Master's Programme in Automotive Systems
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AVD Minor Project, 5 Credits

# Sidecar Racing Dynamics

Non-linear tire and passenger movement modeling


Client: **Team Weekers Techniek**
HAN Supervisor: Professor René Gerritsen,
Department of Automotive Systems, HAN University of Applied Sciences.

# Acknowledgement

This report has been developed to describe in detail the execution of the project and the key steps taken throughout and serves as an agreement among the following parties: Project Team, HAN University, Project Supervisor Mr. Rene Gerritsen and the problem owner R Weekers Techniek. The objective of this project is to make a working vehicle model of the sidecar thereby, optimizing the steering characteristics and suspension parameters.

Through this project, the team focuses to understand, model and simulate the behavior of a sidecar under various test scenarios. Later providing the model to the problem owner, through which they can simulate the sidecar and tune accordingly.

The project would not be successful without the support of all the team members and the following people. Our gratitude goes out to Mr. Rene Gerritsen for his constant feedback, support, and guidance. We would like to extend our sincere gratitude to the problem owners Rogier Weekers and Remco Moes, for providing us with the necessary information and feedback through the entirety of this project. The project group would like to appreciate the contribution by 'Milliken Research Group' and 'Calspan Tire Research Company' for providing the specific tire data. Our extended thanks goes to Mr. Thorsten Hirth representing Öhlins suspension AB, for providing an opportunity and information regarding the testing of the suspension. Last but not the least, we would like to thank Mr. Thymen Kamerling and Dr. Saskia Monsma, for providing their invaluable feedback and suggestions towards the project.

# Front matter

**Project title:** Sidecar racing dynamics

**Name of the group:** Team Sidecar Racing.

**Student details:**


| Project Members | Student Number | Mail id |
|---|---|---|
| Abhinanda Kalsi Nagaraja | 662522 | A.Kn@student.han.nl |
| Frédérick Wentzel | 660395 | FS.Wentzel@student.han.nl |
| Manish Varma Raathimiddi | 644781 | MV.Raathimiddi@student.han.nl |
| Ronnie Edavattathu | 653271 | R.Edavattathu@student.han.nl |
| Sarvajith G | 645425 | S.Guruprakash@student.han.nl |
| Somyadeep Dutta | 649122 | S.Dutta4@student.han.nl |


**Module:** MES Advanced vehicle dynamics

**Company:** R. Weekers Techniek

**HAN Supervisor:** Mr. René Gerritsen

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# Summary

Previous groups who worked on this project focused solely on implementing the passenger movements or suspension behavior and non-linear tire behavior using the contact force library, individually. This project is focused on bringing these two works together and providing better outcomes.

In this project, the sidecar was modeled in MATLAB Simscape multibody platform. Along with this, the passenger movement is also modeled. The non-linear behavior of the tire is executed using the TNO Delft tire model. The tire data for the model is obtained by contacting the "Milliken research group", who provided the data for our tire specification for driving/braking and cornering conditions.

The major takeaways from this project are:

1. A complete working model of a sidecar with the passenger movement.
2. Model also includes the non-linear behavior of the tire, which allows the simulations to take place at higher speeds and obtain more realistic data.
3. A complete documentation of the modelling procedure of the complex sidecar model has been given in the report.
4. A detailed test plan according to ISO standards for the problem owner, which can be used during the sidecar testing.
5. A few recommendations of different sensors and data acquisition hardware's that the problem owner can buy.
6. Finally, a detailed list of recommendations for the problem owner and for the HAN supervisor for future projects. This helps in redefining the modeling process which results in a more realistic model visually as well as dynamically.

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# Chapter 1

# Introduction

## 1.1 Background

A sidecar is a motorbike with three wheels and two crew members, one driver and one passenger. While the driver drives the sidecar, the passenger's task is to lean into the correct side of the sidecar during corners to improve the stability of the vehicle. During early days, the sidecar drivers used to lay over the engine and the passenger had to be inside a bucket that was attached to the side of a motorcycle. Over the years, sidecar racing has seen multiple modifications to make racing exciting and safer for the passenger[4]. This is achieved by replacing the bucket seat with a platform that makes the passenger be mobile, which increases normal loads on that particular side of the tire. This ensures that the tire is always in contact with the road at high speeds. The aerodynamic aspect has also improved a lot with newer sidecars having fairings all around them. Older sidecars exposed the driver and the passenger more, while in the newer generations both the driver and the passenger are tucked nicely inside the fairing.

The sidecar racing is organized under FIM, which is called as 'Fédération Internationale des Clubs Motocyclistes'. There are two classes in sidecar racing, F1 and F2. In the F2 class, the pilot lays above the engine. In the F1 class, the driver kneels in front of the engine. Another difference between the F1 and F2 sidecar is that the F2 sidecar is much shorter and also has a tubular frame. The F1 sidecar is longer and has a monocoque chassis[2]. Where before the F1 class would race with 1000cc engines and the F2 class with 600cc engines, this is not always the case anymore. The F1 class is slightly shifting to 600cc engines as well. Both classes are not allowed to have any suspension on the side wheel. This means that the side wheel hub is rigidly connected to the frame.

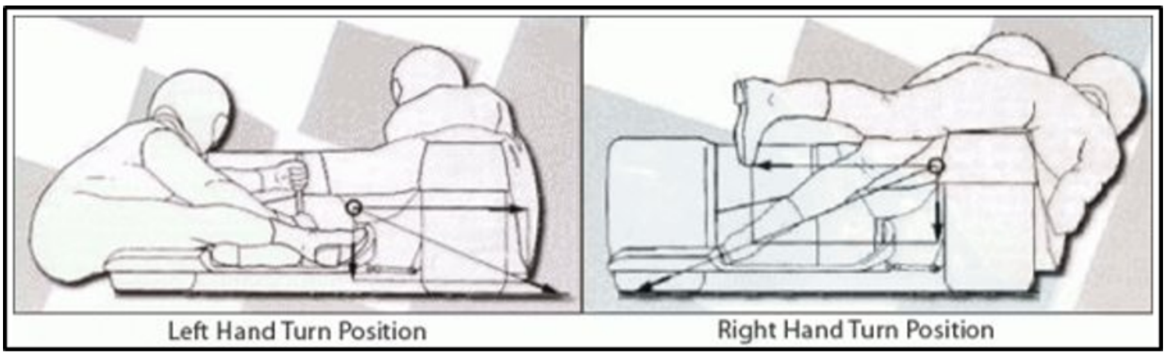


Figure 1.1: Passenger movement during left and right turn

This minor project is about modeling the steering, suspension, and tire behavior of a sidecar including passenger movement. The client for this project is Team R Weekers Techniek. This company is owned by Mr. Weekers himself, and the company focuses on machine technology. The sidecar team is from the Netherlands, participating in the ‘Open Dutch Championship’ (ONK). They drive a self-build F1 chassis with a 600cc Yamaha engine. Team Weekers has been active in sidecar racing since 2017. Driver Rogier Weekers and his passenger Remco Moes runs the team. The responsibility of the driver is to maneuver and control the sidecar, whereas the passenger seated behind can move freely left to right on the platform. This communicates that the passenger can also affect the stability or handling of the sidecar. Therefore, perfect teamwork is required from both the driver and the passenger to ensure good handling.

## 1.2 Problem definition

As in all the other classes of motorsport, the handling of a vehicle can be decisive to win a race, and thus the setup of the vehicle is one of the most important subjects. This is also the case with sidecar racing. Currently, all the sidecar teams set up their sidecar based on experience and knowledge. The behavior of a sidecar, however is not specific. Due to the sidewheel, the behavior during left and right corners is different as well as the sliding behavior of the tires. In addition, there is also the influence of the passenger. To gain an understanding of the dynamic behavior of the sidecar, team Weekers would like to have a vehicle model of their sidecar. Finally, understanding the sidecar’s behavior could also help in optimizing the dynamic behavior.

The vehicle model will majorly focus on modeling vehicle dynamics subsystems. There are some pivotal parameters that can be very crucial in the handling behavior of a sidecar vehicle such as the offset between the front wheel and rear wheel, camber angle, toe angle of both front and side wheels. The limitation in modeling such a vehicle is that no prior models of 3 wheeled vehicles have been extensively built before, which means extremely limited resources about dynamic behavior and modeling can be found.

| **Project Groups** | **Previous Group 1 (20/21)** | **Previous Group 2 (20/21)** | **Current Group (21/22)** |
|---|---|---|---|
| **Suspension type** | Double wishbone suspension. | No suspension. | Multilink suspension. |
| **Tire behavior** | Nonlinear tire model. (Contact force library) | Linear tire model. | Nonlinear tire model. (MF tire model) |
| **Passenger movement** | Excludes passenger movement. | Includes passenger movement. | Includes passenger movement. |
| **Steering** | Provided directly to the wheel. | Provided directly to the wheel. | Depicts the actual steering kinematics. |

Table 1.1: Group models

In the previous year, two other project groups tried to make a linear and nonlinear tire model, respectively. As the chassis was not finished, which meant no test data could be gathered, therefore the model could not be validated. The differences between the different models from the previous and current groups can be found Table 1.1.

As can be seen, this year’s group will try to implement the nonlinear tire model and the passenger movement into one vehicle model, as well as the newly designed front suspension.

## 1.3 Project objective

1. Determine the handling characteristics of the new chassis for different steer and suspension geometries. Nonlinear tire behavior and passenger movement must be considered while determining the handling characteristics of the sidecar.

2. Next to the model, the group will also produce a test plan in order for Team Weekers to know which data they will need to collect, to validate the model at a later date.

## 1.4 Research question

A research question can be devised which acts as a question to summarize the main goal of this project and helps in formulating the project conclusion. The main question will be stated as:

*What is the steering & suspension geometry that majorly influences the handling and stability characteristics of a vehicle?*

### 1.4.1 Sub-research questions

1. How to replicate a sidecar in Simscape Multibody?

2. How does non-linear tire model work and how to implement in our model?

3. How to mimic the movements of a passenger in the side car?

4. What are the parameters to be logged and what sensors to be used?

## 1.5 Approach: Waterfall model

Based on the unavailability of testing conditions and the duration of this project 'The waterfall model' was adapted. The reason behind choosing this model is that, because of the advantages that this model has to offer. Some of the advantages are that this is a short-term project with low-risk modeling and if there are any errors, the model can be re-called. Hence, according to this model, the project was broken down into activities that resulted in a deliverable. Different stages of this project can be found in Figure 1.2.

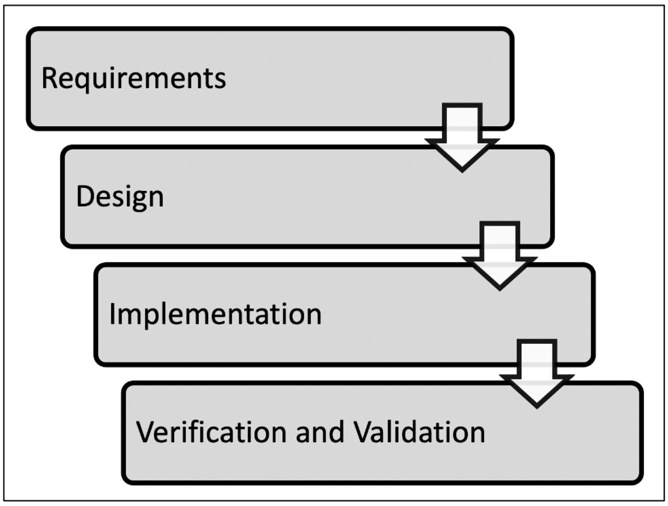


Figure 1.2: Different stages of the project based on waterfall model

### 1.5.1 Requirements

In this stage, the requirements from the project client and educational institution/project supervisor were analyzed and processed. The problem definition and project objectives are a result of this phase. Some of the requirements are:

1. Model should be flexible and easily modifiable.
2. The model must be robust and should mimic the original sidecar behavior. (e.g. camber variations)

### 1.5.2 Design

In this stage, the previously mentioned requirements and project objectives were studied, and the needed software is chosen. In addition, to come up with a start, a literature survey was performed. With the knowledge gained from this study, a simplified model could be made.

### 1.5.3 Implementation

During this stage, the simplified model was extended with the needed features such as the nonlinear tire model and the passenger movement. In addition, to impersonate the 3-D sidecar, modeling was done in Solidworks and by using an add-on plugin in MATLAB, it was directly imported to the Simscape workspace. This resulted in a model automatically created by the Simscape environment. Also, a proper model with multiple A-arm as requested accompanied by camber variations due to load transfer and which also contains an MF tire model with actual tire data was implemented.

### 1.5.4 Verification and Validation

In this phase, the parameters were tuned and checked. In addition, dynamics and steady-state simulations were carried out. All tests cases were simulated according to ISO standards. A subjective validation is performed based on a video provided by the problem owner. The results from these tests were analyzed and a conclusion and recommendation was formed.

### 1.5.5 Outline of the minor project report

From the above-mentioned approach, this report has been divided into certain categories which explain how this project unfolds. Each category explains in detail the approach strategies and the reason behind this approach. In the end, the appendix section will give a much more comprehensive review of certain aspects of the project which require more explanation. This report is dissected into the following categories:

1. Introduction
2. Literature survey
3. Methods
4. Results and discussion
5. Additional discussion
6. Conclusions

7. Recommendation

This report is preceded by the preface and the summary at the beginning and later ends with the appendix section.

# Chapter 2

# Literature survey

Literature survey is the most basic and important step which has to be done in order to get an in-depth understanding of the project and what steps have to be taken next. This activity behaves as a bridge between our knowledge and the recent research that has been accomplished in 3 wheeled vehicles field. The foundation of this project is based on the work of the last two groups. The important research survey which was required for the project is listed down below accordingly:

## 2.1 Sidecar design:

1. Team Weekers Techniek has created a document that meticulously explains each and every aspect of the vehicle design. It also mentions the requirements and the current setups of the sidecar. The document contains the 'FIM Sidecar World Championship Regulations', which give a clear vision about the design and optimization restrictions. The certain parameters stated, helped during the modeling phase of the sidecar in Simscape Multibody[13].

2. MATLAB Racing Lounge provided an exceptional education to teach modeling in simscape multibody. They broke down different aspects of the modeling into different videos and gradually increased the complexity of modeling. Different type of simulations was also displayed. One of the most important topics with respect to the project which they taught effortlessly was 'Parameter optimization'. The same method was used to optimize the straight-line stability in the model. This one tool offers the best optimization solution rather than performing with huge for loops[3].

3. Previous reports gave a preview of the data and the types of testing that had to be done in order to show how the optimization of the sidecar works. Apart from this, the report also showed different parameters that can be optimized to enhance the handling behavior of the sidecar. The suggestions and recommendations were taken into consideration while modeling and verifiying[14][10].

## 2.2 Modeling:

All the axis systems and the units during modeling are strictly based on ISO standards

1. GENTA & GENTA - The book mentions the influences of camber and toe angles on the lateral forces and ultimately how it affects the handling of the vehicle. The book also orates about the nonlinear behavior of the tire, how is Pacejka's model built, and the

parameters that influence the change in tire behavior. It explicitly speaks about the peak and sliding values of the lateral forces, which are one of the paramount parameters that are required by .tir files. Handling behavior of the vehicle with respect to changes in conditions and parameters[11].

2. TNO Delft tire - In a Simscape multibody environment, tires are considered as a force element that behaves like a spring and damper system and provides force in the direction perpendicular to the road after interacting with the road surface. The forces and moments obtained during this are highly non-linear. Therefore, a model like the TNO delft tire is required to analyze the non-linearity behavior of the tire. This tire model uses a semi-empirical modeling approach and makes use of the 'Magic Formula' model to analyze and calculate the forces and moments. The MF-Tire/MF-Swift Guide helps in understanding every part of tire modeling starting from how to install the software to explaining the complex parameters and coefficients that are required in the .tir file. The guide also helps the user to differentiate between different versions of models based on the requirements[6][7].

## 2.3 Optimization parameters:

One of the major objectives of this project is to suggest the best geometry by optimizing the steering and suspension geometry of the sidecar. Therefore, it is highly necessary to understand the working and effects of various steering and suspension parameters that influence the overall behavior of the sidecar. Some of the key parameters which were identified from the literature survey are:

1. Camber angle: Camber angle is the angle measured from the vertical axis to the wheel mid-plane. The camber angle is said to be positive and negative when the wheel leans away and towards the body of the vehicle respectively. Camber generates an additional lateral force called 'camber force' or 'camber thrust', the direction of this force depends on the orientation of the camber angle[11]. A negative camber angle gives camber thrust inwards to the vehicle, this makes the vehicle more stable in a straight line.

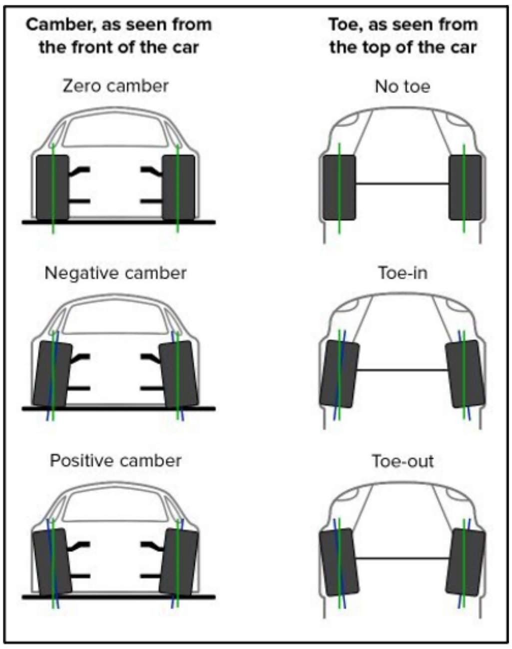


Figure 2.1: Sign conventions for camber and toe angles

2. Toe angle: Toe angle is the angle measured from the horizontal axis to the mid-plane of the wheel when viewed from the top. The toe angle is said to be positive (Toe in) and negative (Toe out) when the wheel points towards and away from the body of the vehicle respectively[11].

3. Kingpin axis and Trail offset: Although these parameters play a vital role in suspension behavior, these parameters were excluded from the modeling perspectives on the advice of the problem owner as they have issues using these parameters. This is because under braking, the chassis is experiencing diving behavior. This is causing the suspension behavior to vary and resulting in an unstable behavior of the sidecar[13].

# Chapter 3

# Methodology

## 3.1 Simplified model

One of the earliest approaches to understand the modeling of the sidecar behavior in the Simscape environment was done with this model. This model concentrates on the distribution of normal load on all three wheels, implementation of highly simplified suspension and optimization parameters into the model. Firstly, the coordinates of the chassis were imported into the file solid on Simscape multibody. The COG of the sidecar chassis was identified. Concerning the COG, the suspension for this model was developed. This is highly simplified as a prismatic joint act as a connection between the chassis and the connecting rod. The damping parameters were given to the joint to mimic the simplified characteristics of the suspension. This allowed only a single degree of freedom which is the translation motion in the vertical direction. An axle between the chassis and the wheel depicts the movements of the a-arms. The uprights were not considered for this model. Although MF tire was considered in this model, the tire parameters were not added to this due to its unavailability.

## 3.2 Complex CAD model

Another approach that was tried was converting the CAD drawings into a Simscape model. MATLAB supports '.xml' format files import from selected CAD packages to which SOLIDWORKS is one of them. Using the command 'smimport' the CAD assembly could be loaded into Simscape, which automatically converts the assembly into a model using the blocks and joints available in the library. In case a constraint from the CAD file is unknown for the Simscape software, the software will replace it with a fixed joint. Due to these unwanted joints and connections between solid subsystems, the model did not perform as desired. Hence the model had to be examined by checking every block, joint, and connection after which the unwanted ones had to be removed. Even after debugging the model, it did not behave as wanted. The sidecar would not settle and it keeps on bouncing when trying to establish contact with the road. After many days of trying to make the model work, this approach was deemed to be un-doable for the time available. Further explanation is given in the additional discussion 7.

## 3.3 Final model

The first model had a lot of simplification, which did not satisfy the problem owner because the camber variation was not captured in the simplified model. Hence to overcome this problem, the arm geometry was replicated, and all the distances of the A-arms are considered concerning the COG of the sidecar chassis. The dimensions reference of the COG was taken from the CAD model. The COG was calculated using the mass properties option under evaluate section in SOLIDWORKS. After that an individual arbitrary reference frame was considered in MATLAB which was located at the rear most end of the chassis and the distances to the COG was then considered from this point in CAD as well. The distance of COG from this arbitrary point was then defined in MATLAB and hence the location of COG was confirmed for further reference dimensions of other components. The coordinates and the transforms for each component were measured in SOLIDWORKS and a precise measurement up to 2 decimal places was followed. The multilink suspension setup was nearly approximated to a double-wishbone suspension. This setup contains the front and rear uprights as well, the other ends of the A-arms are connected to the uprights. The camber angle variations are given to the upright itself, this mimics the same thing which happens in the sidecar itself. As per the requirements by the problem owner, the rear lower arms of the suspension must be parallel to the ground and perpendicular to the upright. Restrictions like these were successfully implemented in this model. The steering assembly is exactly implemented as per the given CAD model. This gives us increased flexibility to vary the camber angle and toe angle concerning the upright. Apart from this, the steering input is also given to the handlebar, which has a steering ratio of 1. Accurate mass distribution is achieved across all three tires once the tire has established contact between itself and the road. One of the additional leaps in this model is the use of MF tire data. The tire data was obtained from Milliken and for the different tire behavior and conditions. The data obtained from the tire data is updated to the .tir file. A detailed section on how the tire data has been extracted is explained in the TNO Delft tire modeling section 3.5.

In order to mimic the multi link suspension behavior into the final model. A vertical input was provided to the wheel, based on the force generated at the suspension in the complex model, mean value of force was calculated and was simultaneously matched in the final model by altering the damping co-efficient and equilibrium position of the suspension. However, aerodynamic forces were neglected for all the above models.

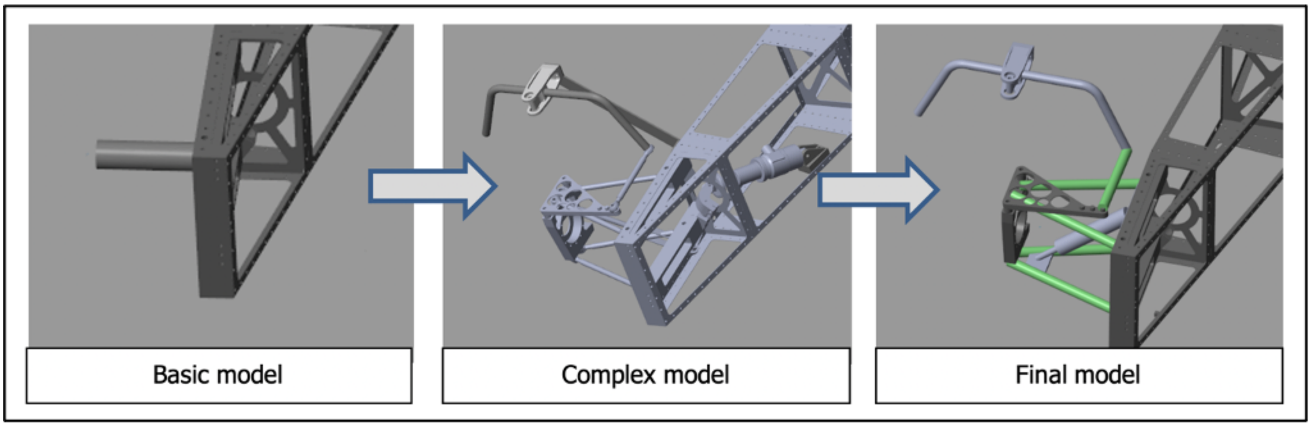


Figure 3.1: Model evolution

## 3.4 Passenger modeling

One of the requirements for the model was to also implement the movement of the passenger. This was done by using a point mass and moving it along the lateral or x-axis depending on the steering input. When the steering angle is zero, meaning the sidecar is going straight, the point mass is situated in the midpoint between the side wheel and the main chassis. When the steering angle is bigger than zero, the sidecar would be going to the left. In this case, the point mass moves towards the center-line of the side tire. If the steering angle is smaller than zero, meaning a right turn, the point mass moves towards the center-line of the main chassis. In the model, these positions were implemented by using a variant source that reads the steering input and then, depending on the steering input sends the correct coordinates to the point mass. To mimic the movement of the passenger going from one position to the other, a signal builder is used. This way the speed at which the passenger is moving can be changed for a more realistic scenario.

A previous version of the sidecar model used fixed points to which the point mass would jump depending on the steering input. However due to the sudden movement, this gave a lot of distortion to the simulation results. The present version mentioned above, not only deals with this problem, but is also more accurate to the real world behavior of the passenger movement.

## 3.5 TNO Delft tire model

cOne of the objectives of this project is to use the TNO Delft tire in our modeling process of the sidecar. To develop the tire model subsystem, the MF-tire block from SimMechanics 2G library was used. MF tire, as the name suggests, stands for the standard Pacejka Magic Formula for tires. It provides fast and robust road-tire contact forces and moments that can be effortlessly simulated on the Simulink platform. The Pacejka model is regarded as a reliable model extensively tested and validated for various conditions. The MF tire model uses ISO sign conventions as depicted in Figure 3.2. The model uses 'Tire Property File' which comprises all the parameters required for the tire. Some of these parameters were changed as per the obtained tire data[15]. These include the tire physical specifications, nominal load, inflation pressure, etc. These tire specs are provided in appendix D. The nominal load on the tires was taken from the average load on all tires.

Modeling this particular tire is very tricky because, to obtain good tire behavior, one should know the exact details of the tire and should also have the tire testing data in hand. Since tire data is a very well-guarded secret, it is impossible to find it on the internet. Therefore, communication was established with the Milliken research group and they were willing to share the tire data. The obtained test data are for the following tires[5]:

1. Front wheel: Avon 8.2"/20.0"-13"
2. Side wheel: Avon 10.0"/20.0"-13"
3. Rear wheel: Avon 10.0"/20.5"-14"

The tire testing for FSAE TTC is conducted by:

1. Calspan Tire Research Company:
2. Cooper Tire and Rubber Company.
3. Keizer Aluminum Wheels and Diamond Racing Wheels.

The .tir file helps the MF tire to imitate the same behavior of the tire that is being used. Therefore, it is of utmost importance to extract the necessary information from the tire data and update it in the .tir file. A total of eight rounds of testing has been done and at each round, different tires have been used[6]. Based on the complete tire name, one can identify under which round of testing does it belong. The data available is already filtered and can be

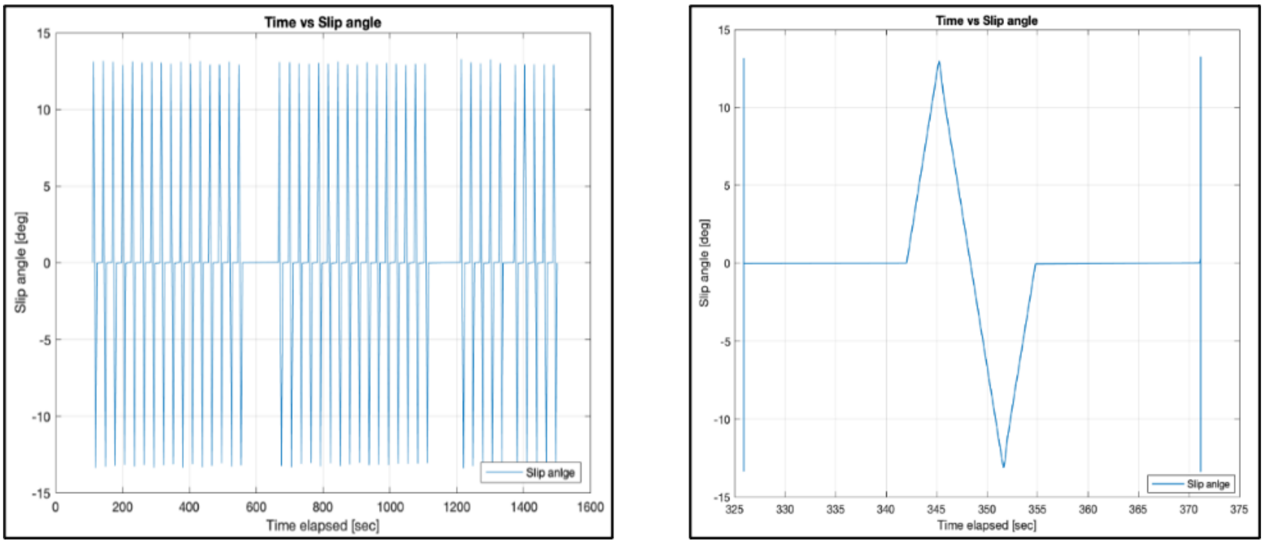


Figure 3.2: (a) Entire run of the tire slip angle (b) Single slip angle sweep extracted from the run data

readily used to update in the .tir file. Based on the simulation parameters, the tire data has to be taken out from the bunch of data. The data can be segregated through slip angle and slip ratio sweep. One sweep cycle varies from a negative near zero slip angle to its maximum value and then passes through zero to its lowest value and finally ends back up to a positive near-zero value as shown in Figure 3.2 (b). This ends one cycle of the slip angle sweep[7]. The same is repeated for the slip ratio. Based on these sweeps, one can extract the data based on the tire inflation pressure, inclination angle, vertical loadings, etc.

Using the above-mentioned sweep method, the data required for testing is extracted in MATLAB based on several parameters like speed, inflation pressure, etc. Some of the information required such as tire width, aspect ratio, rim radius etc, were straightforward and was taken from the website[1]. Important graphs like slip ratio vs normalized longitudinal force and slip angle vs normalized lateral force, some of the data points have a lot of deviations throughout the run. Hence it was difficult to find the peak value. Therefore, only these data have to be processed by curve fitting process through systems identification. Whereas, in this case, both the graphs had less deviations, so it was plotted without curve fitting tool.

Some of the required parameters by the .tir file are given down below:

1. Free tire radius
2. Nominal section width of the tire
3. Nominal rim radius
4. Tire inflation pressure
5. Nominal wheel load
6. Tire vertical stiffness
7. Minimum and maximum valid tire inflation pressure
8. Minimum and maximum allowed wheel load
9. Minimum and maximum valid wheel slip

10. Minimum and maximum valid slip angle
11. Minimum and maximum valid camber angle
12. Longitudinal friction Mux at Fznom
13. Longitudinal slip stiffness Kfx/Fz at Fznom
14. Lateral friction Muy
15. Maximum value of stiffness Kfy/Fznom
16. Load at which Kfy reaches maximum value

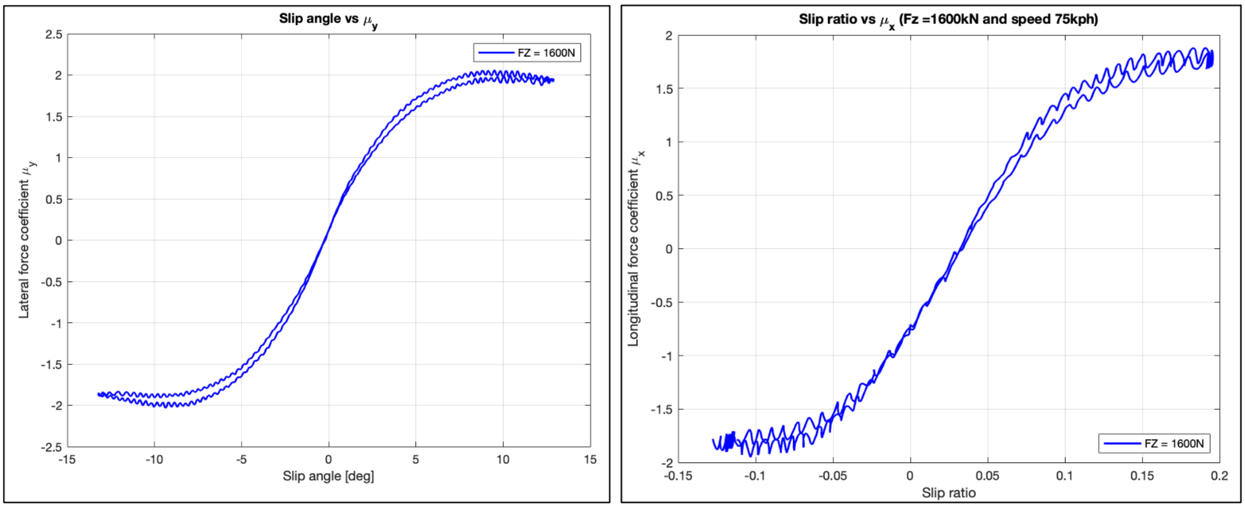


Figure 3.3: (a)Slip angle vs $\mu_y$ (b) Slip ratio vs $\mu_x$

# Chapter 4

# Results and discussion

This chapter analyses the results of certain simulations that has been performed on the sidecar. The outcomes of these simulations and the results are justified based on the obtained plots.

## 4.1 Load distribution

One of the initial and simplest techniques to realize if the sidecar has created a contact with the road and how much load each tire is exerting on the ground is determined through this graph Figure 4.1. The graph depicts the load values on each wheel which fairly mimics the actual sidecar load distribution. Apart from this, the graph also talks about the stability of the sidecar once it is dropped on the ground. The sidecar takes less than 10 seconds to settle down completely.

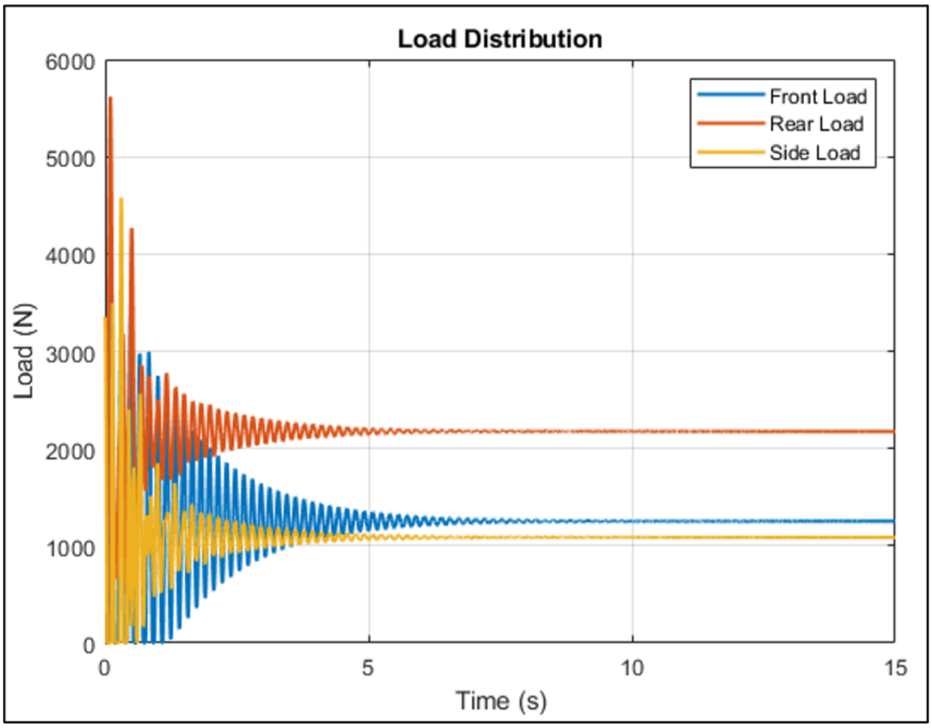


Figure 4.1: Load distribution on each wheel when the sidecar is dropped on ground

The two reasons for increased settling time are due to the fact that the side wheel is not equipped with a suspension, and another is due to the inaccurate location of the center of gravity.

## 4.2 Straight line stability

The sidecar geometry is very unsymmetrical with front and rear wheels having an offset between them on one side, and a side-wheel on another. The moment magnitude created by the combination of the front and the rear wheel is more than the one created by the contact patch of the side wheel about the COG. This tends the sidecar to naturally drive more towards the left side when viewed from the top view thus affecting the straight-line stability. To validate this behavior of the sidecar in the model, a straight line stability test was performed in a Simscape Multibody environment at different speeds of 90, 120, 150, and 180Kph respectively. From the obtained graph, the lateral deviation of the vehicle can be learned, which sheds light on the actuality and in-depth modeling done by the group in capturing the pure essence of the dynamics of the sidecar.

As can be interpreted from the plot, showing the position of the vehicle in global XY coordinates, at higher speeds of 180 Kph the lateral deviation decreases when compared to a vehicle speed of 90Kph at the same longitudinal position of 150m, due to the presence of combined slip. Thus, at the higher velocity, the longitudinal force dominates over the lateral component.

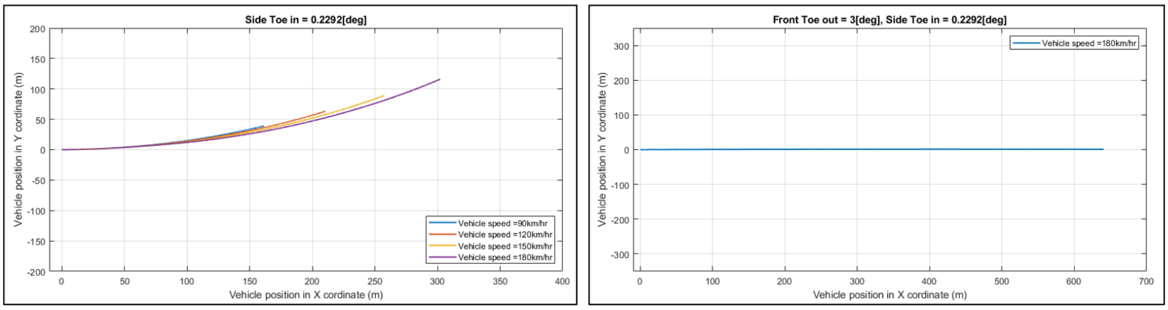


Figure 4.2: Straight line stability (a) before and (b) after parameter tuning

When consulted with the problem owner, they indicated that the driver can still maintain a straight-line trajectory even with 2 fingers on the steering handle. They also informed that the sidecar's parameters are tuned based on the driver's feelings. Since the exact values of the tuned parameters were unknown, the parameter estimation toolbox was used in order to tune the front and side wheel toe angle respectively.

## 4.3 Steady state

A steady-state test is performed to evaluate the steering characteristic of the sidecar, along with measuring the extent to which the driver could throttle the sidecar to negotiate a specific radius turn.

From the below Figure 4.3 it is noticeable that the lateral force for a left turn is more when compared to the scenario when the vehicle takes a right turn. This is owing to the fact that when making a left turn, the front and rear wheels are loaded more due to load transfer than the side wheel, resulting in an increase in lateral force. While the side wheel is the only one contributing much of the lateral force in the case of a right turn, this perfectly explains why the overall lateral force is smaller in a right turn. The lateral acceleration in the case of a left turn sums up to a value of 0.92g while in the case of a right turn the value drops to 0.82g.

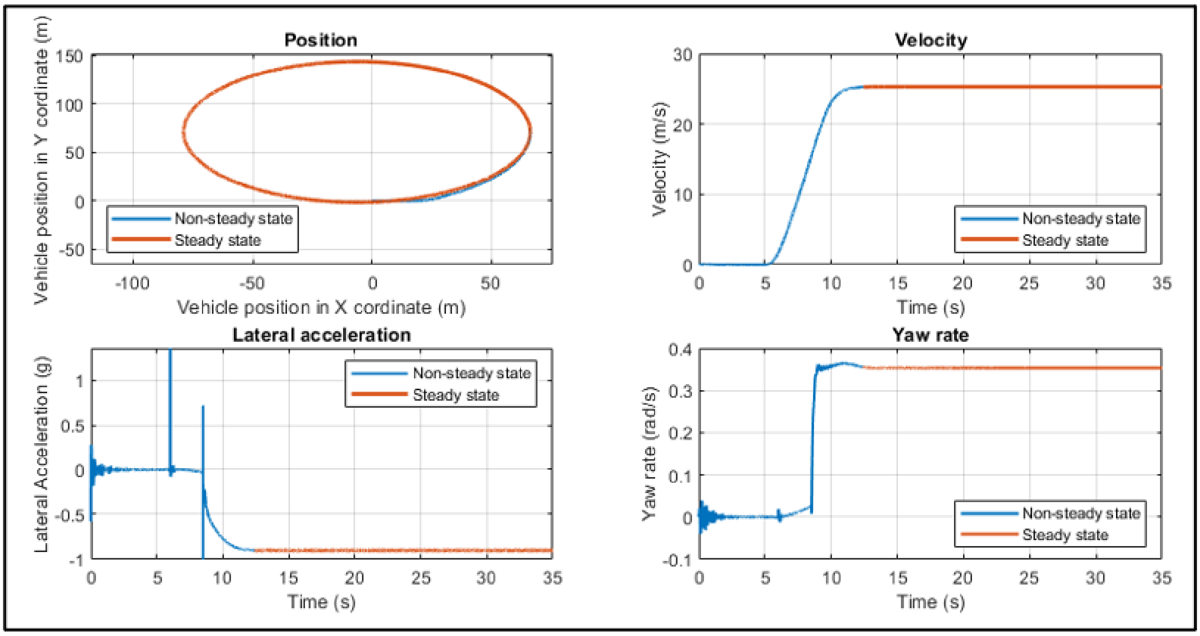


Figure 4.3: Steady state test at 95Kph for a left turn

The product of the lateral force and the moment arm for all the wheel's contact patch for a left turn is more compared to the moment magnitude about the vertical z-axis for a right turn, thus in a steady-state condition the yaw value is more for a left turn compared to the right turn.

*Note: The initial phase of lateral acceleration and yaw rate plots have oscillations as the vehicle is not settled on the ground. The sudden peaks in graphs are caused due to passenger movement. This will be applicable to the rest of the graphs plotted below.*

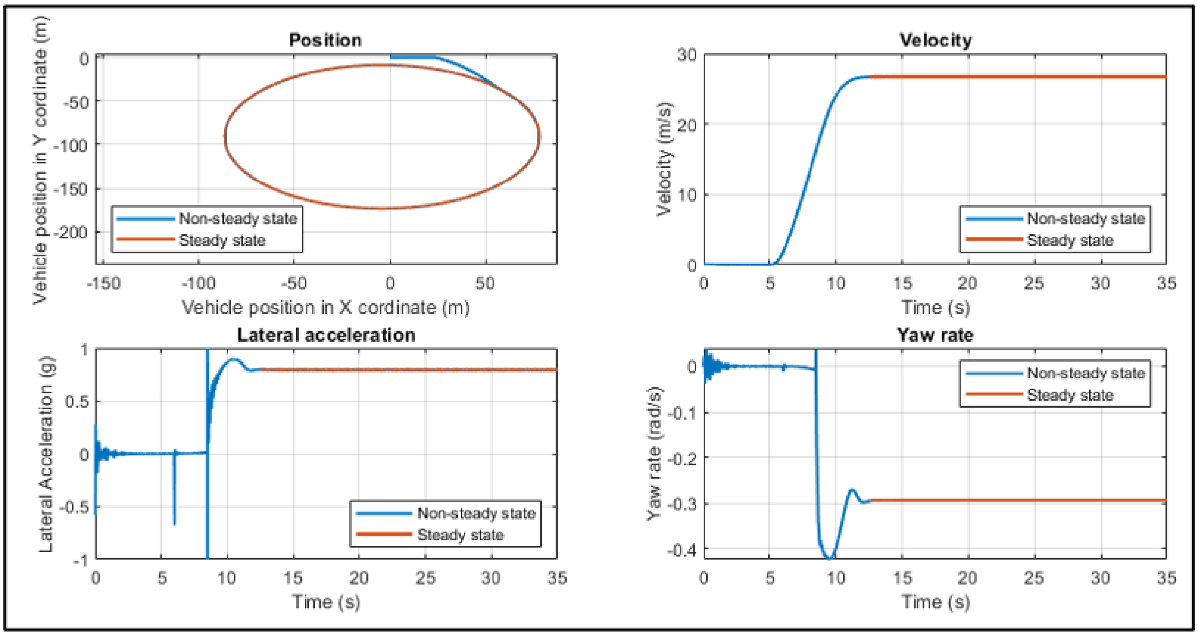


Figure 4.4: Steady state test at 95Kph for a right turn

## 4.4 Handling behavior

To analyze the handling behavior, the model is tested under steady-state conditions where it is given a step steer with a constant velocity input. The test is repeated for different constant speeds for both left and right turns, further, the plots of trajectory traced, lateral acceleration, and yaw rate is visualized.

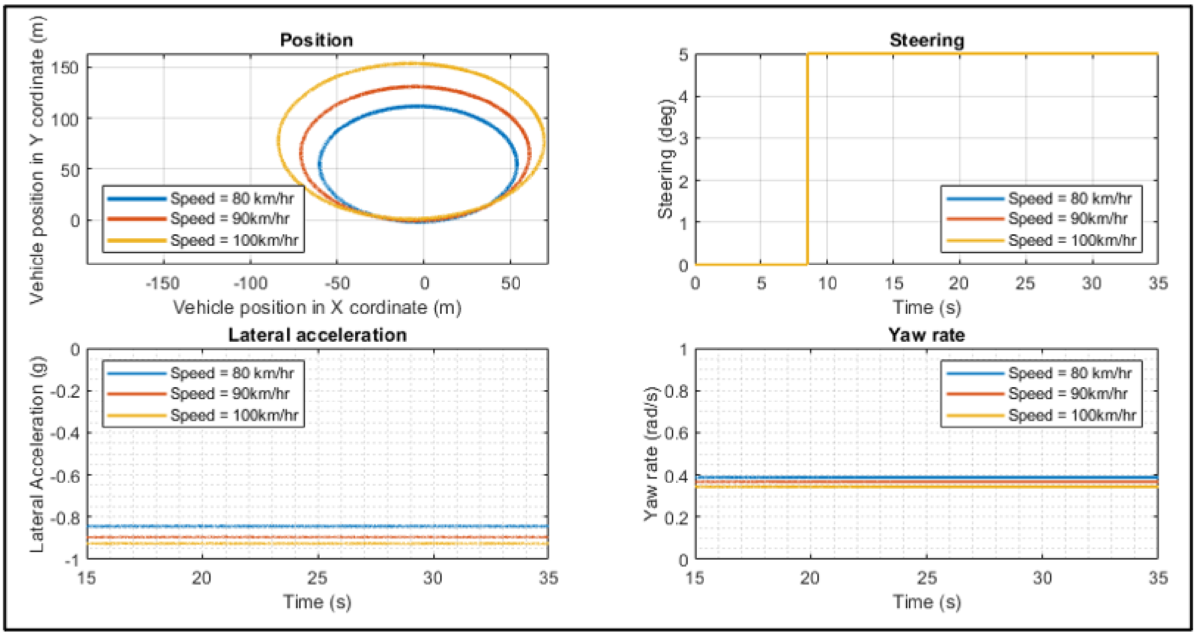


Figure 4.5: Steady state test for left turn at different speed with constant steering input

The radius of the trajectory traced by the model for a steering input of +5 degree with velocity of 80 Kph as seen in the Figure 4.5 is 55m. Comparing both left and right hand turns at similar speed, it is observable that the sidecar makes a much smaller radius during left turn than the right. This behavior is also true for increasing speeds. Therefore, this shows that the sidecar oversteers during left and understeers when turning into the right.

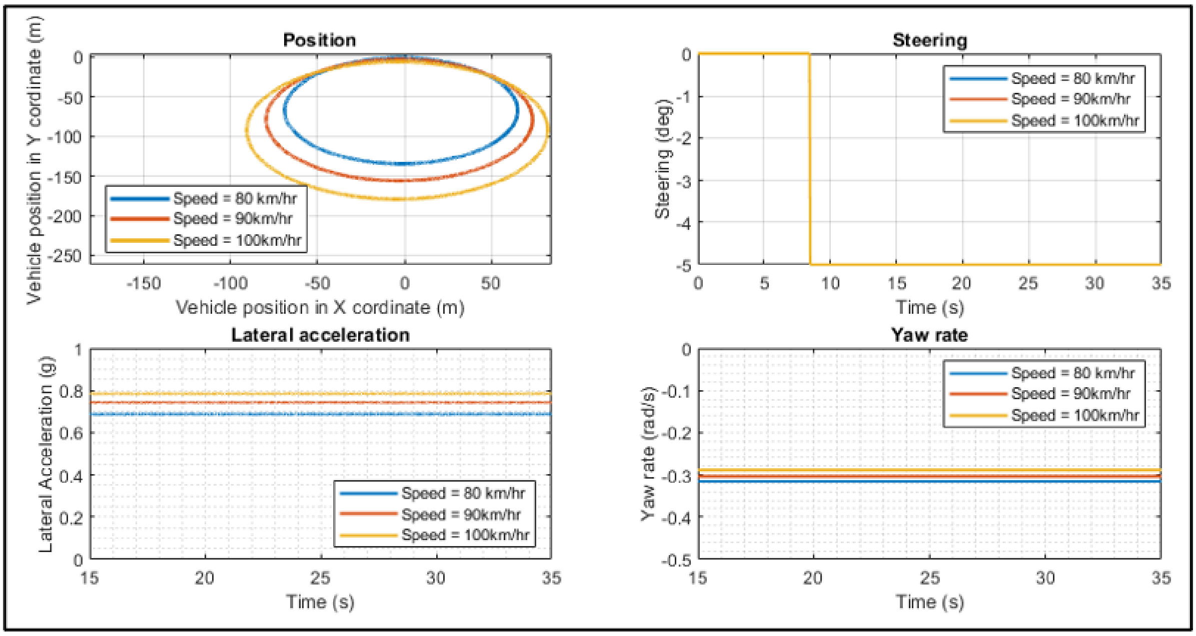


Figure 4.6: Steady state test for right turn at different speed with constant steering input

From the lateral acceleration plot Figure 4.6 of understeered right turn vehicle, the value peaks at 0.82g while against the over steered left turn of 0.9g. The yaw rate of the right turn is 0.3 rad/s where as the left turn has a higher yaw rate of 0.4 rad/s. Thus reassuring steering behavior as expected.

## 4.5 Tire data comparison

This test is done at 95 Kph for a left turn, in order to compare the tire data obtained from Calspan with the standard data that is provided by the MF tire. The graphs show the difference in model response that the exact tire data can provide. It is highly clear that the data acquired from Calspan provides a different result than the data present in the standard tire file provided by the MF file. The change in the response behavior of the sidecar is due to the vaguely provided crucial values such as longitudinal and lateral slip stiffness, slip angles. Once the exact values of the tire specification and parameters are provided to the tire, the MF tire model behaves exactly like the tire that is being used by the user.

The radius of the circle is decreased by 5-6 meters while the lateral acceleration remains almost the same. Whilst there is a huge difference in the sidecar behavior that can be noticed in the graph of yaw rate. From the lateral acceleration Figure 4.7, it can be seen that the acquired data is providing a higher lateral acceleration than the standard TNO data. When discussed with the client, he suggested that the lateral acceleration experienced is close to 1g for that particular speed. Therefore, it can be seen from Figure 4.7(a) acquired data was coming close to realistic situations. It is evident that for higher speeds that the acquired data shows much more stable yaw rate response than that of TNO data which is clearly visible in Figure 4.7(b).

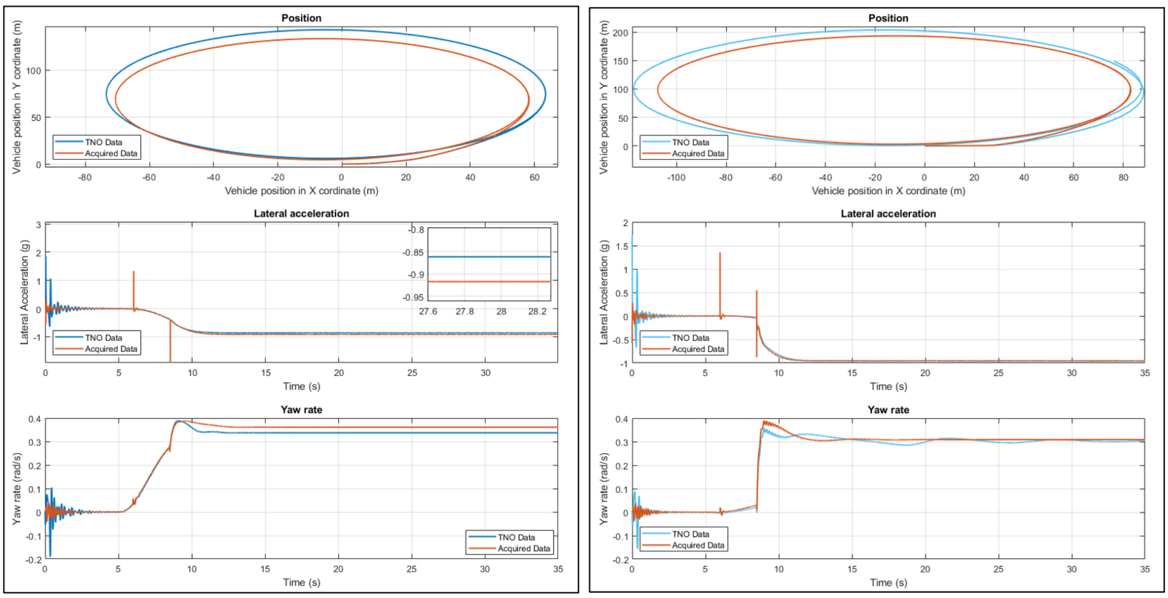


Figure 4.7: Steady state test to determine the difference between TNO vs acquired .tir file (a) 90Kph and (b) 115Kph.

## 4.6 Dynamic test

To analyze the dynamic behavior of the model, a step steer of 10 degrees in each direction is simulated at 8.5 sec for a ramp velocity input of 80Kph. From the Figure 4.8, there is a difference in both the velocities at about 10 seconds for the right turn because the lateral acceleration reaches the peak value, and it dominates over the longitudinal component (combined slip). Since vehicle handling behavior has to be derived from steady state circular test, dynamic test will help in confirming the behavior that has been derived from the steady state test. Figure 4.8 shows the same handling behavior as can be seen in the Figure 4.3.

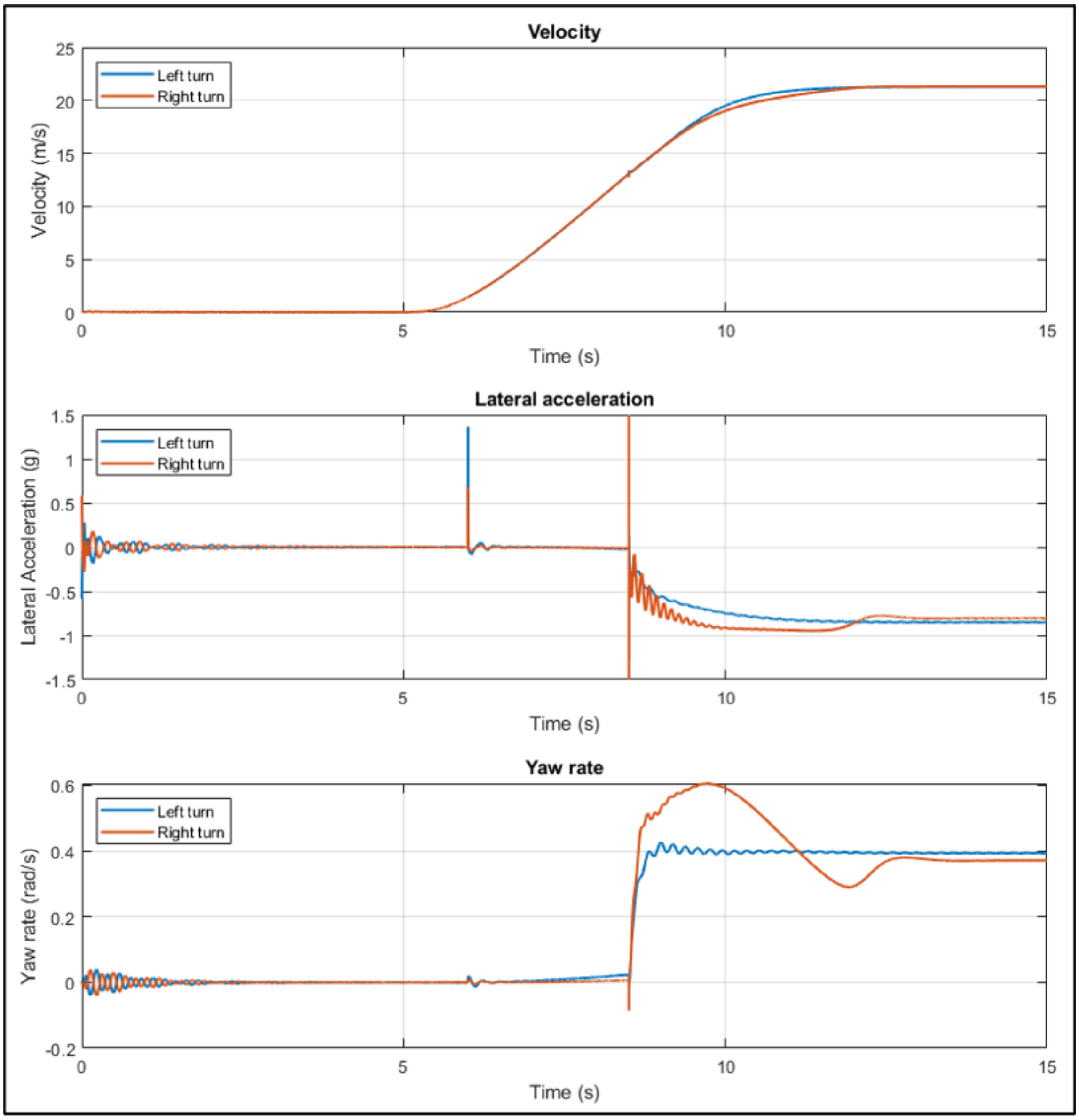


Figure 4.8: Difference in vehicle response during dynamic test for left and right turn

## 4.7 Suspension stiffness

To analyze the effect of suspension stiffness on the handling behavior, the vehicle is performed a steady-state right and left corners with 30% variation on either side of the front default spring stiffness of 70000 N/m. While cornering to right with spring stiffness of 49000 N/m the vehicle traces a radius of around 80m which is smaller than that of using default spring stiffness. Here the vehicle shows less understeer behavior with a decrease in spring stiffness. Similarly, when performing a left turn where the vehicle is already oversteered, now shows less oversteer behavior tracing a comparatively larger circle (of radius 75 m) the default suspension setup.

While investigating with spring stiffness of 91000 N/m, the vehicle exhibits more understeered behavior for a right turn with a radius of around 85m. Similarly, when performing a left turn, the model shows more oversteered behavior, tracing a comparatively shorter circle of radius around 70m.

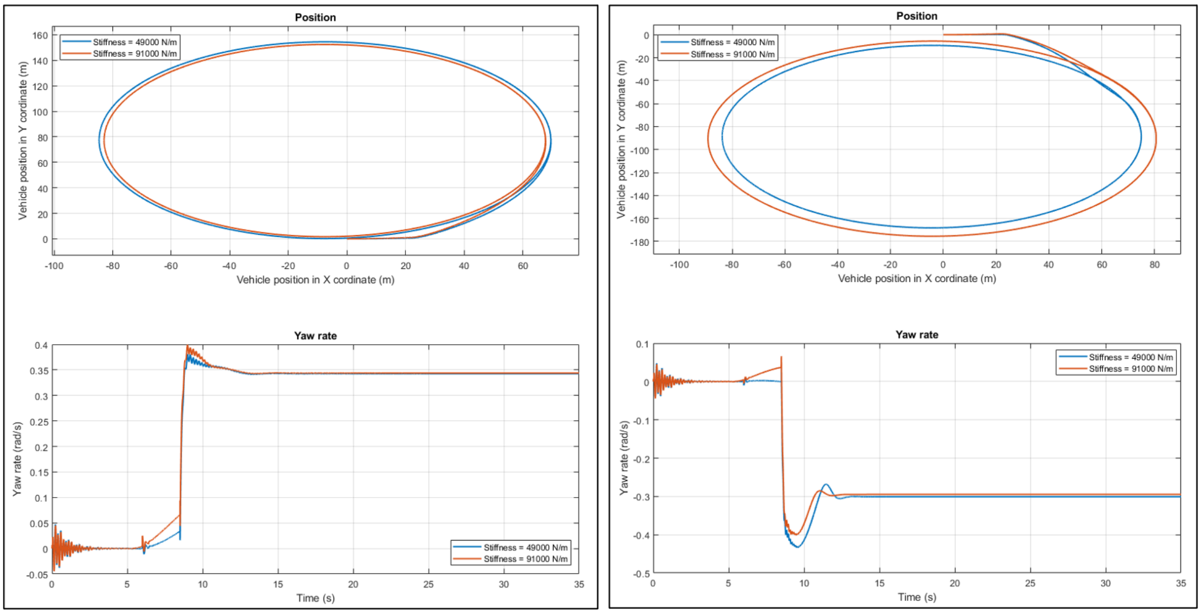


Figure 4.9: Steady state test to analyse the sidecar behavior by varying front suspension stiffness by ±30%

# Chapter 5

# Sensitivity analysis

Sensitivity analysis is performed to verify the model and to ensure that the model is performing as expected. Through this analysis, conclusion can be drawn regarding the best setup for the sidecar based on the straight path and number of right and left hand turns.

## 5.1 Front wheel camber

As specified by FIM regulations, the camber angle was varied from $\pm 3$ degrees with a step of 1.5 degrees. The step size was considered due to the fact that the difference observed were not significant for a change in steps of 1 degree.

For a negative camber angle, the wheel is tilted towards the chassis of the sidecar, whereas the opposite is true for the positive camber. With respect to the left turn for a negative camber (Figure 5.1 a), the camber force/camber thrust adds on to the lateral force produced by the front tire at the contact patch. This increases the overall lateral force produced by the sidecar at the COG. This causes the vehicle to turn into the corner faster and reduce the radius of the circle. As the camber is increased (-ve to +ve), the camber thrust is reduced, which directly affects the circle radius, thereby increasing it. For a positive camber, the camber thrust acts away from the center of the circle, which reduces the overall lateral force of the sidecar which automatically results in an increased radius of the circle. As the positive camber increases, more camber thrust acts in opposite direction and the radius of the circle increases. This camber behavior of the sidecar can exactly be seen in Figure 5.1.

From the neutral position (0 camber), the diameter increases and decreases approximately 1m and 0.5m respectively from 123.4m, whereas the lateral acceleration remains almost unchanged at 0.9g for varying camber angles. Although the yaw rate increases, the increments are very low for change in camber angles from +3 to -3 degrees.

But on the other side of the turn (right)(Figure 5.1 b), the camber thrust generated by the positive camber angle sums up the lateral force and increases the total lateral force of the sidecar. Thereby decreasing the radius of the circle. The visa-versa is also true for negative camber. The increase in circle diameter is more significant in this turn, with the lowest being 140m and increasing all the way to 154m for camber angle differing from +3 to -3 degrees. Although the lateral acceleration proportionally increases with camber angle from -3 to +3 degree, the difference is minor.

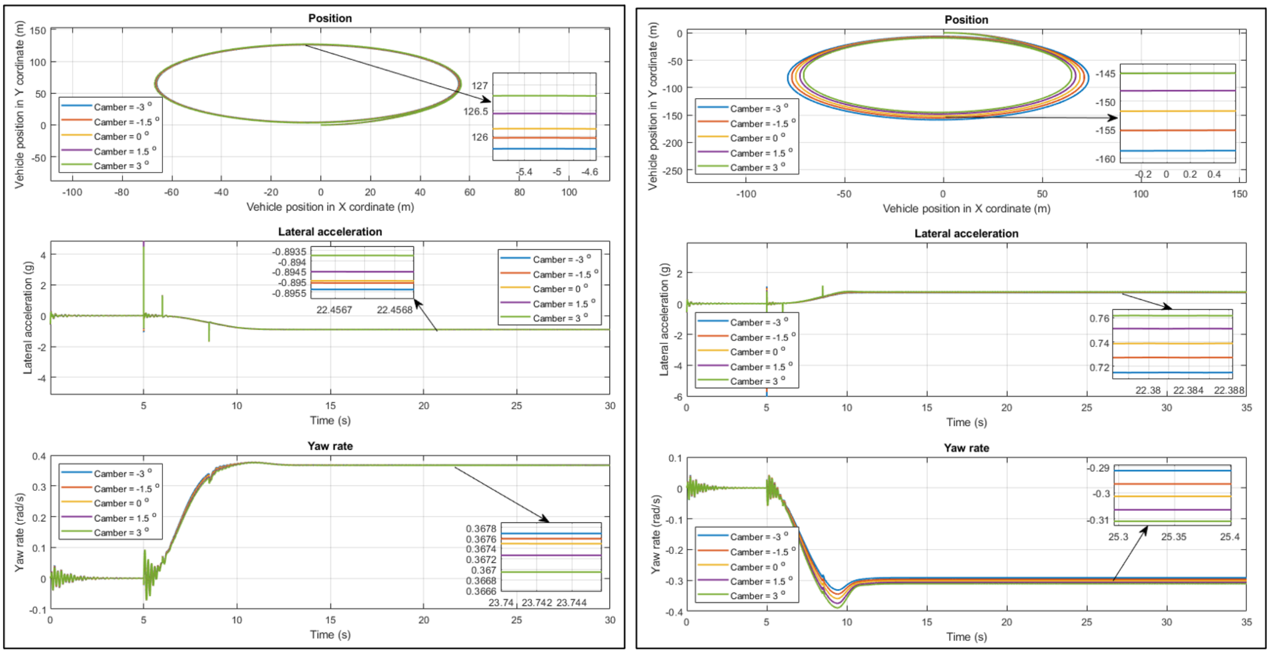


Figure 5.1: Plots for varying front wheel camber angle for left and right turn respectively

## 5.2 Side wheel camber

The effect of camber angle on the side wheel is synonymous with the behavior of the front wheel. However, the effect is seemingly large when the sidecar turns towards the right. This is because the side wheel is also configured with a small toe in value. Therefore, the combination of lateral force from the toe-in and the negative camber adds up considerably with the lateral force and corners with a much smaller radius.

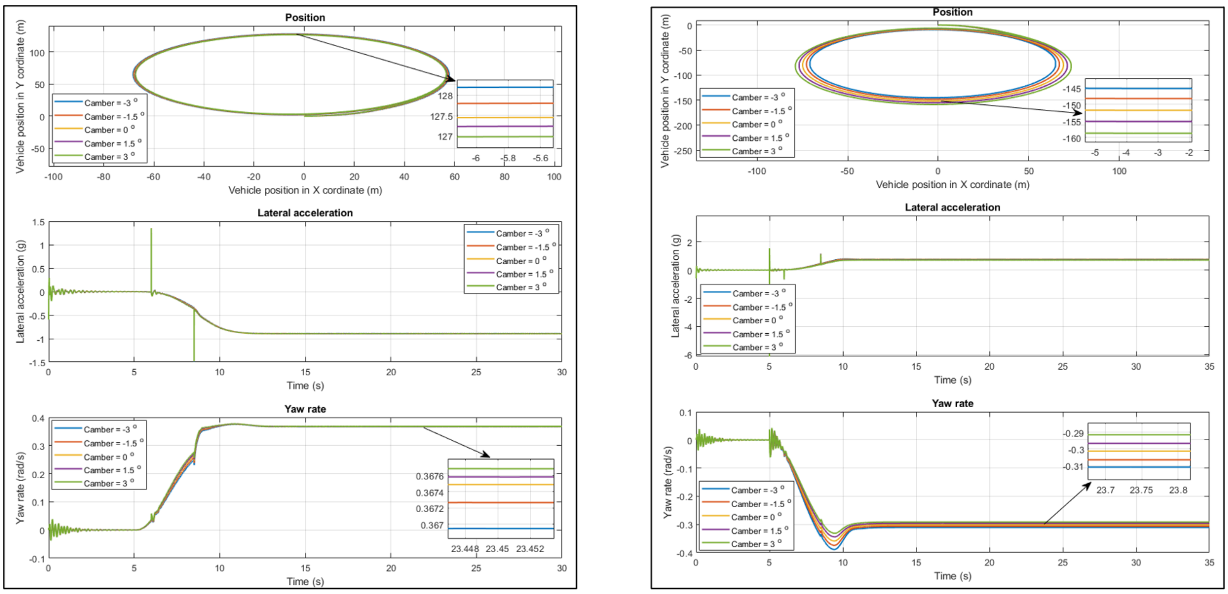


Figure 5.2: Plots for varying side wheel camber angle for left and right turn respectively

For left turn, the combination of lateral force from positive camber creates a strong total lateral force that overpowers the opposing lateral force produced by the side wheel toe-in and pulls the vehicle into the corner which results in a reduced cornering radius. Whereas for the right turn, negative camber contributes alongside the toe-in and increases the overall lateral force. Hence the circle becomes smaller for this setup. This behavior can be observed from the Figure 5.2 (b) for the camber angles 0, -1.5, and -3 degrees respectively.

## 5.3 Front wheel toe

The toe angle of the front wheel was varied according to the upright construction. The step size considered is due to the fact that the availability of the toe settings on the sidecar. A provision of 3 slots was given on the upright where the handlebar can be fixed. This connection changed the toe settings of the sidecar. Therefore, in order to mimic the exact design of the sidecar, these settings were chosen. There are 3 settings namely T1, T2, and T3. The T1 setting offers a very small value of toe out, whereas the T2 and T3 settings offers toe in with an increasing in value.

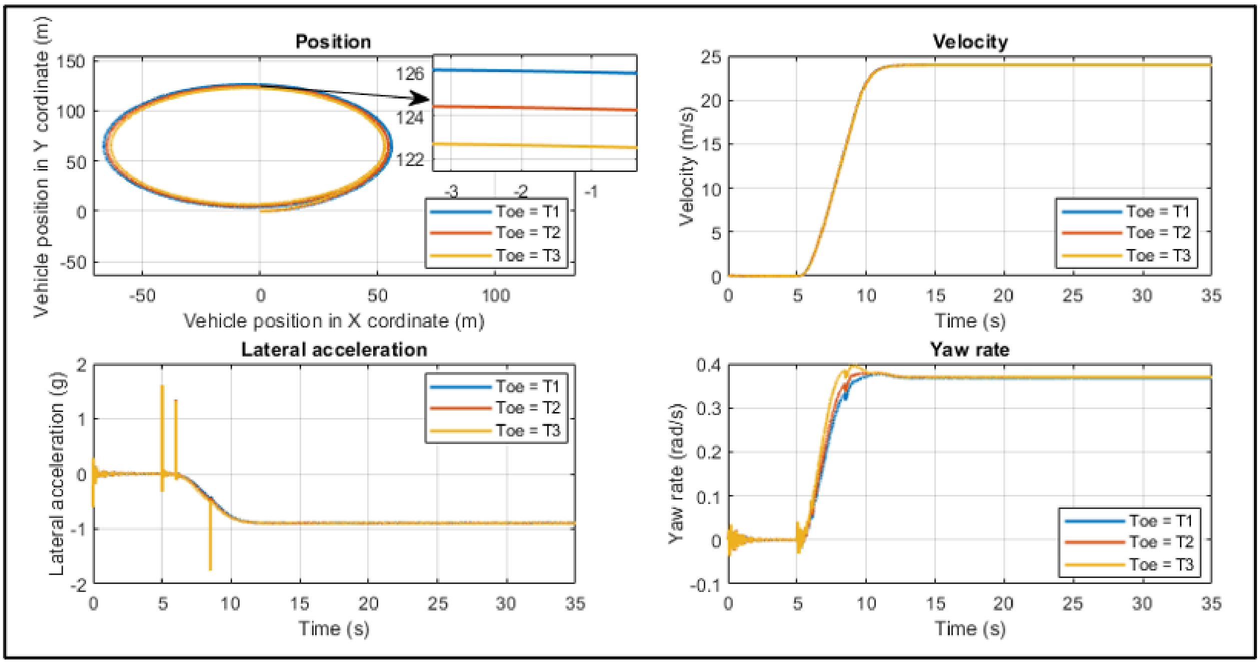


Figure 5.3: Plots for varying front wheel toe angle based on settings for left turn

For a toe-in, the wheel is tilted towards the sidecar, whereas the opposite is true for a toe-out. During left turn cornering Figure 5.3, the T3 setting produces a larger side force due to toe in, which adds on to the lateral force produced by the front tire at the contact patch. This increases the overall lateral force produced by the sidecar at the COG. This causes the vehicle to turn into the corner faster and hence reducing the circle radius. As toe in (T2) is reduced, the side force is also reduced, which directly affects the radius of the circle, thereby increasing it.

For a toe out (T1), the side force acts away from the center of the circle, which reduces the overall lateral force of the sidecar which automatically results in the increase of circle radius. This toe behavior of the sidecar can exactly be seen in the Figure 5.3. But on the other side of the turn (right)Figure 5.4, the side force generated by the toe out sums up with the lateral force and increases the total lateral force of the sidecar. Thereby decreasing the radius of the circle. The opposite is true for toe-in settings and the circle radius increases.

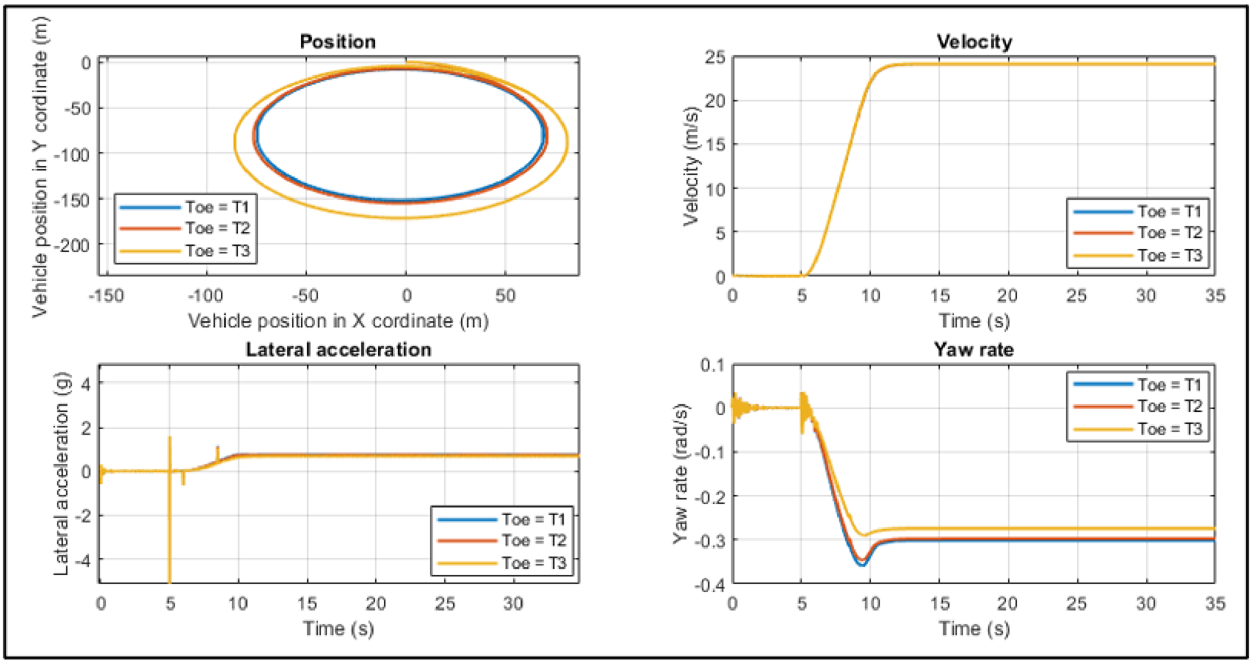


Figure 5.4: Plots for varying front wheel toe angle based on settings for right turn

## 5.4 Offset

The offset represents the lateral displacement of the front tire with respect to the rear tire when viewed from the top. According to the FIM regulations, this offset can be varied up to 75mm towards the chassis side, the neutral position would be coinciding exactly with the rear wheel of the sidecar. According to the steering geometry of this model, there exists an offset of 65mm towards the chassis side. This position is considered as the initial position for this analysis. Therefore, an increase and decrease of the offset by 10mm will throw light on the behavior of the sidecar for change in offset during cornering.

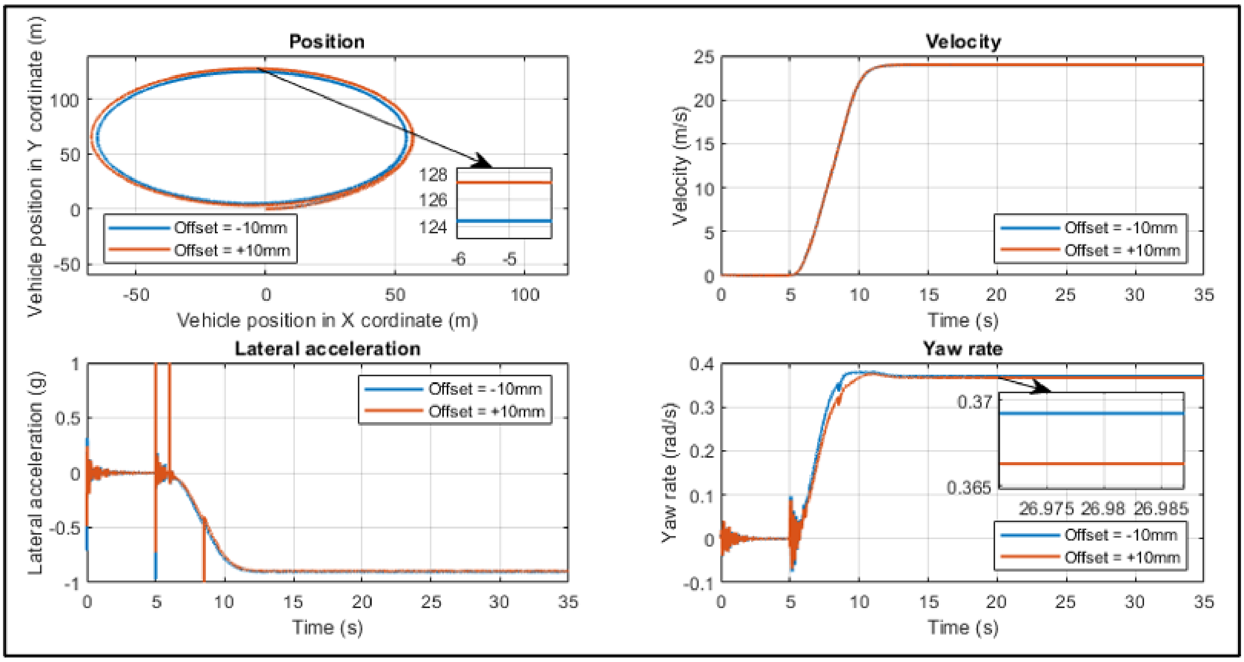


Figure 5.5: Plots for varying $\pm 10mm$ of offset for left turn

During left-hand turns, as the offset increases (moving towards the chassis[-10mm]), the attitude of the sidecar changes which causes the radius of the circle to reduce and thereby increasing the oversteer behavior of the sidecar[11]. Whereas, the opposite holds true for the right hand turn, causing the vehicle to understeer more and thus increasing the radius of the circle. However, the efffect of understeer behavior for right turns are negligible. These effects are observable in the position plot.

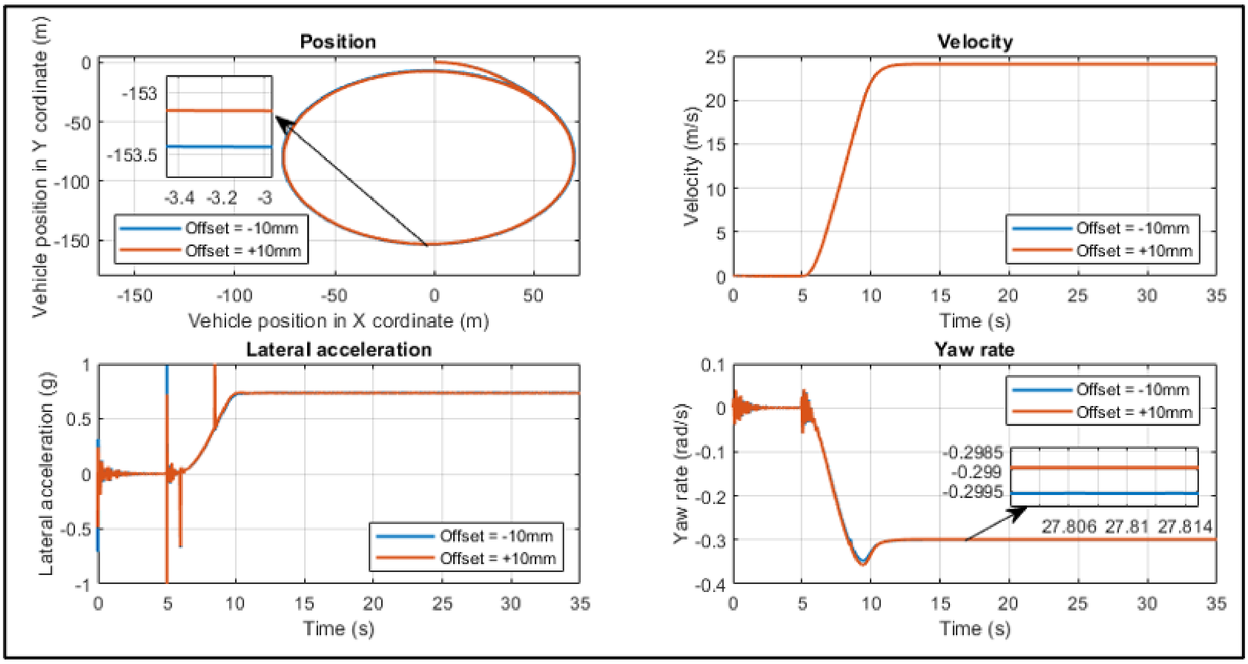


Figure 5.6: Plots for varying $\pm 10mm$ of offset for right turn

# Chapter 6

# Validation

The idea of gathering actual test data is to plot, study and find the relevance to the results concluded by the simulations of previous groups. However, the problem owners had built a completely new sidecar which has major changes compared to the previously modeled sidecar. The current build consists of a multilink geometry for both the front and rear suspension and also a step down of the engine capacity from 1000cc to 600cc.

Since the team does not own a data acquisition toolkit, an alternate method was decided to try and collect data from 'physics toolbox accelerometer' android app through smartphones. The team also had a couple of wireless GPS data loggers through which the GPS coordinates were logged. These GPS loggers were Qstarz Extreme 10Hz and serve the major purpose of logging the GPS coordinates of the vehicle at the time it's functioning. Through these logged values, a 2D map of the track is generated along with lap time measurements. The GPS loggers used on the test day were not functioning properly and therefore the data was not logged. The data collected from smartphones also did not serve the purpose because it was almost close to impossible to find out the time at which the sidecar was cornering a specific circle without GPS coordinates. For these reasons, the validation of previous models was not successful.

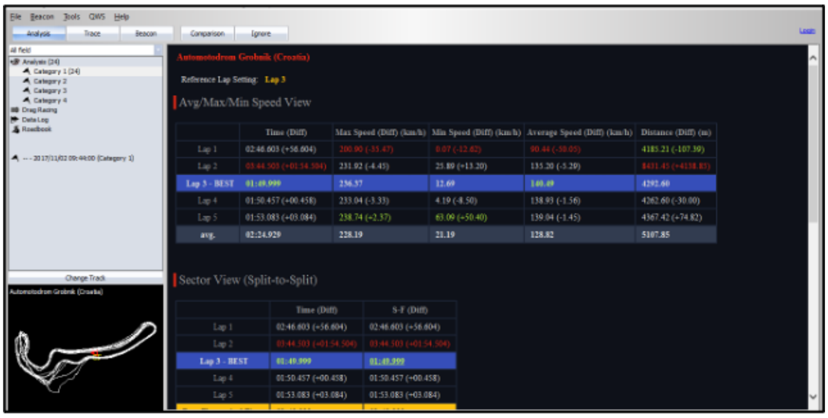


Figure 6.1: Basic layout of readable data in Qracing software

The validation of this model was not possible due to several reasons such as unavailability of test track, lack of data measuring equipment, and rapid increase in Covid cases. Since the physical validation of the model was not possible, a subjective approach of validation to the model as per SAE J1441[12] was opted. During the discussion with the client, Mr. Remco Moes (driver & passenger) shared a video of sidecar racing which has real-time information displayed such as vehicle speed, GPS location, and lap time. He asked the team to estimate the lateral acceleration based on the video and compare it against the model.

A corner was chosen at random and the corresponding radius was estimated through Google maps. The radius of the chosen right-hand corner was 22.34m and the vehicle speed encountering the turn, based on the video was approximately 50Kph. The hand calculation suggested that the lateral acceleration experienced by the sidecar at this turn is approximately 0.8g. The model was simulated with this vehicle speed to match the radius by varying the steering. The corresponding lateral acceleration of 0.61g was obtained. The difference in lateral force obtained here is because the sidecar, under simulation is making the circle radius larger by 3m.

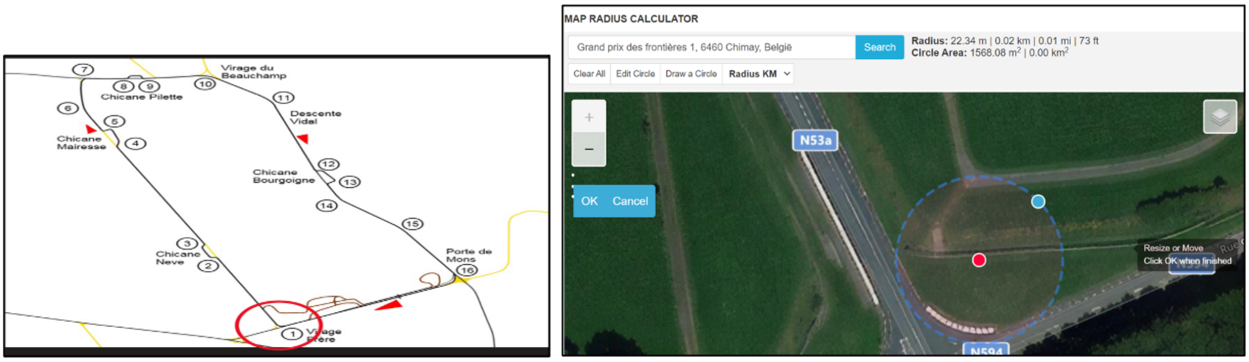


Figure 6.2: (a)Map of the racing circuit. (b)Calculation of circle radius on Google maps

Furthermore, there is a delay in the vehicle speed displayed in the video and the radius measured is at the end of the road. Thus, the lateral acceleration obtained is more of a rough estimate. But the handling behavior of the model encountering a right turn, understeer is experienced by the driver/ passenger was validated by comparing it against the steady state test.

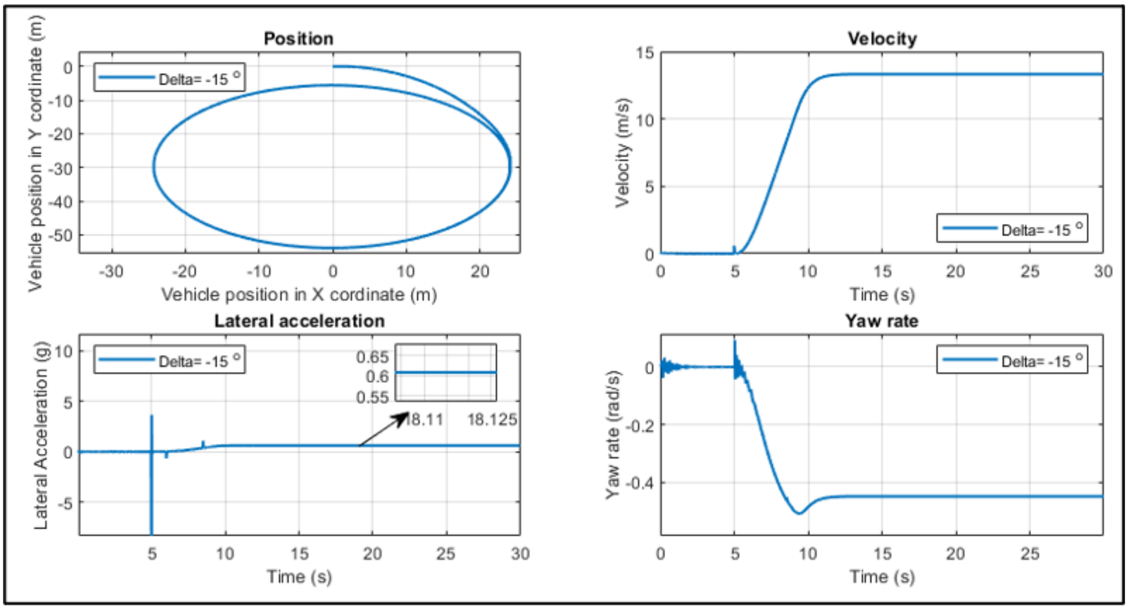


Figure 6.3: Plot for validation based on the data from video and google maps

# Chapter 7

# Additional discussion

Limitations faced with complex CAD model/ disadvantages of CAD import method compared with other models:

1. The issues faced for this model were major regarding the contact generation between the vehicle wheels and the road surface. One of the major contributors to this issue was the difference in the static length between the front and rear damper.

2. The procedure of rectifying and resolving the problem of deleting unnecessary joints and connections for the block model is sometimes based on the hit and trial method and can consume a lot of time.

3. The suspension behavior is erratic most of the time and the provided input commands fail to process. No matter how logical the values are provided, the issue persists.

4. After consulting with some faculties at the university and also after exchanging some emails with MathWorks, it was highly recommended to model the sidecar by defining each component individually in SimMechanics environment.

5. The previous step in our approach is also a big challenge and is very time-consuming because the individual components themselves have axis issues which also include some unnecessary offsets, which are difficult to define in MATLAB. A similar issue remains for the rest of the 300 or so components.

6. For example, one of the A-arms is supposed to be defined, the reference axis with which it was initially designed is at a big offset. Now when it is being defined in the SimMechanics environment, the rigid transforms and dimensions should be provided considering the global axis of the entire system in MATLAB and also the assumed individual design axis.

7. MATLAB won't provide us errors when we can observe that the system is not working appropriately in the SimMechanics which makes it challenging to comprehend. For example, while contact generation the rear wheel dips significantly under the road surface, for which there is no error from the software and eventually results in unsuccessful settlement.

8. The errors are not elaborate enough and are very limited. Some of the errors that were observed regularly were degenerate mass with respect to six DOF blocks, singularity error, and tolerance error.

9. Due to the presence of numerous joints and rigid transforms each having certain specific state targets and intricate angles respectively cause the model to be highly complex which directly translates to higher computational times which requires more CPU performance, which is lacking at the moment.

| | Simple model | Complex model | Final model |
|---|---|---|---|
| **Summary** | To summarize this model, it contains a basic approach towards modelling with the least number of components. | A completely different approach towards Simscape modelling with maximum number of components possible hence more detail. | A combination of both the simple and complex resulting into more realistic results. |
| **Suspension type** | The suspension used is based on a single solid shaft which fails to mimic the actual real-world kinematics. | The exact suspension from CAD is replicated into MATLAB also achieving the real-world multilink motion. | Approximated multilink geometry in form of double wishbone format, which made testing and contact modelling procedures easier. |
| **Working of the suspension** | A solid shaft approximates the working motion in only vertical direction; hence the system cannot have any camber angle variation. | The suspension motion on individual subsystem level can be achieved, but the tire road contact is the phase where the model fails and doesn't perform as expected. | The double wishbone setup with actual hardpoints on the chassis and upright ensures that all the important dynamics are obtained which will eventually reflect over the magnitude of forces we get for our simulations. |
| **Modeling reference** | COG is the point of reference for defining the entire model | The block model is obtained based on software algorithms and is completely based on the .xml export from commercial CAD package. | The approach of modelling from COG is same as the simple but the rest components defined are based on accurate measurements referred from step assembly provided. (2 decimals precision) |
| **Conclusion** | Ultimately the simple model cannot be used further as the results or plots generated from it would have no relevance to the real world. | The complex model cannot be used because defining each and every joint block and ensuring all the equilibrium position, state targets and other parameters to be correct is out of scope for this project. | The approximated double wishbone setup helps us to successfully build the model and further investigate over the vehicle dynamic properties of the sidecar. |

Table 7.1: An overall summary of all the 3 models, modeled in this project

# Chapter 8

# Conclusions

The conclusion that can be drawn from this project is that the objectives and the problem owner's requirements are satisfied. These include modeling the passenger movements, use of the TNO Delft tire model. Apart from this the team provided a detailed report of the test plan that can be used to test the sidecar. This document also consists of distinctive data acquisition hardware required to perform various tests as suggested in appendix A and various parameters that have to be logged through it, to validate this model.

This model was not only able to predict the sidecar handling behavior through a steady-state test as expected but also performs the dynamic tests accurately. The sidecar model was successful in capturing the camber variations which the clients had asked specifically. The nonlinear behavior of the tire was modeled using the TNO Delft tire model, this was a huge leap forward because the team was successful in obtaining the required tire data. The comparison graph between the obtained tire data and the standard data proves that the tire data is necessary for the tire model to behave exactly like the tire that is being used on the sidecar. Simplifications in the model which had to be done, to implement the type of suspension that is being used on the sidecar. However, the behavior of the suspension is the similar as the original one.

The main research question that this project was focused on, is finding the optimal steering and suspension characteristics of the sidecar. Through various tests and analyses, it can be said that there is no distinct parameter that entirely affects the handling behavior of the sidecar. Depending on the number of turns and straights present on a racetrack, the suspension and steering parameters can be adjusted accordingly. If the sidecar has to be focused on the straight-line stability, then the front and side-wheel have to be toe out and toe in respectively. These two parameters can be varied slightly to tune the straight line stability, since the geometry of the sidecar is more favorable and will readily turn into left-hand turns. Several parameters can be tuned to make the sidecar turn into right-handers easily, these are increasing positive camber for the front wheel and increasing negative camber for side wheel, increasing the offset value and finally decreasing the suspension stiffness, all these parameters changes will reduce the circle radius making it easier to corner the right-handers. While increasing the front wheel toe-in will cause a significant reduction in the radius of the circle of the left turn, on the contrary, the right turns are very difficult to maneuver/negotiate.

An actual validation of the model through sidecar testing was not possible due to the unavailability of the data acquisition systems and race track. Therefore, a subjective validation was opted, and based on the driver and passenger feel and observations, this model has been validated. Apart from this, a small validation has been done by considering a corner of a circuit and measuring its lateral acceleration. This was compared against the final model and the obtained results were neighboring. The lateral acceleration of the actual sidecar is more than the model, this is because the aerodynamic forces are neglected in the model.

As requested by the client, this model has a lot of flexibility in terms of changing the steering parameters such as the front and side wheel's toe and camber and the lengths of the A-arms. Based on the build of this model, other parameters that are not included in this study such as castor and trail can also be varied. This shows the adaptability of the model. Relating from the sensitivity analysis, it can be said that the model is robust based on non-transilience behavior. Therefore, this model is a huge leap forward in the right direction in terms of improvements, flexibility, adaptability, and robustness. To further improve the model, a few recommendations have been suggested in the following chapter.

# Chapter 9

# Recommendations

Through the recommendations, this project aims to put forward a road map for further research and development of the sidecar. This proposal will help Team Weekers Techniek to improve their sidecar thereby winning more races, meanwhile favoring the students to learn and utilize their skills in different domains of vehicle dynamics. Some of the immediate steps that the next group should be working on are:

1. First and foremost, this model has to be validated. Therefore, it is of the utmost importance to arrange all the necessary data acquisition hardware to go for testing.

2. One of the most important parameter is the centre of gravity of the sidecar. This location has not been measured yet. Due to this, the given location is not precise. Therefore, the sidecar location has to be measured immediately.

3. This team also took the liberty to contact the 'ÖHLINS RACING A.B.' to obtain information regarding the suspension. A representative name Mr. Thorsten Hirth, strongly insisted the students to visit the company's service centers to test the suspension and record the data themselves. This is a great experience to learn about suspension and later use it in their modeling. The details regarding this are provided in appendix C.

4. The multilink suspension sub-assembly has to be modeled in Solidworks and then imported into Simscape Multibody. This ensures the students to focus on the vehicle dynamics aspect of modeling rather than CAD modeling.

Additional recommendations or objectives for the future groups are listed below:

1. If the roll axis of the sidecar is calculated, then the front and rear suspension can be modeled easily in Simscape Multibody with respect to those roll centers. This method will provide accurate roll angle as an output as opposed to roll rate.

2. The next milestone for the fourth coming students could be to focus on driver behavior modeling. The movement of the passenger has to be synced with the driver steering inputs. Thereby creating a closed loop feedforward controller.

3. Since this group has developed a basic simulator platform, upcoming groups can perform scenario-based testing by creating their own circuits or scenarios. This project can be a huge leap in the development of the sidecar.

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# Appendix A

# Test plan

## A.1 Introduction

The client for this project is Team R Weekers Technik. The sidecar team is from the Netherlands, participating in the 'Open Dutch Championship' (ONK). They drive a self-build F1 chassis with a 600cc Yamaha engine. The driver Rogier Weekers and his passenger Remco Moes run the team. Team Weekers has been active in sidecar racing since 2017. The testing of this sidecar is of paramount importance because to validate this model. By doing so, the problem owners can rely on this model to in order to tune their sidecar through this model and then analyze the behavior, instead of changing and testing it physically, subsequently saving a lot of time, energy and money in doing so.

Two Types of testing are required in this situation, the steady state circular behavior and the lateral transient response. These two tests do not cover the behavior of the car for all driving conditions but give the necessary information towards better understanding of the handling behavior.

During testing, the inputs to be considered are the steering wheel angle, sidecar velocity (controlled by the throttle position), while measurements will be taken for the outputs in the form of lateral acceleration, roll angle and yaw rate. Other outputs, needed for model validation, like body slip angles in addition to lateral forces (developed at the wheels level) will be calculated.

## A.2 Objective and tasks

### A.2.1 Objective

The main goal of these tests is to understand the vehicle behavior and to log the variation of the physical parameters related to vehicle handling. This data will be used later to improve and validate the model made for the sidecar.

### A.2.2 Tasks

Testing will require performing various tests for multiple times and data logging/acquisition. The main tasks considered in this plan are:

1. Preparing the vehicle for testing.
2. Checking if the measurement and data acquisition systems are functional and calibrated.

3. Documenting the track and weather conditions.

4. Driving the vehicle as per the ISO Standards (Performing the test).

5. Logging the data in specific periods when the sidecar is in the required conditions.

6. Keeping up with the schedule and making sure to complete all the required tests.

7. Acquiring data, plotting, and analyzing it.

8. Test reporting.

## A.3 Scope

The sidecar will be tested to visualize and document its dynamics and steady state behavior during cornering and maneuvers. Testing of the sidecar consists of driving it on the track and logging the parameters related to handling behavior and needed in the modeling. The tests covered in this plan are:

1. Steady State Circular Behavior.

2. Lateral Transient Response.

There are various methods to perform these tests. Each method provides different information related to the handling behavior of the vehicle. Therefore, multiple ways were chosen in a manner to acquire as much information as possible about the handling behavior.

## A.4 Testing strategy

The strategy followed for the tests consists of completing one test with all the considered methods before moving to the second. In such strategy, all the testing conditions should be valid, and measurements will be considered only in this case. This way the handling behavior of the vehicle is acquired in a proper way for each of the various specific cases.

The tests will be done in an alternative way (i.e., Considering both turning possibilities) to reduce tire wear and heat concentration in one part of the wheel. Example: If the first test considers driving the car in a circular trajectory while turning to the right, the next one will be the same while turning to the left.

## A.5 Hardware requirements

The Hardware used in these tests is acquisition systems and software rather than machines and benchworks. The hardware needed is as mentioned below:

1. A data logging and acquisition hardware (DAQ).

2. Sensors connected to the DAQ for measuring the previously mentioned inputs and outputs.

3. CAN bus, V-Box and data conversion system.

4. Memory stick to transfer data from the DAQ to a computer.

## A.6 Environment condition

Environmental conditions have a major impact on the test results. Weather and track conditions should be satisfactory to consider that testing was done properly. These conditions are split into track conditions and weather conditions. The track conditions:

1. Dry track.
2. Smooth and not containing irregularities/obstacles that could lead to vertical disturbances.
3. There should be no water spots on the vehicle trajectory.
4. Moderate asphalt temperature.

The weather conditions:

1. Low to null wind speed.
2. No precipitations.
3. Moderate temperature to prevent fast tire heating.

Any variation in these conditions will lead to low-quality tests results and, in some conditions, unusable data.

## A.7 Test description and sequence

Two types of tests will be performed, where multiple methods are used to obtain the required variables. In these tests, some methods are chosen from which the required data can be gathered. A description of the tests and the methods used are written below.

Tests will be performed as per ISO standards. The exact procedure will be followed for both tests. For the steady state circular behavior, the ISO 4138 fifth edition (2021) is followed, and the ISO 7401 third edition (2011) is followed for the lateral transient response test.

### A.7.1 Test description

A short description is carried out to give a better understanding on how the tests will be performed. First the steady state circular behavior test is described followed by a description of lateral transient response test.

1. Steady State Circular Behavior Test

   This test is done to study the vehicle handling behavior during cornering mainly and to acquire the steering characteristics of the vehicle (understeered, neutral steered or oversteered). The steady state circular behavior requires driving the car with either constant speed, constant steering wheel angle or on a fixed circular trajectory with constant radius. It is called steady state because the sidecar velocity should be constant to exclude any additional behavior related to accelerating or braking. Three methods can be followed to perform this test[8].

**Steady sate circular behavior with constant trajectory radius:**

Description: The trajectory radius is kept constant means the vehicle follows a fixed circular trajectory, the speed is kept constant and the driver figures out the steering angle needed to keep the car on track once this is achieved, data is recorded for 3 seconds for all parameters. The starting car speed is the minimum possible to get the Ackermann steering angle, afterwards the velocity is increased slowly between one testing speed and the following. The limit is achieved when the lateral acceleration of $4\text{m/s}^2$ is reached. Depending on the driver's experience, higher lateral acceleration tests can be performed.

2. Lateral transient response test

   This test in done to study the vehicle handling behavior for the cases of lane switch of maneuvers. The overall trajectory in this type of test is a straight line and the velocity is kept constant as much as possible. The methods used in this test will give results in time and frequency domain. Having the behavior in both domains will give a better understanding of the complete handling behavior for various inputs. In the case of the considered tests, the random input test will cover the frequency domain while the first two will cover the time domain[9].

   **Transient response with step input:**

   Description: The sidecar is driven straight with constant speed, a step input at the level of the steering wheel is made by turning the steering wheel to a specific angle as fast as possible and keeping the steering angle constant. Measurements starts once constant speed is achieved and ends after 3 seconds from achieving constant steering wheel angle.

   **Transient with double lane change input:**

   Description: With the help of ISO 3888-2 the double lane change maneuver will be done. The sidecar is driven straight with constant speed, a double lane input at the level of the steering wheel is made by turning the steering wheel to a specific angle then in the opposite direction to reach the negative of this angle and then back to angle 0 degrees and this again mirrored similarly for double lane change. This input should be done in 3 or 4 seconds maximum. Measurements starts once constant speed is achieved and ends after 2 seconds from achieving 0 degrees steering wheel angle. Measurements are taken for a combined time of 12 minutes; each logging should be for at least 30 seconds. Lateral acceleration should not exceed $4\text{m/s}^2$.

### A.7.2 Testing sequence

Testing will start with the steady state circular behavior, once finished the lateral transient response will follow. The number of tests for the latter is higher than the first and excessive tire wear could happen. The order of the tests is chosen based on this reason.A detailed sequence is found in the Test day B.

## A.8 Control procedures

Some preparation should be done before testing to make sure that the acquired results are useful and describe the actual behavior of the vehicle.

1. Documentation of the vehicle specifications: Mass, load and pressure at each wheel, tire track, wheelbase, offset.
2. Documentation of the tire specifications and condition.
3. Documentation of the sensors and measurement equipment accuracy and specifications.
4. Documentation of the weather and road conditions.
5. Check the calibration of the measurement equipment.

Other conditions should be taken care of during the whole testing period

1. Tires temperature should be kept in the range of normal driving conditions.
2. Tests should be carried out in the normal driving conditions and should never reach extreme limits.

Whenever overheating of the tires is noticed, testing will stop until the tires cool down. In case of incident, if the problem can be fixed easily, some adjustments will be made, and testing can be resumed otherwise testing will be postponed to another day if possible. If not, testing will be cancelled. In case of change of weather conditions, testing will be carried out until it is no longer possible to keep testing within the conditions specified in the ISO standards. The change of weather will be documented.

## A.9 Parameters

Various parameters are present in the equations of motion for the handling behavior of a vehicle, the handling model also contains these parameters. For this reason, a good knowledge of the parameter's values should be acquired. This knowledge allows the team to make improvements to the model and validate it. The values of these parameters could only be acquired by measuring and logging them during testing. The necessary parameters will be logged while parameters with less priority will be calculated from the acquired measurements.

### A.9.1 Parameters to be logged

The essential parameters leading to a good model will be logged and they are divided into input parameters and output parameters as following

#### Input parameters

1. Steering wheel angle
2. Longitudinal velocity

#### Output parameters

1. Longitudinal velocity
2. Lateral acceleration
3. Yaw rate
4. Roll angle
5. GPS location

## A.10 Roles and responsibilities

Roles and responsibilities are split between the testing team where each member has specific tasks to accomplish. Once these tasks are properly done, testing can be considered as successful. The main tasks and responsibilities are as mentioned below.

1. Preparing the sidecar:
2. Implementing the DAQ and V-Box:
3. Driver and the passenger:
4. Checking the DAQ and calibration:
5. Documenting the road and weather conditions:
6. Keep up with the time schedule and make sure all tests are done:
7. Start/ stop logging the data in the optimal periods during testing:
8. Acquiring the data into a computer:
9. Test reporting

## A.11 Data logging

The procedure of data logging for the current sidecar configuration is quite important for the reasons mentioned in the previous sections. Some basic data logging approach can be achieved for the very beginning by using accelerometers and potentiometers and a data acquisition system. The accelerometer can be configured and mounted on the sidecar chassis to have an estimate of lateral acceleration of the entire sidecar in $m/s^2$. These values can easily be converted into g's and be tallied with the simulation results.

The damper travel for the front and rear wheel can be useful as well to determine the pitch and dive motions of the sidecar. As the sidewheel does not comprise of any suspension it is difficult to calculate the roll angle or roll rate of the system through damper travel and therefore a strain gauge method can also be used to determine the expansion and compression rate of dynamic components in suspension. For example, strain gauges can be mounted on the push rods of the front and rear suspension and for the sidewheel at a similar axis and orientation on the upright, and the data from these gauges can be logged for a high-speed turn maneuver and attempts could be made to determine the roll rate and roll angel. This helps the team to determine appropriate suspension stiffness for the front and rear suspension to minimize the lateral and longitudinal losses and maximize in terms of cornering speeds and lap time.

If the previous methods turn out to be difficult or tedious for some reason, a sophisticated data acquisition system can be mounted to the sidecar which may provide the required parameters directly to the consumer/problem owner, thereby reducing the heavy amount of calculations and conversions needed to be done in the conventional way. More detail regarding the senors can be found in previous reports[14][10].

## A.12 Schedule

Proper time schedule required to conduct test plan has been mentioned/explained in the below section named Test day B.

## A.13 Dependencies

Testing will depend on:

1. Track road conditions.
2. Weather conditions.
3. The presence of all persons assisting in the realization of the tests.
4. The availability/Readiness of the sidecar equipped with the required tools.

## A.14 Risks/Assumptions

Some unexpected situations can lead to cancelation of the testing in the specified dates. These are as following:

1. Bad weather conditions.
2. Strict lockdown measures related to COVID-19 pandemic, where testing is prohibited.
3. Inability of the main tests performing members to be present in the specified day.
4. Unavailability of test senors.

If testing cannot be done in the specified date, another date will be considered (of possible) otherwise testing will be canceled and the team will rely on papers to validate/verify the model.

# Appendix B

# Test day

Brief explanation has been already given in test plan, need to follow these steps accordingly to achieve proper results and to finish test as per time scheduled.

## B.1 Vehicle parameters

The below shown vehicle parameters has been provided by the client.

| Parameters | Values |
|---|---|
| **Load on the front wheel** | |
| **Load on the rear wheel** | |
| **Load on the side wheel** | |
| **Total mass (m)** | |
| **Wheelbase (l)** | |
| **Offset** | |
| **Sidecar width (w)** | |
| **COG position from front axle (a)** | |
| **COG position from rear axle (b)** | |
| **COG position from bottom/top (z)** | |
| **Tyre specs (For 3 wheels)** | |

## B.2 Pre-checks:

The goals of pre-check are to focus on identifying and fixing problems by reducing measurement error, and ultimately improving data quality. The pre-checks will be done partially at the HAN and the other part related to placements and connections of sensors to the V-box will be done just before entering the track. The parameters to check are:

1. Tire pressure on 3 wheels.
2. Fuel level.
3. Coolant liquid.

4. Offset and calibration.
5. No additional weight.
6. Oil level.
7. Warm-up test.

## B.3 Time schedule

On test day, a basic time management possible tasks or actions which are intended to take place in the given sequence of chronological order. The time mentioned here might vary a little in case on unexpected circumstances. The testing sequence will begin with a warm up and finding the Ackermann steering angle then proceeding to the lateral transient response and steady state circular tests.

| **Activities** | **Schedule** | **Time allotted (min)** |
|---|---|---|
| **Arrival time** | | |
| **Warm-up runs** | | |
| **Lateral transient response test** | | |
| **Steady state circular test** | | |
| **Re-take test (In-case if any error occurs)** | | |
| **Departure time** | | |

## B.4 Logbook

Note: Multiple copies of printout will be carried for both tests (Steady state and transient response test).

### B.4.1 Steady state circular test

**Test conditions (steady state test)**

| **Test method** | **constant** | **Speed** | **Steering-wheel angle** |
|---|---|---|---|
| Constant radius test | Radius | Fixed | Varying |

### B.4.2 Steady state circular test

**Measurable**

The following variables shall be measured.

1. Lateral acceleration.
2. Steering-wheel angle.

3. Yaw rate.
4. Longitudinal velocity.
5. Lateral velocity.
6. Roll angle.

| | |
|---|---|
| **Date** | |
| **Start time** | |
| **End time** | |
| **Direction (note what is applicable)** | |
| **Test conditions (note what is applicable)** | |
| **Desired speed** | |
| **Test track radius** | |
| **Data acquisition (name)** | |
| **General comments (If needed)** | |

### B.4.3 Transient response test

| | |
|---|---|
| **Date** | |
| **Start time** | |
| **End time** | |
| **Direction (note what is applicable)** | |
| **Test conditions (note what is applicable)** | |
| **Type of steering input** | |
| **Test method** | |
| **Data acquisition (name)** | |
| **Desired speed** | |
| **General comments (If needed)** | |

# Appendix C

# Information

This appendix contains the information regarding testing of the suspension damper. Please do follow the instruction to test the suspension.

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Thanks for your request.
As there are over 250 different TTX 36 dampers with various different specs, settings and clicks, it´s impossible to give you a general damping force overview. I´d suggest the following.
Find out the dampers article number, which can be found on the damper´s cylinder head (beginning with two letters followed by 4 digits. e.g. BM 4681). With this information, contact one of our service centers in the Netherlands and ask for the possibility to run the damper on the dyno. You can have the damper tested at different speeds and settings. This way you can get an overview of the damping forces of that specific damper.

You can find our service centers in Netherland, following this link:
https://www.ohlins.eu/de/products/motorcycle/dealer/netherlands/?f=Servicecenter

If you have further questions please feel free to contact me.

Best Regards
Thorsten Hirth
Workshop Manager & Product Specialist MC R&T
ÖDTC

ÖHLINS DTC (DISTRIBUTION & TEST CENTER)
Gottlieb-Daimler-Str. 25
D-53520 Meuspath
Germany

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# Appendix D

# Obtained tire data parameters

The obtained tire data parameters from the from Milliken research groups are:

| **Symbols** | **Parameters** | **English units** | **S.I. units** |
|---|---|---|---|
| **FX** | Longitudinal force | Lb | N |
| **FY** | Lateral force | Lb | N |
| **FZ** | Normal force | Lb | N |
| **MX** | Overturning moment | ft-Lb | N-m |
| **MY** | Rolling resistance moment | ft-Lb | N-m |
| **MZ** | Aligning torque | ft-Lb | N-m |
| **P** | Inflation pressure | psi | Kpa |
| **N** | Wheel rotations per minute Road speed | rpm | rpm |
| **V** | Slip - Longitudinal | mph | kph |
| **SL** | Slip ratio | - | - |
| **SR** | Slip ratio | - | - |
| **IA** | Camber angle | deg | deg |
| **SA** | Slip angle | deg | deg |
| **RL** | Loaded radius | in | cm |
| **RE** | Effective rolling radius | in | cm |
| **ET** | Time elapsed | sec | sec |
| **TSTI** | Tread surface temperature inboard | F | C |
| **TSTC** | Tread surface temperature center | F | C |
| **TSTO** | Tread surface temperature outboard | F | C |
| **RST** | Road surface temperature | F | C |
| **NFX** | FX/FZ (Normalized longitudinal force) | - | - |
| **NFY** | FY/FZ (Normalized lateral force) | - | - |
| **NFR** | FR/FZ | - | - |

# Appendix E

# Sign conventions

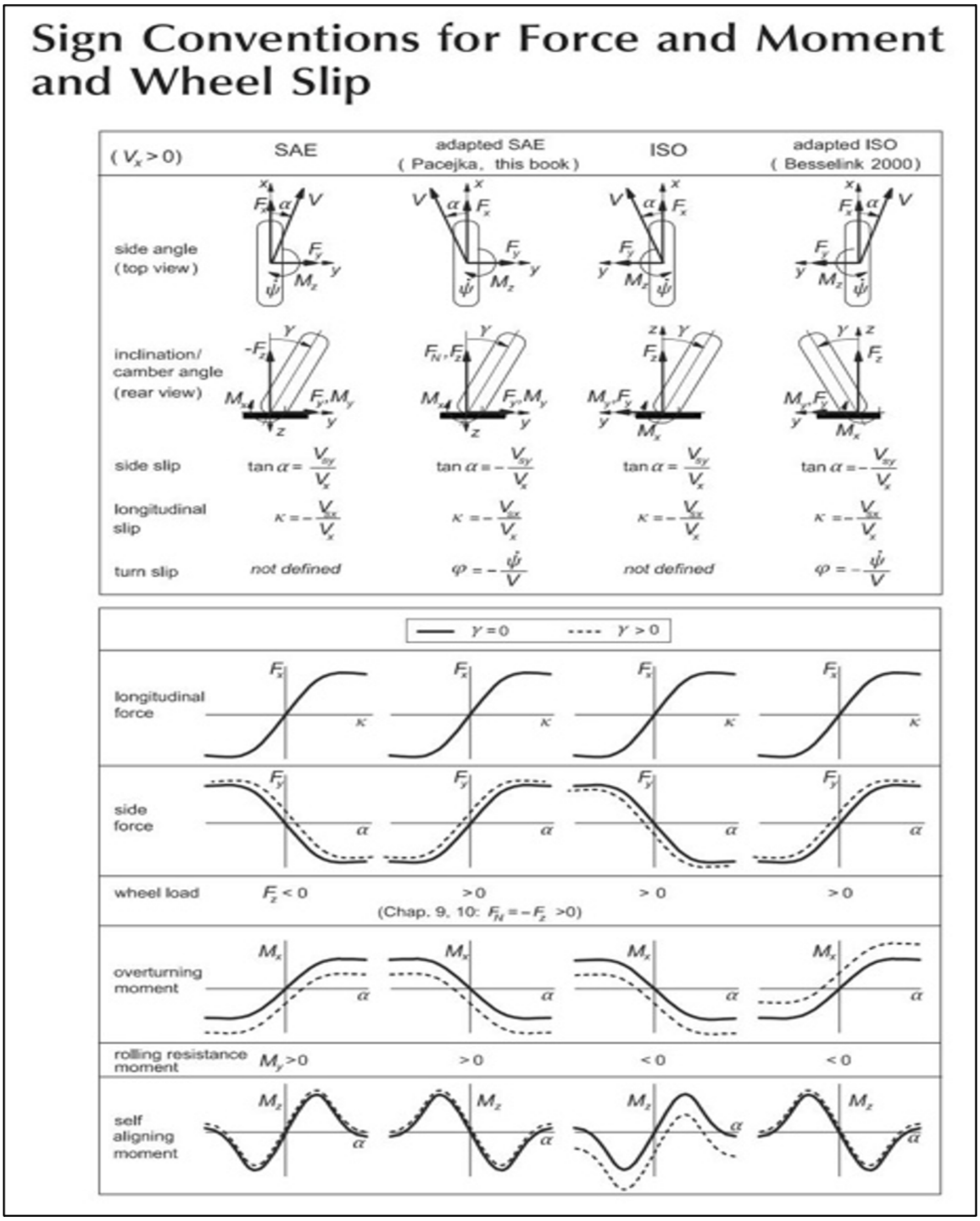


Figure E.1: Different sign conventions

# Appendix F

# Problem owner requirements

| | | **Current** | **Wanted** |
|---|---|---|---|
| **Dimensions** | Wheelbase front-rear (mm) | 2150 - 2200 | 2150 - 2200 |
| | Wheelbase side-rear (mm | 1150 - 1200 | 1150 |
| | Offset front-rear (mm) | 0 - 75 | 30-60 |
| | Side beam (mm) | 305-350, h-b | free |
| | Height beam (mm) | 250-350 | free |
| | Engine (mm) | ong. 470 x 470 x 470 | ong. 470 x 470 x 470 |
| | Platform (mm) | ong. 800 x 800 | ong. 800 x 800 |
| **Wheels** | Inner diameter (mm) | 286 | 288 |
| | Front width (mm) | 253 (outside) | 230, 9 inch (inside) |
| | Width rear-side (mm) | 312 (outside) | 280, 11 inch (inside) |
| | Outer diameter front-side | 50.4 cm | 50.4 cm |
| | Outer diameter rear | 52 cm | 52 cm |
| **Front suspension** | KPI | 6 degree | 0 |
| | Caster | 6.5 degree | 6 to $\pm$3 degree |
| | Scrub radius | 12 - 28 mm | 0 |
| | | | |
| | Camber | 0 | 0 |
| | | | |
| | Fixation points A arm | 215 mm | min 215 mm |
| | Brakes | Ventilated disc, 4 pistons | |
| **Rear suspension** | Camber | 0-3 degree at compression | 0-3 degree at compression |
| | Toe angles | Straight | Straight |
| | Brakes | Ventilated disc, 4 pistons | |

| | | | |
|---|---|---|---|
| **Side suspension** | Camber | 0-3 degree | 0-3 degree |
| | Toe angles | Toe in 2mm on 1m | Toe in 2mm on 1m |
| | Brakes | Single disc, 2 pistons | |
| **Chassis** | | Straight | Straight |
| | Weight distribution | 37-63%, front-rear | min 40-60%, front-rear |
| | Weight front (kg) | 123 | 130 |
| | Weight rear (kg) | 210 | ong. 197 |
| | Weight side (kg) | 109 | 115 |
| | Weight total (kg) | 442 | 442 |
| | | | |
| | Chassis to wheels | See drawing | 280, free |
| | Chassis to centre engine | 260 mm | max 260 mm |
| | Turning point steering wheel | Centre wheel - 20 mm offset | free |
| **Front suspension** | KPI | 6 degree | 0 |
| | Brake pedal | 66cm "spinnekop", 121cm steering wheel 6.5 degree | Min 66cm "spinnekop", 121 cm steering wheel |
| | Cooler | Max width 350mm | Min 350mm |
| | Height beam | 250-305 mm | 250-305 mm |
| | width beam | 230-250 mm | 230-250 mm |
| | | | |
| **Upright** | Discs | 269 mm | max 270 mm in diameter |
| | Brakes caliper | 269 mm | max 270 mm in diameter |
| | Max steer angle | 18-20 degree | min 20 degree |

Table F.1: Translated version of the sidecar specification from Team R Weekers Techniek document