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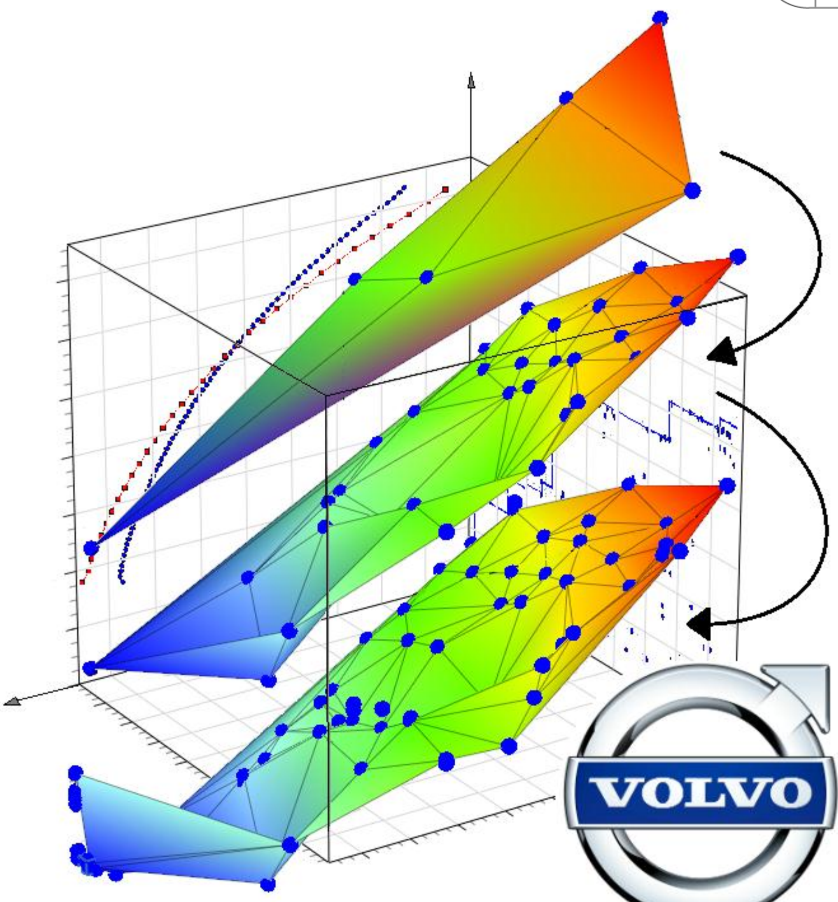

Using optimization to auto-correlate suspension characteristics to K&C measurements

A study in cooperation with Volvo Car Corporation

Master's Thesis in the Automotive Engineering Programme

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Department of Applied Mechanics
Division of Vehicle Engineering and Autonomous Systems
Vehicle Dynamics Group
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2013
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Cover:
Continuous exploration of the design space and optimization of a response based on two design variables.

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ABSTRACT

Computer aided engineering is becoming an increasingly important tool in the automotive industry since it can reduce development time of new vehicles. However, in order to draw the same conclusions from test and simulation results it is important that the behaviour and characteristics of a simulation model match test data. Traditionally, to ensure that a suspension simulation model is accurate, it is correlated by a manual adjustment of the parameters in the model. This is time-consuming and error-prone. By automating the correlation process using a suitable optimization technique and a properly defined procedure, the process can be performed faster and the quality of the results can be improved since more parameters and objectives can be included. The aim of this study was to develop a well-defined correlation procedure, with minimal user input, that optimizes parameters in a suspension model so the behaviour of the model matches test data. A design of experiment study was conducted to analyse the influence of suspension parameters on corresponding suspension characteristics, and based on this a suitable correlation method and optimization model setup could be defined. By running the correlation procedure in the optimization software HEEDS MDO, connected with ADAMS/Car, suspension characteristics could be correlated to measurement data. The defined auto-correlation procedure was found to be effective and a front suspension assembly was successfully correlated to physical kinematics and compliance measurement results. However, the baseline suspension model has to be modelled correctly and include all the necessary variables in order to fully correlate the suspension simulation model. Some of the correlated suspension parameters were found to have optimized values outside normal production tolerances, in order to compensate for limitations in the simulation model, such as rigid modelling of components. By using the defined auto-correlation procedure, the correlation time was reduced and it is recommended that HEEDS MDO is used for future correlation of suspension assemblies. If the setup of the optimization model is adjusted, the defined correlation procedure can also be used to create suspension simulation models of competitor vehicles or optimizing suspension design concepts to meet requirements.

Key words: Vehicle dynamics, Auto-correlation, Optimization, K&C measurements, Suspension characteristics, ADAMS/Car, HEEDS®

Användning av optimering för att auto-korrelera hjulupphängningskaraktäristik mot mätdata
En studie i samarbete med Volvo Cars
Examensarbete inom fordonsteknik
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Avdelningen för fordonsteknik och autonoma system
Fordonsdynamiksgruppen
Chalmers tekniska högskola

SAMMANFATTNING

Datorstödd konstruktion blir ett allt viktigare verktyg inom fordonsindustrin då det kan reducera utvecklingstiden för nya fordon. För att dra samma slutsatser från fysiska prov och simuleringsresultat är det viktigt att simuleringsmodellens uppförande och egenskaper matchar testdata. För att säkerställa att en hjulupphängningsmodell är tillräckligt noggrann korreleras den traditionellt sett genom en manuell justering av parametrarna i modellen, vilket är tidsödande och felbenäget. Genom att automatisera korreleringsprocessen genom att använda en passande optimeringsteknik och ett väl avvägt tillvägagångssätt, kan processen utföras snabbare och kvalitén på resultatet kan förbättras eftersom fler parameterar och målvärden kan inkluderas. Målet med den här studien var att utveckla en väldefinierad korreleringsprocedur, med minimalt input från användaren, som optimerar parametrarna i en simuleringsmodell av en hjulupphängning. En känslighetsanalys genomfördes för att studera parametrarnas inflytande på hjulupphängningens egenskaper, och baserat på denna kunde en passande metod och optimerings-konfiguration definieras. Genom att köra korreleringsproceduren i optimerings-programmet HEEDS MDO, i anslutning till ADAMS/Car, kunde hjulupphängningens egenskaper korreleras mot chassimätdata. Den definierade proceduren visade sig vara effektiv och en modell av en framvagnshjulupphängning korrelerades framgångsrikt mot resultat från fysiska mätningar. Dock måste grundmodellen av hjulupphängningen vara korrekt modellerad och inkludera alla de nödvändiga variablerna för att möjliggöra en fullständig korrelering av simuleringsmodellen. Några av de korrelerade hjulupphängningsparametrarna visade sig ha optimala värden utanför de normala produktionstoleranserna. Detta för att kunna kompensera för begränsningar i simuleringsmodellen, så som stelkroppsmodellering av komponenter. Genom att använda den definierade korreleringsproceduren kunde korrelering utföras fortare och det rekommenderas att HEEDS MDO används för framtida korrelering av hjulupphängningsmodeller. Om konfigurationen för optimeringsmodellen justeras kan den definierade korreleringsproceduren användas för att skapa hjulupphängnings-modeller av konkurrenters fordon eller för att optimera hjulupphängningskoncept så att de uppfyller kravspecifikationen.

Nyckelord: Fordonsdynamik, auto-korrelering, optimering, chassimätdata, hjulupphängning, HEEDS®

Contents

Preface

This thesis work has been conducted as a partial fulfilment of the requirements for the Master of Science degree in Automotive Engineering at Chalmers University of Technology, Sweden. In this study optimization software has been used to auto-correlate the suspension characteristics of a vehicle simulation model to kinematics and compliances measured in a physical vehicle. This study has been performed from January 2013 to June 2013 and is a part of the long term goal, to lower the development time for new vehicles. All activities were performed at the CAE Vehicle Dynamics division, Volvo Car Corporation, Sweden.

The work has been carried out with Sérgio da Silva and David Fredriksson as supervisors. I would like to thank them for their guidance and support, which have been essential for the study and my personal development. I would also like to thank my colleagues at the CAE Vehicle Dynamics & Active Safety group, and especially Max Boerboom, for encouragement and kindness throughout the project. It has been a pleasure to work with all of you.

Special mentions should go to my examiner Mathias Lidberg who inspired me to a future career within vehicle dynamics. Finally, it should be noted that the continuous generosity and encouragement from Hans Wendeberg and Charlotta von Koch have made the years at Chalmers to an excellent time of my life. For that I will always be grateful.

Erik Wendeberg

Göteborg June 2013

Erik Wendeberg

Notations

Abbreviations

CAE	Computer Aided Engineering
DOE	Design of Experiments
FEA	Finite Element Analysis
K&C	Kinematics and Compliances
LC	Load case
MDO	Multi-Disciplinary Optimization
MO	Multi-Objective
RMS	Root Mean Square
SHERPA	Simultaneous Hybrid Exploration that is Robust, Progressive & Adaptive
WLC	Wheel center

Suspension parameter abbreviations

ARB	Anti-roll bar	
LLF	Lower link front	(hardpoint)
LLR	Lower link rear	(hardpoint)
LWB	Lower ball joint	(hardpoint)
LWD	Lower damper	(hardpoint)
LWS	Lower spring	(hardpoint)
RIB	(Tie) Rod inner ball joint	(hardpoint)
ROB	(Tie) Rod outer ball joint	(hardpoint)
SAR	Steer arm	(hardpoint)
SFF	Sub-frame front	(hardpoint)
SFR	Sub-frame rear	(hardpoint)
UPB	Upper ball joint	(hardpoint)
UPBBI	Upper ball joint bushing inclination	(hardpoint)
UPS	Upper spring	(hardpoint)
WLC	Wheel center	(hardpoint)
llf	Lower link front	(bushing)
llr	Lower link rear	(bushing)
sff	Sub-frame front	(bushing)
sfr	Sub-frame rear	(bushing)
upb	Upper ball joint	(bushing)

Table and equation notations

ConViol	The amount by which a constraint is violated (0 if the constraint is met)
Fx,Fy,Fz	Stiffness in local x,y,z directions
LinWt	Linear weight (default value is 1 for objectives, 0 for constraints)
N	Number of increments
Ncon	Number of constraints
Nobj	Number of objectives
Norm	Normalization value for an objective or a constraint
Obj	Response value for an objective
QuadWt	Quadratic weight (default value is 0 for objectives, 10000 for constraints)
S	Sign for the objective (-1 for minimization, +1 for maximization)
Tx,Ty,Tz	Rotational stiffness in local x,y,z directions
dx	Increment size
x,y,z	Coordinates in longitudinal, lateral and vertical direction respectively
y	Simulation actual curve
y’	Measurement target curve

1 Introduction

Computer aided engineering (CAE) is used throughout the entire product development cycle and is becoming an increasingly important tool since it can decrease development time of new vehicles, which is essential to be a competitive in the automotive industry of today. If simulation models can be used to study the vehicle behaviour and characteristics, fewer test vehicles and less time-consuming tests are needed. However, it is important that the behaviour of the simulation models match test data in order to draw the same conclusions from test and simulation results.

By cascading full vehicle dynamic behaviour requirements into targets on subsystem level, it is possible to compare suspension characteristics from simulations and physical tests. To study the suspension characteristics, kinematics and compliances (K&C) in the suspension system are measured physically and simulated for specific load cases. Based on these results, adjustments can be applied to suspension parameters on component level (typically hardpoint geometry of bushing stiffness) to correlate the CAE model.

The traditional way of doing this using a manual adjustment of the model has drawbacks; it is time consuming, error-prone and highly depending on engineering experience. As a result, correlations of the vehicle models are done to seldom and with too low confidence. By automating the correlation process, using a suitable optimization technique and a properly defined procedure, it can be performed faster and the quality of the results can be improved since more parameters and objectives can be included.

1.1 Scope

The goal of this thesis work is to develop a well-defined optimization procedure to perform an automated correlation of a vehicle simulation model to test data and to investigate how suspension parameters influence corresponding suspension characteristics, i.e. how wheel movement is affected by kinematics and compliance in the suspension system at various load cases.

During the investigation, a dynamic multi-body suspension model of McPherson strut type has been correlated. It is assumed that the suspension system is laterally symmetrical and only the left side is correlated to corresponding measurement data. Only suspension characteristics which have been measured in a K&C test rig have been studied and no additional measurements have been performed for this study. In addition, no full vehicle model has been created and simulated; only a front suspension assembly has been investigated. Only existing vehicle data, suspension models and optimization algorithms have been used in the study.

1.2 Contribution

In summary, the major contribution of this Master's thesis project is a well-defined correlation procedure that:

- Performs an effective correlation and decreases the correlation time of suspension models.
- Increases the confidence level of correlation since hundreds of variables can be included and increases the quality of simulation model results.
- Studies the influence of suspension hardpoint geometry and bushing stiffness (suspension parameters) on suspension characteristics.

1.3 Approach

In this study the optimization software, HEEDS® MDO (from now on called HEEDS), has been connected to a multi-body dynamics simulation model in ADAMS/Car in order to run the optimization process. The suspension characteristics have been calculated with the ADAMS solver and are then evaluated against K&C measurement data from the target vehicle in the optimization software. The suspension parameters in the suspension simulation model are then changed based on the hybrid optimization strategy SHERPA®, which is provided in HEEDS. This process is repeated to optimize suspension parameters and thereby correlate the corresponding suspension characteristics to K&C measurement data. In order to develop a standard optimization procedure various configurations have been analysed. For further information regarding the optimization software and multi-body simulation software refer to the manufacturer's websites [1] and [2], respectively.

1.4 Previous research

Previous studies have been performed in order to analyse the influence of suspension parameters and to correlate suspension characteristics to meet certain requirements. A few of them are presented in this section to clarify what the state-of-the-art research and development (R&D) within this subject is today.

A correlation of suspension characteristics, using HEEDS and ADAMS/Car, has been performed by CAE Value [3]. By making a modification of some of the parameters in the ADAMS/Car DEMO model and keeping the original suspension characteristics as target values the model was correlated back towards its original characteristics by simulating suspension behaviour for selected load cases. The study showed that HEEDS can be connected to ADAMS/Car in order to perform multi-event optimization of suspension characteristics and that the optimization strategy, SHERPA, proved to be successful in finding a feasible design proposal.

A sensitivity analysis regarding structure parameters to suspension kinematics characteristics has been performed by Feng J., Song J. and Zheng S. [4]. The suspension structure geometry parameters were optimized using design of experiment (DOE) methodology in order to reduce change of wheel angles for parallel wheel travel. The optimization design method was successful in providing a technical support for development of suspension structures and resulted in a vehicle with increased handling stability compared to the original one.

1.5 Report overview

Chapter two gives a brief overview of the optimization model, which was a central part of the study. The multi-body dynamic suspension model used in this study is explained in Chapter three. The physical measurement procedure and corresponding data processing are presented in Chapter four. Results regarding suspension parameter influence, optimization model configurations and correlation method development are presented in Chapter five. The findings and correlation challenges are discussed in Chapter six and concluding remarks are given in Chapter seven. Finally, the recommendations for future studies are presented in Chapter eight.

2 Optimization model

The optimization model, which is a central part of this study, was based on the layout used in HEEDS MDO, containing a core optimization loop with simulation, responses and variable change based on the optimization algorithm, see Figure 1. Inputs, which will be described in the following sections, are necessary in order to run the optimization. The inputs to the model have been varied to find a suitable *configuration* of the optimization model. Scripts have been used to connect HEEDS with ADAMS/Car and to initiate the simulation procedure (see Appendix F).

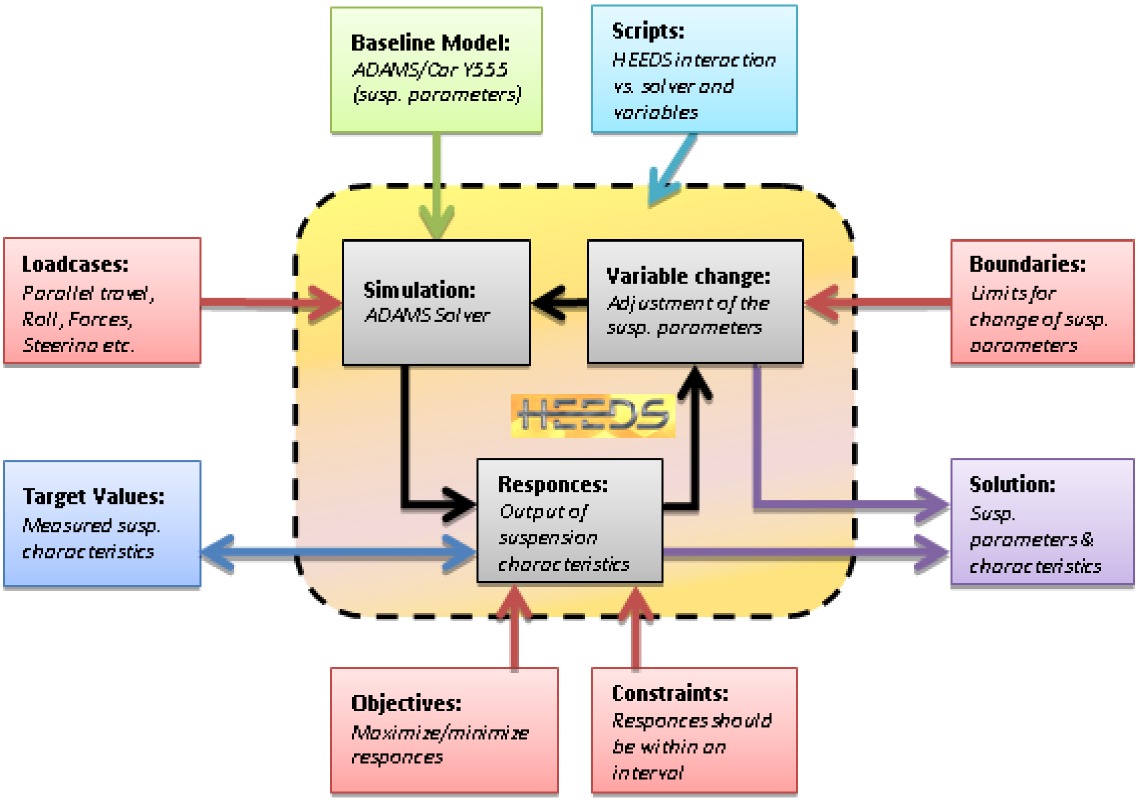


Figure 1: Layout of optimization model

2.1 Variables and responses

The suspension model (simulation block in Figure 1) can be described as an equation system with input suspension parameters and output suspension characteristics. To optimize the suspension characteristics, i.e. responses, and thereby correlate the simulation suspension model, an adjustment of suspension parameters, i.e. variables, was necessary. All of the suspension parameters should be varied to make sure that there are enough variables to solve the equation system, i.e. to find the optimal solution and perform the correlation.

A design of experiment study (DOE) was performed to enhance knowledge regarding suspension parameter influence on characteristics and to find out which characteristics and load cases are needed to optimize the suspension parameters. The types of suspension parameters (variables) which have been investigated in this study are:

- Hardpoint coordinates (x,y,z)
- Bushing stiffness scale factors (Fx,Fy,Fz,Tx,Ty,Tz)

A study of suspension characteristics has been performed that forms the selection of responses to analyse. Together, the chosen responses in the list below, describe the resulting wheel movement from various load cases (which are explained in Section 4.1), which forms characteristics that can be compared to K&C measurement data.

- Toe angle
- Camber angle
- Caster angle
- Wheel centre position
- Tyre load

In addition to the responses above, some additional responses have been included to create extra equations and targets that can facilitate the optimization. All the investigated suspension characteristics are presented in Appendix B.

2.2 Objectives and constraints

The optimization problem in this study was to minimize the differences between the characteristics of the simulation model and the measured vehicle. Performance values, based on objectives and constraints, were used to evaluate the quality of the solutions. The objectives and constraints, which are based on suspension characteristics target values (K&C measurement data), were defined in two ways:

- *Constraints* were set as an interval which the responses must be within to achieve a feasible solution, normally the target value ± an error tolerance.
- *Objectives* should be minimized or maximized, e.g. minimization of the error between a response and a target value.

Curve fitting can be used as an objective in HEEDS by minimizing the root-mean-square (RMS) value of the deviation between the curves. The RMS curve fit method is represented mathematically with Equation 2.1, where N is the number of data points, and y_i and y_i' are the target and actual value at point number *i*, respectively. According to the formula, the curves are closer to match when the RMS value is smaller [5].

$$RMS = \sqrt{\left(\left(\frac{1}{N}\right)\sum_{i=1}^{N}(y_i - y_i')^2 dx\right)} \tag{2.1}$$

Equation 2.2 defines the performance value of each design which was used to rate the quality of the design proposals [5]. As mentioned above, it is based on objectives and constraints. A high performance value indicates that the solution is promising and consequently; Equation 2.2 was used to find the most suitable designs and thereby optimize the suspension assembly. It includes both linear and quadratic weighting of both objectives and constraints. Notice that

$$\sum_{i=1}^{Nobj}\left(\frac{LinWt_i \cdot S_i \cdot Obj_i}{Norm_i} + \frac{QuadWt_i \cdot S_i \cdot Obj_i^2}{Norm_i^2}\right) - \sum_{j=1}^{Ncon}\left(\frac{LinWt_j \cdot ConViol_i}{Norm_j} + \frac{QuadWt_i \cdot ConViol_j^2}{Norm_j^2}\right) \tag{2.2}$$

When linear and quadratic weight variables were set to their default values, the calculation of performance rating could be simplified to Equation 2.3. This means that the contribution to the performance rating from objectives was linear and the contribution from constraints was quadratic. In addition, weighting of constraints was intentionally high to make sure that infeasible solutions achieved a low performance rating and more suitable design proposals were studied further instead.

$$-\sum_{i=1}^{Nobj}\left(\frac{LinWt_i \cdot Obj_i}{Norm_i}\right)-\sum_{j=1}^{Nobj}\left(\frac{QuadWt_i \cdot ConViol_j^2}{Norm_j^2}\right) \tag{2.3}$$

The final equation is the normalized sum of all objectives and constraints, using linear and quadratic weighting respectively. Once the constraints were satisfied, only the objectives contributed to the performance value evaluation resulting in Equation 2.4. A design proposal equal to the optimal solution will result in zero performance rating.

$$-\sum_{i=1}^{Nobj}\left(\frac{LinWt_i \cdot Obj_i}{Norm_i}\right) \tag{2.4}$$

2.3 Optimization algorithm

The optimization algorithm which mainly has been used in this study is called SHERPA (Simultaneous Hybrid Exploration that is Robust, Progressive and Adaptive), which is provided as one of the standard algorithms in HEEDS. It actually consists of multiple search methods which are used simultaneously (not sequentially) and takes advantage of the best attributes of each method. SHERPA is a combination of global and local search methods, and the number of different optimization methods used at the same time is ranging between two and ten [6].

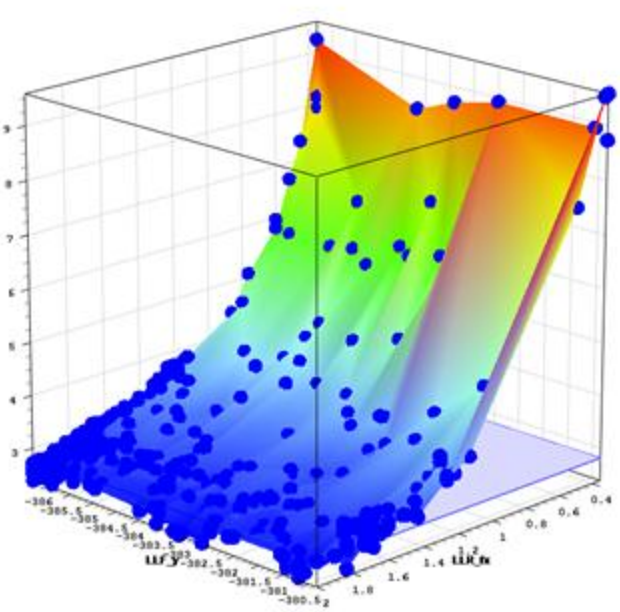


Figure 2: Example of a design space with two variables

During the optimization SHERPA gathers knowledge about the design space for each evaluation and adapts the search methods and the tuning parameters as the design space is explored. Figure 2 shows a response surface based on two variables which becomes increasingly detailed as the design space are explored. This response surface shows how the variables influence the resulting suspension characteristic. By continuously exploring the response surface no initial knowledge about the design space is needed before the optimization. In addition, a large number of variables can be used since the optimization algorithm will gain knowledge for each evaluation and eventually do the necessary changes to the correct variables [6].

Another opportunity was to use a multi-objective (MO) optimization with a slightly modified algorithm; MO-SHERPA. Instead of the performance ratio described in Section 2.2 where the objectives are summarized, it handles the objectives independently which can be useful when the objectives are in conflict with each other. By doing this it could explore the Pareto front and provide a set of optimized solutions with trade-offs between the objectives [7]. In order to develop an optimization strategy, the performance of both algorithms has been investigated to find out which one that was most suitable for this kind of optimization.

2.4 Variable boundaries and resolution

In order to limit the change of the variables, boundaries were defined for each variable. Normally production tolerances would be a reasonable limit for the boundaries, but since the model contains rigid bodies the compliance might differ and wider boundaries have therefore been defined for the bushings to compensate for the stiffer behaviour. During the study, hardpoints have been changed within ±3 mm and bushings stiffness scale factor have been modified within +100% or -50% (doubled or halved).

The *variable resolution*, i.e. the number of points within the boundaries, has been studied to find a suitable step size for the variable changes during the optimization. Wide boundaries might be required to find a feasible solution of good quality.

The *distribution* of the values can be defined as a uniform or Gaussian distribution, so the optimization algorithm focus more or less on the baseline design and can adjust the variables choice based on the production diversity. In addition, the number of suspension parameters included in the optimization can be reduced if the influence is known. The variable configurations can be set individually, i.e. different configurations can be used for all suspension parameters. A schematic sketch of the variable configurations is presented in Figure 3.

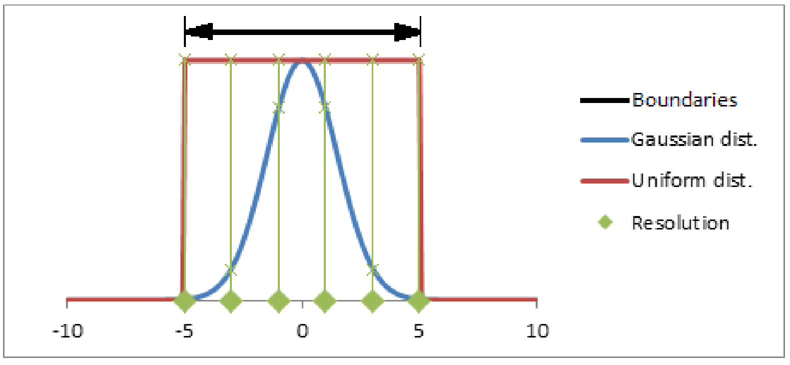


Figure 3: Variable configurations

3 Multi-body suspension simulation model

During simulations a suspension assembly has been analysed using ADAMS/Car. The model which was used in this study is a front suspension of McPherson strut type. Only the left-hand side suspension characteristics have been analysed since the CAE model is almost symmetrical.

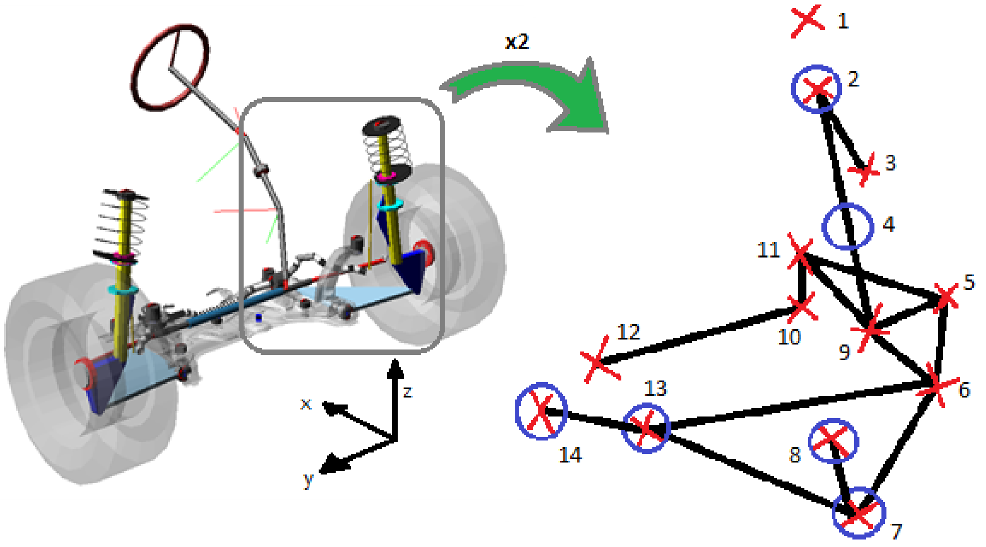


Figure 4: McPherson strut front suspension assembly and structural model

The suspension simulation model consists of a multi-body assembly with a suspension structure presented in Figure 4. The suspension parameters of interest generally consist of hardpoints and bushings which have been numbered and are described in Table 1.

Table 1: Suspension parameters

Point #:	Suspension parameter(s):	Type:	Abbreviation(s):
1	Upper ball joint bushing inclination	Hardpoint	UPBBI
2	Upper ball joint	Hardpoint & bushing	UPB & upb
3	Lower spring mount	Hardpoint	LWS
4	Strut flexibility ratio	Bushing	-
5	Wheel center position	Hardpoint	WLC
6	Lower ball joint	Hardpoint	LWB
7	Lower link front mount	Hardpoint & bushing	LLF & llf
8	Sub-frame front mount	Hardpoint & bushing	SFF & sff
9	Lower damper mount	Hardpoint	LWD
10	Tie-rod outer ball joint	Hardpoint	ROB
11	Steering arm	Hardpoint	SAH
12	Tie-rod inner ball joint	Hardpoint	RIB
13	Lower link rear mount	Hardpoint & bushing	LLR & llr
14	Sub-frame rear mount	Hardpoint & bushing	SFR & sfr

To change the behaviour of the CAE suspension model, in order to correlate it, the following suspension parameters have been adjusted during the correlation procedure:

- Hardpoint positions
- Bushing characteristics
- Spring properties
- Bump-stop and rebound-stop characteristics
- Anti-roll bar stiffness

3.1 Baseline suspension configuration

The CAE suspension model consists of a large set of variables, where the influence of the respective parameters on suspension characteristics can vary quite significantly. The baseline setup of the vehicle model, which will act as input for the first evaluation, is presented in Appendix A. Some of the variables in the baseline setup might have limited or no influence on the suspension characteristics, consequently all of the suspension parameters do not need to be varied during the optimization. The method regarding the selection of variables is further discussed in Section 2.1.

3.2 Rigid and flexible bodies

The CAE suspension model contains both rigid and flexible elements. Anti-roll bar and steering knuckle steer arm were modelled with several small linear beam elements which are connected sequentially, allowing a linear deformation and change of geometry and corresponding stiffness. The sub-frame in the suspension model was a flexible body with deformations based on a finite element analysis (FEA). Springs were compliant with linear stiffness. Bushings, bump-stop and rebound-stop were flexible but non-linear with stiffness curves defined in specific property files. The remaining of the components is rigid, but some compliance (e.g. in strut) were modelled by using additional bushings.

3.3 Coordinate system

The coordinate system used in this study was the chassis coordinate system (see Figure 4), which is used as standard both in ADAMS/Car and the K&C test rig.

- X – Longitudinal direction, positive rearwards
- Y – Lateral direction, positive to the right-hand side of the car
- Z – Vertical direction, positive upwards
- Rotations, e.g. roll, pitch and yaw, are based on the right hand rule unless stated otherwise.

For the left hand side of the suspension; wheel toe-in angle is regarded as positive, a wheel plane with the top inclined outwards laterally corresponds to positive camber angle and a wheel steering (kingpin) axis which is inclined rearwards at the top defines a positive caster angle. Bushings are defined in the chassis coordinate system, except the lower control arm front and rear bushings which are rotated -90 degrees around the vertical axis (causing the local X-direction to unite with the chassis Y-direction).

4 K&C measurement data

Data from a K&C measurement of a physical vehicle, which was performed in a K&C test rig, was used as target values for the optimization (as discussed in Section 2.2). But in order to use HEEDS the raw data files had to be formatted, filtered, and finally imported into HEEDS. Since HEEDS curve-fitting objective could only handle curves which are one-to-one, a polyfit function (trendline) was used in MATLAB to create a polynomial function which described the suspension characteristics as one-valid-functions on load case intervals corresponding to the standard measurement procedure.

4.1 Quasi-static load cases

The following quasi-static K&C events have been measured in a K&C test rig and can be simulated in ADAMS/Car. The reference load case of the vehicle during physical K&C measurements was Kerb+2 (total weight of vehicle with standard equipment, all necessary operating consumables and two 75 kg passengers), the vertical load in the CAE simulation model has been adjusted to a corresponding level.

- *Vertical motion* – A displacement controlled parallel wheel movement over a specified jounce interval (max jounce / max rebound movement).
- *Roll motion* – A displacement controlled vehicle body rotation over a specified roll interval (± max roll movement). Wheel movement are prevented vertically.
- *Lateral force* (*opposite)* – A force controlled lateral movement of the wheel. The forces are applied in anti-phase (counteracting laterally) at ground level.
- *Lateral force (30 mm offset)* – A force controlled lateral movement of the wheel. The force is applied in-phase 30 mm to the rear of the wheel center at ground level.
- *Drive force* – A force controlled longitudinal movement of the wheel. The force is applied in the wheel center in order to resemble propulsive forces acting on the suspension.
- *Brake force* – A force controlled longitudinal movement of the wheel. The force is applied at ground level in order to resemble brake forces acting on the suspension.
- *Steer motion* – A displacement controlled movement of the steering rack. The movement corresponds to a specified steering wheel angle interval (± max steering wheel angle).

As mentioned above, the K&C test rig uses a roll measurement technique based on rotation of the vehicle body; however it shall be mentioned that the corresponding measurement technique in the standard ADAMS/Car K&C event are based on a locked vehicle body position and a counter-phase vertical wheel motion.

5 Results

The results from the parameter influence study, optimization procedure development and simulation model correlation are presented in the following sections.

5.1 Suspension parameter influence

The results of the design of experiment study, which are presented in Appendix C, show the effect of hardpoint position or bushing stiffness variation on a selection of suspension characteristics. Generally, the results show that suspension hardpoint positions have a high overall influence on both kinematics and compliances, and that bushings have practically no influence on kinematics. However, some bushing may have a high influence on the compliance based characteristics.

According to the parameter study the lower control arm inclination around the x-axis have a major effect on most vertical- and roll characteristics. In addition, it generally has a large influence on load transfer and the lateral camber compliance. The parameter study indicates that a change of caster angle has a limited effect on kinematic characteristics, which is in line with results of previous research [4]. However, according to the DOE study, caster angle related hardpoints also have a high influence on lateral compliances and drive- and brake steer characteristics.

Tie rod inclination around the x-axis influences toe angle characteristics for vertical-, roll motion, drive- and brake force load cases. Longitudinal inclination of the tie rod is mainly influencing the drive- and brake steer characteristics, but also the toe change during both the lateral in-phase force load cases. Generally, the lateral force in-phase load cases show a similar pattern with regards to variable influence.

The lateral damper inclination has a high influence on the camber characteristics for vertical- and roll load cases, but shows low effect on other characteristics. The DOE also confirms that the static camber angle is set by the inclination between the lower and higher ball joints in the strut arm and that the steering ratio is mainly affected by the distance between the outer steering rod ball joint and the caster axis.

5.2 Optimization method and correlation procedure

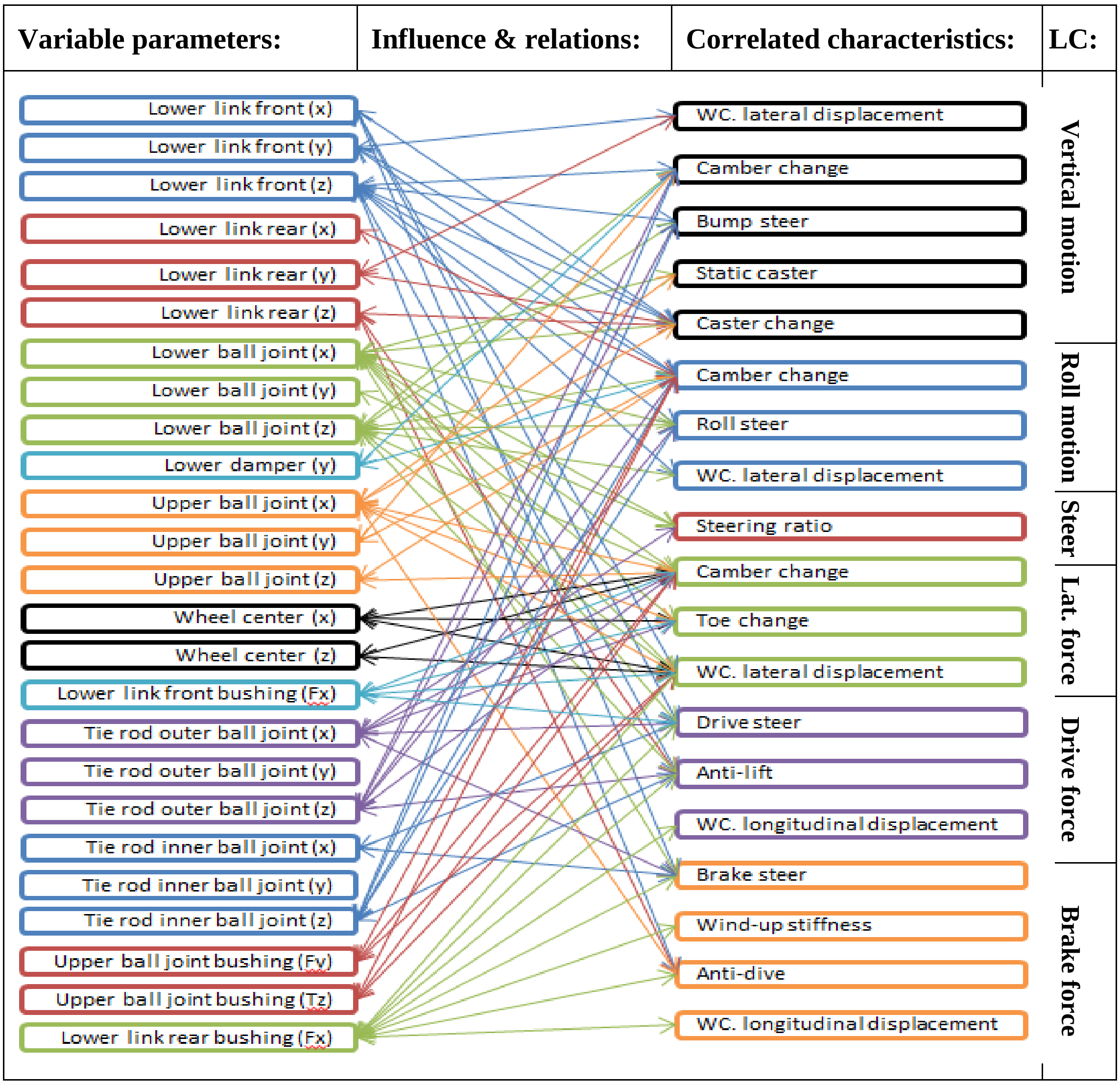
The results of the suspension parameter influence study forms a matrix, which gives a simplified view on how a parameter adjustment results in a change of the corresponding suspension characteristics. Based on that knowledge it was possible to select certain load cases and suspension characteristics that should be ran in order to correlate the suspension parameters, creating a suitable optimization method.

In addition, several optimization configurations have been investigated in order to find an input setup that maximizes the performance of the optimization model. Together with the optimization method this forms a procedure that can be used for correlation of suspension systems.

5.2.1 Correlation methodology

The most influencing suspension parameters and their relation to each other and the corresponding suspension characteristics are presented in Table 2. Together they form expressions which can be used to correlate the characteristics. However, as the result indicates, the suspension system is complex with regards to variable influence. Since most of the parameters are connected they cannot be optimized individually, which means that a full correlation method which includes all suspension parameters (variables) and all the necessary suspension characteristics is required to find a feasible design proposal.

Table 2: Suspension parameter influence and relations



The full correlation takes advantage of HEEDS ability to handle more than one hundred variables and still maintain performance. However, each evaluation is time-consuming since data for all load cases will be processed and several evaluations are needed to gather sufficient knowledge regarding how variables affect the design space. The results (Appendix C) also show that some characteristics are related, e.g. the wind-up stiffness and longitudinal compliance, and that an optimization of one characteristic might be enough to correlate several other characteristics as well.

5.2.2 Optimization configurations and convergence

In addition to the correlation method itself, various optimization configurations have been investigated to find a suitable basic setup for the correlation procedure. Convergence of the performance rating has been compared using different configurations (described in Section 2.2 – 2.4) and the best solutions during all the evaluations have is presented to show how the optimization methods influence the performance rating and corresponding optimization level. The same objectives and constraints were used for all configurations to get comparable performance ratings.

The results regarding variable distribution are presented in Figure 5 and indicate that a uniform distribution of all variables, which is the standard option in HEEDS, leads to a faster convergence of the design proposal quality. After all the optimization iterations the performance rating is higher for the configuration with uniform distribution.

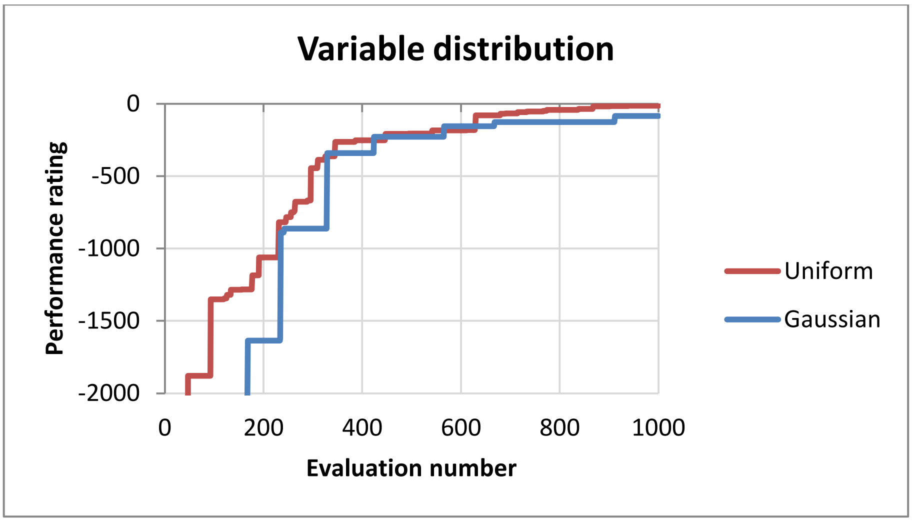


Figure 5: Performance influence of variable distribution

The influence of variable resolution was studied by using two variable configurations with 21 and 101 steps for all variables respectively. The results show that although a low resolution leads to a more rapid increase of performance rating initially, a higher resolution is needed to achieve a design solution which is feasible (see Figure 6).

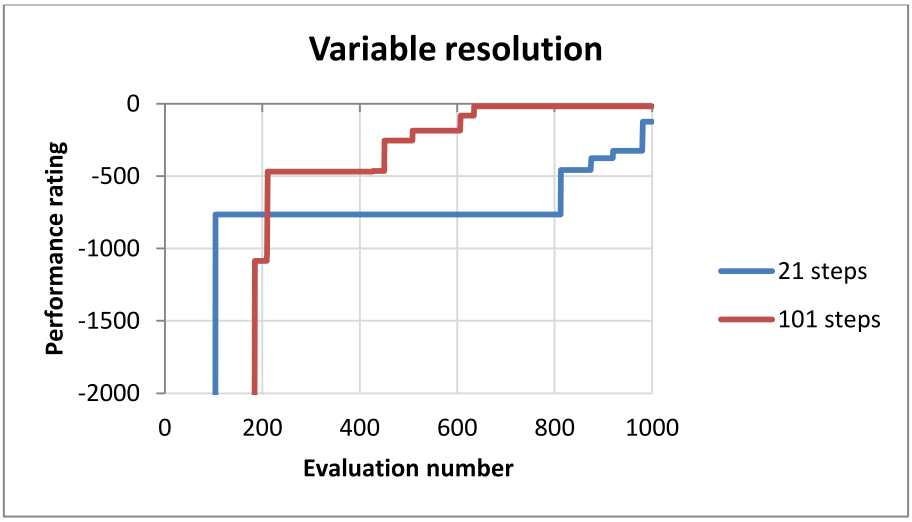


Figure 6: Performance influence of variable resolution

The findings regarding the number of variables related to optimization performance and convergence is presented in Figure 7. The results clearly show that a configuration with a lower number of variables give a faster convergence and a faster increase of the performance rating compared to a configuration which includes variables with low influence as well.

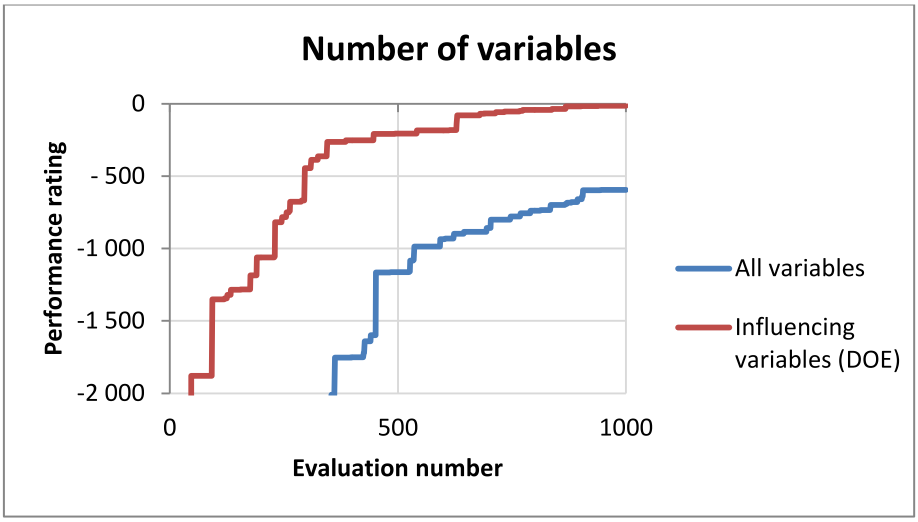


Figure 7: Performance influence of number of variables

The variable boundaries for all variables have been varied to investigate how variable boundary level influences the optimization performance and convergence of the solutions. The result, presented in Figure 8, indicates that higher boundary levels initially leads to a slower increase of the performance rating, but eventually results in a performance rating that is similar, or even higher, than the standard scenario.

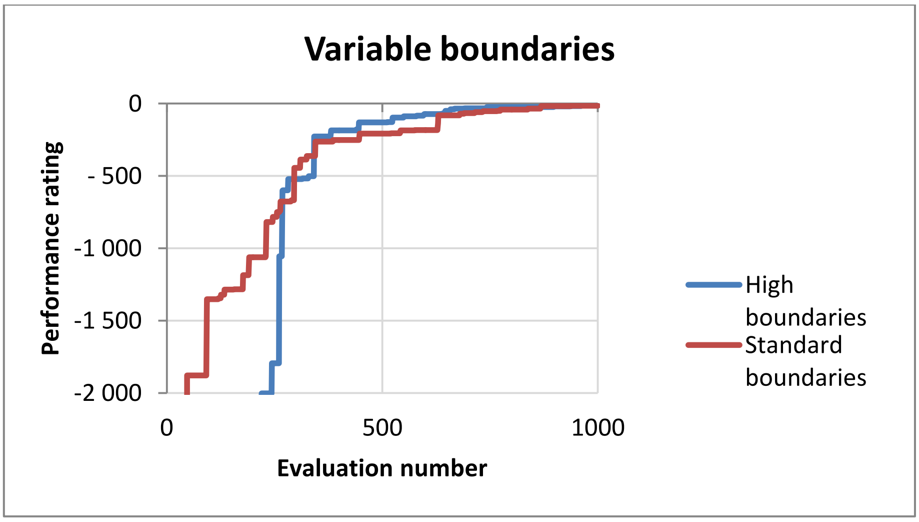


Figure 8: Performance influence of variable boundaries

In the investigation regarding choice of optimization algorithm the two standard algorithms in HEEDS were tested with regards to optimization performance and convergence time (see Figure 9). The results indicate that the performance rating increases faster with SHERPA but that MO-SHERPA has advantages when the performance rating converges, since it explores the trade-offs between objectives.

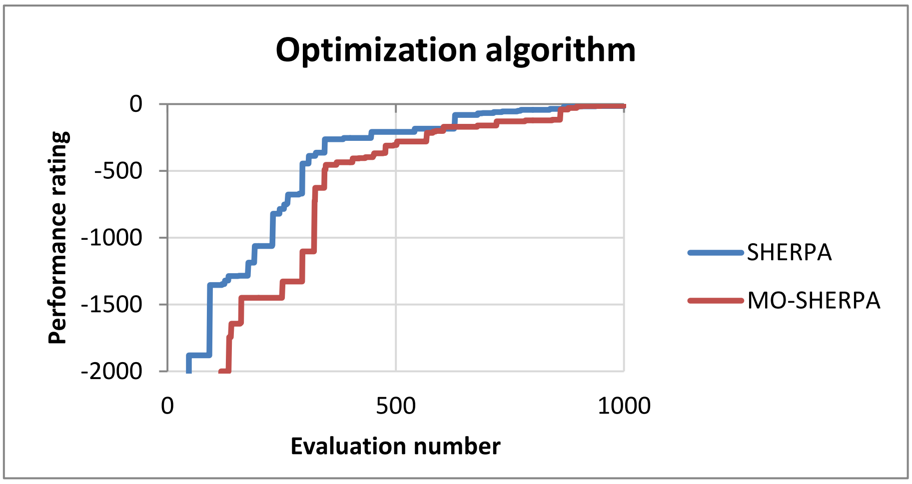


Figure 9: Performance influence of HEEDS optimization algorithm

Finally, the configuration of the constraints has been studied in order to find a suitable setup. As mentioned in Section 2.2, a constraint is an interval with a high and low boundary that the actual value must be within to maintain a high performance value. The resulting definition of the interval boundaries is based on the target values for suspension characteristics and is described by Equation (5.1) and Equation (5.2):

$$Constraint_{i,upper} = +\left(0{,}15 \cdot \sqrt{Target_i^2} + 0.005\right) + Target_i \quad (5.1)$$

$$Constraint_{i,lower} = -\left(0{,}15 \cdot \sqrt{Target_i^2} + 0.005\right) + Target_i \quad (5.2)$$

The definition results in constraints boundaries that are deviating ±15% from the target value, plus/minus an extra value of 0.005 to increase the relative constrain levels for characteristics with small absolute target values (close to zero). A schematic sketch of the constraint levels are presented in Figure 10.

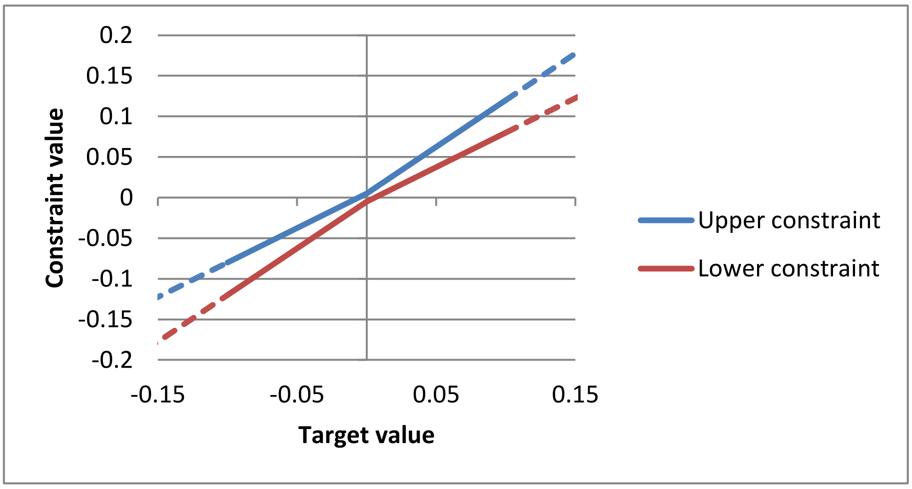


Figure 10: Sketch of constraint levels based on target values

5.3 Correlated K&C results

By using the defined optimization method with a suitable optimization configuration, a correlation of the suspension model has been performed. The correlation results are summarised in Appendix D, where it is shown how well certain suspension characteristics fulfils the constraints and target values. By using the correlation procedure it was possible to find a design proposal that significantly improved the investigated suspension characteristics.

The major improvements can be seen on the compliance related characteristics e.g. drive and brake steer. The kinematic characteristics have also been improved considerably. Graphs which describe some of the suspension characteristics are presented in Appendix E. It can be seen that most of the curves for simulation and measurement data are coinciding around the design ride height region, but are slightly less accurate at full bounce and rebound suspension travel.

The results also show that some counter-acting characteristics could not be fully correlated. For example, the longitudinal wheel center stiffness is too high (too low displacement) when exposed to a braking force but too low when exposed to a drive force. A similar problem is the lateral camber angle compliance and lateral wheel center compliance which could be improved significantly, but not completely. To achieve a correlation of the model, several suspension parameters have been changed over the production tolerances. Especially stiffness scale factors for the bushings at the lower control arm mounts have been changed drastically.

6 Discussion

In this chapter, the findings are explained and correlation challenges are discussed in order to clarify how well the defined correlation procedure performs the desired correlation. In general the optimization procedure was successful in providing a feasible design proposal with suspension characteristics similar to the corresponding characteristics of measured test vehicle but improvements to the model and additional measurement data could improve the performance of the defined correlation procedure.

6.1 Suspension parameter influence

During the DOE study the shape analysis of suspension characteristics curves (e.g. Camber angle vs. vertical wheel position) are limited to analyse gradients and static values around the static equilibrium position. This means that other variables might have high influence on characteristics that cannot be seen in the results of the DOE study. It is important to remember that the DOE study does not perform the actual correlation; it only enhances the knowledge about how to create a suitable correlation method. In future correlation projects the suspension parameter influence can be evaluated after the actual correlation and no initial DOE is needed.

Generally, the results show that suspension parameters cannot be changed individually to correlate a certain suspension characteristic. Since most of the suspension parameters influence several characteristics, SHERPA needs to gather good knowledge of the design space before adequate changes can be applied and the suspension model can be correlated. The bushings mainly affect the compliance related suspension characteristics, while hardpoints have a high influence on both kinematics and compliance based characteristics.

6.2 Correlation procedure development

The SHERPA optimization algorithm shows great performance when all objectives can be fulfilled and no trade-offs have to be made. In this study SHERPA is faster, but when the solutions starts to converge due to counter-acting objectives, MO-SHERPA shows better trade-off capability and eventually achieves higher performance values compared to SHERPA. Which one that is most suitable highly depends on the quality of the simulation model and the measurement data. In previous studies the ADAMS/Car demo model has been tweaked and then re-correlated, which is a typical example of where SHERPA is beneficial; an optimization problem which has a solution that the model is able to fulfil without making trade-offs.

The boundary levels are a crucial part of the variable setup since they define the size of the design space which is explored by the optimization algorithm. The global maximum point must be included in this space to find the optimal solution but on the other hand a large design space increases the optimization time since more exploration is needed. The boundary configuration which was used in this study might not be the best in another correlation study; it depends on the initial quality of the model.

The variable resolution has to be high enough to be able to find a solution that fulfils the demands. With a low variable resolution the design space can be explored faster, but many maximum (or minimum) points will not be found and thereby the performance rating will be limited. However, in this study it cannot be concluded that the configuration with a low variable resolution converged properly. Generally HEEDS seems to handle large variable resolutions, thanks to the smart exploration of the design space provided by SHERPA, and normally the standard resolution in HEEDS of 101 values for each variable was sufficient to find feasible design proposals.

In this study a uniform distribution of the variables proved to be more suitable, but it is likely to depend on the quality of the baseline model and production variations in components. Many of the suspension parameters were changed almost to the boundary levels to find a feasible solution. While using a Gaussian variable distribution, the chance that the algorithm should try these adjustments is reduced, and thereby the uniform distribution proved to be more successful.

A parameter study is essential when doing a manual correlation since the equation system grows rapidly with the increasing number of variables and needs to be simplified. When doing an automated correlation, HEEDS does not need an initial DOE study thanks to (MO-)SHERPA that continuously adapts the optimization algorithm as the design space is explored. Since the full correlation method includes most of the variables (suspension parameters) and suspension characteristics it is likely that it can be applied on suspension assemblies of different designs.

However, as the results indicated, the increased number of variables will lead to longer convergence time of the performance values since the exploration of the design space will be more complex and more variables should be tuned. In this study, the model was slightly pre-optimized and some parameters that affected many characteristics (e.g. ride height) were set manually before the correlation to make the design space less complex and lower the required number of evaluations (see Section 6.3.1).

6.3 Correlation challenges

During the study some challenges related to the correlation were encountered, and consequently actions were taken to limit or avoid reduced correlation performance. Generally, the challenge is to include all necessary variables and to make sure that the sub-systems are modelled in a correct way; otherwise a good correlation cannot be achieved. In the following sections the main correlation challenges are presented.

6.3.1 Ride height

Due to production variations in springs or a different reference kerb weight during measurements, the static ride height of a measured vehicle can vary substantially from the design position in the simulation model. A variation in ride height will change the suspension geometry and cause an offset between the characteristics, making the correlation process harder (if not impossible), since some of the hardpoints might need to be changed more than is possible with regards to the variable boundaries.

In this study, the ride height of the simulation model has been adjusted to correspond to measured K&C data. The ride height adjustment level was based on wheel rise measurements on the physical reference vehicle, which indicated a deviation of +7 mm from the design ride height level. Adjustments were applied to the simulation model (and not to the measurement K&C data) mainly due to the following reasons:

- Model should be correlated to measurement data, not the opposite.
- Hard to correctly modify measured characteristics that are force controlled (since a faulty ride height will have unknown influence on e.g. load transfer).
- Basic ride height adjustment option already available for simulation model.

6.3.2 Steering gear

Limitations in the steering gear model with regards to modelling of friction in the steering gear, makes a correlation of lateral in-phase force steer characteristics harder. During the K&C measurements the vehicle was turned off, and no steering servo was active, however the steering gear (including servo) in the vehicle simulation model was still activated and was not removed during the study since that would decrease the performance (friction in steering gear should still be present when vehicle is turned off) and make the correlation procedure more complicated. Instead more focus has been given to correlate the model to the lateral anti-phase force characteristics since they are not influenced by the steering servo and sub-frame (forces are cancelled out).

6.3.3 Model flexibility and bushing properties

As mentioned in Section 3.2, most of the suspension components in the simulation model are rigid, which should lead to a stiffer behaviour of the suspension. During the correlation the optimization software will try to compensate for this, most likely by decreasing the stiffness of bushings. Due to this effect, it might be necessary to set variable boundaries (for bushings) higher than production tolerances since the model contains rigid components. This also means that the correlation quality can be reduced by including measured bushings with correct stiffness properties, since the suspension characteristics are affected by the total compliance in the system.

In this study, bushing stiffness progression curves was only scaled. Since the shape of the stiffness curve might be incorrect, the correlation of some compliance characteristics was not valid for the entire load case interval. This affects especially the longitudinal force load cases. Regarding the tyre model in ADAMS/Car, tyre flexibility is only active in vertical direction, which means that suspension characteristics based on tyre contact patch position (e.g. lateral could not be correlated since the physical vehicle was measured with regular flexible production tyres.

6.3.4 Static equilibrium data

Suspension characteristics values at the ride height position were not included in measurement data from the physical vehicle, instead nominal vehicle specification values have been used to offset the suspension characteristic graphs from zero-position at static equilibrium to values that match output from simulations. Figure 11 shows how this affects the suspension characteristic curves.

By using this method it is possible that target data is corrupted, since the measured vehicle might differ from the nominal specification and thereby an optimal correlation may not be possible. On the other hand, if simulation data would be offset to zero at ride height position the influence of some variables cannot be studied and they become harder to correlate. Static wheel spindle angles (toe and camber) were varied independently to other characteristics in the CAE model by using separate variables.

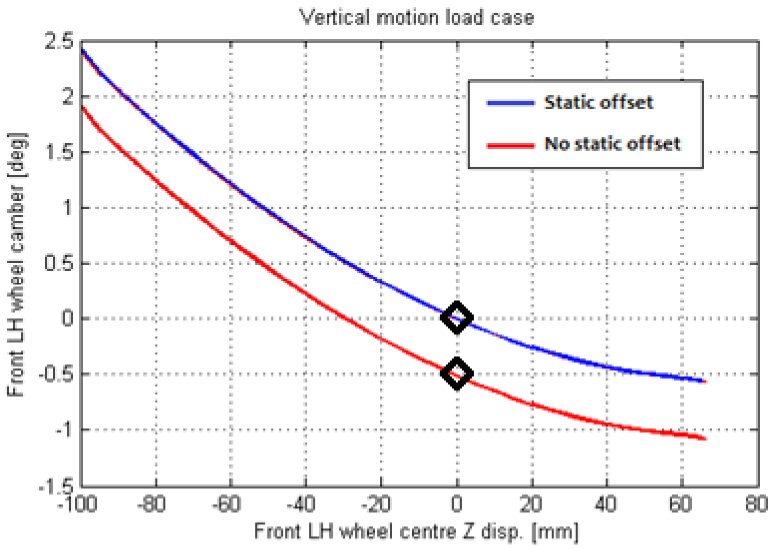


Figure 11: Static offset of suspension characteristics

Some measurement data, especially tyre load during longitudinal load cases, are unclear due to the small variations. Some difference between the static tyre loads for various load cases is present in measured data, thus a single static value (which corresponds to all load cased) during simulations cannot be set. To compensate for these deviations, manual adjustments of static wheel load characteristics have been performed to achieve similar static values for simulation and measurement data. This will also increase the performance of the curve-fit algorithm.

6.3.5 Measurement technique used in K&C load cases

Roll characteristics could not be fully correlated using the current model. This may be due to the differences in K&C measurement procedures. In this study the front suspension were simulated separately in ADAMS/Car but front and rear suspension characteristics were measured simultaneously on the physical vehicle, which can influence suspension characteristics.

As mentioned in Section 6.3.3, there are differences with regards to the tyre lateral and longitudinal stiffness between the simulation model and the physical vehicle. In addition, no bushing preload was used in the simulation model but is likely to be present in the physical model since the bushings are mounted at full rebound position and the vehicle body is lowered to the desired ride height afterwards.

7 Conclusions

By using HEEDS MDO and the standard optimization algorithm SHERPA, auto-correlation of a dynamic multi-body vehicle suspension model is possible if the suspension model is correctly defined. By using automated optimization of suspension parameters the correlation time can be reduced drastically. The in-detail conclusions regarding the study are presented in the following sections.

7.1 Parameter influence

According to the DOE study, bushings have limited or no influence on suspension characteristics during kinematic load cases (vertical- and roll motion) but noticeable influence during compliance load cases (lateral-, drive- and brake force). Some bushings generally have low influence and could be excluded from the correlation study if simplifications are needed (during a manual correlation).

Generally, bushings in the suspension linkage show higher parameter influence than sub-frame bushings. Since the suspension movement is the sum of kinematic and compliance movement, bushings located at highly influencing hardpoints will have a higher effect on suspension characteristics. Hardpoints show high influence for both kinematic and compliance load cases. All hardpoint coordinates do influence suspension characteristics and hence none of them should be ignored during correlation.

7.2 Correlation methodology

Normally the standard weight on objectives and constrains of 1 and 10000 respectively should be used. However, if suspension characteristics and corresponding constrains are counter-acting, more important suspension characteristics can be weighted higher in order to prioritize correlation of them, on behalf of the other ones. In addition, if the measurement data for a specific suspension characteristic is of low quality, the weight can be lowered (or even set to zero) to reduce influence of potentially faulty input data.

It is crucial to define the objectives and constrains properly in order to find the optimal solution. If not all constrains are fulfilled, the algorithm may strive to fulfil them even if that would make a lot of other characteristics wrong. In addition, the curve-fitting objectives using RMS values, which are used for fine-tuning of the suspension characteristics, are only used when the constraints are fulfilled.

When the suspension can be fully correlated SHERPA is the most suitable optimization algorithm to use. However, if there is trade-offs between various objectives and constraints the MO-SHERPA algorithm will probably find a better solution. To be able to perform a successful auto-correlation it is important to define the variable boundaries properly to make sure that an optimal solution can be found while the size of the design space is still kept as limited as possible.

The study show that HEEDS can handle a high variable resolution and that a high resolution is needed to achieve feasible results. The main advantage with a lower variable resolution is a faster scan of the design space. However, it is likely that global maximum/minimum points in the design space cannot be found since the mesh is too coarse. The variable should therefore be set based on known variable influence and known production variations in the corresponding components, or the variable resolution should be set high enough to maintain performance even though the data is unknown. The standard resolution of 101 levels is high enough to achieve feasible correlations.

Due to a linear approximation in the parameter study, the parameter influence (DOE study) results will only be valid for models similar to the baseline design. A correlation procedure that, based on the parameter influence study, sequentially optimizes suspension parameters to corresponding characteristics is hard to define since most parameters influence several characteristics and are dependent of each other. In addition, it is likely to run into problems if the method is applied to a suspension model of different type or a model with a baseline design with low correlation level. The full correlation method is more flexible since it takes all variables, responses and load cases into consideration at all times, but the drawback is increased simulation time.

7.3 Suspension modelling limitations

Generally the model shows low hub flexibility, which affects the camber and toe compliance. To compensate for the lack of toe compliance the steering arm thickness can be lowered, but the problems regarding the camber compliance persists. Camber compliance can be increased by lowering the stiffness of the strut, but according to the results that will cause too high lateral wheel center stiffness.

Due to shape variations of the bushing stiffness progression curves some of the suspension characteristics cannot be fully optimized using linear bushing scaling. Since only the linear ranges of the bushing stiffness curves are valid, the correlation is only valid for the corresponding limited load case interval. In addition, since no friction is modelled, some of the characteristics are hard to optimize since the correlated model could achieve faulty values to compensate for friction in for example the steering gear. Fortunately, the lateral anti-phase force load case can be used for correlation of toe characteristics since forces are counteracting in the steering rack. However, steering column compliance properties cannot be correlated with the current steering system.

The subsystems on the model must be correctly defined in the baseline model (e.g. the correct steering gear ratio must be set in the steering gear model). The optimization software can handle production variations in the physical vehicle, while extreme deviations will be outside the feasible variable boundaries. This investigation shows that all parameters cannot be fully optimized by the optimization tool, since the necessary variables are not included in the study, due to modelling errors, or variations in the measurement technique used in the K&C measurements.

The automated optimization tool cannot correlate the suspension model if faulty parameters remain unadjusted. It is therefore important that all the subsystems, e.g. power steering assistance, are correctly defined before the auto-correlation since the optimization tool mainly handles variables in the suspension system. If the above mentioned modelling limitations are handled, auto-correlation of a dynamic multi-body vehicle suspension model is possible. The correlation time of a suspension assembly can thereby be lowered to below one week including the setup of the optimization model, compared a manual suspension correlation which can last considerably longer.

8 Recommendations

Currently the K&C simulations in ADAMS/Car are run in batch mode. In order to speed up the evaluations and thereby achieve a faster or better correlation the simulations should be run in binary mode. This eliminates the time required to load the suspension assembly and approximately 20% (currently half a minute of evaluation time) of the simulation time can be saved at each evaluation. In order to save even more time the simulations can be simplified by using higher step size for input displacements and forces, however, only if correlation fidelity can be maintained.

An initial manual tuning of vehicle ride height level in the simulation model will facilitate the correlation substantially, since a faulty ride height of the model will require large variable changes (often outside of boundaries) to acquire a feasible solution. Wheel rise measurements on the physical vehicle should be used as input for the tuning, and the final adjustment should be made by matching the track variation at wheel center position curves which are highly dependent on the ride height position.

Static values for camber-, toe- and caster angle should be measured at the K&C test rig to offset output measurement K&C data and make it fully comparable to corresponding suspension characteristics output data from simulations. Another option is to offset all characteristics to zero level at static equilibrium position, however, potentially valuable information will be lost which can make the correlation harder. For future studies it should be ensured that suspension characteristics curves (both from measurement- and simulation data) contain data points at static ride height position, since constraints and objectives are defined based on values extracted there. Otherwise performance rating will be calculated by using interpolation.

To increase simulation model accuracy the wheel hub bushing should be included to compensate for toe angle and camber angle change due to compliance in the steering knuckle and wheel bearing. Similarly, the strut flexibility bushing should be activated to enhance the correlation of camber related characteristics. In addition, the steering subsystem should be developed further in order to match the behaviour of the measured vehicle. A model that includes friction in the steering gear would increase simulation accuracy, especially at lateral in-phase force load cases.

In this study, only the front axle has been simulated. However, to include possible effects on full vehicle level (e.g. body compliance) a full vehicle K&C simulation should be run. Finally, variables for parameterization of bushing stiffness should be included to create a non-linear modelling which enables full auto-correlation of the CAE suspension model.

During future physical measurements, it is important to consider which characteristics and measurement techniques that should be used to correspond to CAE simulations and thereby facilitate future auto-correlation of vehicle models. By doing this a lot of time can be saved with regards to implementation of a new optimization method. If suitable measurement data is provided from a K&C test rig, future optimization procedures can be based on the method used in this study.

If the CAE models are correctly defined and comparable K&C measurement data exists the correlation time and costs can be reduced by using auto-correlation. It is therefore recommended to use HEEDS for future auto-correlation of suspension models. The major improvements in the future can be achieved by introducing more parameters in the CAE suspension components (e.g. parameterized bushings) and define a suitable measurement strategy for the K&C test rig.

9 References

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10 List of figures and tables

The figures and tables used in the report are presented in this section.

10.1 List of figures

10.2 List of tables

Appendix A – Investigated suspension parameters

Parameter:	Abb:	Criteria:	Direction:	Baseline value[1]:	Final value[1]:
Lower link front	LLF	Position	X,Y,Z	0.00, 0.00, 0.00	-0.80, -2.92, -0.70
Lower link rear	LLR	Position	X,Y,Z	0.00, 0.00, 0.00	-0.88, 2.70, 1.00
Lower link outer	LWB	Position	X,Y,Z	0.00, 0.00, 0.00	-0.97, 0.74, 2.26
Lower damper	LWD	Position	X,Y,Z	0.00, 0.00, 0.00	0.20, -3.96, -0.76
Lower spring	LWS	Position	X,Y,Z	0.00, 0.00, 0.00	-1.94, -2.40, -3.52
Steering rod inner	RIB	Position	X,Y,Z	0.00, 0.00, 0.00	-0.02, 0.42, -1.44
Steering rod outer	ROB	Position	X,Y,Z	0.00, 0.00, 0.00	-1.12, 0.48, 2.06
Steering arm[2]	SAH	Position	X,Y,Z	0.00, 0.00, 0.00	**-1.12, 0.48**, -0.08
Sub-frame front	SFF	Position	X,Y,Z	0.00, 0.00, 0.00	*0.00, 0.00, 0.00*
Sub-frame rear	SFR	Position	X,Y,Z	0.00, 0.00, 0.00	*0.00, 0.00, 0.00*
Upper ball joint	UPB	Position	X,Y,Z	0.00, 0.00, 0.00	5.96, 2.00, -3.18
Upper bushing inclination	UPB-BI	Position	X,Y,Z	0.00, 0.00, 0.00	*0.00, 0.00, 0.00*
Upper spring[2]	UPS	Position	X,Y,Z	0.00, 0.00, 0.00	**5.96, 2.00, -3.18**
Wheel center	WLC	Position	X,Y,Z	0.00, 0.00, 0.00	2.98, -0.28, 2.56
Bump stop	-	Clearance	-	0.0	7.7
Rebound stop	-	Clearance	-	0.0	-2.7
Lower link front bush	llf	Stiffness factor	Fx,Fy,Fz Tx,Ty,Tz	1.0, 1.0, 1.0, 1.0, 1.0, 1.0	0.325, *1.0*, *1.0*, 1.385, *1.0*, 1.43
Lower link rear bush	llr	Stiffness factor	Fx,Fy,Fz Tx,Ty,Tz	1.0, 1.0, 1.0, 1.0, 1.0, 1.0	1.875, *1.0*, *1.0*, 1.66, *1.0*, 1.155
Sub-frame front bush[3]	sff	Stiffness factor	Fx,Fy,Fz Tx,Ty,Tz	1.0, 1.0, 1.0, 1.0, 1.0, 1.0	*1.0*, 1.1, *1.0*, *1.0*, *1.0*, 0.975
Sub-frame rear bush[3]	sfr	Stiffness factor	Fx,Fy,Fz Tx,Ty,Tz	1.0, 1.0, 1.0, 1.0, 1.0, 1.0	0.8, 0.8, *1.0*, *1.0*, *1.0*, 0.8
Upper ball joint bush	upb	Stiffness factor	Fx,Fy,Fz Tx,Ty,Tz	1.0, 1.0, 1.0, 1.0, 1.0, 1.0	1.3, 0.835, *1.0*, *1.0*, *1.0*, *1.0*
Steering column bush	scb	Stiffness factor	Tz	1.0	*1.0*
Strut flex bush	-	Ratio	-	0.00	-1.32
Anti-roll bar	ARB	Thickness	Outer radius	0.0	1.6
Steering arm	SAR	Thickness	Outer radius	0.0	-3.36

1: All values except stiffness factors (which are dimensionless) are presented in mm.

2: At least partly depending on other hardpoint position (values written in bold font are dependent).

3: Sub-frame bushings are changed symmetrically on the left and right side of the model.

Note: Due to confidentiality most of the baseline values are set to zero in the public version of the report. All variables were not changed in this correlation (values written in italic font are constant).

Appendix B – Investigated suspension characteristics

Characteristic:	Response:	Load case:	Unit:	Objective:	Constraint:
Static toe	Toe angle	Static equilibrium	deg	Yes	Yes
Static camber	Camber angle	Static equilibrium	deg	Yes	Yes
Static caster	Caster angle	Static equilibrium	deg	Yes	Yes
Bump steer	Toe angle	Vertical motion	deg/m	Yes	Yes
Camber compensation	Camber angle	Vertical motion	deg/m	Yes	Yes
Caster compensation	Caster angle	Vertical motion	deg/m	Yes	No
Ride rate (stiffness)	Tyre load	Vertical motion	N/mm	Yes	No
Roll steer	Toe angle	Roll motion	deg/m	**No**	**No**
Camber compensation	Camber angle	Roll motion	deg/m	**No**	**No**
Roll rate (stiffness)	Tyre load	Roll motion	N/mm	**No**	**No**
Drive steer	Toe angle	Drive force	deg/kN	Yes	Yes
Longitudinal stiffness	Wheel center	Drive force	mm/kN	Yes	Yes
Load transfer (anti-lift)	Tyre load	Drive force	%	Yes	**No**
Brake steer	Toe angle	Brake force	deg/kN	Yes	Yes
Wind-up stiffness	Caster angle	Brake force	deg/kN	Yes	Yes
Longitudinal stiffness	Wheel center	Brake force	mm/kN	Yes	Yes
Load transfer (anti-dive)	Tyre load	Brake force	%	Yes	**No**
Lateral force steer	Toe angle	Lateral force	deg/kN	**No**	**No**
Camber compliance	Camber angle	Lateral force	deg/kN	Yes	Yes
Wheel center variation	Wheel center	Lateral force	mm/kN	Yes	Yes
Lateral force steer	Toe angle	Lateral force opp.	deg/kN	Yes	Yes
Camber compliance	Camber angle	Lateral force opp.	deg/kN	Yes	Yes
Wheel center variation	Wheel center	Lateral force opp.	mm/kN	Yes	Yes
Lateral force steer	Toe angle	Lateral force offset	deg/kN	**No**	**No**
Camber gain	Camber angle	Lateral force offset	deg/kN	Yes	Yes
Wheel center variation	Wheel center	Lateral force offset	mm/kN	Yes	Yes
Steering ratio	Toe angle	Steering input	deg/deg	Yes	No

Note: Characteristics with no objectives or constraints have no active targets and are only correlated passively. This might be due to unclear K&C target data or due to limitations in the vehicle model- or simulations.

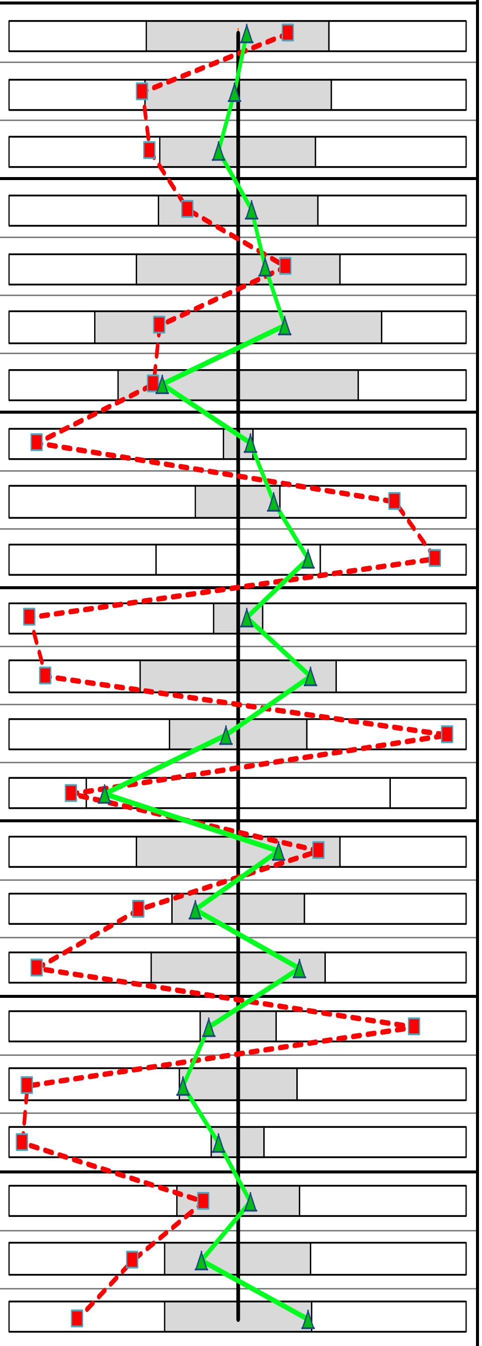
Appendix C – Suspension parameter influence

		KINEMATICS								*COMPLIANCES*												
		Vertical motion				Roll motion			Steer	Lateral force			Lateral force off			Drive force			Brake force			
		Camber change	Bump steer	Static caster	Caster change	Camber change	Roll steer	WC lat. disp	Steering ratio	Camber change	Toe change	WC lat. disp.	Camber change	Toe change	WC lat. disp.	Drive steer	Anti-lift	WC long. disp.	Brake steer	Wind-up	Anti-dive	WC long. disp.
HARDPOINTS	LLR x	0%	0%	-1%	-2%	20%	0%	2%	0%	0%	0%	-7%	0%	0%	-8%	9%	-2%	-8%	8%	8%	2%	-8%
	LLR y	1%	0%	-1%	3%	0%	0%	0%	0%	0%	0%	0%	0%	8%	0%	9%	2%	1%	8%	0%	-3%	0%
	LLR z	-12%	-10%	2%	-97%	20%	-10%	6%	0%	0%	0%	0%	0%	8%	0%	0%	-71%	0%	3%	0%	100%	0%
	LLF x	2%	-2%	-2%	-1%	0%	-3%	-3%	0%	0%	0%	29%	0%	0%	31%	23%	0%	10%	27%	-8%	1%	9%
	LLF y	-4%	3%	0%	-4%	20%	3%	5%	0%	0%	0%	0%	0%	0%	0%	0%	-4%	-6%	0%	6%	4%	-6%
	LLF z	100%	-76%	-3%	100%	-100%	-77%	-100%	5%	0%	0%	14%	0%	0%	8%	0%	100%	0%	0%	0%	-98%	0%
	LWB x	-5%	7%	-95%	-37%	0%	23%	8%	-85%	-67%	-91%	-50%	-50%	-67%	-100%	-41%	1%	-4%	-43%	0%	-5%	-2%
	LWB y	5%	-2%	1%	2%	0%	3%	-3%	-10%	0%	0%	0%	0%	8%	0%	-14%	5%	7%	-14%	-7%	-6%	7%
	LWB z	-79%	79%	-6%	-8%	80%	80%	84%	0%	-67%	-9%	-14%	-50%	-8%	-23%	5%	-29%	-3%	3%	5%	1%	-4%
	WLC x	-3%	1%	-5%	-13%	0%	-13%	-3%	0%	33%	100%	21%	25%	100%	69%	0%	-7%	0%	0%	0%	11%	0%
	WLC y	-2%	0%	0%	-2%	20%	-7%	-2%	5%	0%	0%	0%	0%	-8%	0%	5%	-4%	-1%	3%	1%	5%	-1%
	WLC z	0%	0%	0%	0%	0%	0%	14%	0%	33%	18%	21%	25%	8%	23%	0%	4%	5%	-3%	-2%	-4%	5%
	LWD x	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	11%	0%	0%	0%	10%	0%
	LWD y	-86%	-8%	0%	0%	80%	-10%	-16%	0%	0%	0%	0%	0%	0%	0%	0%	3%	0%	0%	0%	1%	0%
	LWD z	13%	1%	0%	0%	-20%	0%	2%	0%	0%	0%	-7%	0%	8%	-8%	0%	0%	0%	0%	0%	0%	0%
	UPB x	9%	1%	100%	46%	0%	-13%	0%	-15%	33%	27%	-14%	50%	42%	-23%	-5%	-3%	0%	-3%	0%	-17%	0%
	UPB y	69%	7%	1%	1%	-60%	3%	13%	0%	0%	0%	-7%	0%	0%	0%	0%	-1%	1%	0%	0%	-1%	0%
	UPB z	-15%	-2%	7%	6%	20%	-3%	-3%	0%	33%	0%	-7%	0%	0%	0%	0%	-1%	-1%	0%	-2%	-1%	0%
	LWS x	0%	-2%	2%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	8%	0%	-2%	0%	0%	0%	-3%	0%
	LWS y	19%	2%	0%	0%	-20%	3%	2%	0%	0%	0%	-7%	0%	8%	0%	0%	-1%	0%	0%	0%	0%	0%
	LWS z	-10%	-1%	0%	1%	20%	0%	-2%	0%	0%	0%	0%	0%	0%	8%	-5%	0%	0%	0%	0%	0%	0%
	RIB x	0%	1%	0%	-1%	0%	3%	0%	-5%	0%	9%	0%	0%	17%	0%	-45%	-1%	-4%	-43%	0%	1%	-2%
	RIB y	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	8%	0%	-5%	0%	-1%	-5%	0%	0%	0%
	RIB z	37%	100%	1%	-1%	-40%	100%	0%	5%	0%	-9%	-7%	0%	-8%	-8%	9%	-32%	1%	14%	0%	-5%	1%
	ROB x	-2%	-6%	1%	1%	0%	-7%	0%	100%	0%	-45%	-7%	-25%	-92%	0%	45%	2%	4%	51%	0%	0%	2%
	ROB y	0%	-1%	0%	0%	0%	0%	0%	10%	0%	-9%	0%	0%	-17%	0%	5%	0%	1%	8%	0%	0%	0%
	ROB z	-32%	-89%	0%	1%	40%	-87%	0%	-10%	0%	-9%	0%	-25%	0%	8%	-14%	29%	-1%	-14%	0%	4%	-1%
BUSHINGS	upb Fx	0%	0%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-5%	-1%	1%	3%	-4%	-1%	-1%
	upb Fy	10%	1%	0%	0%	60%	-3%	-10%	0%	100%	18%	-57%	100%	17%	-69%	0%	1%	0%	0%	0%	0%	0%
	upb Fz	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	upb Tx	-4%	0%	0%	0%	0%	0%	-2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	upb Ty	-3%	0%	0%	2%	0%	0%	-2%	0%	0%	0%	0%	0%	0%	0%	-5%	2%	1%	0%	-1%	-2%	1%
	upb Tz	10%	1%	0%	0%	60%	-3%	-10%	0%	100%	18%	-57%	100%	17%	-69%	0%	1%	0%	0%	0%	0%	0%
	sff Fx	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	sff Fy	0%	0%	0%	0%	0%	3%	3%	0%	0%	0%	14%	0%	-8%	23%	0%	0%	0%	0%	0%	0%	0%
	sff Fz	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-7%	0%	0%	0%	0%	-1%	0%	0%	0%	1%	0%
	sff Tx	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	sff Ty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	sff Tz	0%	0%	0%	0%	0%	3%	3%	0%	0%	0%	14%	0%	-8%	23%	0%	0%	0%	0%	0%	0%	0%
	sfr Fx	0%	0%	1%	1%	0%	3%	2%	0%	33%	-9%	43%	0%	0%	38%	5%	-1%	3%	3%	-2%	2%	3%
	sfr Fy	0%	0%	0%	0%	0%	0%	0%	0%	33%	9%	36%	0%	8%	38%	0%	0%	0%	0%	0%	0%	0%
	sfr Fz	0%	0%	0%	0%	0%	0%	-2%	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%	0%	1%	-3%	0%
	sfr Tx	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	sfr Ty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	sfr Tz	0%	0%	0%	0%	0%	0%	0%	0%	33%	9%	36%	0%	8%	38%	0%	0%	0%	0%	0%	0%	0%
	llr Fx	2%	-1%	7%	12%	0%	3%	-5%	5%	0%	18%	21%	0%	25%	31%	-100%	29%	100%	-100%	-100%	-42%	100%
	llr Fy	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	llr Fz	0%	0%	0%	-1%	0%	-3%	0%	0%	0%	0%	0%	0%	0%	0%	9%	-1%	-4%	8%	5%	2%	-4%
	llr Tx	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-1%	0%
	llr Ty	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%	-2%	-1%	2%
	llr Tz	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	llf Fx	-2%	1%	-1%	-2%	0%	3%	3%	0%	33%	-45%	100%	25%	-33%	92%	27%	-3%	4%	16%	-2%	3%	3%
	llf Fy	0%	0%	0%	0%	0%	0%	-2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	llf Fz	0%	0%	-1%	-3%	0%	-3%	0%	0%	0%	0%	0%	0%	0%	0%	27%	-6%	-14%	24%	14%	8%	-14%
	llf Tx	1%	0%	0%	1%	0%	0%	-2%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	-1%	0%
	llf Ty	0%	0%	0%	0%	0%	0%	-2%	0%	0%	0%	7%	0%	0%	0%	0%	1%	3%	-3%	-4%	-1%	3%
	llf Tz	1%	0%	0%	1%	0%	0%	-2%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	-1%	0%

Note: A positive value corresponds to a positive change for a positive input (±1mm for hardpoints, ±10% stiffness for bushings. “x” = Position, “Fx” = Stiffness, “Tx” = Rotational stiffness.

Appendix D – K&C correlation results

	Suspension characteristic:	K&C target:	Base-line:	CAE final:	Improvement:	Correlation DNA: (----- = Baseline, ----- = Correlation, ----- = Target value)
Static load	Static toe	1.00	1.11	1.02	82.0 %	
	Static camber	-1.00	-1.16	-1.006	96.5 %	
	Static caster	1.00	0.83	0.96	77.3 %	
Vertical motion	Bump steer	1.00	0.905	1.026	73.0 %	
	Camber change	-1.00	-0.928	-0.96	44.9 %	
	Caster change	1.00	0.918	1.049	40.1 %	
	Ride stiffness	1.00	0.895	0.905	9.5 %	
Drive force	Drive steer	1.00	-3.4	1.267	93.9 %	
	Long. stiffness	1.00	1.564	1.127	77.6 %	
	Load transfer	-1.00	0.263	0,737	64.6 %	
Brake force	Brake steer	-1.00	-2.903	-0.917	95.6 %	
	Wind-up stiff.	-1.00	-1.311	-0.884	62.5 %	
	Long. stiffness	1.00	1.462	0.973	94.2 %	
	Load transfer	-1.00	-1.320	-1.253	20.3 %	
Lateral force	Lat. force steer	1.00	1.157	1.078	50.6 %	
	Camber change	1.00	0.731	0.888	57.5 %	
	Track variation	1.00	0.600	1.227	69.2 %	
Lat.opp force	Lat. force steer	-1.00	1.818	-1.454	83.7 %	
	Camber change	1.00	0.333	0.826	74.1 %	
	Track variation	1.00	-0.932	0.814	90.7 %	
Lat.off.force	Lat. force steer	1.00	0.908	1.033	61.8 %	
	Camber change	1.00	0.744	0.911	65.5 %	
	Track variation	1.00	0.611	1.167	56.3 %	



Note: Data have been normalized to the target values to maintain confidentiality.

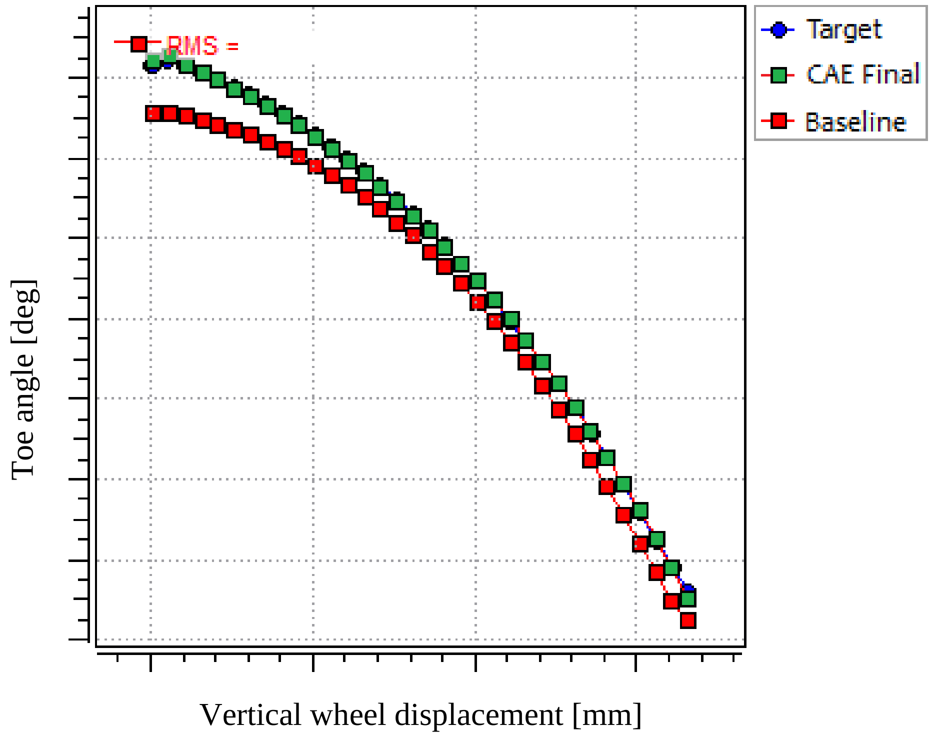
Constraint intervals which are active are marked with grey bars.

Baseline describes the initial characteristics of the model (before correlation) and CAE final is the results for the final correlation of the suspension model.

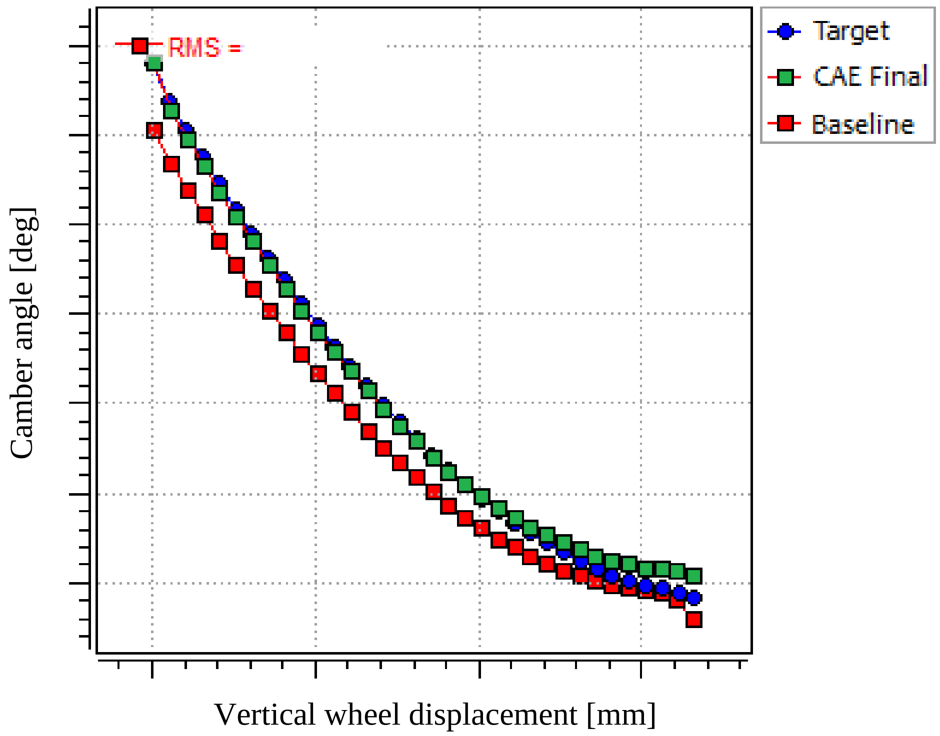
The improvement is described as how much of the initial error that has been reduced (0% = equivalent to baseline value, 100% = equivalent to target value).

Appendix E – Graphs of suspension characteristics

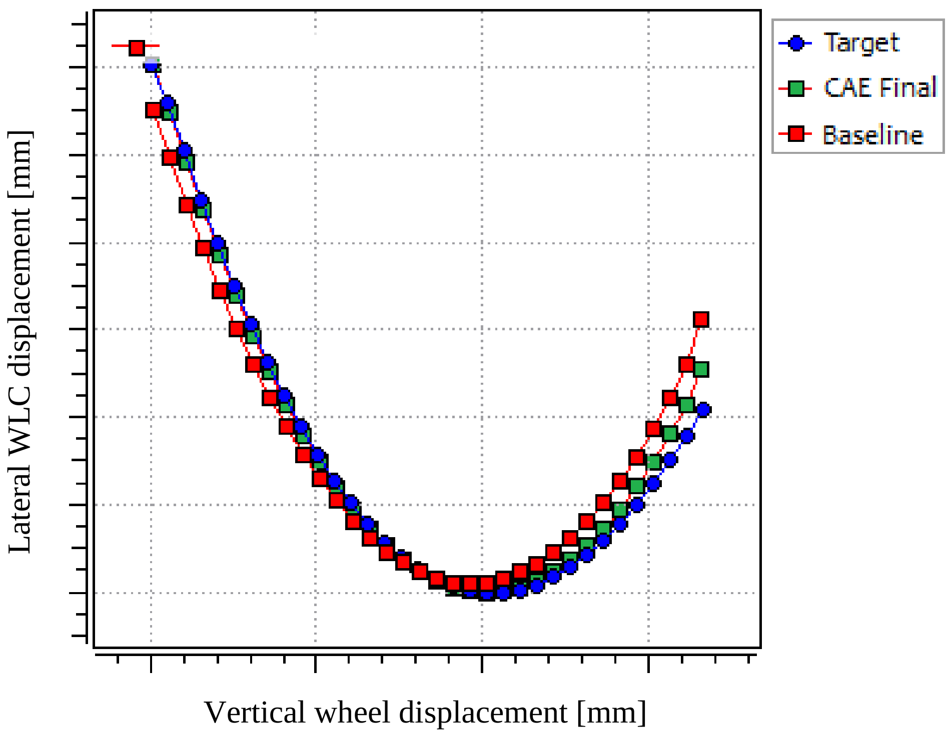
Bump steer



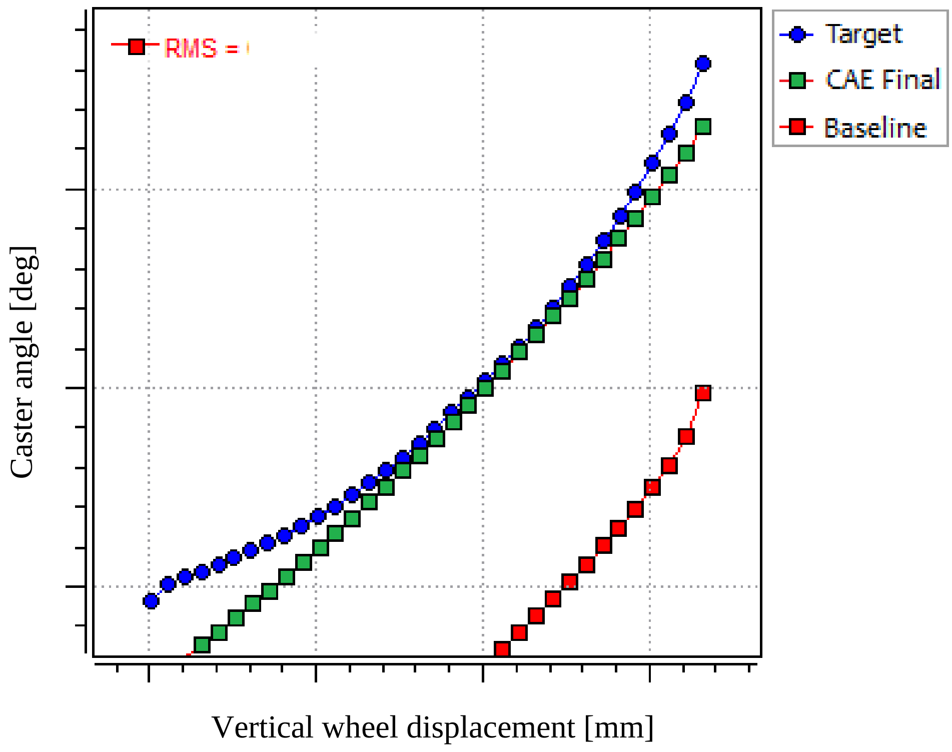
Camber change



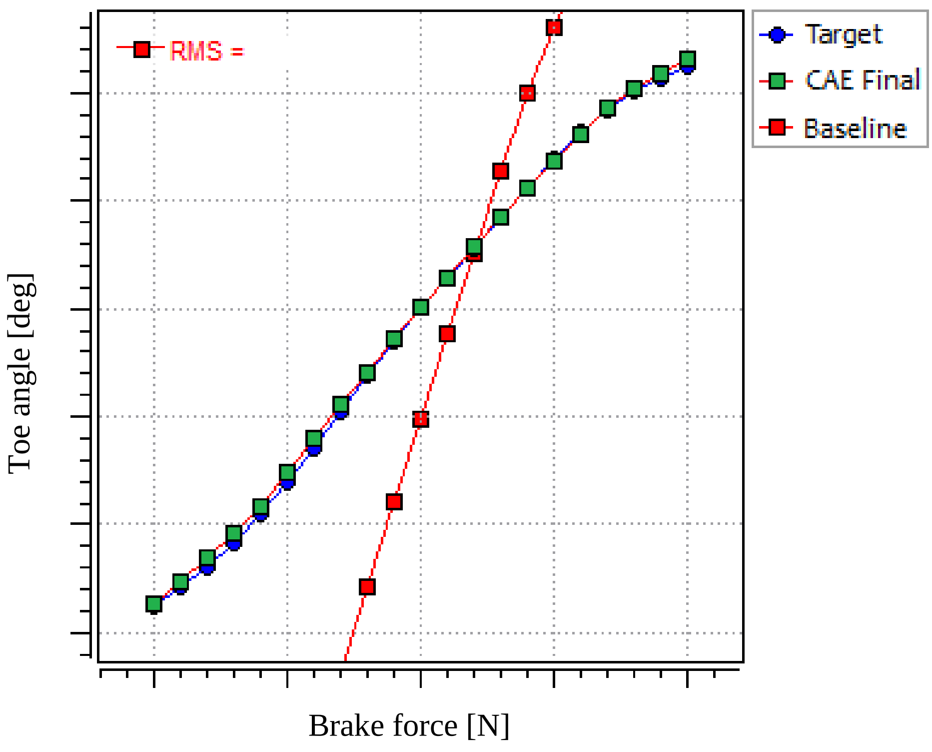
Track variation



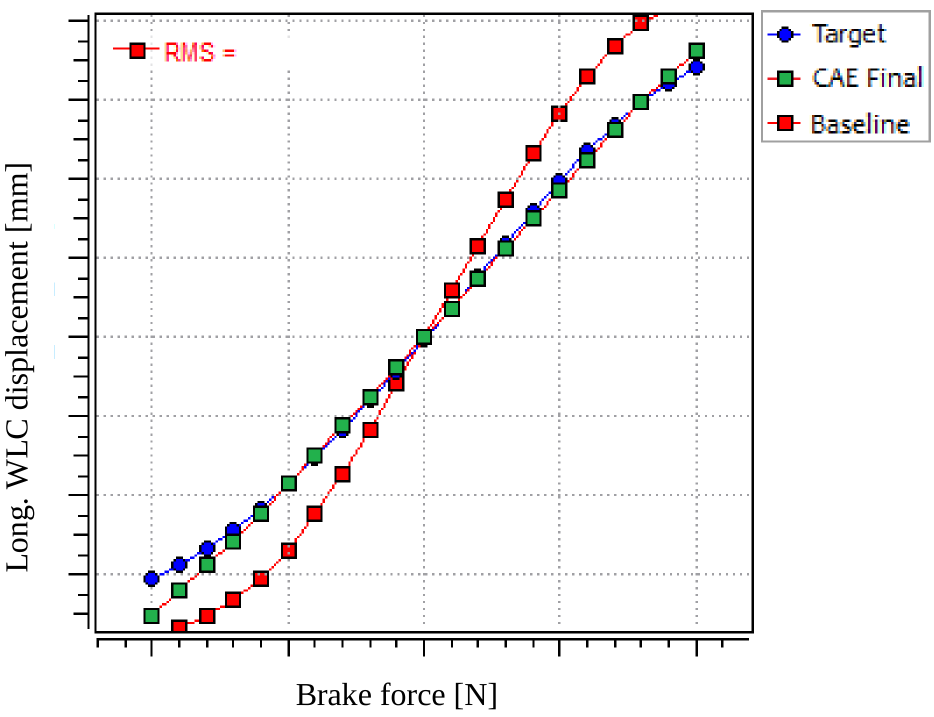
Caster change



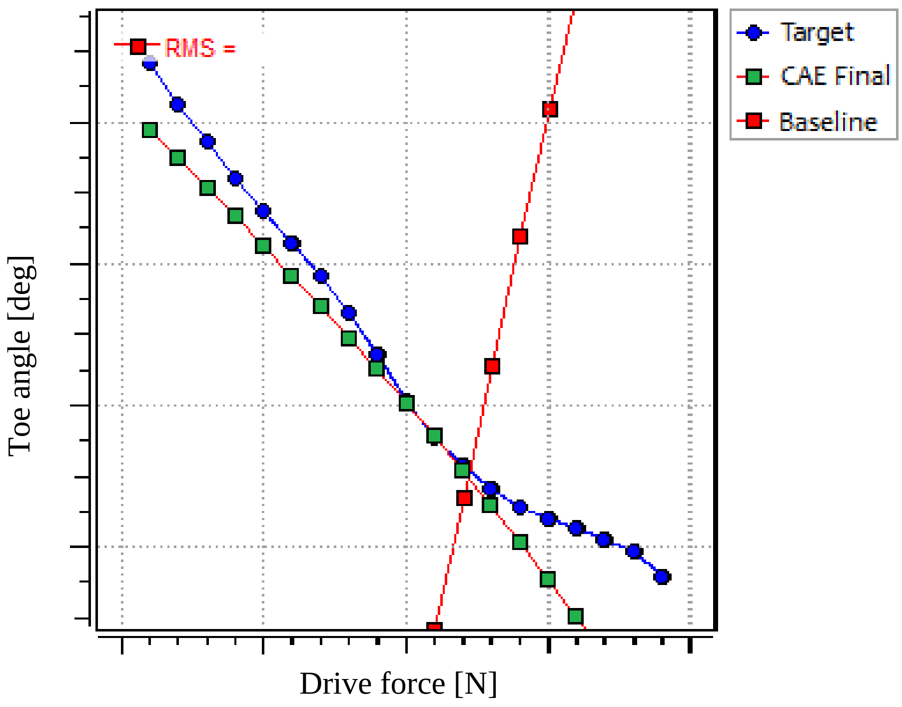
Brake steer



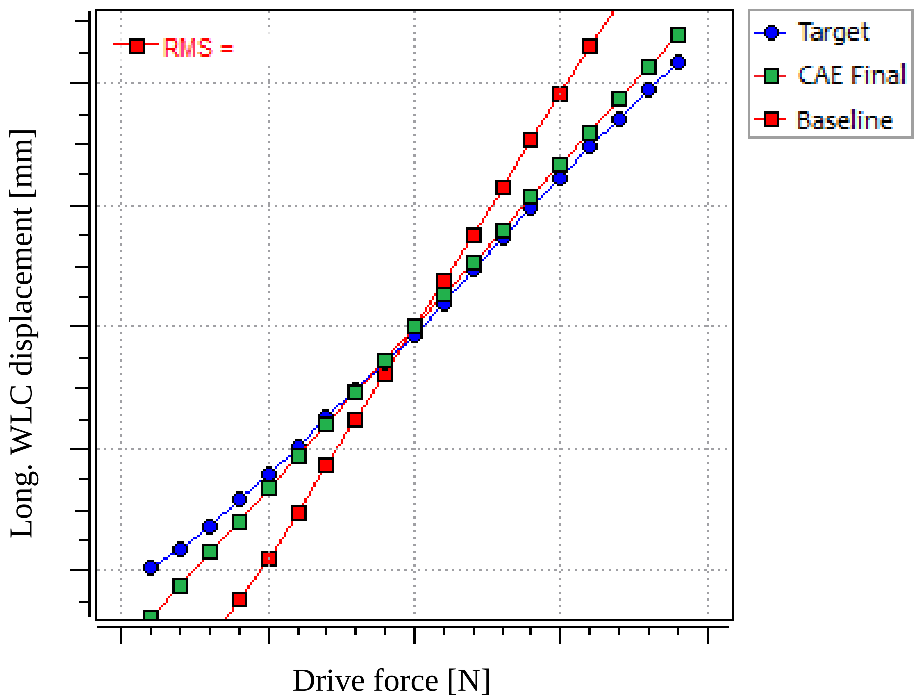
Longitudinal WLC stiffness



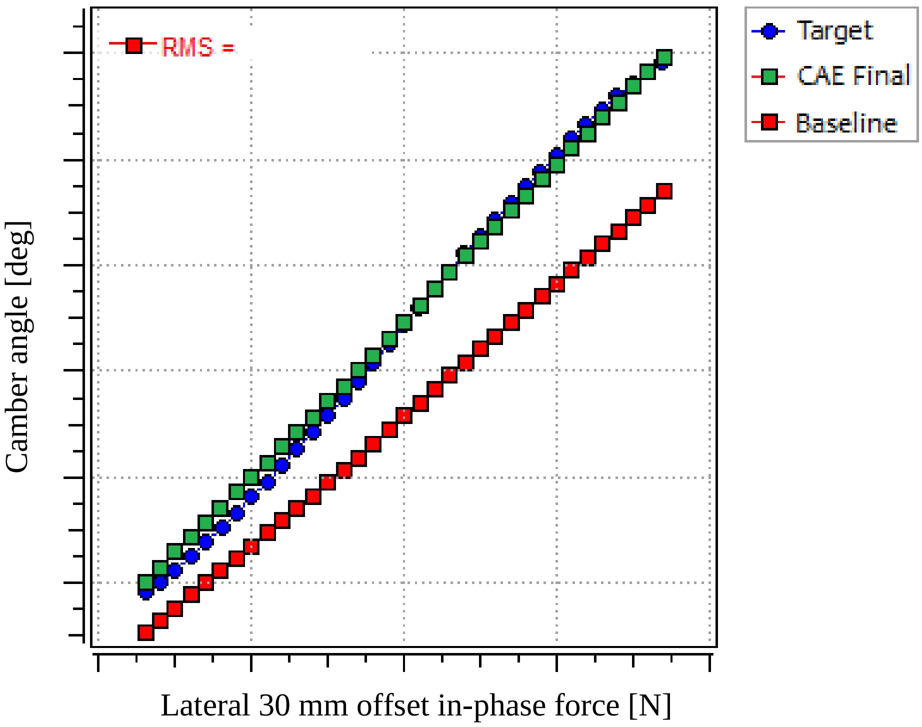
Drive steer



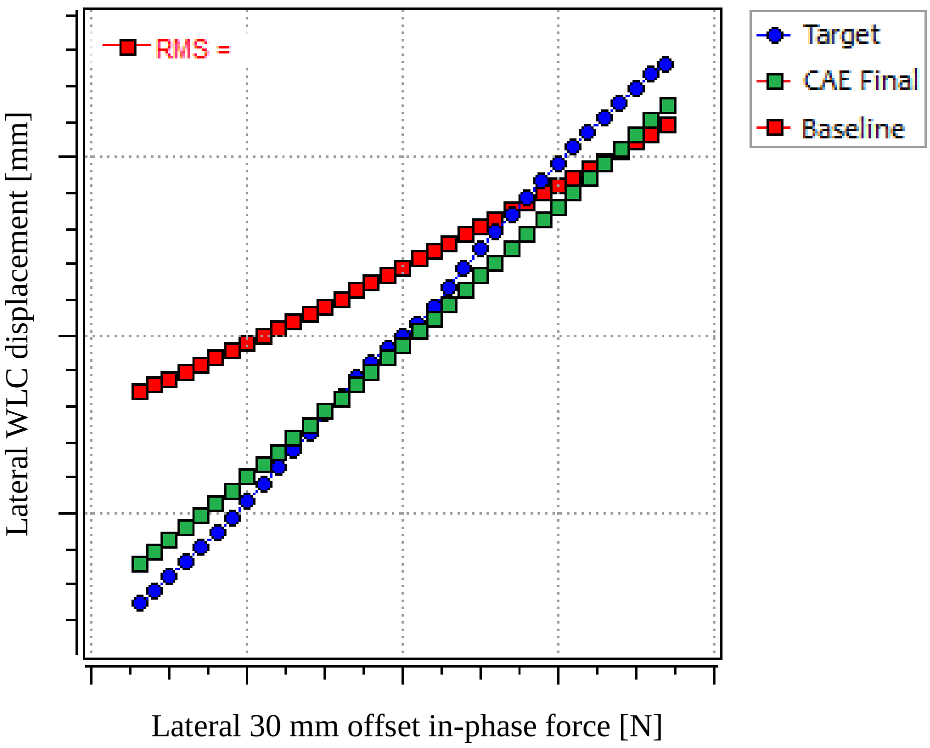
Longitudinal WLC stiffness



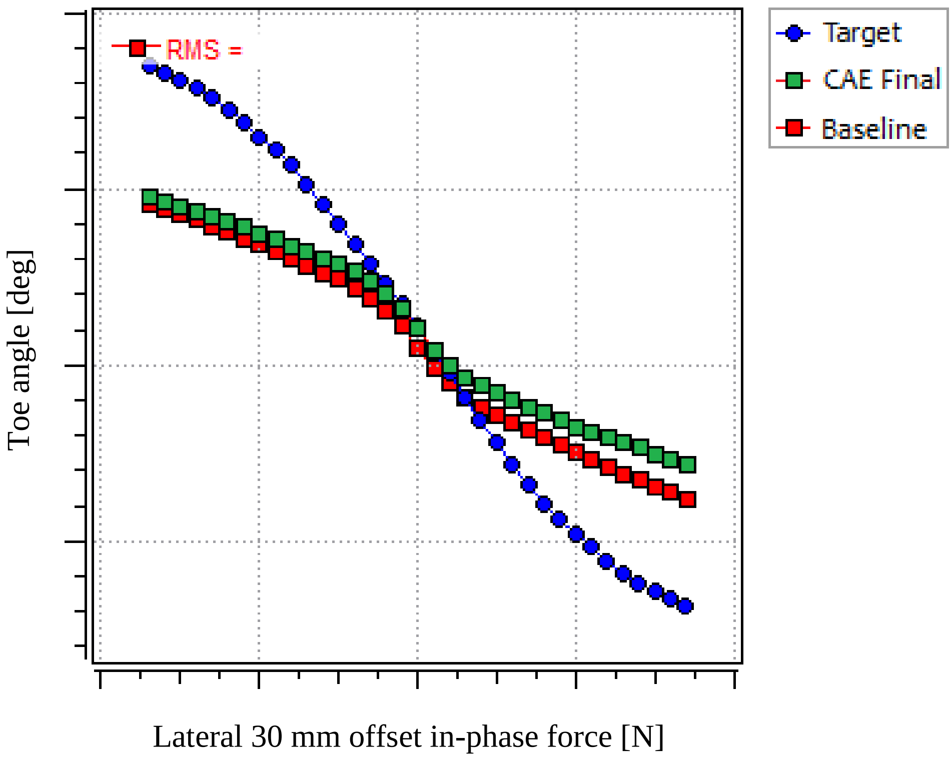
Camber change



Lateral WLC stiffness



Lateral force steer



Appendix F – Simulation scripts

In order to connect the vehicle model in ADAMS/Car and to start simulations in the ADAMS/Solver, bat-scripts have been written to perform the following sequence:

- Start ADAMS/Car in batch mode.
- Load the baseline simulation model
- Make the variable changes
- Run the defined K&C events in the ADAMS/Solver
- Copy the result files to the optimization working directory
- Close ADAMS/Car and exit the evaluation

In addition, the variables and responses have been tagged in the input, and output files for the simulations respectively. During the study, scripts with the following format were executed sequentially in order to use the correlation procedure:

- Run_acar.bat
- Acar_start.bat
- Model_mod.cmd

Due to confidentiality, scripts are not presented in the public version of the report.