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Vehicle Dynamics Simulation Method Development

Master's thesis in Automotive Engineering

JOSEF DAGSTRÖM

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Division of Vehicle Engineering and Autonomous Systems
Vehicle Dynamics Group
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Abstract

Designing a successful car today cannot be done by focusing on one specific area. It is a complex product and has to fulfill targets within many different areas such as safety, vehicle dynamics, durability, noise & vibration, design, and many more. To come up with the best solution, compromises have to be made. Compromises that cannot be done without collaboration between the different areas.
To assure a better multidisciplinary design a method for conceptual design has been developed in this thesis project. Also the effects of flexible components in vehicle handling has been studied. This to enhance the integration between suspension design and other disciplines in early development phases. The thesis defines a number of simulation models and the co-operative work flow between them. All the simulation models, from a bicycle model to a full vehicle simulation model with flexible components, were created, verified and evaluated for their usabilities. The simulation models provided good results compared to existing data and the thesis showed that the most detailed models were not always the necessary ones to use.

Keywords: Method development, work flow, vehicle dynamics, cross attribute data sharing, vehicle simulation models, CAE integration

Sammanfattning

Att designa en framgångsrik bil idag kan inte göras genom att fokusera på ett specifikt område. Bilen är en komplex produkt och måste uppfylla mål inom många olika områden som till exempel säkerhet, fordonsdynamik, hållbarhet, ljud och vibrationer, design och många fler. För att komma fram till den bästa lösningen måste kompromisser göras, kompromisser som inte kan genomföras utan samarbete mellan de olika områdena. För att säkerställa en bättre multidisciplinär design så har en metod för konceptuell konstruktion utvecklats i detta examensarbete. I avhandlingen presenteras även en studie av hur köregenskaper påverkas av flexibla komponenter. Detta för att stärka integrationen mellan hjulupphängning och andra discipliner i tidiga faser av utvecklingen. Ett antal simuleringsmodeller har skapats i detta projekt tillsammans med en beskrivning av arbetsflödet för hur dessa ska användas i arbetet på ett kooperativt sätt. Alla simuleringsmodeller, från en cykelmodell till en fullfordonsmodel med flexibla kroppar, skapades, verifierades och utvärderades för sina användbarheter. Simuleringsmodellerna producerade bra resultat i jämförelse med tillgänglig data och arbetet visade att de mest detaljerade modellerna inte alltid var nödvändiga att använda för simuleringar.

Preface

This thesis was made as a final implement in the Master of Science degree in Automotive Engineering at Chalmers University of Technology. The thesis was carried out at the CAE vehicle dynamics group at Volvo Cars in Torslanda, Sweden from spring to fall 2013. The work was supervised by CAE Engineer Foad Mohammadi and Sergio da Silva at Volvo Cars and the examiner was Adjunct Professor Gunnar Olsson.
I would like to thank my supervisors and examiner for the possibility to do this thesis, for their help and guidance through out the project and especially for great motivation to do the very best out of it. Special thanks to LMS for providing me with their software Virtual lab and big thanks to Iurie Terna at LMS for the support through out the whole thesis. Finally I would like to thank my co-workers at the CAE vehicle dynamics group at Volvo Cars for contributing with help and a great working enviroment.

Göteborg , October 2013
Josef Dagström

Contents

1 Introduction

1.1 Background

Designing a successful vehicle cannot be done by focusing on one specific area. A car is a very complex product and has to fulfill targets within different areas such as vehicle dynamics, safety, noise and vibrations, packaging, durability, production and many more. This is not a one solution. It is a lot of competition between the car manufacturers to earn market shares and the customers demands better solutions. This makes it challenging to design successful cars today. To come up with the best solution for that product compromises has to be made. Compromises that cannot be done without collaboration between the different areas. To assure a better multidisciplinary design the methods used constantly have to evolve. This thesis work develops a method to create and use vehicle dynamic models with a systematic increase in complexity. The idea is to develop models that can be used cross-disciplines. The thesis studies the effects of component stiffness in vehicle handling. The result enhances the integration between suspension design and other disciplines in early phases of the development.

1.2 Deliverables

The aim of this thesis work is to develop a method for designing a vehicle, focusing on vehicle dynamics. The method is formed around a co-operating system of vehicle simulation models with different complexity that works with the same input data. The quality of the methodology is determined by factors such as:

- Work flow. This is the core and back bone of every method. A distinct and elaborate work flow makes the method reliable and easy to work with. Without a good work flow users will find their own ways of solving problems which will impair cooperation and the results of the work.
- Cross attribute data sharing and multi-domain optimization. The competition from other suppliers and the fact that a car is a very complex product makes it challenging to design a really successful car today. The development can not be focused on one specific area, the car needs to be treated as a complete product. This product will at the end be a compromise between all the different disciplines present during the construction and the method needs to enable this cooperation.
- Analysis scalability. The possibility to be able to choose between different simulation models gives the user better opportunities to solve a problem. The problem of having a simple simulation model is the low amount of decisions that can be made from it. The number of outputs are not that many. On the other hand a very complex model will have problems because it will require a lot of input data. Data that may not be available in certain phases of the project and therefore makes the complex model useless.

Another part of the thesis is to identify limitations of the simulation models. The purpose is to get a better understanding of the data that the individual models delivers. For some simulations, a kinematics and compliance (K&C) model with flexible bushings but without flexible components might be enough to get accurate results. This will contribute to a more efficient development process with better results. The users can easier plan their work and be more efficient by knowing what models they can and cannot solve with the given input. The results of the simulations are going to be more accurate since the users can be confident in their simulation models.

This can be reduced to the following deliverables:

- A cooperative system of vehicle simulation models, based on the same car, but with different complexity.
- A method for how to use those simulation models.
- A study on the boundaries of the analytical capabilities of the vehicle simulation models.

1.3 Scope

- A limited amount of flexible components will be introduced to the front- and rear K&C simulation models.
- Simulation models and analysis will be made on one specific car concept.
- A limited amount of driving events will be studied.
- The method development must be able to co-operate with Catia V5.
- The simulation models that will be created and used are:
  - Bicycle and two-track model.
  - Front- and rear K&C model. Both with rigid and flexible components.
  - Full vehicle model with rigid vehicle body.
- Integration with a PLM system will not be included in this work.

2 Method development

The first part of the thesis was to develop the method by organizing the pre-defined simulation models and define how the workflow for using those were going to look like. This work was done without consideration of what software to use in the method. The strength of that approach was that the method could be implemented regardless of what simulation software that later was going to be used. This also gave the possibility to continuing using the same method in the future even if the available software were going to change.

2.1 Method overview

The first task was to create a flowchart for how the simulation models were organized. The plan was to start with a simple bicycle model and build complexity in a systematic way, creating more and more advanced simulation models. The way the simulation models were organized can be seen in Figure 2.1.1. The inputs and outputs visualize the fact that all the simulation models were referring to the same vehicle. Dependent on what simulation model that was used, different amount of data was needed and delivered.

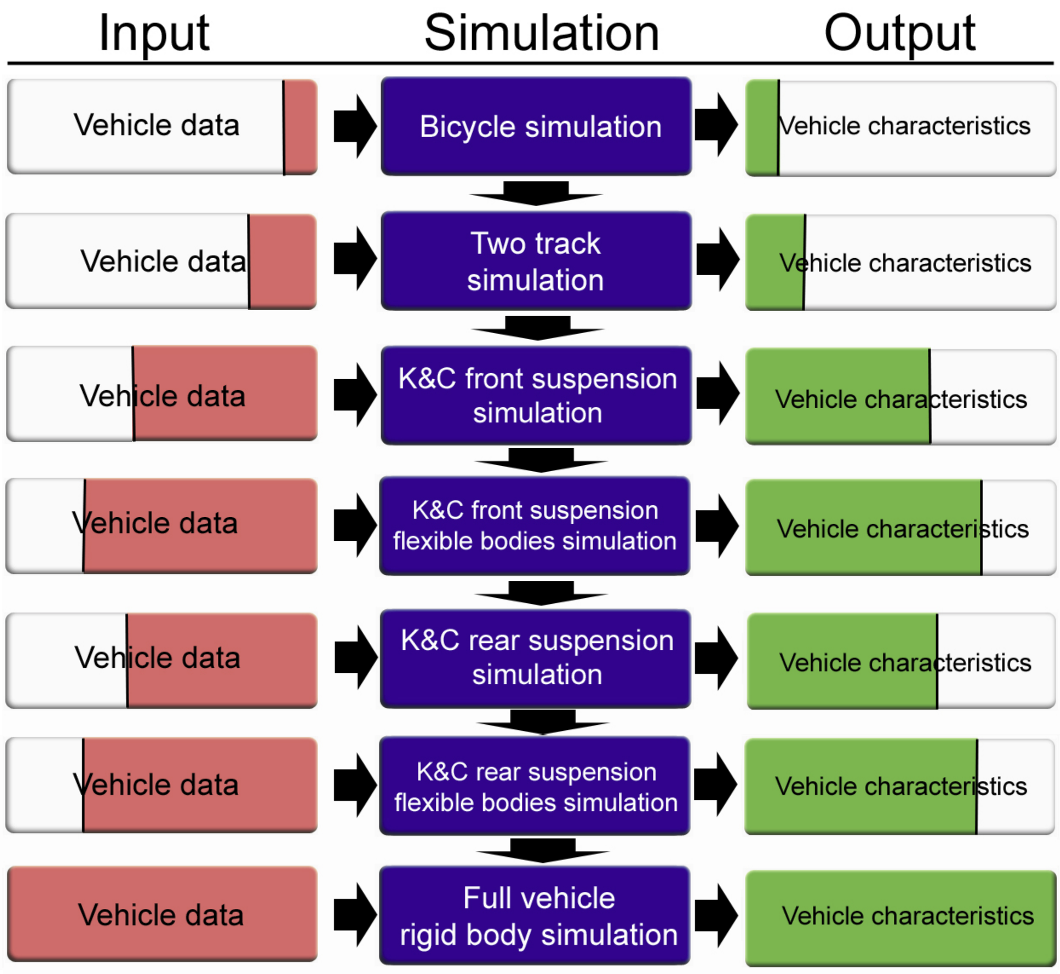

Figure 2.1.1: *An overview of the method*

The purpose behind this organization of simulation models was to have analytical scalability in the method. This made it easier for the user to solve problems due to the variety of models to work with. Simpler models meant that less data were needed and these could therefore be solved, and used, earlier in the project. This variety of simulation models together with an investigation of the boundaries of their analytical capability gave the user the ability to work more efficient and to make earlier and more accurate decisions.

2.2 Workflow

When the overview of the method was defined it was time to dive deeper into the method and define the workflow for each individual simulation model. By looking at Figure 2.1.1 it can be seen that each step contained input data, a simulation model and output data. This can be better seen in Figure 2.2.1. There was a variety of solutions for how to solve this workflow and to find the best way for this method, different solutions were presented and investigated.

Figure 2.2.1: *The workflow of a basic simulation model*

The investigation of the different solutions focused on the input. This was because the input had such a big influence on the simulation result. It was very important that the user always knew what vehicle data that went into the models and, if there was an uncertainty, that it was easy to find. It was also important that there was a connection between the different users inputs to ensure that they were all working with the same vehicle and not with individual configurations of it. These different solutions are presented in section 2.2.1-2.2.3.

2.2.1 Simulation software package

The way a workflow with a simulation software package worked can be seen in Figure 2.2.2. The simulation software handled input data, calculations and output data.

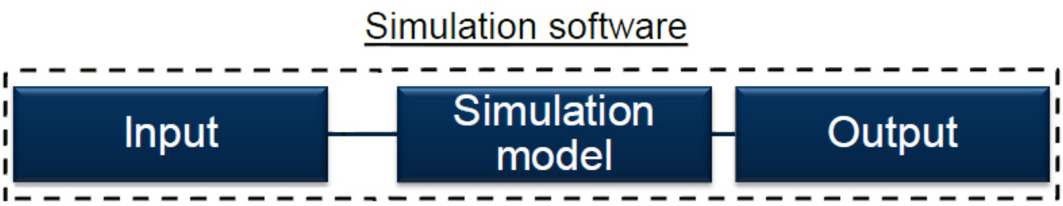

Figure 2.2.2: *A workflow for a solution where a simulation software package is used for all three stages*

- Pros: A simple solution where only one software was needed. The user only had to know one simulation software package to be able to do changes to the model.
- Cons: The vehicle input data was defined purely within the simulation software which was bad for data sharing. Users were changing their vehicle input data within their personal simulation model. Input data that was difficult for other co-workers to take part of. The users needed good knowledge of the software to know where and how to change the input data of the simulation model.

2.2.2 Master file and simulation software package

An illustration of a workflow using a master file can be seen in Figure 2.2.3. The vehicle input data was found and changed both within the simulation software and inside the master file.

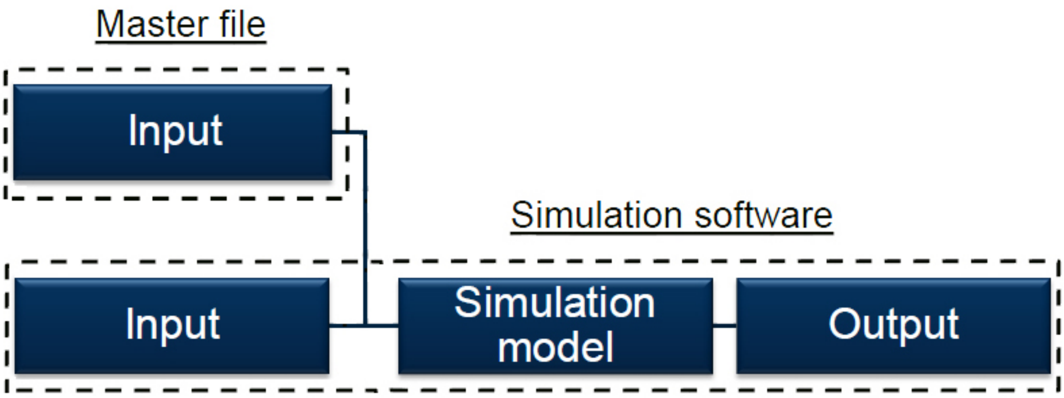

Figure 2.2.3: *A workflow for a solution using the simulation software package for all stages as well as having a master file where input data can be changed*

- Pros: The user was able to chose to change vehicle input data from the master file, a graphical user interface (GUI) created in another software, or from within the simulation software. It did not require any knowledge for how to change vehicle data from within the simulation software package but instead know how to workwith the master file. By sharing the master file, users were keeping track of what their co-workers were doing.
- Cons: It was adding complexity to the method by introducing another software. The solution of having two interfaces for input data always in sync was complex to achieve. It was going to take more time to build the simulation models because of the integration of a master file next to the input interface in the simulation software package.

2.2.3 Data files, master file and simulation software

The workflow for using data files and a master file together with a simulation software can be seen in Figure 2.2.4. In this solution something called vehicle data files were added. The purpose of those were to store all the vehicle data at one common place for everyone in the project to take and to work with as a reference to the master file. The possibility to do changes to the vehicle input data from within the simulation software package was taken away and changes to the simulation model was here only done from within the master file. The simulations were still solved by the simulation software.

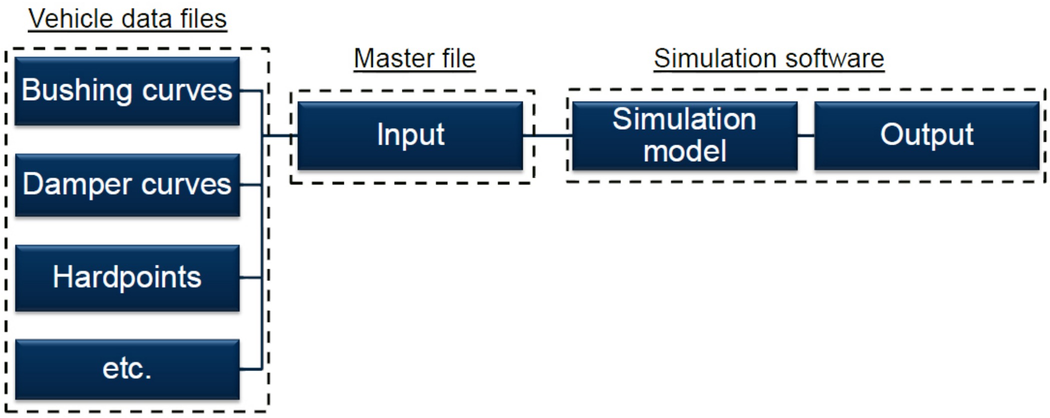

Figure 2.2.4: *A workflow for using the simulation software package for the simulations and post processing and a master file organizing the input data that is taken from global vehicle data files*

- Pros: It had good opportunities for data sharing within the project since all the current vehicle input data were stored at a common, known location. To do changes to the model the user did not have to know the simulation software interface, only the GUI in the master file which was custom build for this method.
- Cons: It added complexity to the method by introducing new softwares for the data files and a master file. It was more time consuming to create the simulation models by the fact that all the data in the master file had to be linked to the simulation model. It was also going to take longer time to set up the simulation models because the vehicle data files were added to the workflow.

2.2.4 Workflow summary

The chosen solution were the one in section 2.2.3 where data files and a master file were added to the workflow. The introduction of those extra functions added complexity to the method and increased the time it took to create the simulation models compared to the fastest way of just using the simulation software package for everything. The gains however was that the user did not have to care about how the model was created or how it worked. The user only had to work with, and do changes in, the master file to provide data to the simulation software. The time it took to create the models increased but the time it took to solve the models was still the same. This solution also affected the cross attribute data sharing and multi-domain optimization in the best way of the different solutions by having the vehicle data stored at one common place for everyone within the project to make use of.

2.3 Master file and data files

When the workflow was set, it was time to continue with the creation of the master file and the data files. The task of the data files was just to contain data. The task of the master file was to organize all the input data in a common GUI, use the vehicle input data files as references and to feed data into the simulation model. It also had to handle more than one configuration and be able to do simple calculations to create curves for example bushing stiffnesses. Other motivations behind the master file were that the user had an interface from which the data in the simulation model quickly and clearly could be identified, and that the user had all the possibilities to change the input data from a user friendly- and evident environment that was fast to learn.

The demands on the software which the master file was going to be created in was therefore:

- Be able to create a GUI that managed the input data to the simulation model.
- Have a user friendly and evident GUI.
- Be able to read data from the data files.
- Be able to do minor calculations.
- Be able to manage configurations.

A software that met all those demands was Microsoft Excel. It was also possible to create a GUI with a programming software such as Python or C++. The problem with a software like that was the time it took to create a GUI. The knowledge of software products were limited and to choose to use a programming software like Python or C++ forced a new time plan for the thesis. There was no time for performing that work in this thesis. Excel was well known, it met all the demands on the software and could therefore solve the problem. It was also a great software to use for the input data files since that data was already shared between different departments in excel format. Due to those reasons Microsoft Excel was chosen to be the software in which the master file and the input files were created. The master file was going to be used for the more complex models. This meant the front- and rear K&C model as well as the full vehicle model. Data that was needed in the master file for the K&C events was the data that was most common to change for a user working with vehicle dynamics. Those were:

- Hard- and orientation points for bushings and joints.
- Damper curves.
- Spring stiffnesses and pretensions.
- Rebound- and bump stop curves and clearances.
- Bushing stiffness curves and damping values.
- Stabilizer radii.
- Toe- and camber angles.

And extra for the front suspension with the steering system:

- Connection- and orientation points for bushings and joints
- Rack data such as compliance and rack/pinion ratio

Data for the components such as masses and inertias were not included in the master file. That data was important when performing K&C events and full vehicle simulations but it was not something that the users actively were able to tweak. This data came from the components and was defined from within the simulation software.

When the data for the master file was chosen, the creation of the master file started. The first step was to create a tab with an overview of all the input data. This can be seen in Figure 2.3.1.

This tab gave the user feedback on which data file that was used for each group of input such as hard points, spring data, damper data etc. It also gave feedback to the user if the data that the master file fed into the

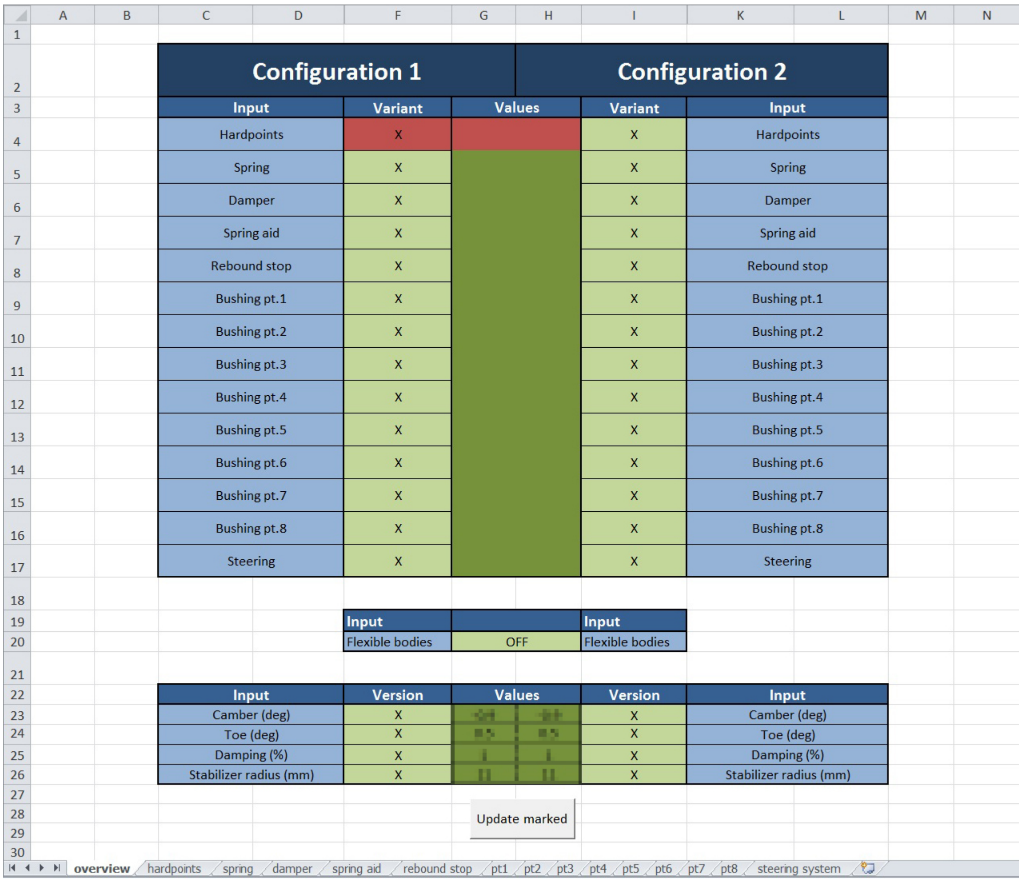

Figure 2.3.1: *The overview tab in the master file. Some of the data is confidential and therefore blurred*

simulations was the same as in the shared data files or if it was modified. That feedback will be explained and is illustrated in Figure 2.3.2.

The variant box, marked as 1, shows what variant of the input data file that is currently used for the hard points. In this case variant X. It can be seen that the box is red. That means that the data fed by the master file into the simulation software is not the same as in the shared data file. The hard points in this master file are thus changed. All the other inputs are using variant X as input as well and the master file is feeding that data unchanged, demonstrated by the green boxes, into the simulation software. Marking 2 gives the user another feedback. This feedback tells the user if the configurations are using the same data for that input or not. The feedback in marking 2 might not look that important when there is only two configurations. But if it instead are fifty configurations it is nice to quickly see if there is any data that might not be the same for all configurations. In this case the only input that is not the same for the two configurations is the hard points data.

The other tabs contained the data fed into the simulation model. One tab for every input in the overview tab. In those tabs with vehicle data the user had a feedback on what specific data that was fed into the simulation model. An example can be seen in Figure 2.3.3 which is the tab for the hard points.

The box marked as 1, in Figure 2.3.3, is red and that means that the value in that box is not the same as the value in the data file for that hard point. It was already shown in the overview tab in Figure 2.3.2 that the hard points data was not the same in the master file as in the data file but in this tab it is more clear what specific data that is changed. All the other boxes are green which means that those values are the same as in the data file. This feedback works in two ways. One is that the user gets feedback when values are changed in the master file. Two is that the user also gets feedback when the input file is changed. This is because the reference values will automatically update when the data file is changed because it is directly linked to the master file. The area marked as 2, Figure 2.3.3, gives the feedback if all values on the row are the same or not. This might again not look very useful for two configurations but if the numbers of configurations increased this feedback will help find the changed value faster. This feedback system works the same way for all tabs.

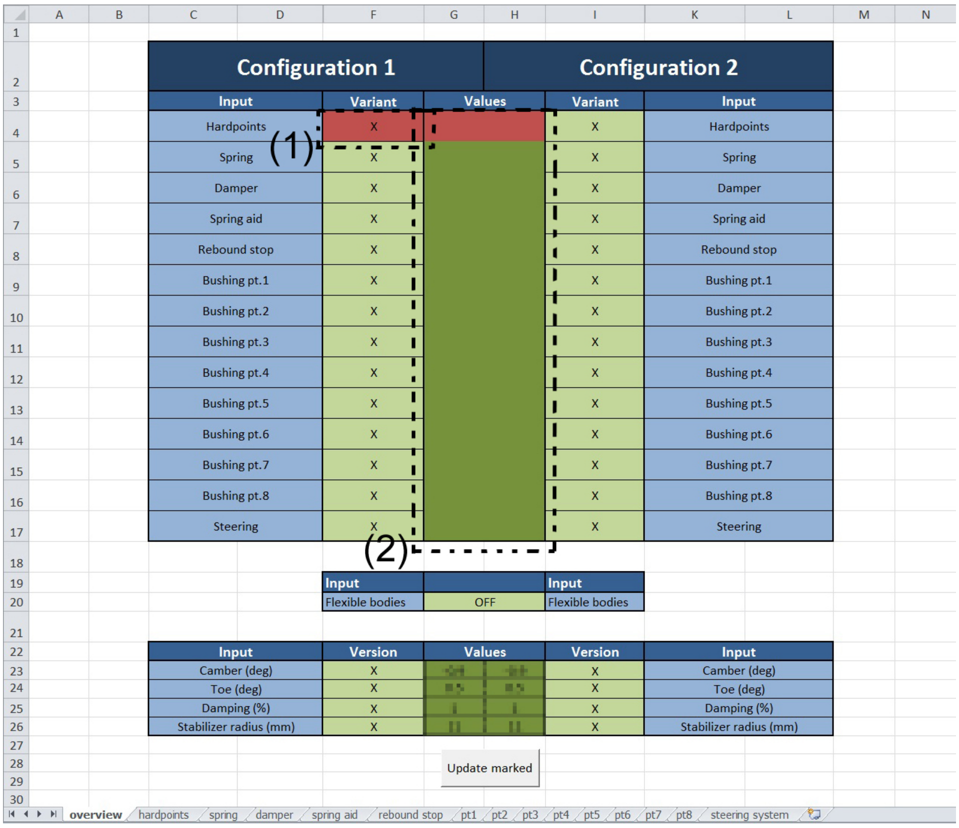

Figure 2.3.2: *The overview tab in the master file with markings of the feedback systems*

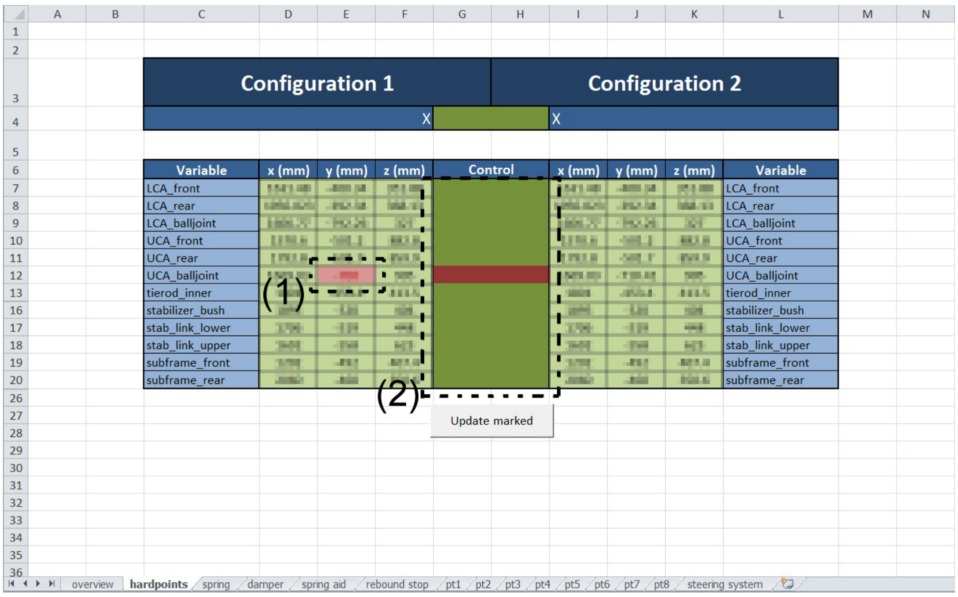

Figure 2.3.3: *The hard points tab in the master file with markings of the feedback systems. The data is confidential and therefore blurred*

3 Creation of simulation models

The overall method was chosen. The overview of the method with data files, master files, simulation models and output data is seen in Figure 2.2.4. The next part of the work was to create the simulation models and make them compatible with the method. The work was done starting with the creation of the simplest model and from there build the other simulation models in the same order that the complexity increased.

There were no restrictions in what software that could be used for the bicycle- and two-track simulation model. For the rigid- and flexible K&C simulation models and the full vehicle model, LMS Virtual Lab (VL) had to be used. This was the Catia V5 based environment that was mentioned in the scope of the project. VL is a 3D finite element, multibody modelling software which can simulate mechanical systems for structural integrity, noise and vibrations, system dynamics and durability.

As mentioned in the scope of the project a limited amount of events were studied for the different models. For the K&C models these were:

- Parallel wheel travel. The wheels are moved vertical and parallel to each other.
- Opposite wheel travel. The wheels are moved vertical and opposite to each other.
- Lateral force. A lateral force is applied on the tire contact patch. The wheel is locked in vertical direction.
- Longitudinal force. A longitudinal force is applied on the tire contact patch. The wheel is locked in vertical direction.
- Steering event. The steering wheel is rotated while the wheel is locked in vertical direction.

And for the full vehicle simulation model:

- Constant radius turn. The vehicle drives a constant turn radius and at the same time increasing the speed very slowly until stability is lost and it cannot drive at the desired radius any more.
- Sine with dwell manoeuvre. The vehicle drives at a constant speed and suddenly gets a steering input. During the steering event the vehicle continue to drive with the same constant speed.

3.1 Bicycle- and two-track model

The first simulation models that were created were the bicycle- and two-track models. These were created to analyse lateral performance of the vehicle and be used to set early design requirements such as wheel base, track width and roll stiffnesses of the vehicle. Because of the small amount of input data no master file was created for these simulation models. The input data was instead found at the same location as the calculations were done and the results were found. The demands on the simulation software that the bicycle- and two-tack simulation model were created in was:

- The user must be able to change the input data.
- Be able to perform calculations.
- Be able to show graphs and report data.
- Be able to communicate with the vehicle data files.

The interface that was chosen to build these simulation models in was Excel. Another software that fulfilled the demands and was able to solve this was Matlab. By using Matlab it was easier to do matrix calculations but the connection to the vehicle data files was not as good as for Excel. Since the connection and collaboration between the simulation models was more important than how easy it was to create the calculations, Excel was chosen. With Excel there was a good connection to the already created vehicle data files since they also were created in Excel. The usage of Excel did also ensure that the complexity of the method did not increase by introducing more softwares. By using Excel, the work and thoughts behind the master file could be used here as well as a base line for the GUI in these simulation models. Because of the low complexity and similarities of the simulation models it was decided to have them in the same interface. This was solved by creating each one of them in a specific tab in Excel.

3.1.1 Bicycle model

This model was created to perform simple calculations to present lateral behaviour of the vehicle. Equation (1) was used to calculate the steer angle as a function of vehicle parameters and the curvature of a constant radius turn at steady state, constant speed.

$$\delta = \frac{L}{R} + \left(\frac{N_f}{C_{\alpha f}} - \frac{N_r}{C_{\alpha r}}\right) \times \frac{V_x^2}{g \times R} = \frac{L}{R} + K_{us} \times \frac{V_x^2}{g \times R} \tag{1}$$

More that was calculated from this model was the understeer coefficient which was calculated with equation (2).

$$K_{us} = \frac{N_f}{C_{\alpha f}} - \frac{N_r}{C_{\alpha r}} = \frac{\mathrm{d}(\alpha_f - \alpha_r)}{\mathrm{d}a_y} \tag{2}$$

The understeer coefficient indicates how fast the difference of slip angle in front and rear changes with lateral acceleration of the car and which axle that is controlling the vehicle. A negative understeer coefficient means that the slip angle is increasing more rapidly in the rear than in the front which gives an oversteered behaviour. Positive understeer coefficient instead showes that the vehicle had an understeered behaviour.

Table 3.1.1: Constans for the bicycle model

Constant	Description
δ	steering angle
L	wheel base
R	Turn radius
N_f	Normal load front tire
N_r	Normal load rear tire
$C_{\alpha f}$	Cornering stiffness of front tire
$C_{\alpha r}$	Cornering stiffness of rear tire
V_x	Longitudinal velocity
g	Gravity
K_{us}	Understeer coefficient

3.1.2 Two-track model

The bicycle model was good to, with simple formulas, describe the vehicle lateral behaviour at low speeds. At higher speeds the vehicle was starting to roll and the effect of body roll had to be considered. To get more accurate results of the lateral performance of the vehicle at steady state turning a two-track simulation model was created. This was still a simple model and it had simplifications like linear roll stiffnesses, a fixed roll center, no consideration of camber changes and equal slip angles on the inner- and outer wheel. The model can be seen together with input- and output data in Figure 3.1.1.

The two-track model was created to again evaluate the lateral performance of the vehicle. This model was used to create handling diagrams to evaluate the behaviour the vehicle close to its limits and also again to evaluating the K_{us} in the linear range. The equations (3) to (9) were used to calculate the performance of the vehicle. To create the handling diagram an iterative process was used to find the correct slip angles for the front- and rear axle at a specific lateral acceleration. Equation (9) was used for this.

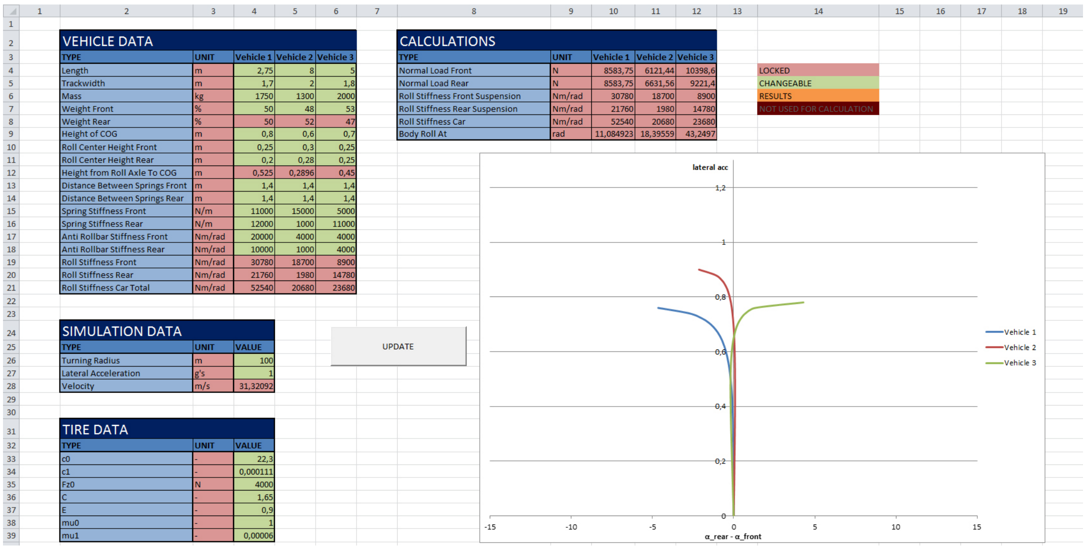

Figure 3.1.1: *The Two-track simulation model with sample data*

$$abs(\phi) = \frac{\frac{m \times V_x^2 \times h_1}{R}}{K_\phi - mgh_1} \tag{3}$$

$$\begin{aligned} \Delta F_{zf} &= \frac{M_f V^2 h_f}{Rt} + \frac{K_{\phi f} \times m \times V^2 \times h_1}{Rt \times (K_\phi - mgh_1)} \\ \Delta F_{zr} &= \frac{M_r V^2 h_r}{Rt} + \frac{K_{\phi r} \times m \times V^2 \times h_1}{Rt \times (K_\phi - mgh_1)} \end{aligned} \tag{4}$$

$$\begin{aligned} F_{zf} &= \frac{N_f}{2} \pm \Delta F_{zf} \\ F_{zr} &= \frac{N_r}{2} \pm \Delta F_{zr} \end{aligned} \tag{5}$$

$$\begin{aligned} \mu_f &= \mu_0 \times (1 - \mu_1 (F_{zf} - F_{z0})) \\ \mu_r &= \mu_0 \times (1 - \mu_1 (F_{zr} - F_{z0})) \end{aligned} \tag{6}$$

$$C_{F\alpha} = C_0 \times F_z (1 - C_1 (F_z - F_{z0})) \tag{7}$$

$$B = \frac{C_{F\alpha}}{\mu \times C \times F_z} \tag{8}$$

$$F_y = \mu F_z sin(Carctan(B\alpha - E(B\alpha - arctan(B\alpha)))) \tag{9}$$

Table 3.1.2: Constants for Two-track model

Constant	Description
ϕ	Roll angle
m	Mass
V_x	Longitudinal velocity
h_1	Vertical distance from COG to roll center axis
R	Turn radius
K_ϕ	Vehicle roll stiffness
g	Gravity
ΔF_z	Wheel vertical load transfer
F_z	Wheel vertical load
μ	Friction coefficient
$C_{F\alpha}$	Wheel cornering stiffness
F_y	Lateral force
α	Slip angle

3.2 Rigid front- and rear K&C suspension model

The rigid front- and rear K&C simulation models were created in VL with an identical approach but as individual simulation models. They were created to simulate the wheel suspension, to evaluate the displacements of, and forces on, the wheel and how toe- and camber angles changed for different analysis events. To create the models, VL's own suspension creation interface was used and the first tab of the interface can be seen in Figure 3.2.1.

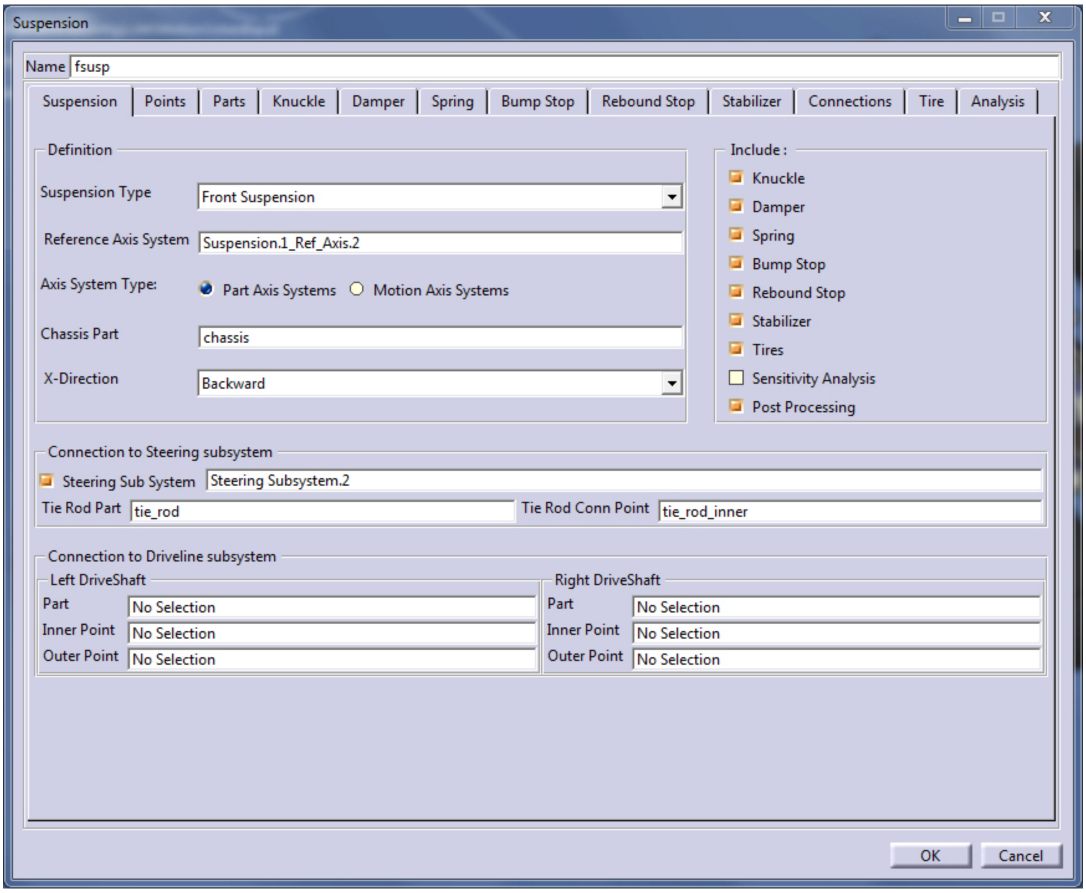

Figure 3.2.1: *The first tab in the suspension creation interface*

The data that was used to create each K&C simulation model with this interface were:

- Hard- and orientation points for bushings and joints.
- Parts including masses.
- Damper curve.
- Spring stiffness and pretension.
- Rebound- and bump stop curve and clearance .
- A simplified anti-roll bar with linear torsional stiffness.
- Connection properties between the parts such as non-linear bushing elements, revolute-, universal- and spherical joints .
- Analysis cases.

The front- and rear K&C simulation models were in this stage ready to be analysed. They were however not fully linked to the master file. The models also had simplified anti-roll bars that had to be exchanged for more realistic ones. New non-linear anti-roll bars were created in VL with beam elements and were added to the two simulation models. To link the master files to the two different simulation models the Catia functions design table and formulas were used. All the data in the master files were first added to the models using the design table function. When the parameters were created in Catia they were linked to the different parameters in VL. To be able to open all the data in the master files in VL, the master files had to be modified. This did not change the functionally of the master files and nothing had to be compromised. A tab with all the data, organized in a specific way, had to be added to each master file to make VL able to read them. When the simulation models contained the non-linear anti-roll bars and was linked to the master files they were ready to be used. The last thing to add to the front K&C was the steering system. The steering system was created using the the steering subsystem interface in VL. The steering system was created by first defining the type of steering system. In this case a system with rack and pinion. The following data was than used to define the steering system:

- Hard- and orientation points for bushings and joints.
- Parts and their masses.
- Connection properties between the parts such as non-linear bushing elements, revolute-, universal- and spherical joints.
- Rack-pinion relation.

When the steering system was fully defined it was connected to the front K&C simulation model with the suspension creation interface and the model can be seen in Figure 3.2.2.

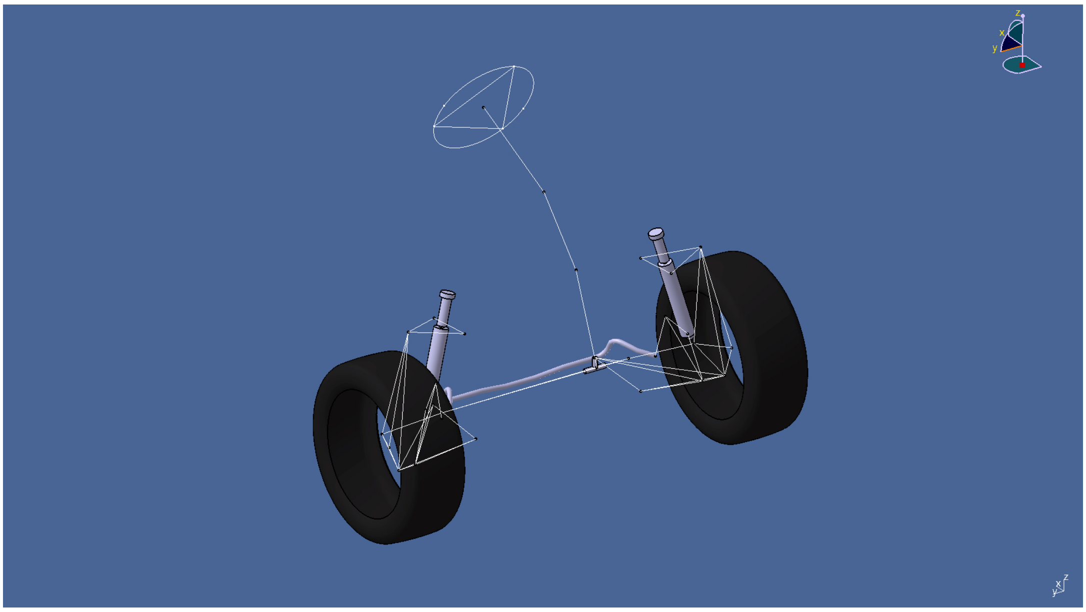

Figure 3.2.2: *A rigid front K&C simulation model*

3.3 Flexible front- and rear K&C suspension simulation models

The next models, in the process of adding complexity to the simulation models, were the front- and rear K&C simulation models with flexible components. To create the flexible K&C simulation models the already created rigid models were used. The new models were performing the same simulations as the rigid K&C models but the introduction of flexible components changed their behaviour. By introducing flexible components the simulation model worked with Finite Elements (FE) models of the components instead of rigid ones. This resulted in new and more results. The components were already created in Catia and since VL is a Catia-based environment the components were opened in the simulation models just by adding the components to the product tree which can be seen in Figure 3.3.1.

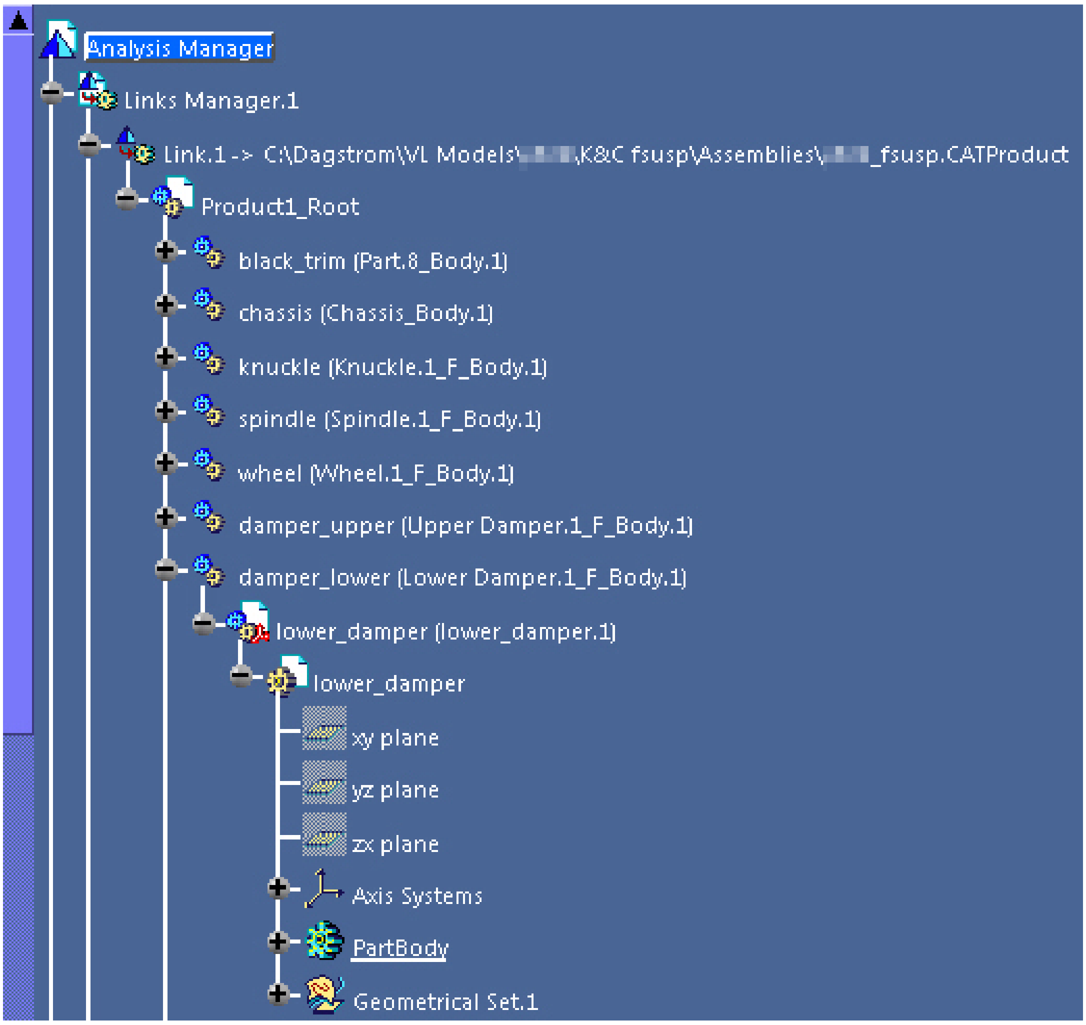

Figure 3.3.1: *A catia product tree*

The benefits of having the components created in Catia was not only that they were opened directly in VL without having to export and import them. This also gave the advantage that when the individual components were updated by the design engineer, the components in the simulation model were updated automatically. When the components were added to the product tree it was time to make them flexible. By chosing the component that was going to be flexible, the generative part structural analysis workbench in VL was opened. In this workbench the support surfaces connecting the component to the hard points were selected. With all the surfaces selected, the mesh and solution set for the component were calculated using Catias' own solver for flexible bodies, Elfini. This was done for every component in the simulation model. When all the components that were added had been turned into flexible components a functionality of having flexible bodies on or off was added to the master file. This can be seen in Figure 2.3.2. Due to confidentiality visualization of the components cannot be made in this report.

3.4 Full vehicle simulation model

The final simulation model that was created was the full vehicle simulation model. This model was used to perform dynamic events such as a constant radius turn, driving in a circle and slowly increasing the speed of the vehicle until it cannot manage to stay at that specific radius any more. This test evaluated the lateral performance and behaviour at the edge of the vehicles capability. The simulation model also performed a sine with dwell manoeuvre where the vehicle first drove straight and then got a steering input. The model was created in VL by first creating a vehicle body with a center of gravity (COG) position, mass and inertia. After that the already created front- and rear suspensions were added to the model. The benefits of having the already created front- and rear suspensions in the full vehicle simulation model were their connection to the master files. The flexible components also had the same connection to design changes. So if design changes were done in the K&C simulation models this showed up in the full vehicle simulation model as well.

When the body and front- & rear suspensions were added they were connected together with the vehicle analysis case in the VL motion workbench which can be seen in Figure 3.4.1 and 3.4.2. In the interface the COG, mass and inertia properties for the total vehicle were added as well which can be seen in Figure 3.4.3. When the properties of the whole vehicle were added, VL recalculated the COG, mass and inertia for the vehicle and updated the earlier created body. The properties were based on the COG, mass & inertia of the full vehicle and front- & rear suspension. A picture of the full vehicle without components can be seen in Figure 3.4.4.

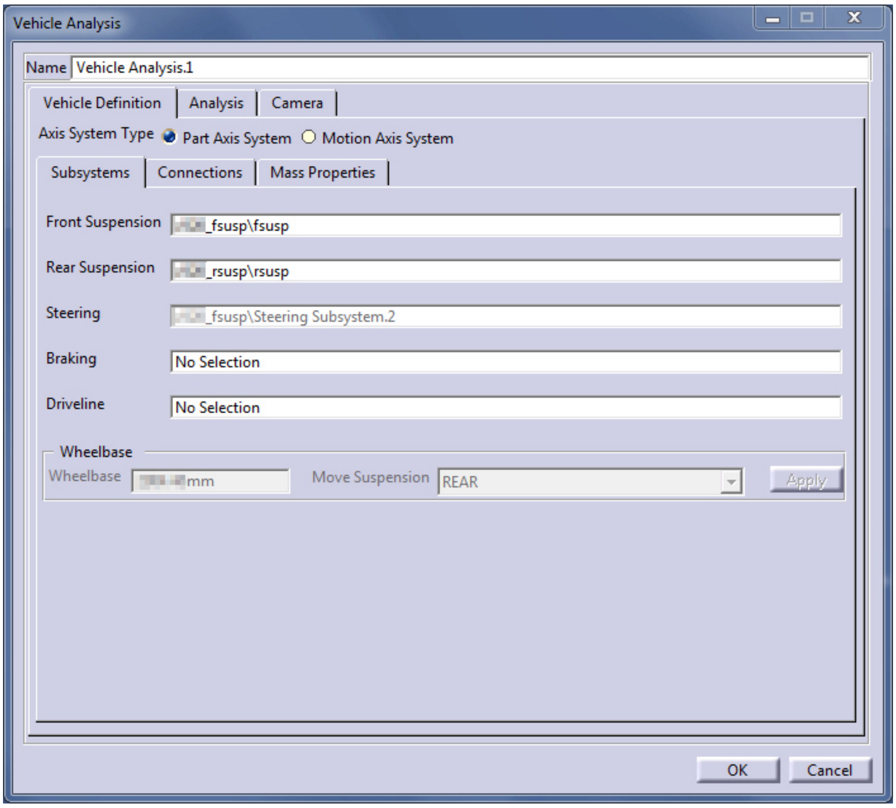

Figure 3.4.1: *The subsystem tab in the vehicle creation interface*

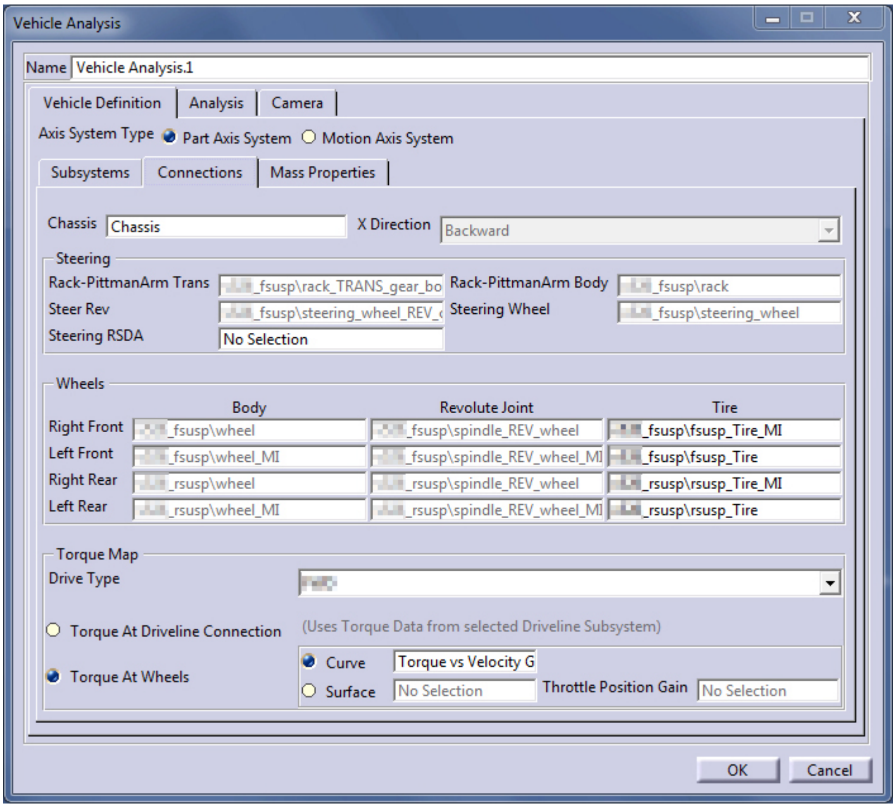

Figure 3.4.2: *The connections tab in the vehicle creation interface*

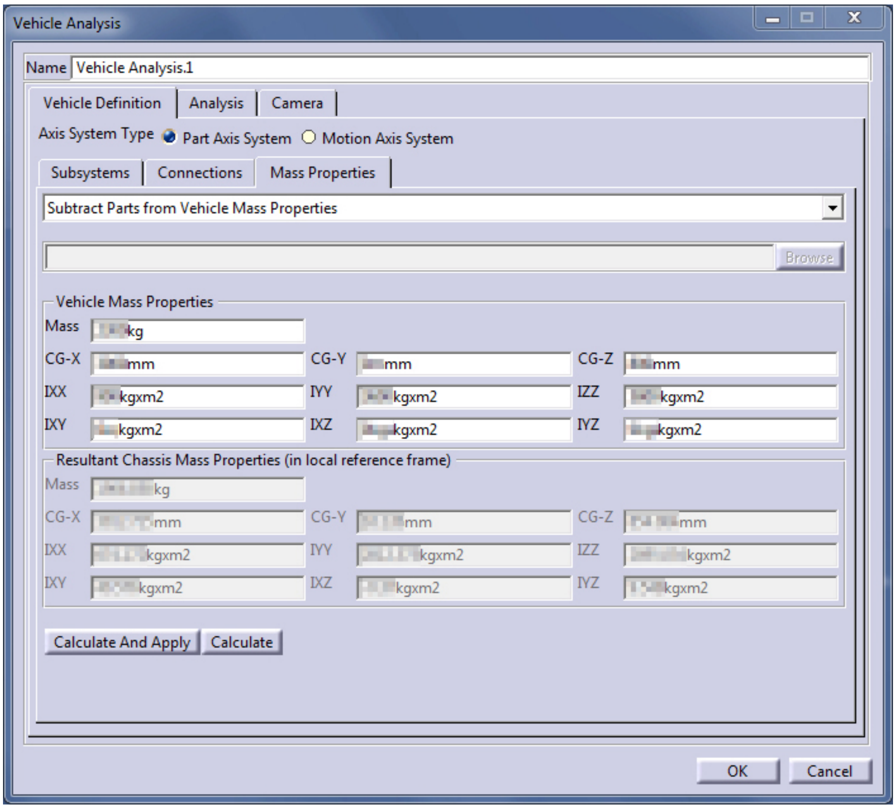

Figure 3.4.3: *The mass properties tab in the vehicle creation interface*

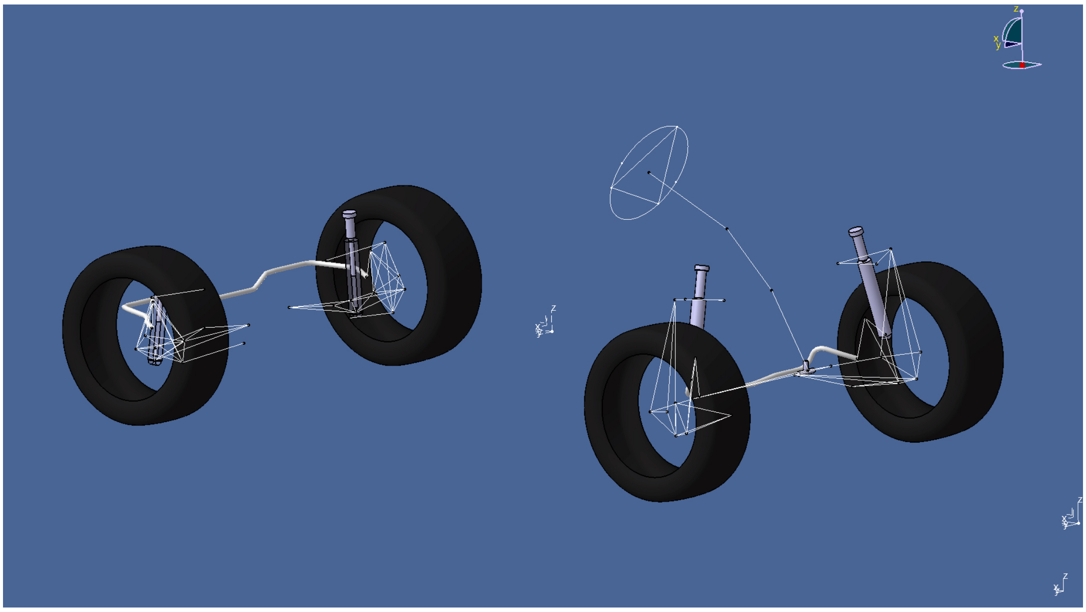

Figure 3.4.4: *The full vehicle model with rigid components*

4 Verification of Simulation Models

To verify the method, a verification that the simulation models worked had to be done as well. The verification was done for all the simulation models but in different ways depending on the model. The bicycle-, two-track- and full vehicle simulation model were verified by changing specific input data to see that the expected results were achieved. The K&C simulation models were compared to results from Volvos current methods. By changing the models it was possible to make the curves for the different methods match even better than what they did but the goal was to make sure that the results from VL were good, not that they were an exact match of the results from Volvo.

4.1 Bicycle and two-track simulation model

Those models were verified by changing the input data and observe how the results changed. Both models reacted the way they where supposed to and two examples can be seen in Figure 4.1.1 and 4.1.2. In the first

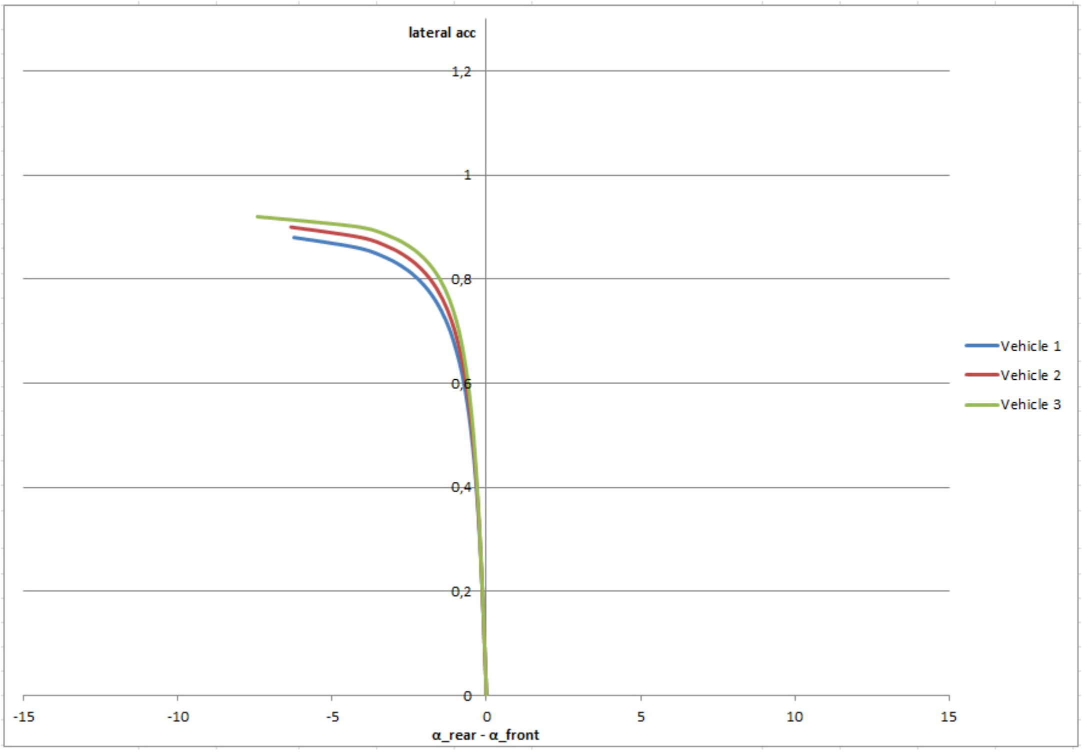

Figure 4.1.1: *Lateral force over slip angles for the two-track model comparing roll stiffnesses in rear*

verification all set-up's had the same data except roll stiffnesses. The vehicles had most of their weight on the front axle. Vehicle 1 was set as a reference, vehicle 2 had increased roll stiffness in the rear and vehicle 3 had both, increased roll stiffness in the rear and decreased in the front. This set-up would make them all understeered and with vehicle 1 scoring the worst- and vehicle 3 the best maximum lateral acceleration. This was also the case and can be seen in Figure 4.1.1. The second verification was also done on three almost identical vehicles. The only thing that was different on them this time was the height of the center of gravity (COG). All vehicles had this time most of their weight distributed on the rear axle. Vehicle 1 had a low COG which increased for vehicle 2 and at last vehicle 3 had the highest positioned COG. This set-up would make all the vehicles oversteered and with vehicle 1 having the best maximum lateral acceleration and vehicle 3 the worst. This was also the case as can be seen in Figure 4.1.2.

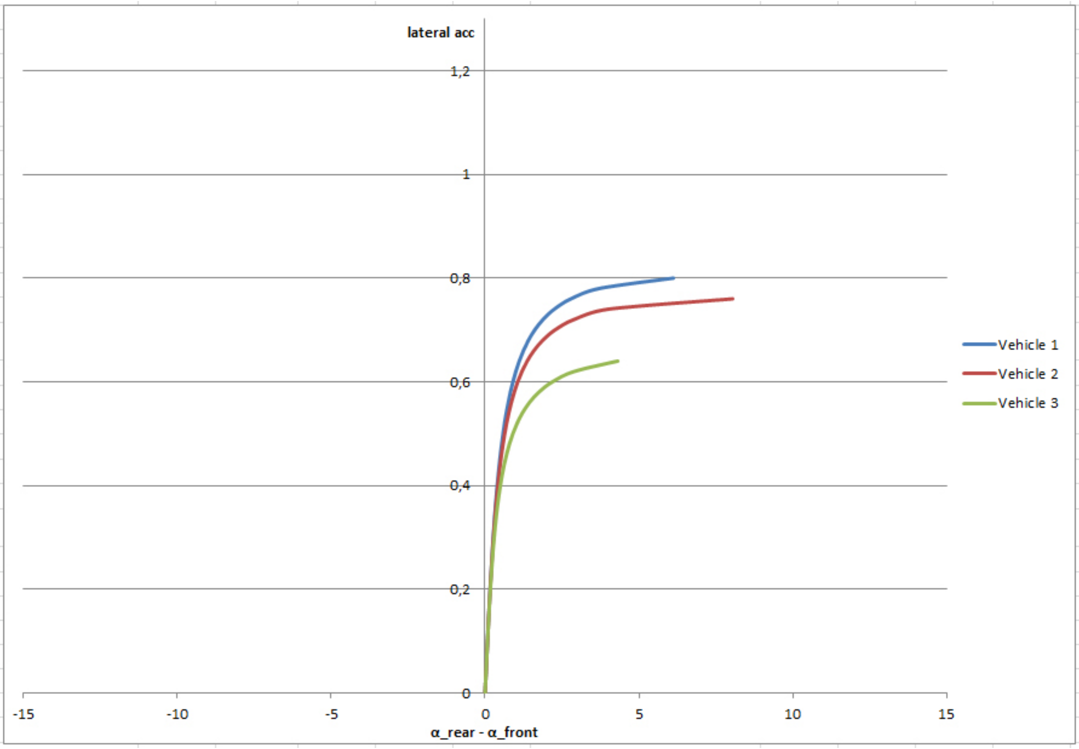

Figure 4.1.2: *Lateral force over slip angles for the two-track model comparing height of the center of gravity*

4.2 Front K&C simulation model

To verify the front K&C model, the results were compared to results supplied by Volvo. Some of the analysis events that was compared can be seen in Figure 4.2.1, 4.2.2, 4.2.3 and 4.2.4. Due to confidential information the scales of the graphs have been taken away.

It can be seen that the front K&C simulation model in VL performs well in comparison to the results supplied by Volvo. In Figure 4.2.1 it can be seen that for the rigid case the two simulation models have almost the same rate of camber change. The compliance of the system in the rigid case comes from the deformation of the bushings and the fact that the rates of camber change is almost equal for the two models gives a good feedback that the bushings are modelled in a similar way. By comparing the camber angle for both the models in Figure 4.2.1 it can be seen that the it differs. This gives a hint that the camber angle at design position might not be exactly the same value for the two simulation methods. For the flexible results it can be seen that the rate of camber change does not match as good as for the rigid case. An explanation for this is that the two simulation models do not use flexible components solved by the same solver, the flexible components in VL are stiffer. In Figure 4.2.3 there is good match between the rigid models. For the flexible models there is a slight difference in the absolute value of the toe angle. This difference is most likely again due to the different solvers of the flexible components. The components in VL showed in Figure 4.2.1 to be a little bit stiffer then the ones in the reference model and this is most likely what is affecting the results here as well.

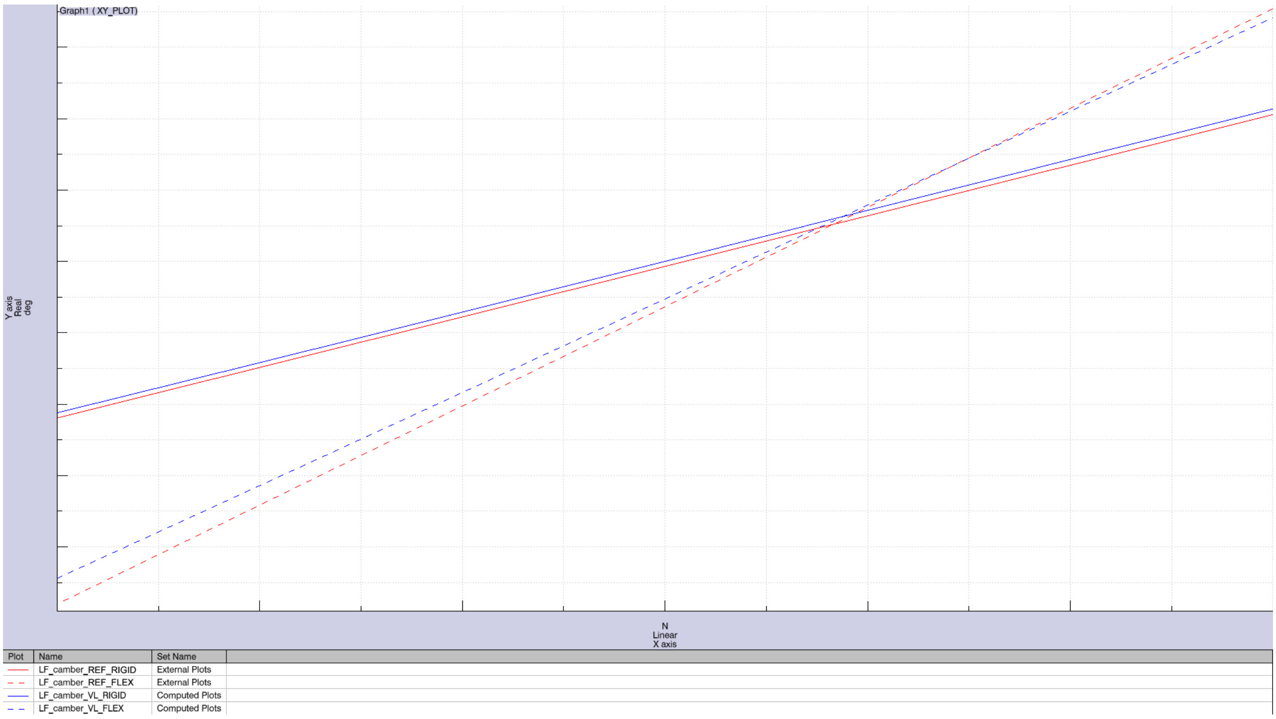

Figure 4.2.1: *Camber angle over lateral force*

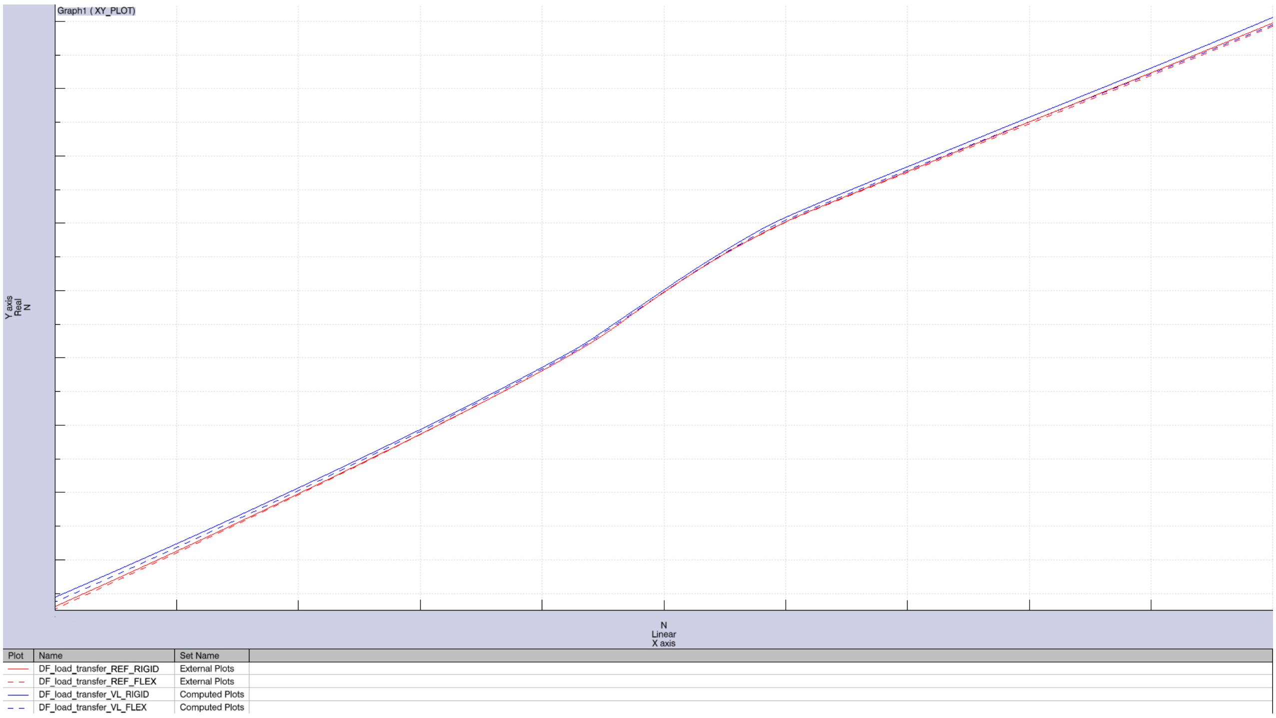

Figure 4.2.2: *Vertical load on wheel over longitudinal force*

Figure 4.2.3: *Toe angle over opposite vertical wheel displacement*

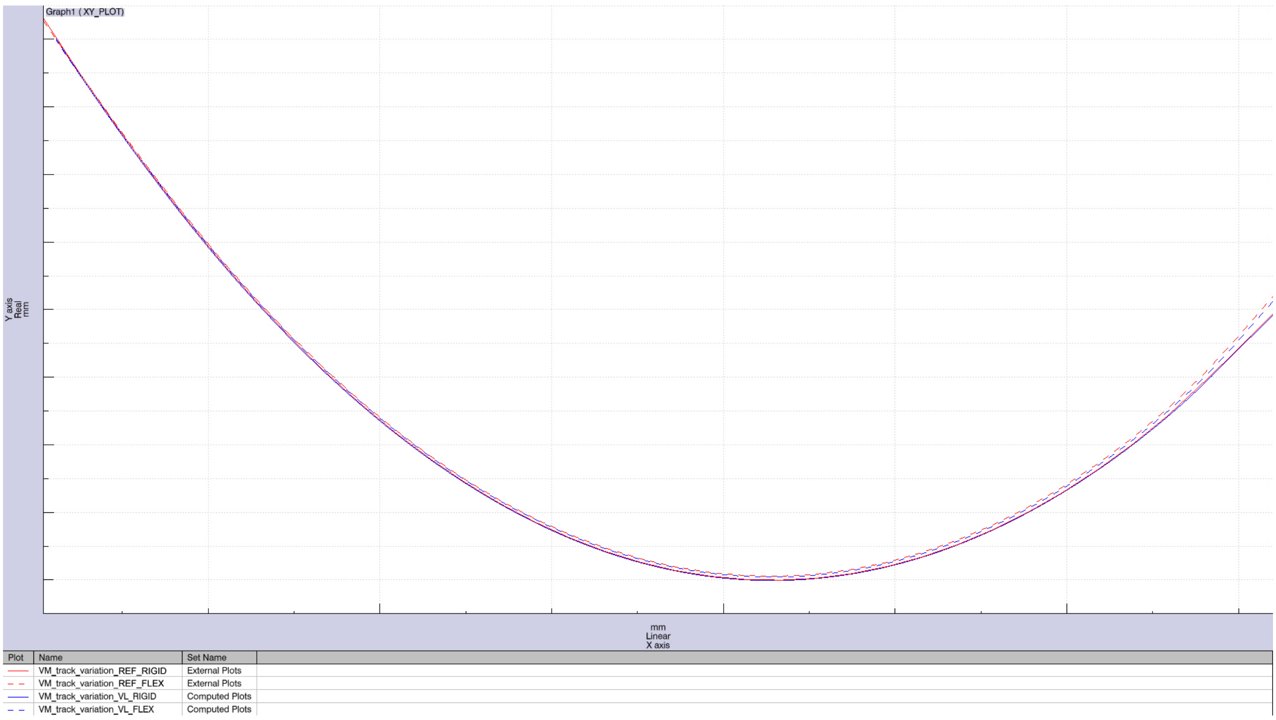

Figure 4.2.4: *Track variation over vertical wheel displacement*

4.3 Rear K&C simulation model

The rear K&C model was also compared to results supplied by Volvo. Some of the analysis events that were compared can be seen in Figure 4.3.1, 4.3.2, 4.3.3 and 4.3.4.

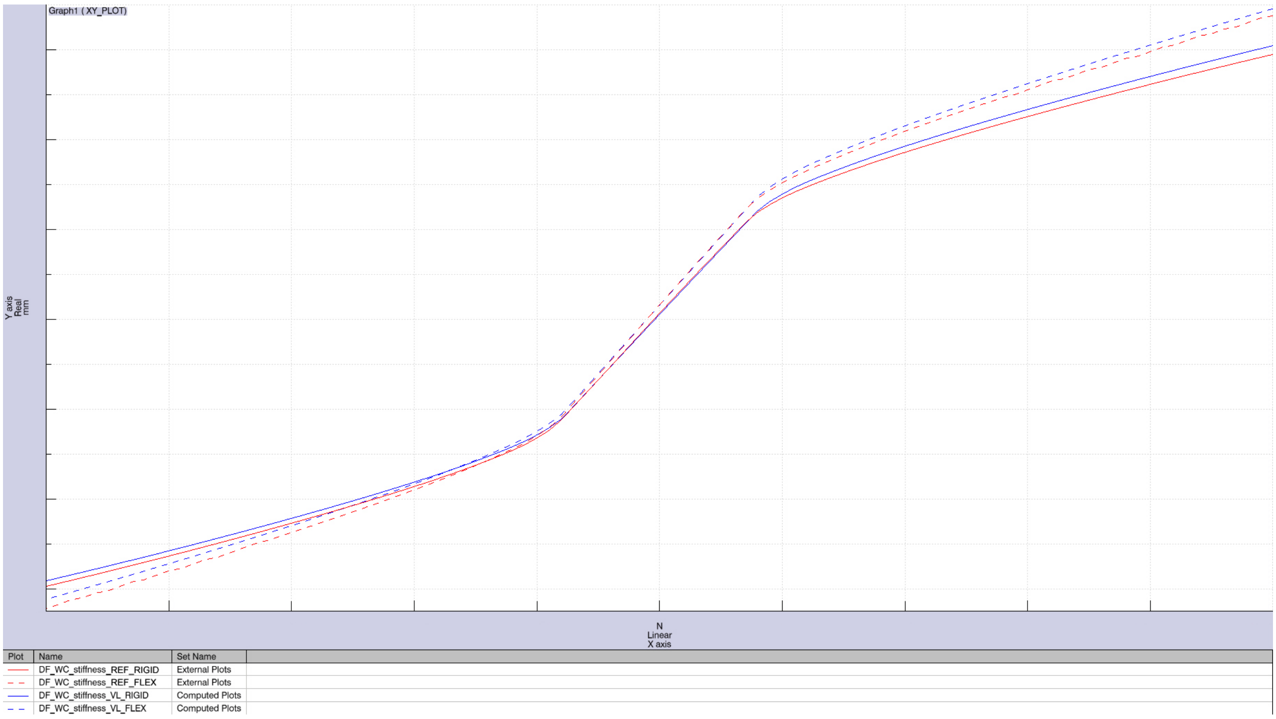

Figure 4.3.1: *Wheelbase variation over longitudinal force*

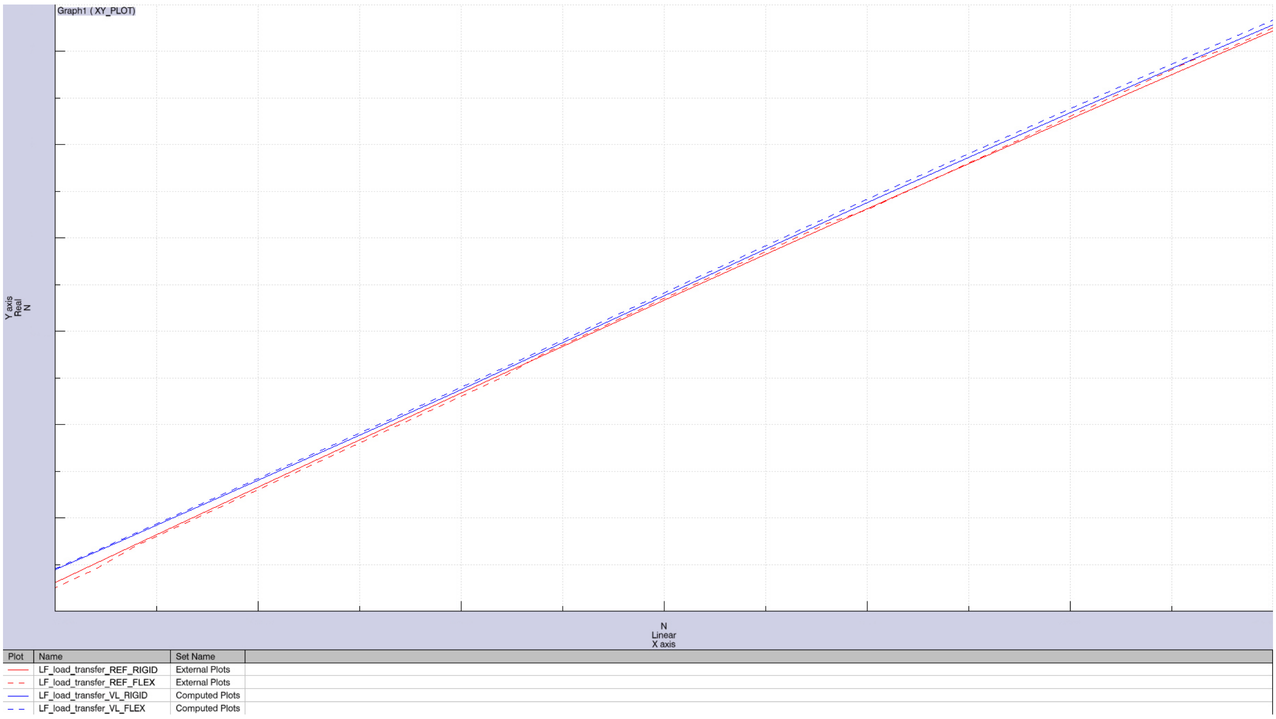

Figure 4.3.2: *Vertical load on wheel over lateral force*

Figure 4.3.3: *Camber angle over opposite vertical wheel displacement*

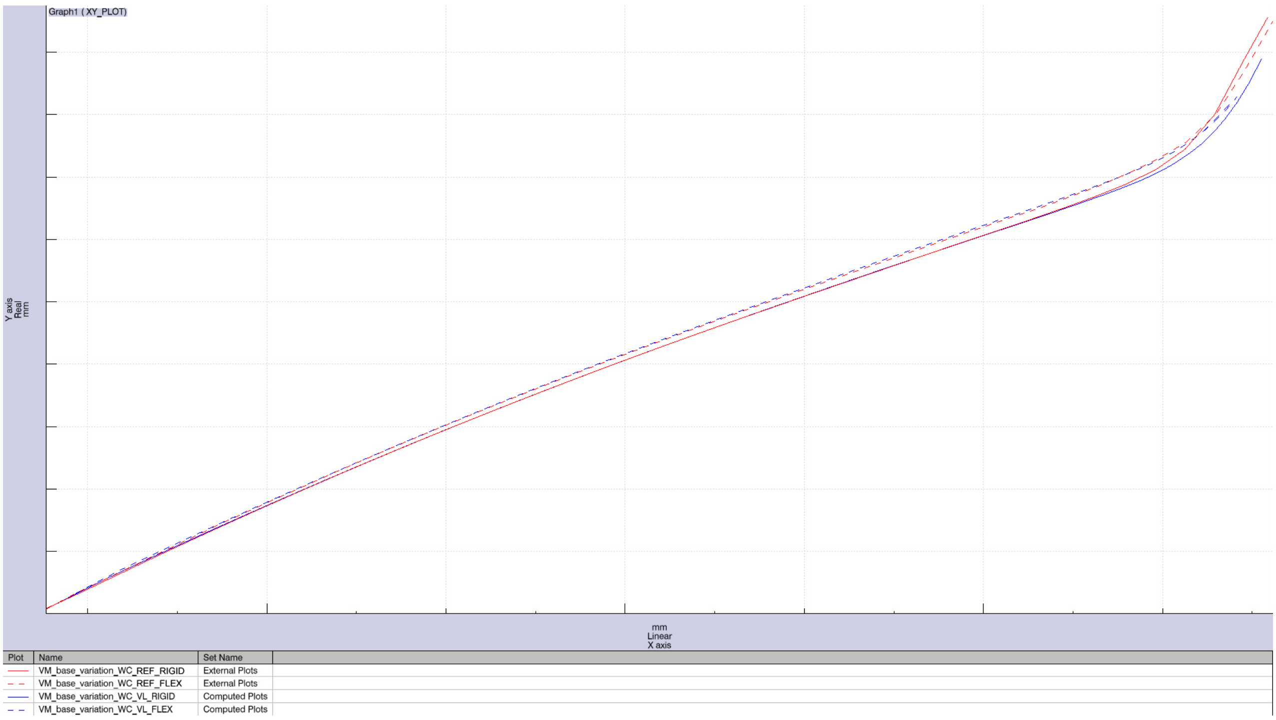

Figure 4.3.4: *Wheelbase variation over vertical wheel displacement*

It is overall a good match between the two methods for the rear suspension as well. During the longitudinal force event in Figure 4.3.1 it can be seen that the VL model is stiffer than the reference model. This is the fact for both the rigid and flexible case. This is a force event and by looking at the graph it can be seen that the compliance comes mostly from the bushing deformations and not the introduction of flexible bodies. That conclusion can be made because without bushings the wheelbase would not have changed at all in the rigid model. The shape of the curve is influenced mostly by to the properties of the bushings.

In the same graph it can be seen that the introduction of flexible components will increase the wheelbase for higher forces but this was expected since the forces will deform the flexible components. In Figure 4.3.2 it can be seen that the two models produce almost the same results. The rate of change is almost the same but the absolute position is a little bit of. The graph shows the vertical load over lateral load and by decreasing the spring pre tension in the VL model the match would have been better. In Figure 4.3.3 it can again be seen that the VL model is stiffer than the reference model. This can not be seen in Figure 4.3.4. This is because the last event is a parallel wheel travel event while the first two are force events. The third one is not a force event but it is a opposite wheel travel event so more forces will be introduced than in the parallel wheel travel event due to the deformation of the anti roll bar. This is why the results in Figure 4.3.4 are closer between the models than the other cases. It has been shown that the results are in fact extremely close between the methods and a simple validation with minimal changes to the VL model is likely to achieve a very accurate match.

4.4 Full vehicle simulation model

As mentioned in the scope of the thesis only a limited amount of driving scenarios was studied during this thesis work. These were a constant radius turn and a sine with dwell manoeuvre. The verification of the full vehicle model was done by comparing the results from different set-ups of the vehicle and see if the results were the ones expected form the changes.

4.4.1 Constant radius turn

With the original set-up it was noticed that the vehicle had an understeered behaviour at the limits of the performance. This can be seen in Figure 4.4.3. By increasing the roll stiffness in the rear, the vehicle was expected to:

- Reach a higher lateral acceleration.
- Have lower body roll.
- Have a slower increase of steering angle.

This results were all achieved and can be seen in Figure 4.4.1, 4.4.2 and 4.4.3. The spike at the end of the simulation is due to the vehicle loosing control.

Figure 4.4.1: *Lateral acceleration over time*

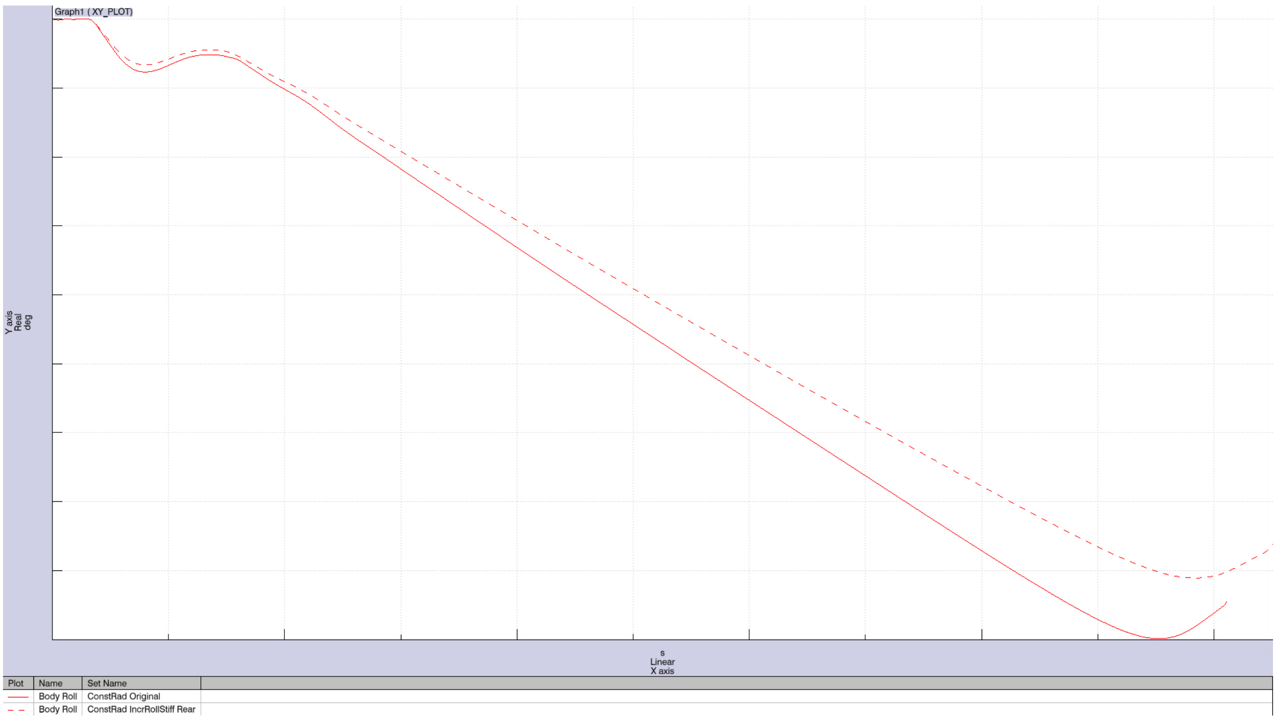

Figure 4.4.2: *Body roll over time*

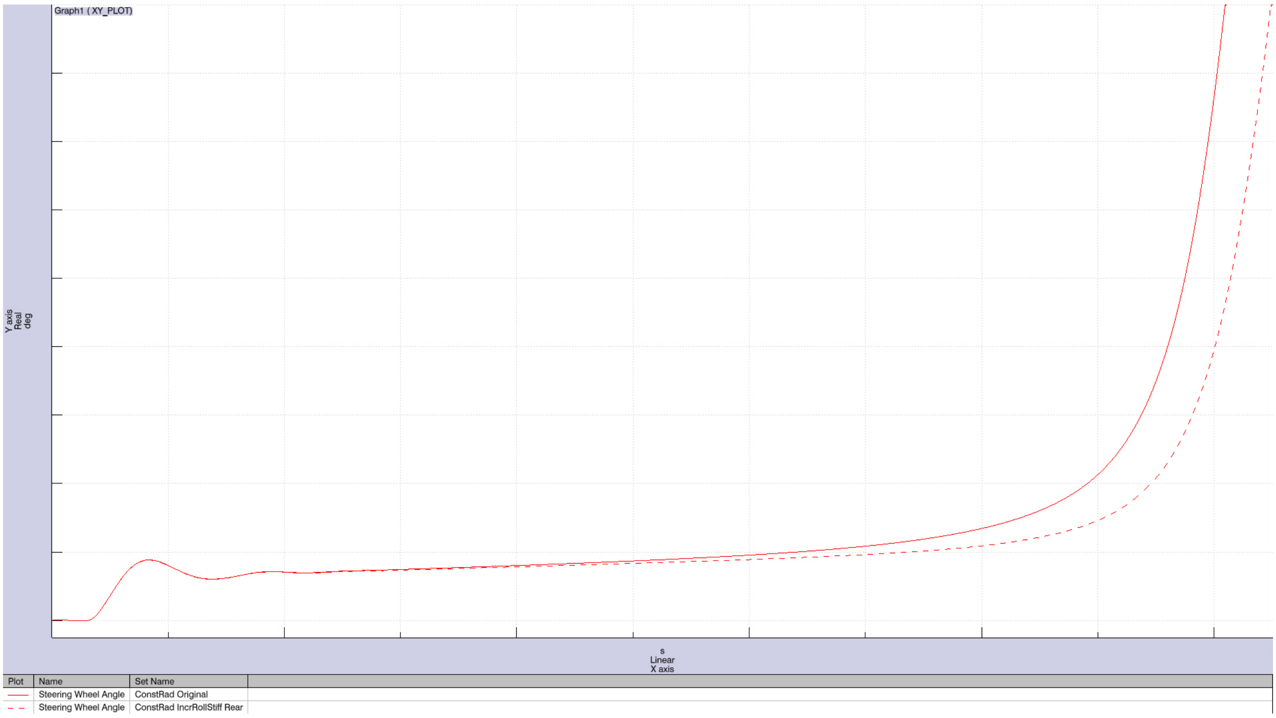

Figure 4.4.3: *Steering angle over time*

4.4.2 Sine with dwell manoeuvre

A sine with dwell manoeuvre was first performed with the original set-up of the vehicle model. After that the same event was performed on almost the same vehicle model. This new vehicle was more understeered and that was achieved by increasing the rollstiffness in the front. The expectations on the model was following:

- Reach a lower peak lateral acceleration.
- Have lower body roll.
- Have decreased yaw rate.

As can be seen in Figure 4.4.4, 4.4.5 and 4.4.6 the simulation model did change as expected in all the cases.

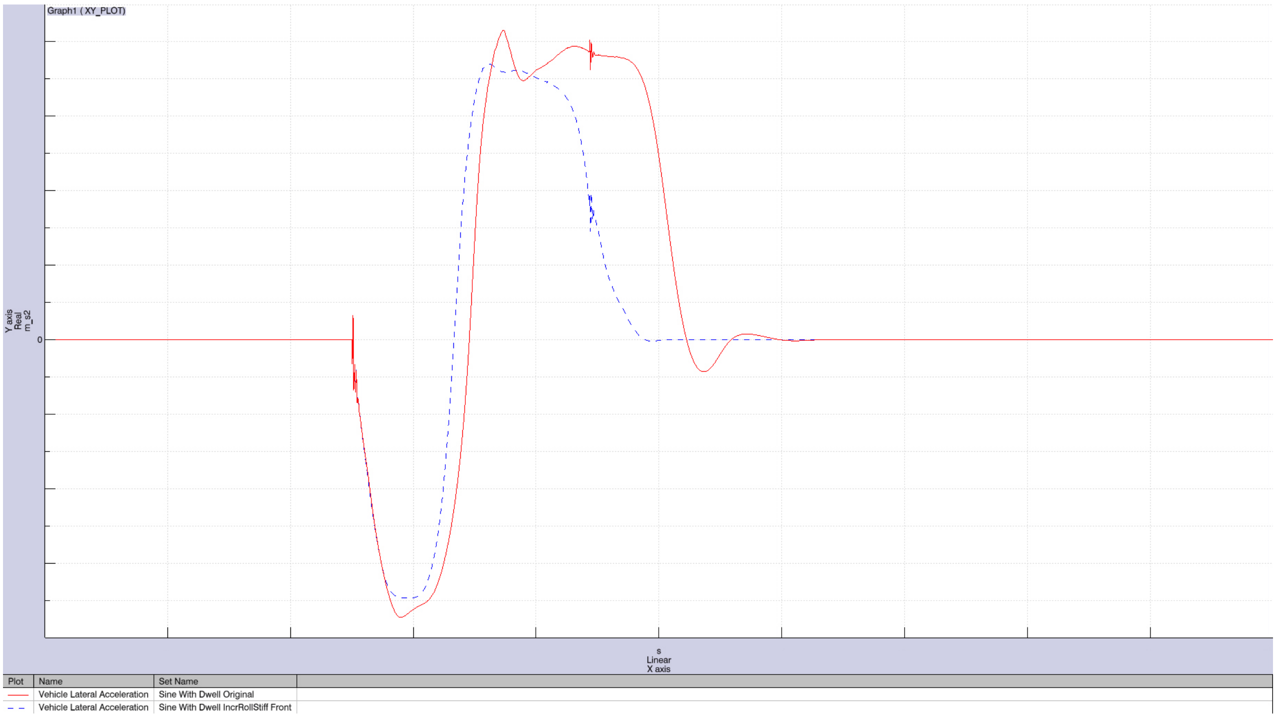

Figure 4.4.4: *Lateral acceleration over time*

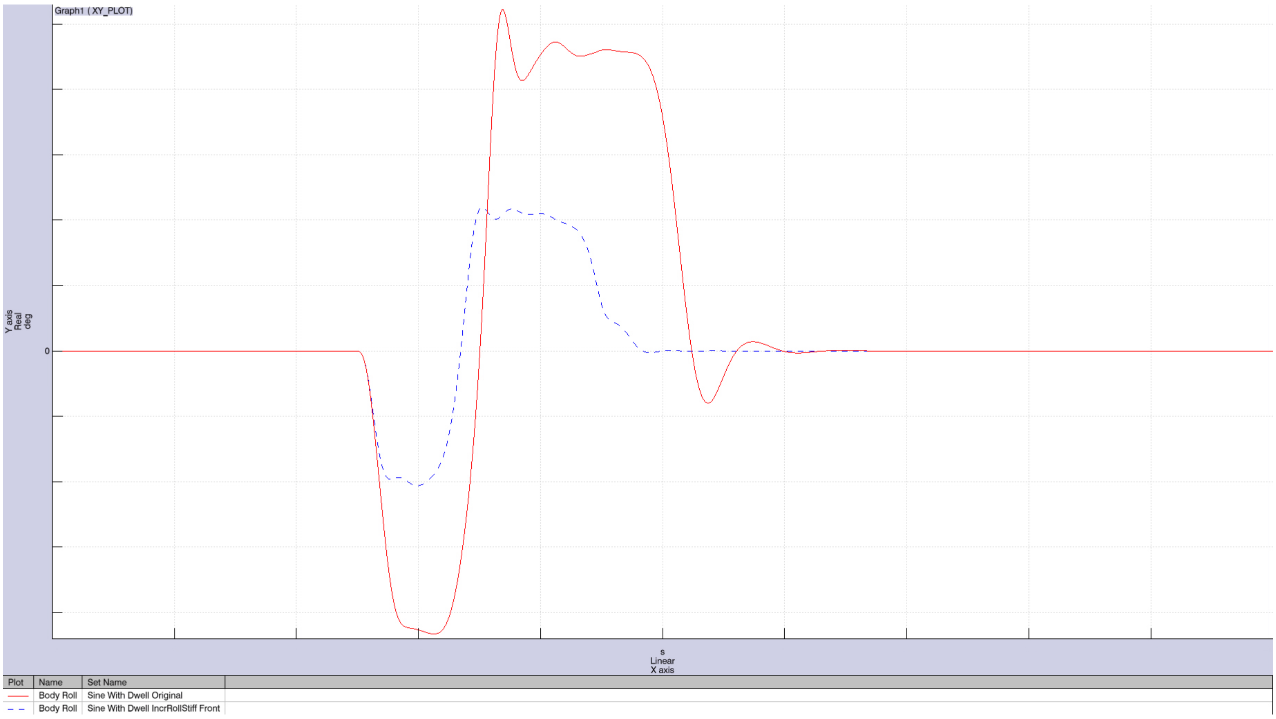

Figure 4.4.5: *Body roll over time*

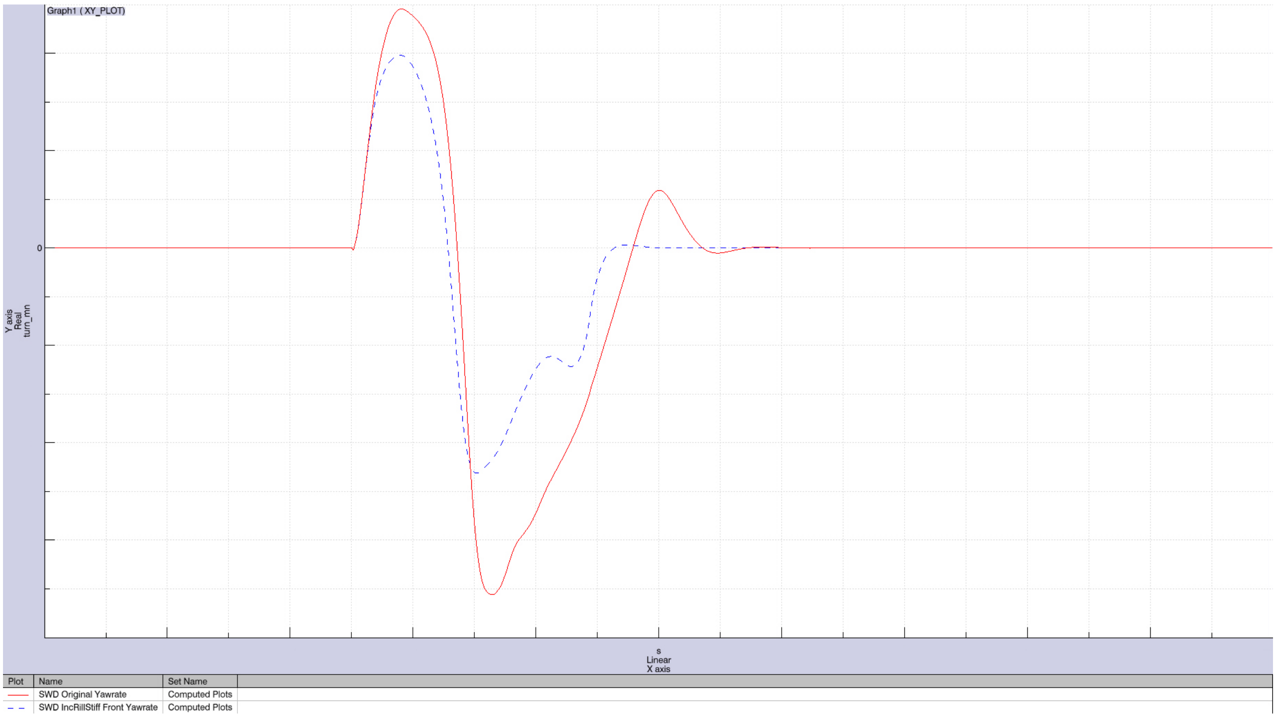

Figure 4.4.6: *Yaw rate over time*

5 Identification of the analytical capabilities of the simulation models

Now it is time to look at the method overview again which can be seen in Figure 5.0.1. The method gives the opportunity to work with a number of models. With more simulation models, together with the knowledge of the analytical capability of them, it will be possible to work more efficient and to take faster, and better decisions.

Faster decision will be made because the user will know from the beginning what model that is needed to get the sought results. If the user wants to know how the wheel base change during parallel wheel travel a K&C simulation model will be used. By knowing the capabilities of the K&C models, the user will know if the rigid model is good enough or not. No work needs to be done to solve them both and compare the result.

In some cases there might not be a noticeable difference in the results from the rigid- and flexible model. Then the user can use the rigid model which will contribute to faster decisions because that model will be faster to solve and can most likely be solved earlier in the project.

Better decisions will be made in cases where it is a big difference in the results between the flexible- and rigid model. Flexible components might not be available and by knowing the capability of the model the user will know that the results from a rigid model should not be fully trusted.

This process was done by comparing the results from the rigid- and the flexible simulation model. Not every possible simulation event were covered but the analysis was made to see if there was any specific trend for the cases that was covered in this thesis. The rigid- and flexible K&C simulation models were compared, as well as the full vehicle using both rigid or flexible components. The results from the front- and rear K&C simulation models were compared together even though they were of different design. It was of interest to see if different suspension designs still had any similarities when it came to what needs to be solved with a flexible model and what not.

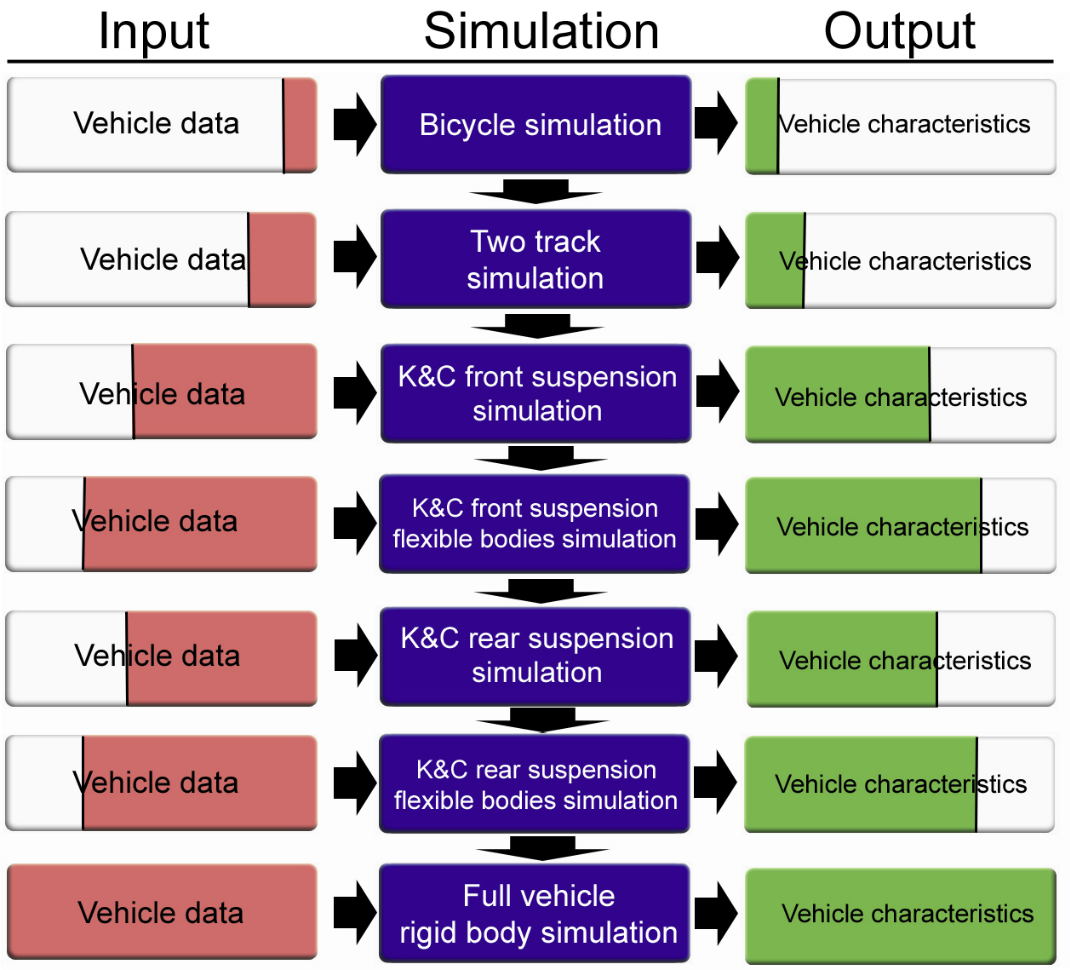

Figure 5.0.1: *Overview of the method*

5.1 Comparison of rigid- and flexible K&C simulation model

From the results of the models created in this thesis it could be seen that there were differences between the flexible- and rigid models for the force-events. This was of course expected since the flexible components will deform when they are exposed to big forces during the lateral- and longitudinal force events and therefore change the behaviour of the suspension. There were however not a big difference in the results for all the force events. For example the normal load on the wheel which, independent of if it was calculated with a rigid- or a flexible model, still got roughly the same results. The results were however not exactly the same due to the way the mass and centre of gravity for each component were put into the simulations. For the rigid model the mass was added by the user and the centre of gravity was calculated from the hard points the component was connected to. For the flexible model the mass and centre of gravity were given by each flexible component. The differences can be seen in Figure 5.1.1 and 5.1.2. From the figures it can be seen that the rigid components were created slightly heavier, for both the front- and rear suspension, than the mass data from the flexible bodies. This can be seen due to the fact that the normal load has the same shape for the both simulation models. The difference is the offset which will change with correct mass and centre of gravity. This means

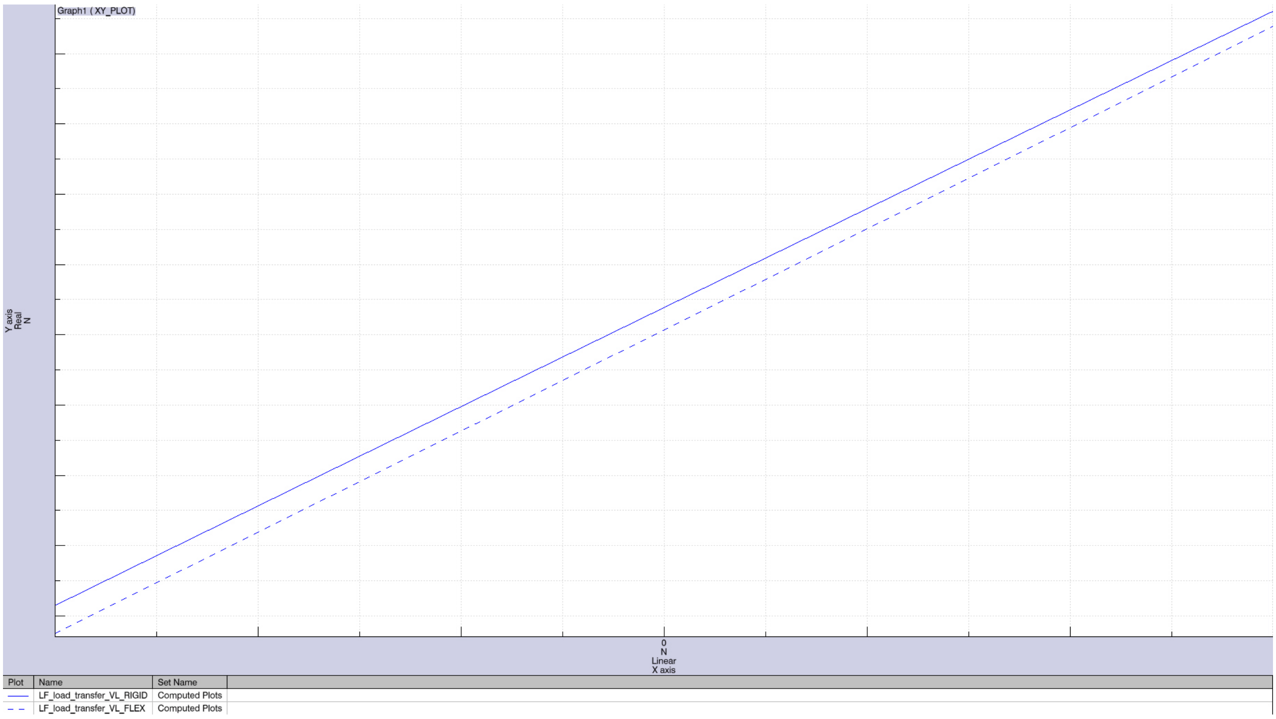

Figure 5.1.1: *Normal load- over lateral force on the wheel for the front suspension*

that the rigid model is the preferable model to use in this example due to faster simulation time and that less data is needed to solve the model. It is however very important that the mass of the components are close to what the flexible components will be. The weight of the unsprung mass has a big affect on the absolute value of the normal load on the wheel. Other than that there was no event, where big forces were introduced, where the rigid- and the flexible suspension model had results close to each other either the front- or the rear simulation model. An example where the difference between the rigid- and flexible simulation model clearly can be seen is in Figure 5.1.3. When the longitudinal force is introduced the wheel will be much more compliant for a model with flexible components compared to a model with rigid components due to the deformation of the components. The user is able to get results from both the models but the results will in this case be much more accurate if the flexible model is used. For the steering event however, it can be seen in Figure 5.1.4 that the rigid- and flexible simulation model give similar results, leading to the conclusion that the rigid model is the preferable here. The mass of the components does not seem to affect the result so this is something that is mostly dependent on the kinematics of the model and could therefore be achieved very early in the process. For the event that introduced the least amount of forces into the system, the parallel wheel travel, it was a slight difference between the front- and rear suspension comparing the flexible and rigid results. The front

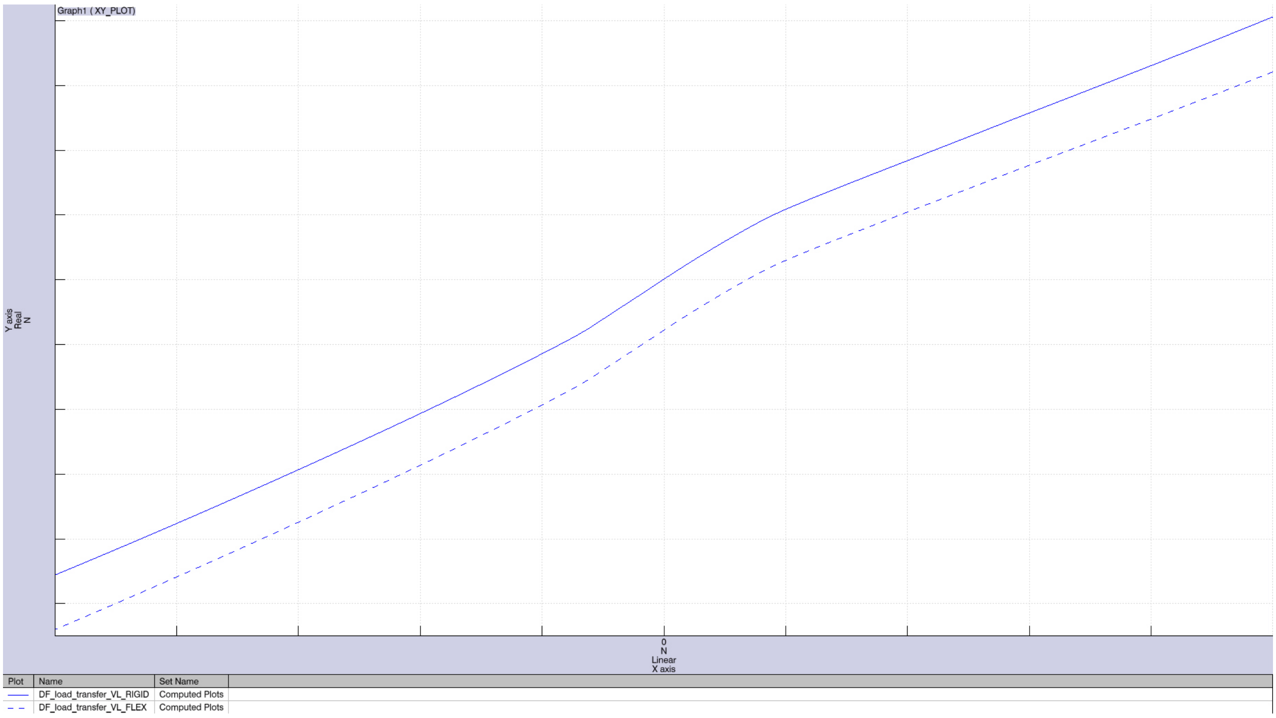

Figure 5.1.2: *Normal load- over longitudinal force on the wheel for the front suspension*

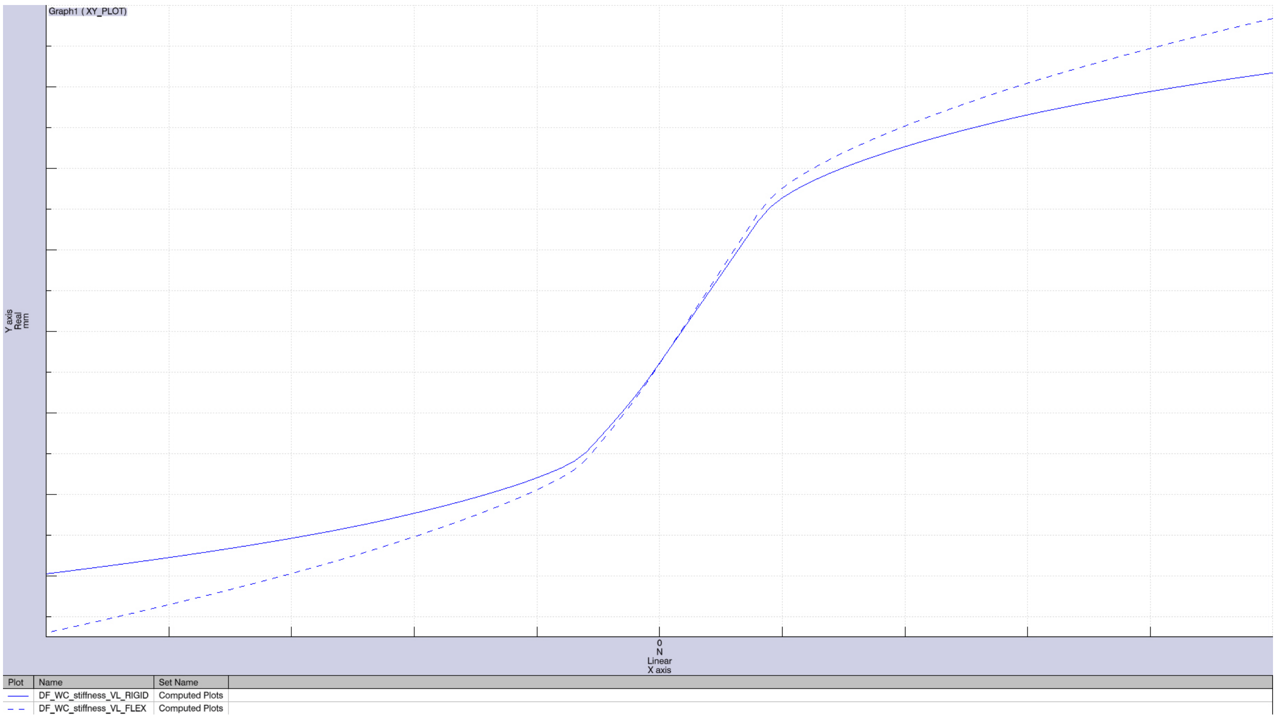

Figure 5.1.3: *Longitudinal compliance over longitudinal force on the wheel for the front suspension*

suspension was not so sensitive to the introduction of flexible components when it came to track width. The wheel base, camber and toe was however more sensitive. In Figure 5.1.5 the track width variation for the rigid- and front simulation model of the front suspension is shown. In Figure 5.1.6 the longitudinal displacement dependent on wheel vertical displacement can be seen. The differences are very small except from the data to the very right. This is where the bump stop is compressed and therefore introducing higher forces in the assembly which makes us again see these differences. This is the case for the event with the normal load on the

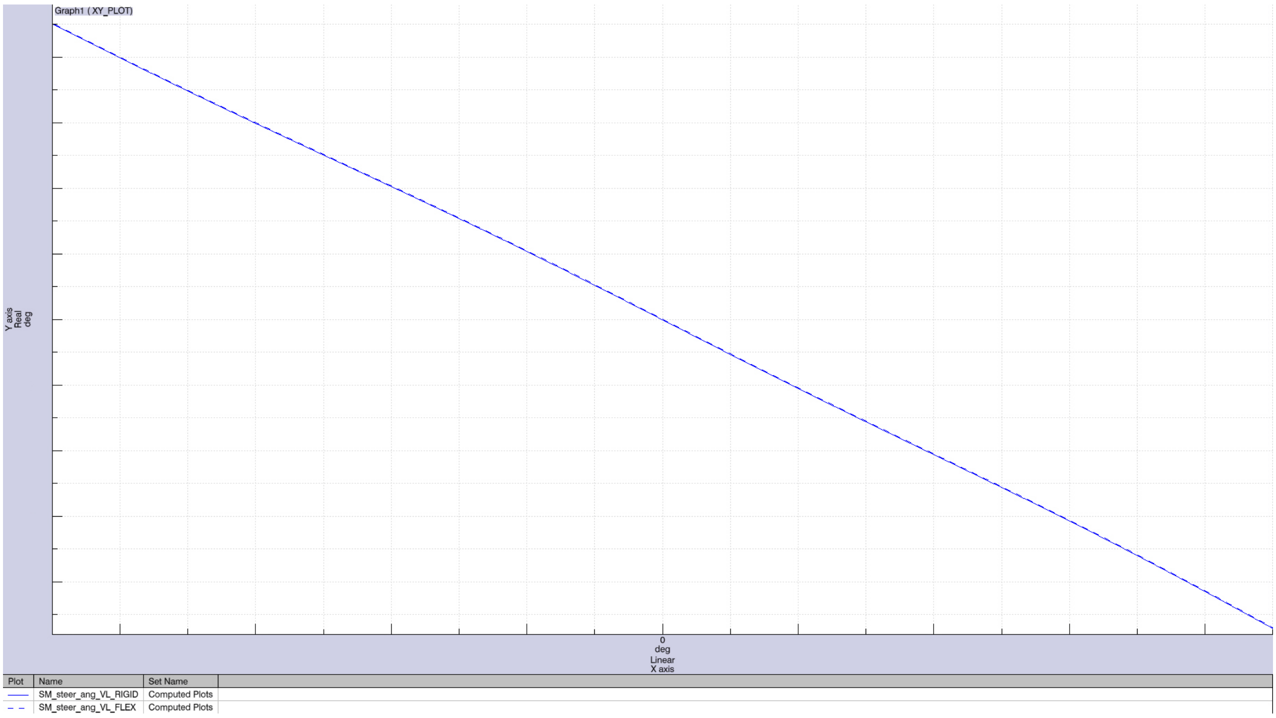

Figure 5.1.4: *Wheel rotation over steering wheel angle for the front suspension*

wheel during parallel wheel travel as well.

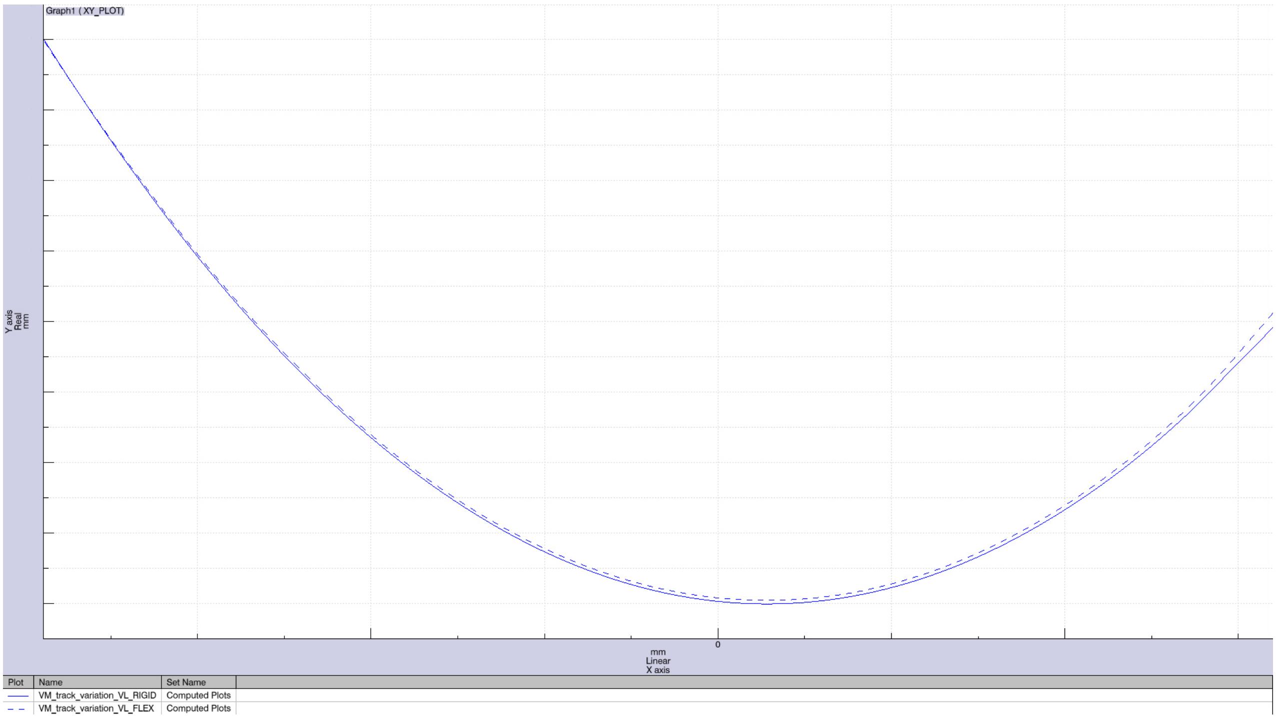

Figure 5.1.5: *Track variation over vertical wheel displacement for the front suspension*

For the rear suspension however it was the camber angle which can be seen in Figure 5.1.7 and track width variation that was not very sensitive to the introduction of flexible bodies for the parallel wheel travel event. The toe angle and wheel base change were however affected by the selection of simulation model.

Figure 5.1.6: *Longitudinal wheel displacement over vertical wheel displacement for the front suspension*

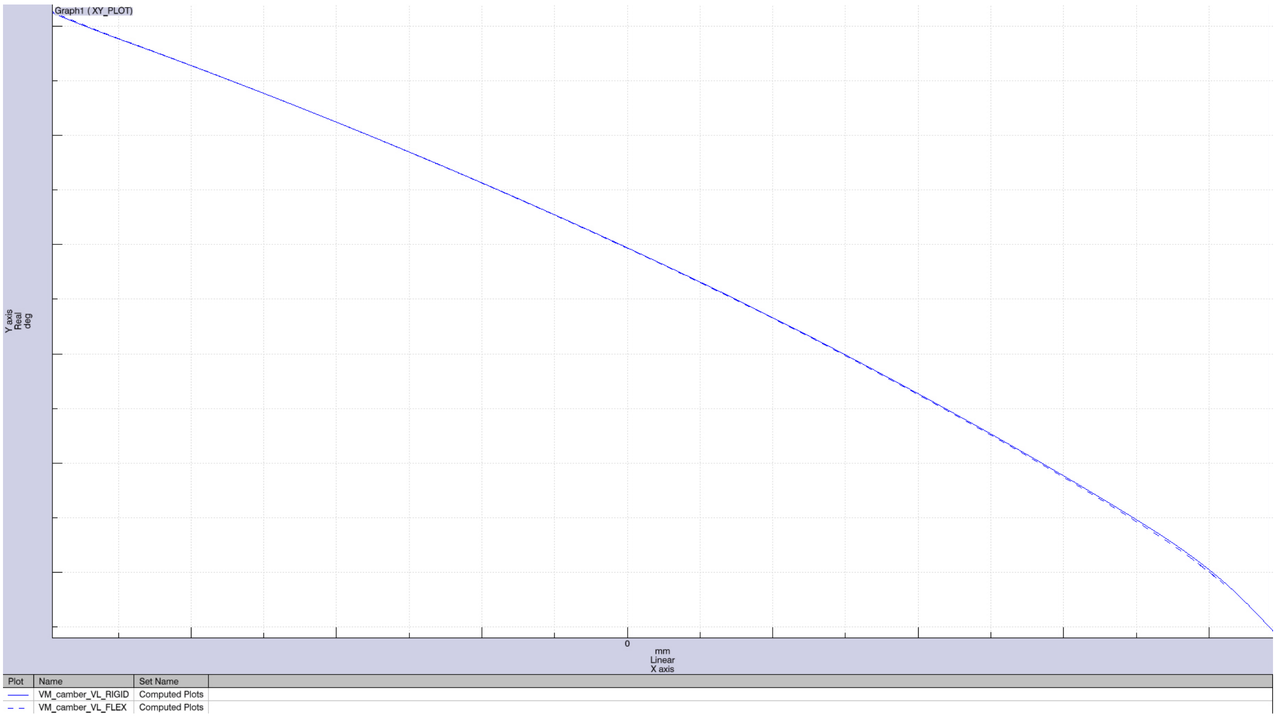

Figure 5.1.7: *Camber angle over vertical wheel displacement for the rear suspension*

5.2 Summary

A summary of the analytical capability of the front- and rear K&C simulation models can be seen in Table 5.2.1 and Table 5.2.2. With the rows to the left identifying the analytical events and the columns on the top the metrics the tables shows for what events, a specific model is recommended to get a specific metric correctly. This kind of analysis should be done for all the simulation models and all the load cases to identify the analytical capability of the models of the method. This to identify the right simulation model for a specific case. What is not covered in this table is the steering event for the front suspension which result was seen in Figure 5.1.4. That result can be solved by the rigid simulation model.

Table 5.2.1: Analytical capability of the front K&C simulation model. *For data where the bump stop is compressed use a flexible K&C simulation model.

	Toe angle	Camber angle	Wheel Base	Track width	Wheel normal load
Drive Force	Flexible	Not performed	Flexible	Not performed	Rigid
Lateral Force	Flexible	Flexible	Not performed	Flexible	Rigid
Opposite wheel travel	Flexible	Flexible	Not performed	Not performed	Flexible
Parallel wheel travel	Flexible	Flexible	Rigid*	Rigid	Rigid*

Table 5.2.2: Analytical capability of the rear K&C simulation model. *For data where the bump stop is compressed use a flexible K&C simulation model.

	Toe angle	Camber angle	Wheel Base	Track width	Wheel normal load
Drive Force	Flexible	Not performed	Flexible	Not performed	Rigid
Lateral Force	Flexible	Flexible	Not performed	Flexible	Rigid
Opposite wheel travel	Flexible	Flexible	Not performed	Not performed	Flexible
Parallel wheel travel	Flexible	Rigid	Flexible	Rigid	Rigid*

6 Summary of the work

So what was done in this thesis was to first organize the pre-defined simulation models. They were organized by building complexity in a systematic way going from a bicycle- to a full vehicle simulation model. When an overview of the method was defined with inputs, simulation models and outputs, the work with the method continued by defining the workflow. The best way to organize it was shown to be with shared vehicle data files, a master file to drive the input to the simulation model and a simulation software to perform the simulations and report the results. With the method and work flow defined the creation of the master file began. A list of demands were defined and the program that suited those demands best was Excel. From Excel the master file was born with a GUI for changing vehicle input data. After this the creation of the simulation models began. It started with the creation of the bicycle- and two-track models. Again demands on the software, which those simulation models were going to be created in, was defined and again Excel was chosen to be the best solution for this method. Both the bicycle- and two-track models were done in the same Excel sheet and without a master file. Due to the small amount of input data there was no point of having a separate master file. The data was instead changed within the simulation model interface. When those models were created the work with VL started. Rigid front- and a rear K&C simulation models were created and also linked to the master file. With the K&C models fully operative, suspension components were added and made flexible to create the flexible K&C simulation models. The last model that was created was the full vehicle simulation model. This was created by using the already created K&C simulation models for the rear- and front suspensions. This gave the full vehicle simulation model the connection to each master file for the front- and rear suspension as well. The system of cooperative simulation models and a method for how to use them was made. It was now time to verify that the models produced good results. This was done differently depending on the simulation model. The results from the K&C models were compared to data produced by Volvo. The other models were verified by comparing a reference model to a new configuration of it to see if the new output data was the expected one or not. With all the models verified and working, the results from the rigid- and flexible K&C models were evaluated and compared. The results from this study was a table with information of what input data, for different events and models, that is needed to give good results.

7 Result of the work

What has been created in this thesis is a shareable simulation methodology. This is a straight forward process and with a short introduction to how the master file works, where to run the simulations and where to find the results, a CAE analyst will fast learn how to perform vehicle dynamics analysis for rigid- and flexible K&C events and also full vehicle events. Not only does this method make the CAE analyst work efficient, it also makes it possible for the analyst to distribute, fully functional and easy to use, simulation models. Vehicle simulations are thus ready and easily available to users with limited or no CAE expertise. An example can be a designer who is interested to do changes to a component. By using the distributed simulation model the designer can see how that change affect the vehicle dynamics attributes. Another example is a technical expert in the field of vehicle dynamics. The expert will have a very good knowledge of suspension design and vehicle behaviour but might not have the knowledge of how to work with different simulation software. With this method the expert is able to perform vehicle simulations independently without going through the time consuming process of learning a new software.

With this method, connected to the Catia V5 platform, it will not only be easy to create and use simulation models. It will also be fast. Here are some examples taken from the author's experience:

- Building a rigid rear or front K&C model from scratch: 40 minutes
  This includes:
  - Add hard points, damper curve, spring pretension and stiffness, rebound- and bump stop stiffness curves and clearances.
  - Add already created beam element anti roll bar.
  - Add preliminary components with mass.
  - Add revolute, cylindrical, spherical, universal joints.
  - Add flexible bushings without damping.
  - Create the analysis cases.
- Link simulation model to Master file: 2 hours
- Add flexible components: 10 minutes/part
  This is dependent on the complexity of the component. In this example it is a one part component
- Change bushing curves, spring properties, spring bump stop data etc will take seconds.
  Depending on how much you want to change but all is changed in the master file
- Update modified flexible components: Automatic
  If the component is build into the simulation model correctly it will be updated automatically. If it is not, it will be the same or less time that it takes to add a flexible component.
- Build full vehicle simulation model: 25 minutes
  This includes:
  - Add a vehicle body with mass and inertia properties
  - Add already created front- and rear suspension models
  - Create two analysis cases

By adding up the numbers it can be seen that a CAE analyst, given the data in the correct format, will be able to create and deliver a rigid- and flexible front- and rear K&C simulation model as well as a full vehicle simulation model with rigid and flexible suspension components in a work day. Depending on earlier experiences of creating vehicle simulation models, the perceived quality of those numbers varies. They will most likely not attract any attention to a person that is not that experienced in the area of creating vehicle simulation models. Fact is however that all the CAE analysts which I have come in contact with, which have extensive experiences in creating vehicle dynamic simulation models, and that have seen those time results find these numbers amazing.

8 Conclusion

The deliverables for this master thesis were:

- A cooperative system of vehicle simulation models, based on the same car, but with different complexity.
- A method for how to use those simulation models
- A study on the boundaries of the analytical capabilities of the vehicle simulation models

All these deliverables were met. All the simulation models were created and work, with the introduction of the vehicle data- and master files, in a cooperative way. The method for how to use the models was created. This method has the advantage that the user do not have to know how the simulation software works to be able to produce results. Instead the user works from the master file to change the vehicle model. The master file gives the user feedback on the data going into the model. It also gives the possibility to work with a set of configurations of the vehicle. A study of the analytical capability of the K&C simulation models was done and as expected, there were differences between the rigid- and flexible model. The study however showed that for some cases the rigid- and flexible simulation model gave close to the same results. This means that adding flexible components, which increases the complexity of the model, does not always add value to the results. Another observation was the difference in analytical capability between the front- and rear suspension model. It was shown that there is no universal rule for what data that can be taken confidently from a rigid model. This will depend on the design of the suspension and should be investigated further.

This method will make it easy to keep track of the latest vehicle data thanks to the interface in the master file linked to the global vehicle data files, central controlled by attribute leaders. It will also encourage collaboration between different disciplines. The vehicle dynamics group will do simulations in the same simulation model that durability is using for their simulations. The same simulation model that the design department will work with to do changes to the components and look at packaging problems. Using the models company wide will reduce overall time to validate models and also increase the quality of the models in use.

The variety of simulation models together with the knowledge of the analytical capability will give better results and contribute to faster decisions with better confidence. The CAE analyst will also have a better understanding for when in the design process which decisions can be made. In the beginning of the design process it will not be a lot of input data available and by knowing the analytical capability of the simulation models the analyst can focus the time and energy on the models that will give good results. Results that hopefully will contribute to new vehicle data. A two-track model can be used to set conceptual measurements for track width, wheel base and roll center height. Data that can be used to start to set the coordinates for the hard points in the K&C simulation models. This can be done early in the process rather then to try to build advanced simulation models that will not contain all the important data to be able to provide good results anyway.

This thesis shows the possibilities and advantages of a method like this within the vehicle dynamics CAE group. It also shows some of the advantages that comes with this method company wide. With an introduction of models that can be used for multi domain optimization the engineers will work more efficient. This means that Volvo either can use the same development time as today to design even better cars, or continue to design good cars but within a shorter time span. This is why I recommend that similar studies should be made within other areas of development within Volvo as well.

9 Future work

This thesis work has not only produced a method for development of vehicles within the area of vehicle dynamics. It has given a better understanding of the the analytical capabilities of the simulation models and also for the overall process of creating models that can be used across different attributes, ensuring the possibility of a better overall system design. Some possible improvements have been identified to make this method even better and following is a list of recommendations for future work.

- Look at co-operation between disciplines. For example vehicle dynamics, component design, durability, packaging. It has been shown in this thesis that this method can be implemented for the vehicle dynamics CAE group at Volvo and to take fully advantage of the opportunities that the method and software gives a dialogue has to be made with other groups as well.
- Add more flexible components to the front- and rear K&C simulation models. The subframe was for example taken out of this work due to its complexity of being modelled as a flexible component. The subframe will affect the results and it should be added to the models as a flexible component as well.
- Make a flexible vehicle body. It has already been seen that flexible components in the K&C simulation models changed the behaviour of the suspension. A flexible vehicle body should be added to the full vehicle model to investigate the effects on the vehicle's handling characteristics.
- Validate simulation data with test data. This was not a part of the thesis and it would be very good to compare simulation data to test data to validate the models.
- Study more driving scenarios. This thesis did only consider driving scenarios evaluating the lateral performance of the vehicle. More events like brake- or acceleration events could be added as well as ride events.
- Investigate the effects of solver settings. The solver settings are a big part for how the simulations are solved and how long it takes to perform them. Optimizing this might lead to simulation models that provide better and faster results. This also includes the solver for the flexible components. There are possibilities to use other solvers like Nastran to solve the flexible components in VL.
- Improve the master file. The master file works well today with the functionalities and feedback to the user but it can still be improved.
- Automatic post processor. Right now this process is manual work but it can be done as an automatic process.
- Integration with a PLM system. This thesis work was done locally from a single computer. To implement this method in a bigger scale the method needs the implementation with a PLM system.
- Hard point driven geometries. In this method there is no direct connection between the components and the hard points. With help of parametrization it is possible to modify the geometries by changing hard point positions. It requires more work by the design department making this possible but it would make it easier to have the geometries change automatically and not manual when a hard point position is changed.

References

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[3] H. B. Pacejka. *Tyre and vehicle dynamics*. Butterworth Heinemann, 2006.

[4] R. Thomson and B. Jacobson. *Lecture Notes for Vehicle Dynamics MMF062*. 2007.

A Censored pictures of vehicle suspension creation interface in Virtual Lab

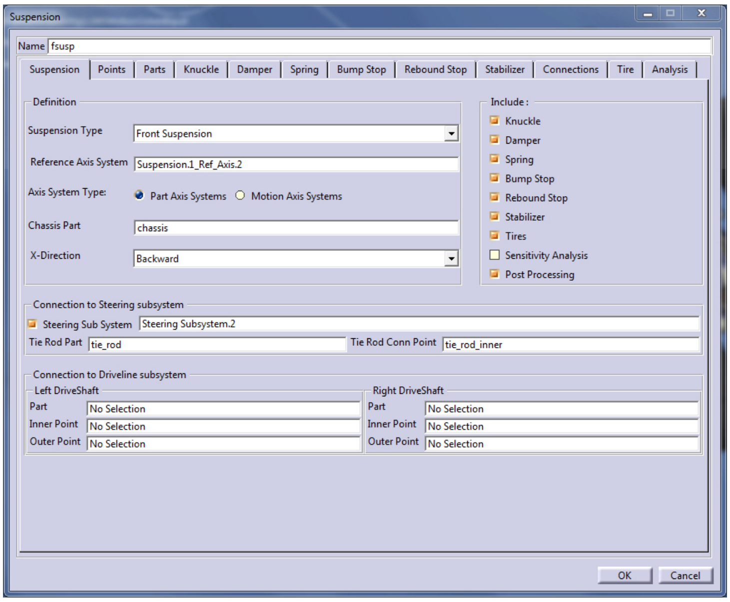


Figure A.0.1: *The suspension tab*

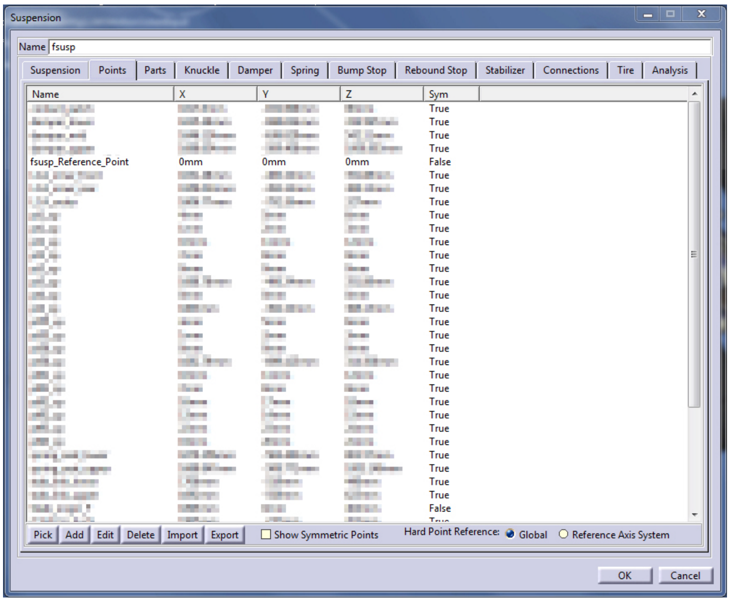


Figure A.0.2: *The hard points tab*

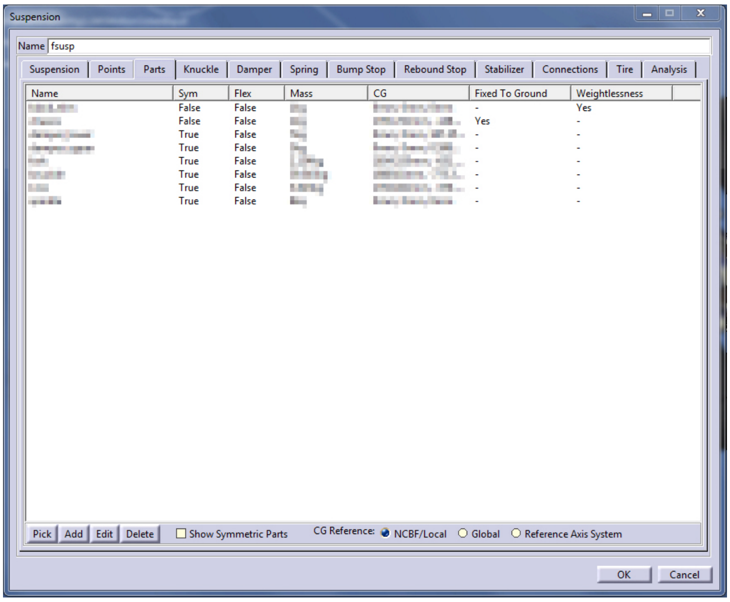


Figure A.0.3: *The parts tab*

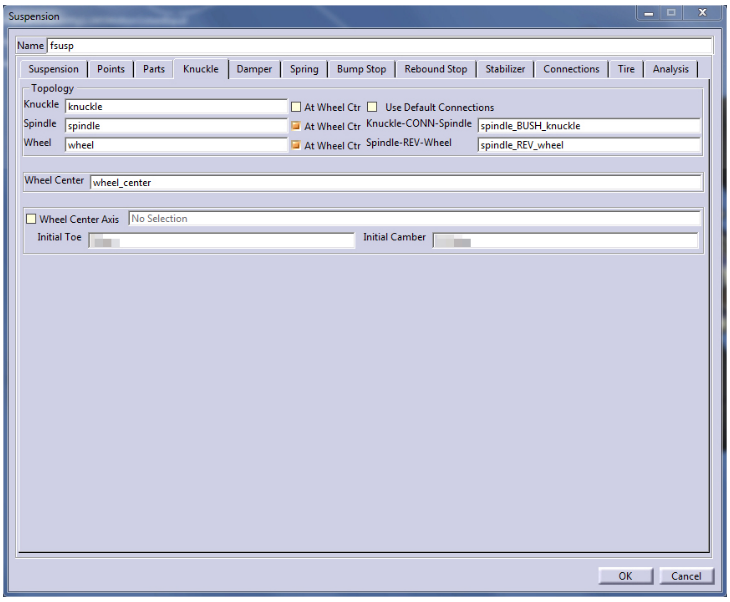


Figure A.0.4: *The knuckle tab*

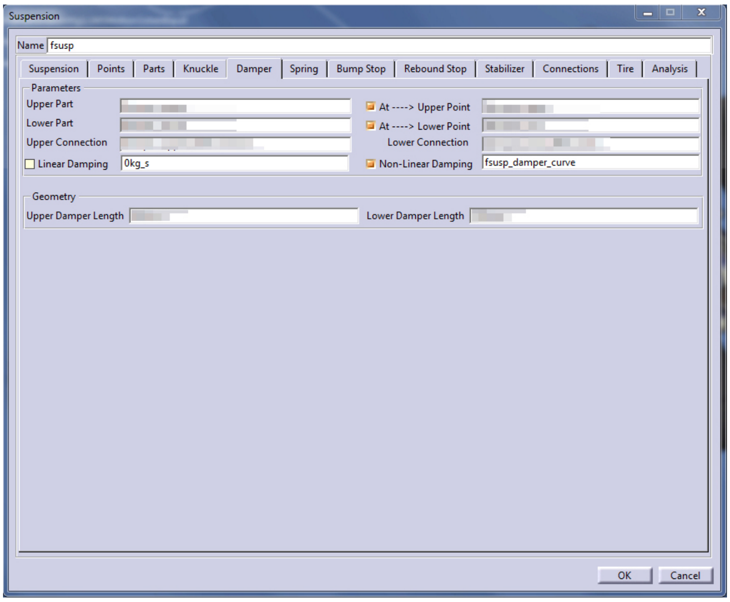


Figure A.0.5: *The damper tab*

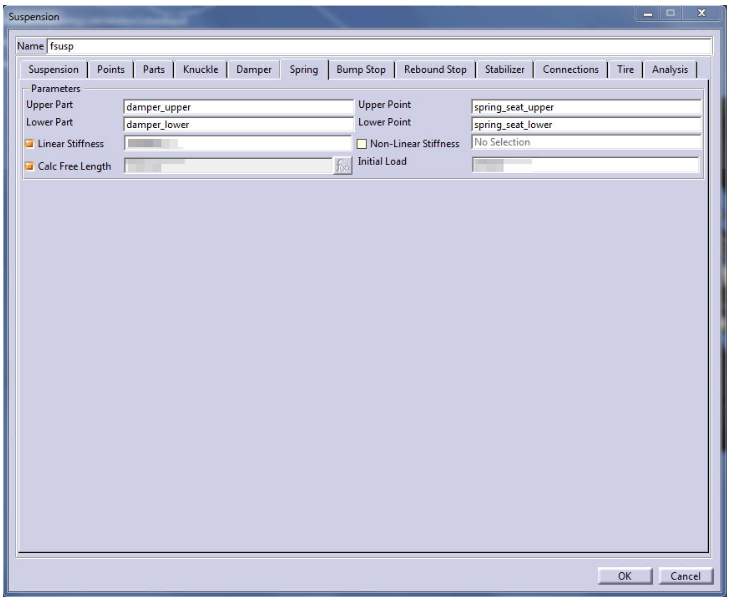


Figure A.0.6: *The spring tab*

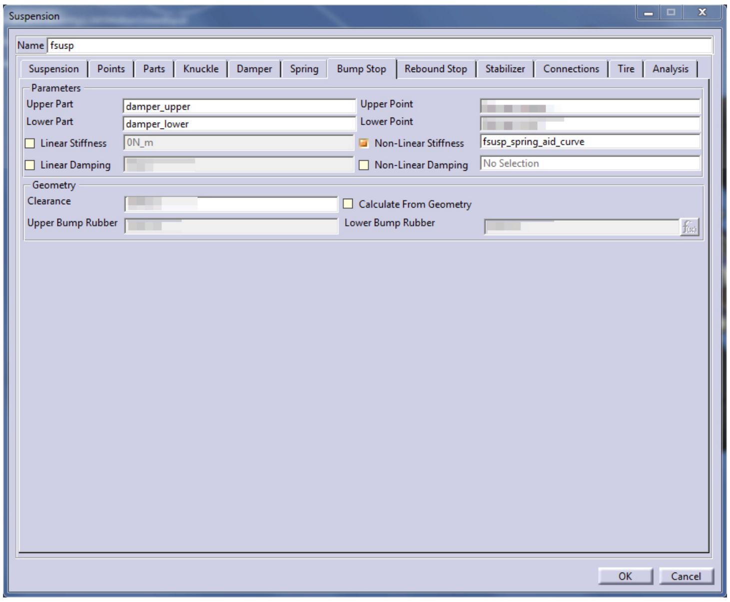


Figure A.0.7: *The bump stop tab*

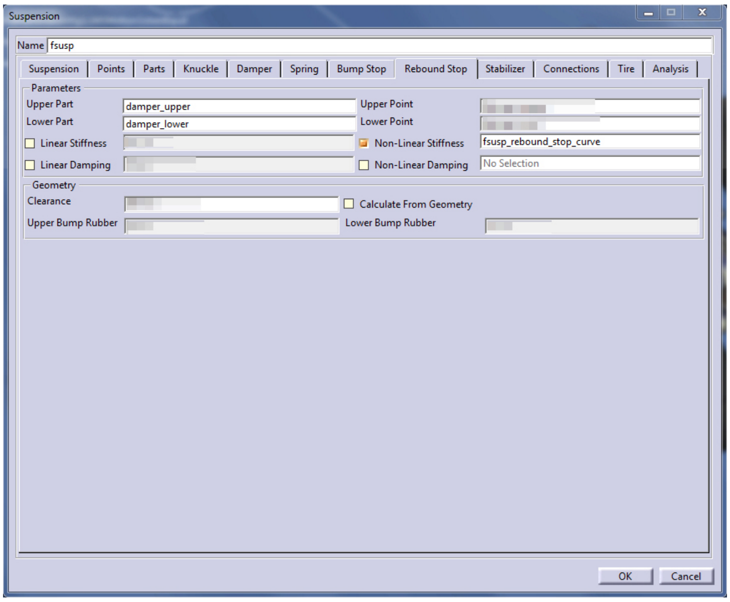


Figure A.0.8: *The rebound stop tab*

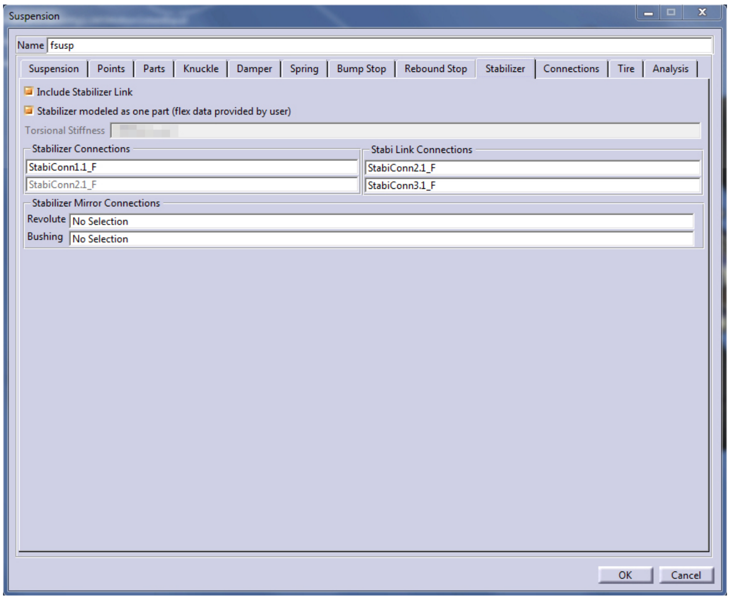


Figure A.0.9: *The stabilizer tab*

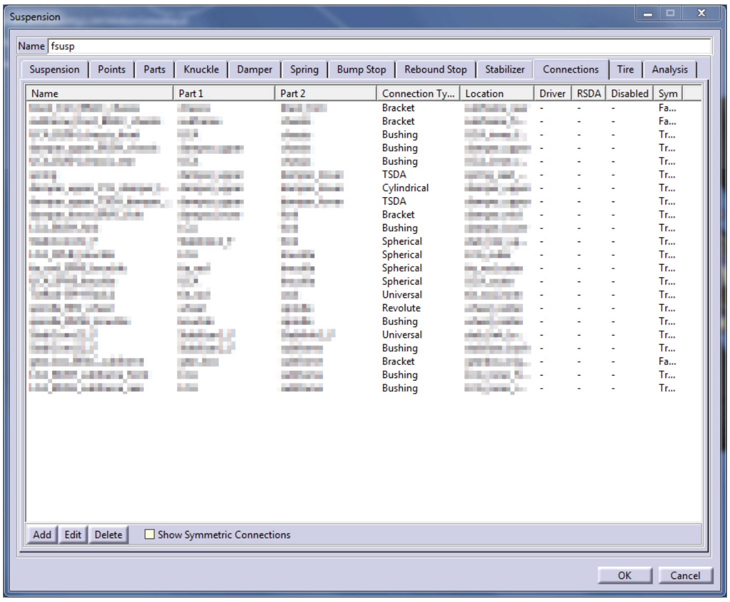


Figure A.0.10: *The connections tab*

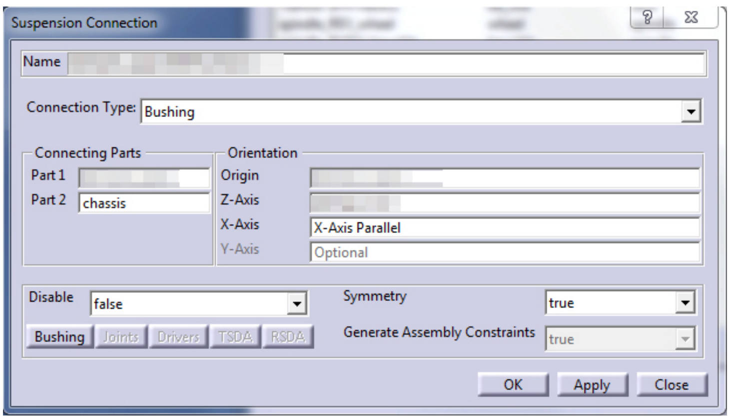


Figure A.0.11: *The interface for the connections setup*

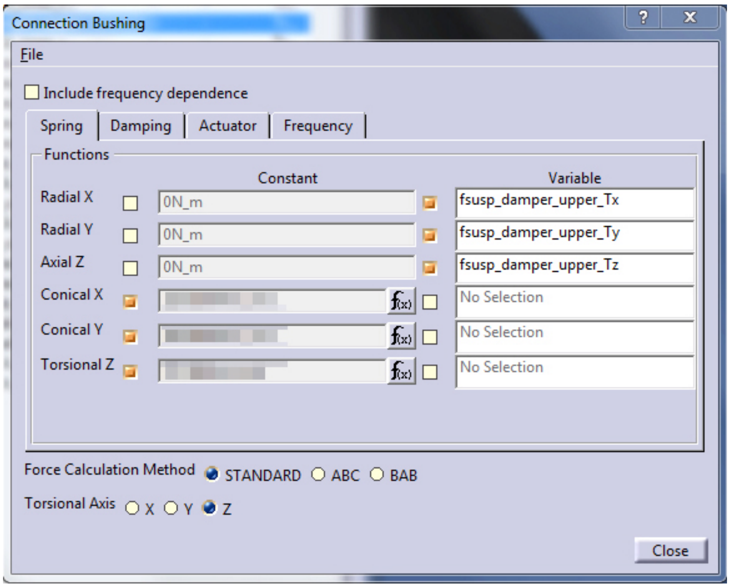


Figure A.0.12: *The interface for the creation of bushings*

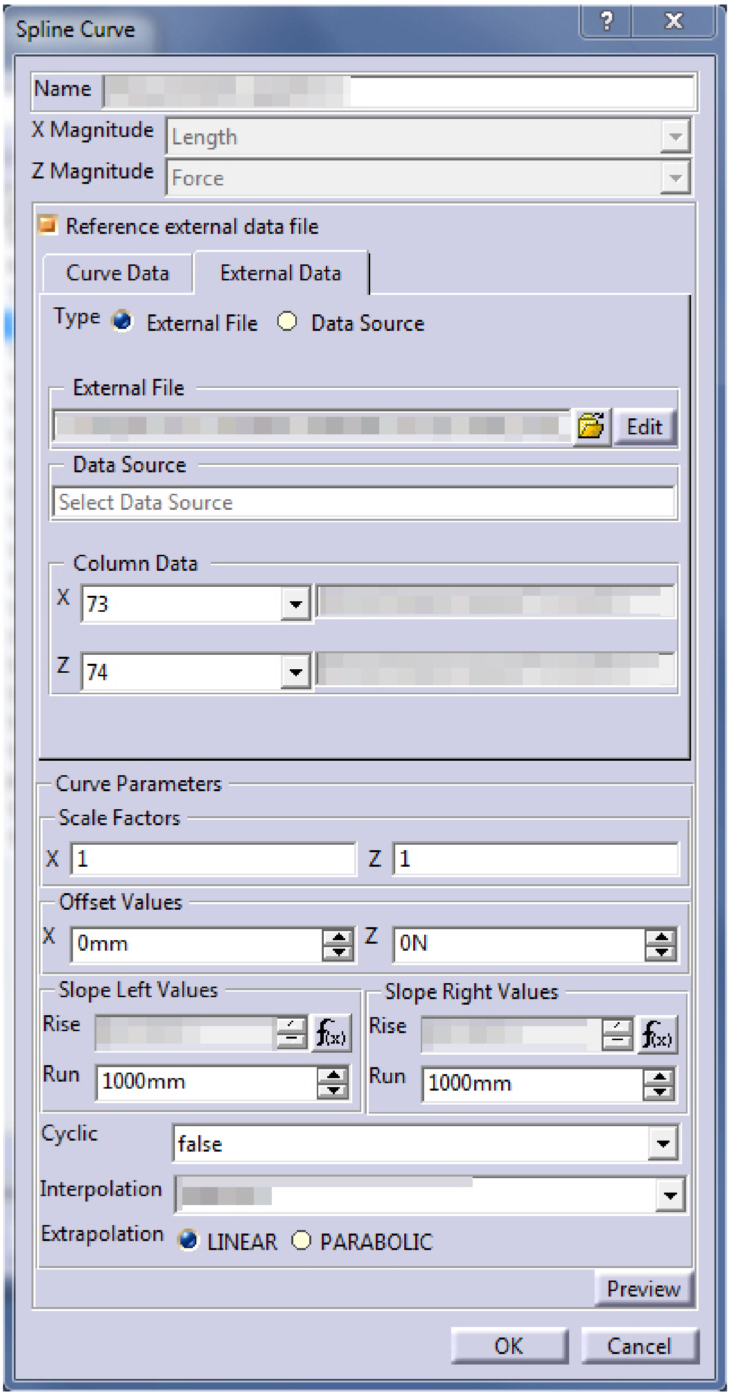


Figure A.0.13: *The interface for using curves for data*

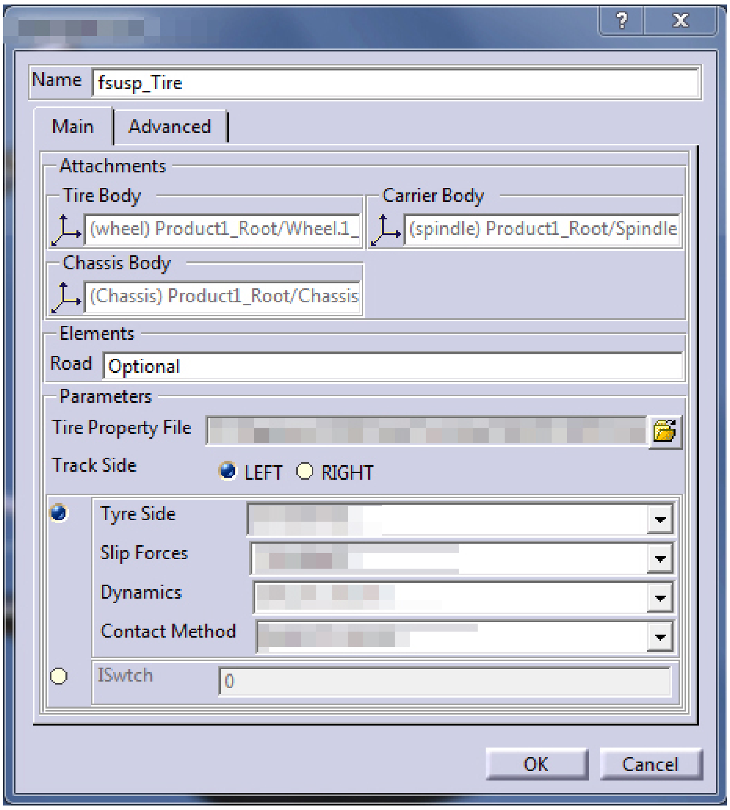


Figure A.0.14: *The tire interface*

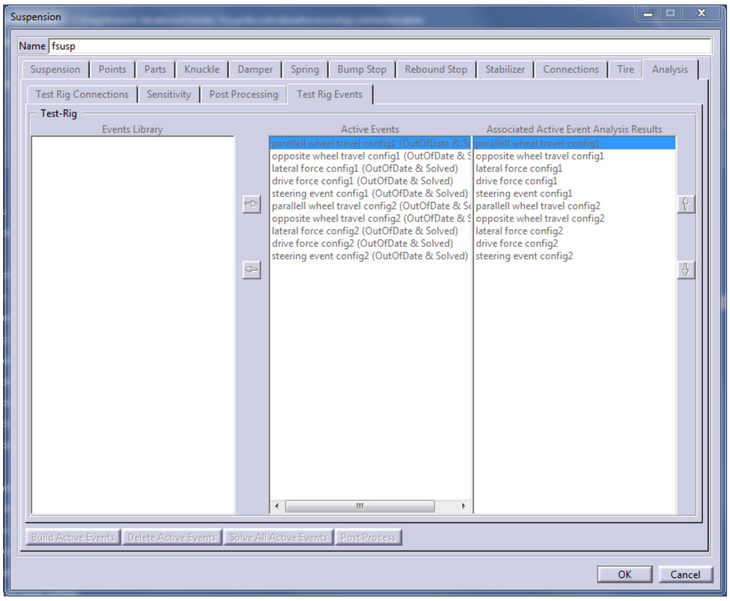


Figure A.0.15: *The analysis tab*

B Censored pictures of full vehicle creation interface in Virtual Lab

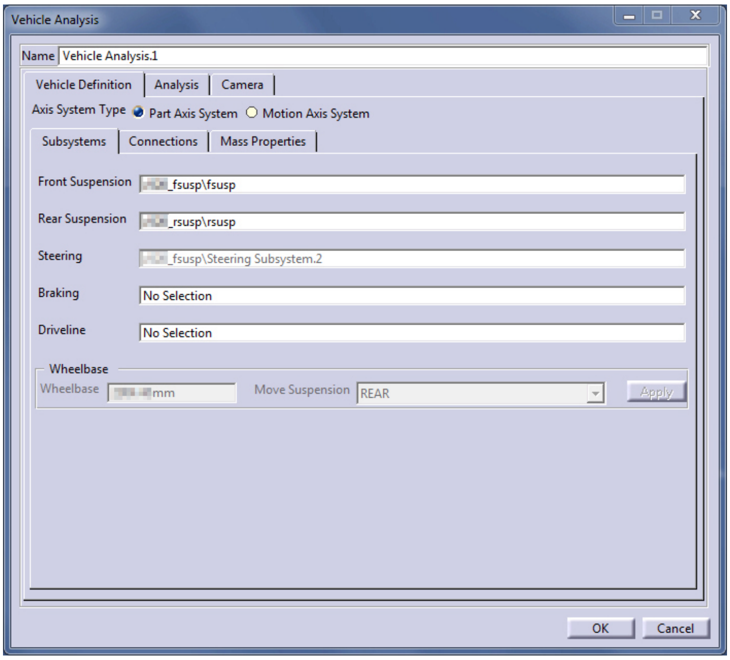


Figure B.0.1: *The subsystems tab*

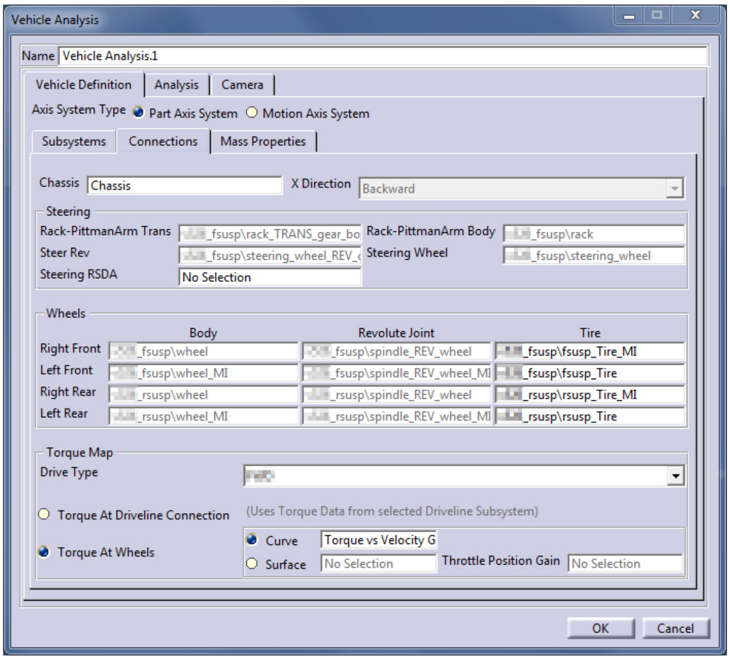


Figure B.0.2: *The connections tab*

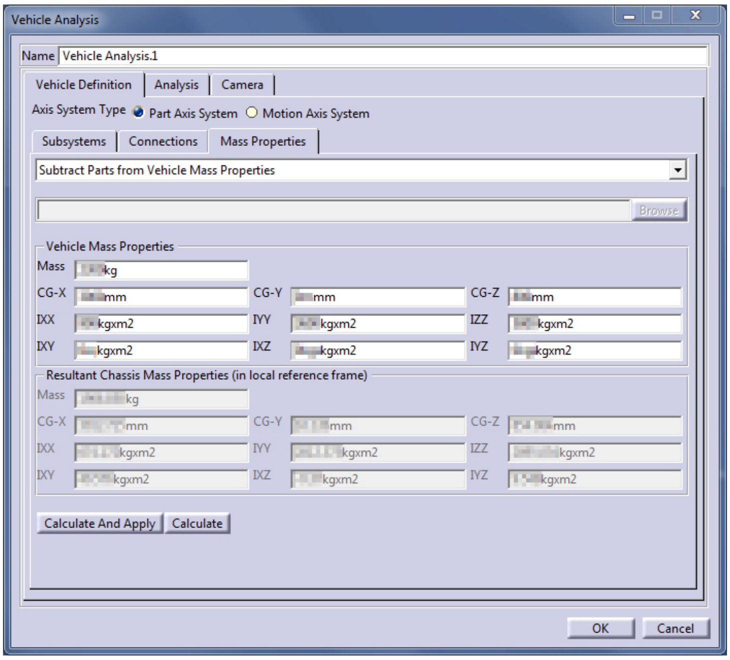


Figure B.0.3: *The properties tab*

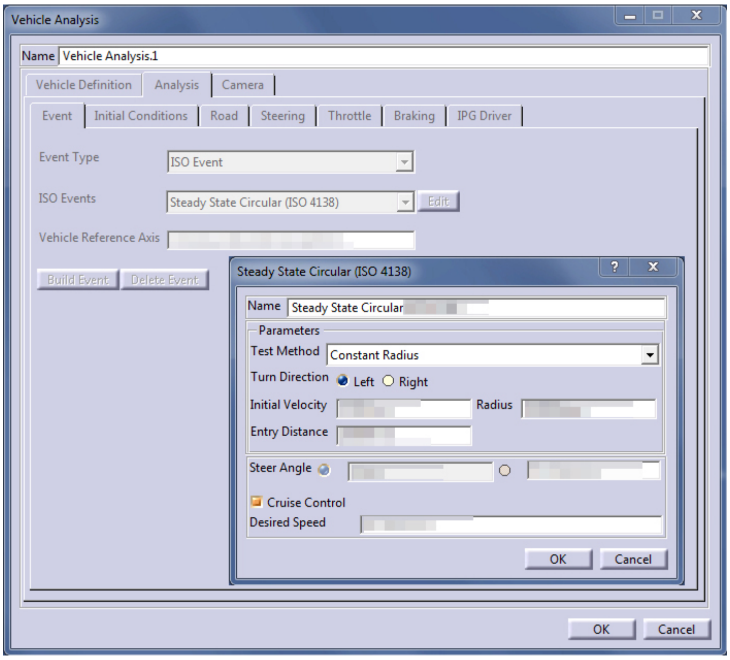


Figure B.0.4: *The analysis event tab*

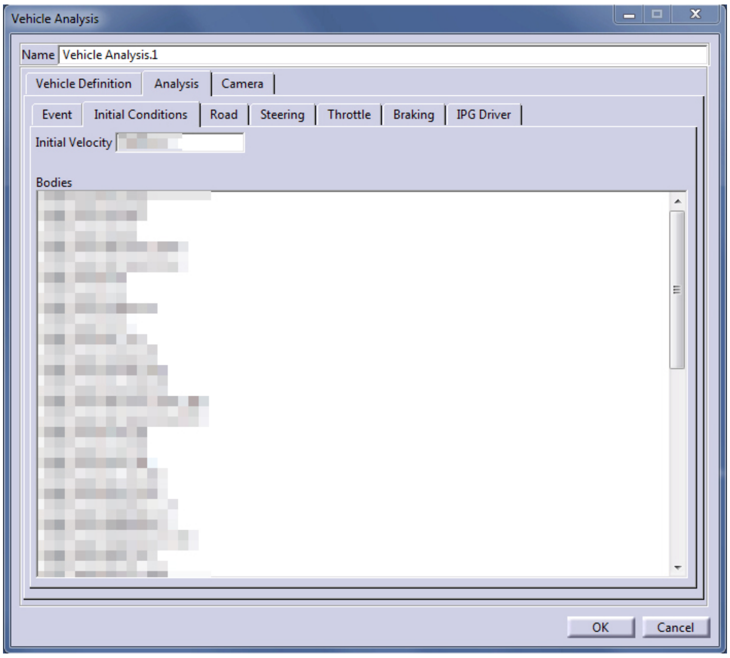


Figure B.0.5: *The initial condition tab*

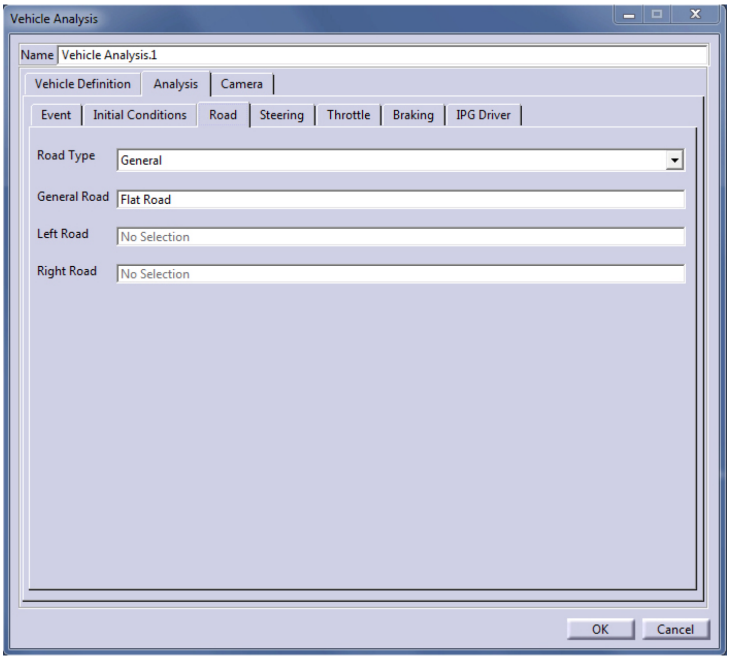
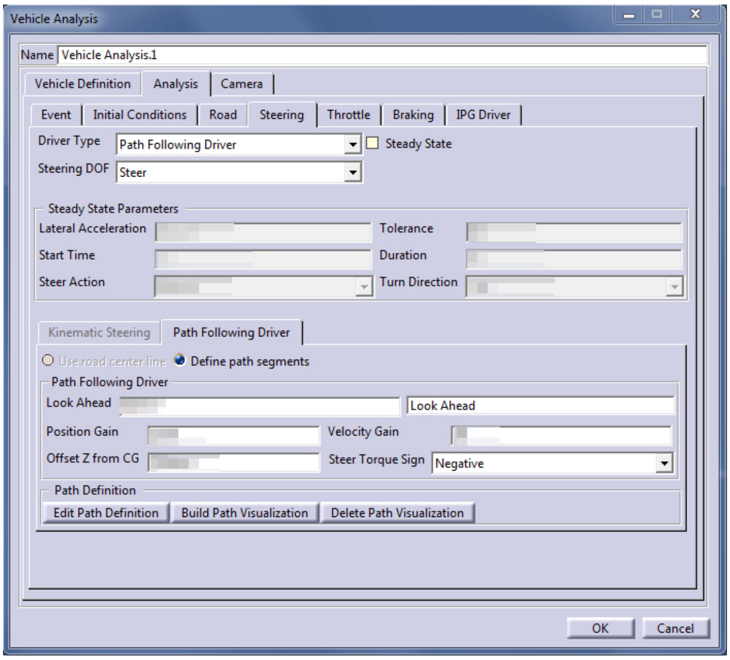


Figure B.0.6: *The road tab*



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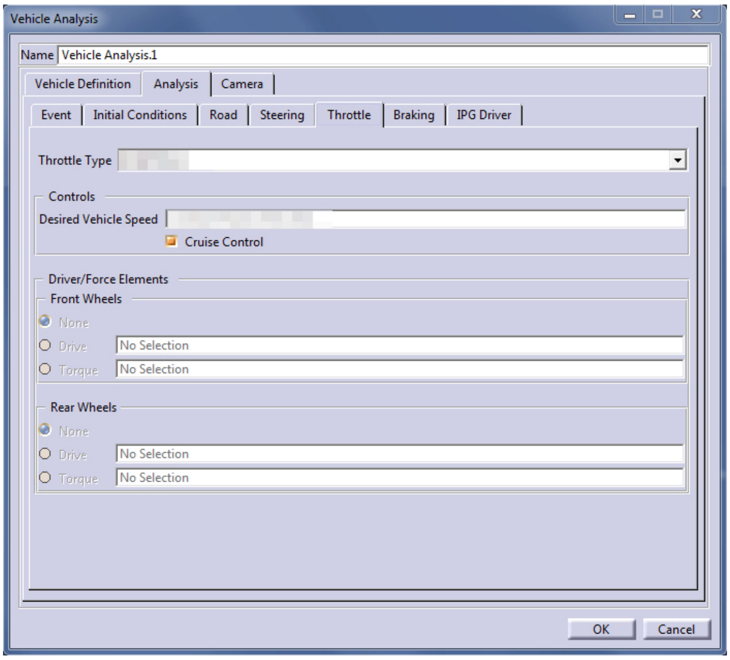

Figure B.0.8: *The throttle tab*