPherson vehicle. Improvements that are desirable are a flatter ride steer curve for linear toe angle change during bump travel. Ride camber can be investigated further as well as methods of improving the roll centre height, especially to the crossover chassis.

Further work on dynamic behaviour, strength and fatigue calculations, cost and weight optimization are activities needed

10 References

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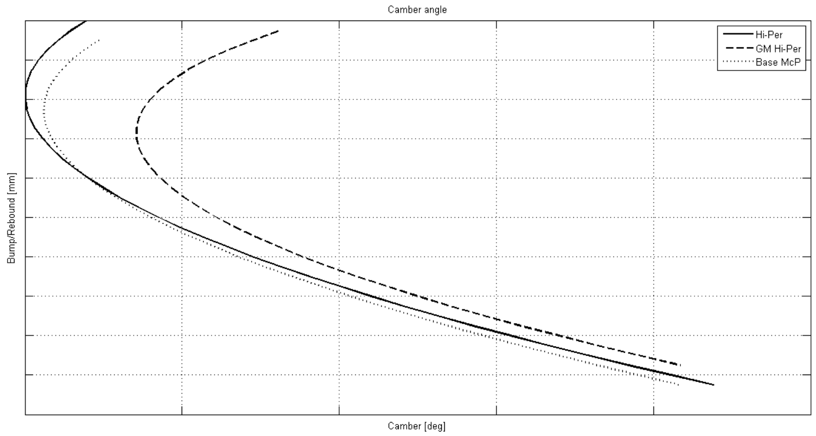
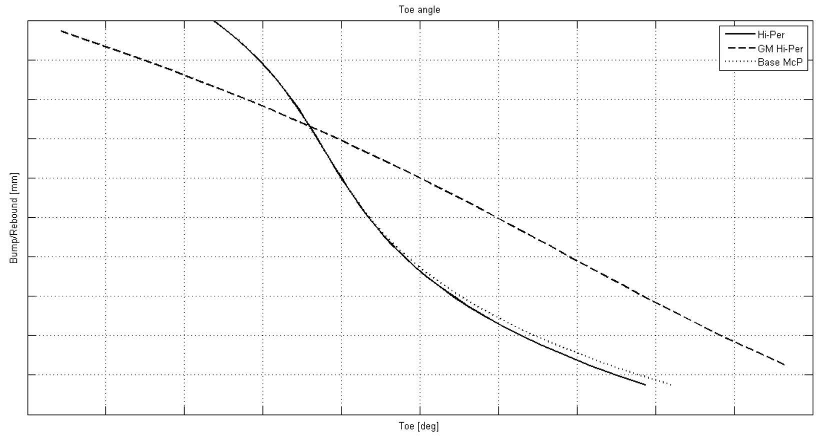
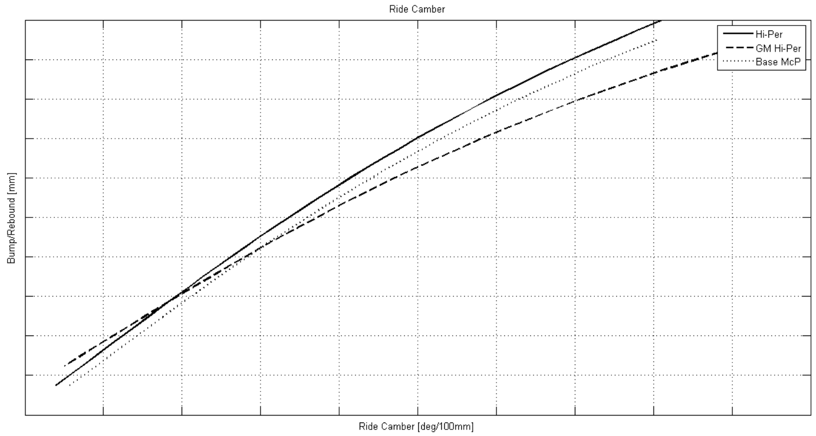
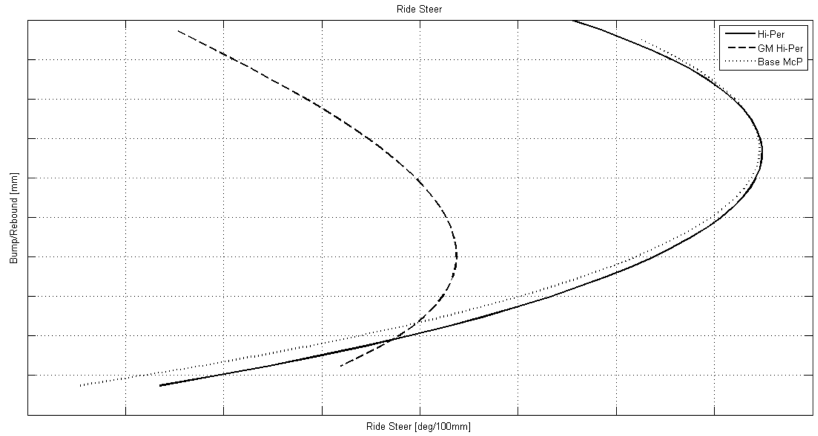
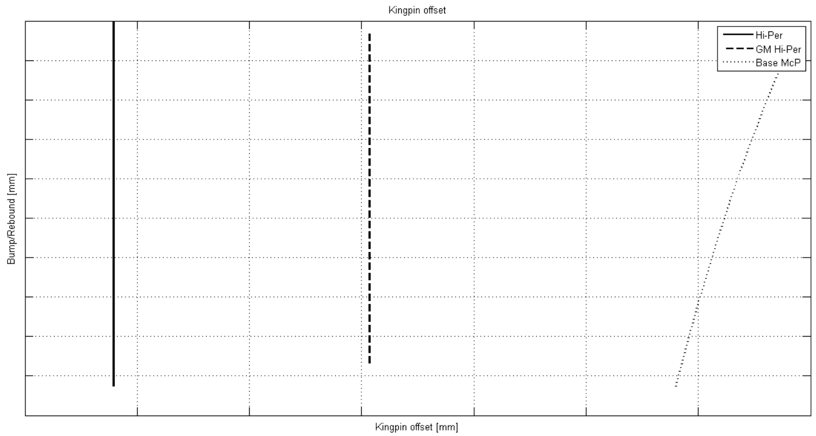
Appendix A – Suspension kinematics

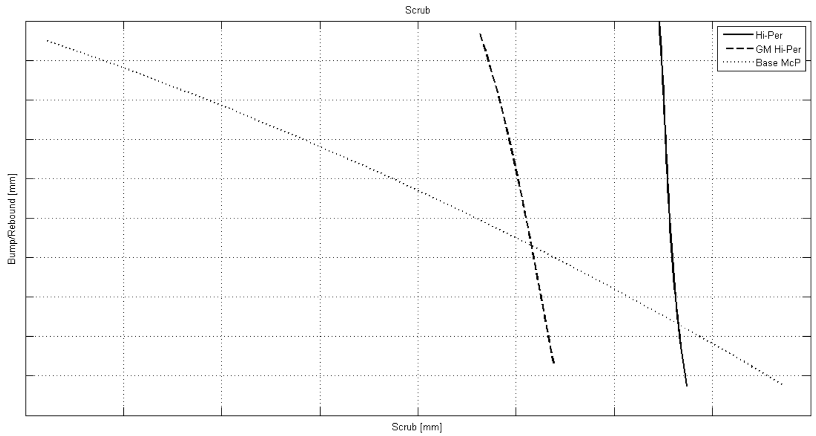


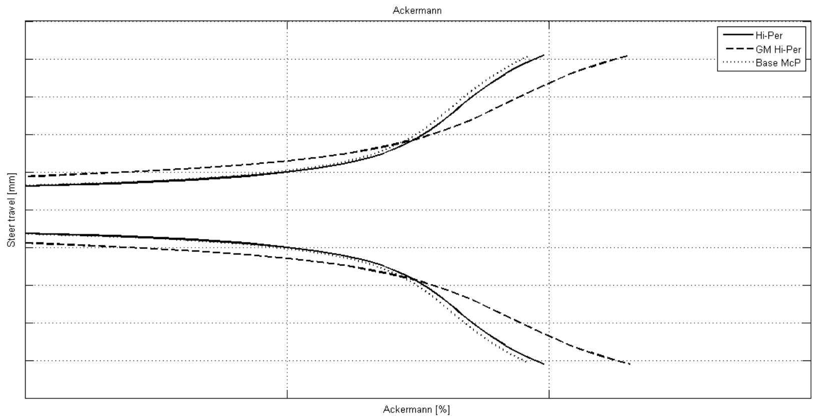


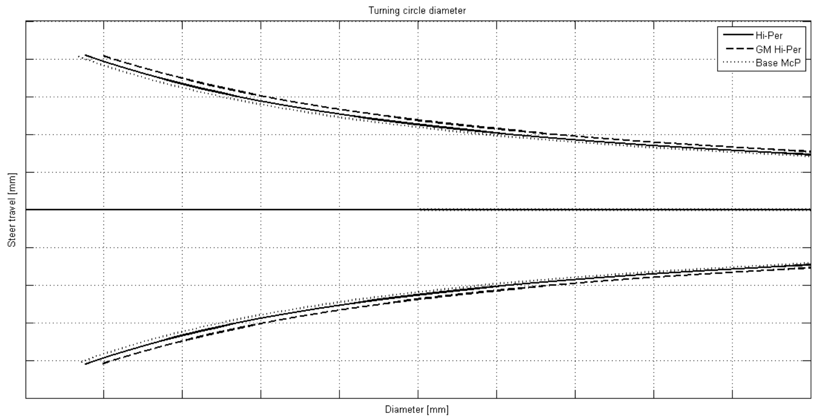





Kingpin offset
Hi-Per
GM Hi-Per
Base McP
Bump/Rebound [mm]
Kingpin offset [mm]


Scrub
Hi-Per
GM Hi-Per
Base McP
Bump/Rebound [mm]
Scrub [mm]


Ackermann
Hi-Per
GM Hi-Per
Base McP
Steer travel [mm]
Ackermann [%]


Turning circle diameter
Hi-Per
GM Hi-Per
Base McP
Steer travel [mm]
Diameter [mm]