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Article · April 2016

DOI: 10.4271/2016-01-0466

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2016-01-0466
Published 04/05/2016

doi:10.4271/2016-01-0466
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Influence of Active Camber Control on Steering Feel

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ABSTRACT

Research of the past century has demonstrated that wheel camber regulation provides great potential to improve vehicle safety and performance. This led to the development of various prototypes of the camber mechanisms over the last decade. An overview of the existing prototypes is discussed in the presented paper. Most of the investigations related to camber control cover open-loop maneuvers to evaluate a vehicle response. However, a driver's perception and his reaction can be the most critical factor during vehicle operation. Therefore, the research goal of the presented study is to assess an influence of active camber control on steering feel and driving performance using a driving simulator. In the proposed investigation, a dSPACE ASM vehicle model has been extended by introducing advanced models of steering system and active camber regulation. The steering system describes dynamics of steering components (upper and lower columns, torsion bar, steering rack and others). It is parameterized and validated for a middle-size passenger vehicle. Camber actuation mechanism is based on the most relevant existing prototype. The proposed camber control system is based on lateral acceleration and yaw rate. Twelve participants drove a driving task with passive and active camber regulation. The results show that active camber control plays a significant role in the subjective assessment of steering feel, and has a corresponding effect on objective driving performance.

CITATION: Roethof, D., Sezer, T., Arat, M., and Shyrokau, B., "Influence of Active Camber Control on Steering Feel," *SAE Int. J. Passeng. Cars - Mech. Syst.* 9(1):2016, doi:10.4271/2016-01-0466.

INTRODUCTION

It is well known that the forces at the tire-road contact play a major role in a vehicle's safety and driving performance, which have always been prominent subjects in the automotive industry. Numerous studies [1] - [4] have shown that the camber angle of the wheel substantially effects these forces and thereby the range of a vehicle's traction, which is of critical value especially in emergency and evasive maneuvers.

A considerable number of active-camber design concepts have been proposed in Appendix A to evaluate possible improvements on vehicle response most of which refer to open-loop maneuvers and therefore leave the driver out, while the driver's perception can be critical to alter the control and response of the vehicle. Therefore one of the focal points of this research is on the influence of the driver together with an actively controlled camber system.

We primarily investigated the influence of the wheel camber on the steering feel and therefore on the overall control of the vehicle; which in turn redefines the safety experience. A high fidelity steering model was utilized to realize the effect of camber variations specifically on lateral force response starting at the tire-road contact through the suspension and steering linkages.

This allowed us to expand our investigation ahead of driving performance (e.g. [5]) and include specifically the steering feel and driver experience on vehicle control systems.

Based on these objectives, the paper is structured as follows. First the effect of camber is explained. Then a review of the published camber actuation systems is presented. This is followed by the control systems. An introduction to the simulator and a detailed description of the steer feedback is then provided. Finally the results with conclusions on our numerical and experimental tests and corresponding recommendations are presented.

EFFECT OF CAMBER

In this paper the SAE tire axis frame [4] is adopted as shown in Figure 1. The camber angle is the angle of the tire around its X-axis, shown in Figure 1 as the γ angle (like a motorcycle leaning into the corner). In the SAE standard the camber angle is defined as the angle between the wheel and the vehicle body, while the inclination angle is the angle between wheel and perpendicular to the road. A negative camber angle is when the wheel is leaning inwards the vehicle, while a positive camber angle is when the wheel is leaning outwards the vehicle.

In modern vehicles, the tire produces a lateral force due to the slip angle α, with characteristics as shown in Figure 2. By increasing the camber angle of the tire the lateral force shifts. An additional effect is the roll-off [4] also shown in Figure 2, which is a characteristic due to the shape of the tire and the combination of camber angle and slip angle.

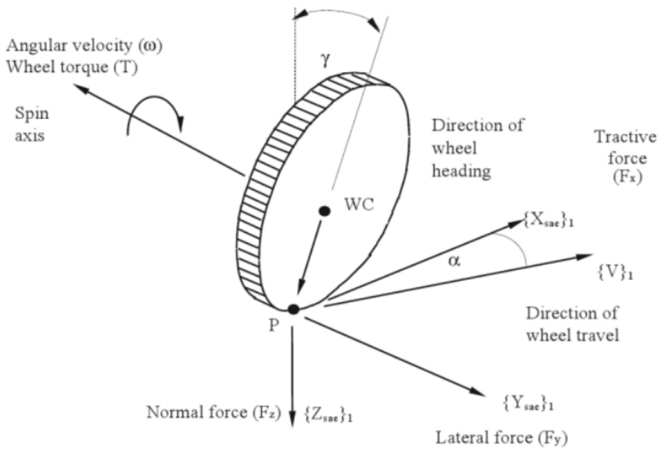

Figure 1. Tire axis frame, the SAE standard [6]

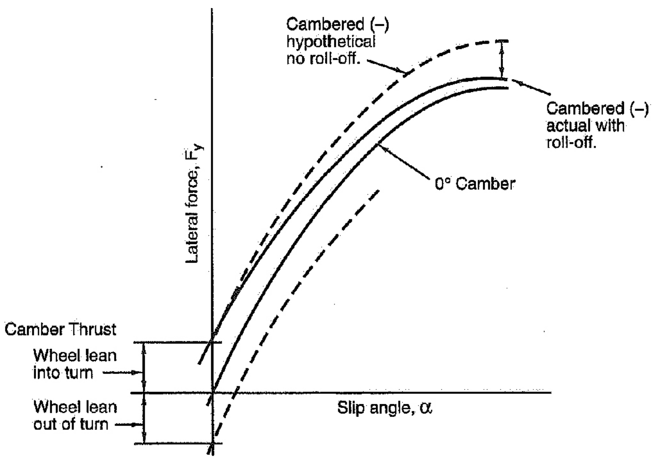

Figure 2. Camber thrust [4]

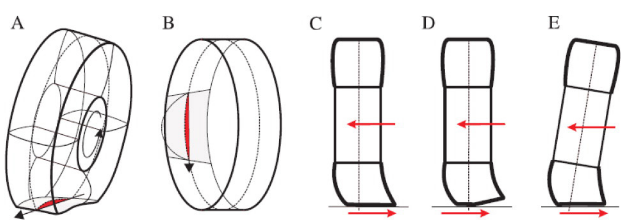

Figure 3. Tire deformation during cornering [7]

In the neutral position of the wheel a large moment will be created due to the applied forces, while the resultant forces of a negative tilted wheel will be mostly loaded in axial direction. This means that the tire is less depended on the cornering stiffness of the wheel in tilted orientation, but this shifts the problem to the contact area of the tire. For a narrower tire with low cornering stiffness, the camber angle will increase the contact area due to the deformation as shown in Figure 3. For a wider tire with high cornering stiffness, a large camber angle will result in a lower contact area due to its stiff square cross-section, it will run on the tire corner. This lead researchers to design and to use rounded cross-section tires e.g. [8]. This design allows maintaining a sufficient contact area on the road surface while tilting the tire. Nevertheless, the shape and stiffness are also very important properties for the tire design of a camber actuated suspension system.

There are multiple studies showing that the lateral vehicle dynamics can be improved with larger camber angles. For example, the authors [1] carried out a comparison study of yaw moment on a circular track with different camber angles. In another study they compare tires under different inclination angles [9]. These studies show that a larger camber angle can increase the lateral forces, the lateral acceleration and yaw rate. However only at the cost of increasing the vehicle roll simultaneously due to the centripetal forces depending on the height of the center of gravity.

REVIEW OF ACTIVE CAMBER MECHANISMS

Researchers have proposed various mechanisms to actuate the wheel camber, which generally differ in a number of aspects including: the camber range, point of actuation, area of use and type of actuation. A comprehensive list of existing camber mechanisms is compiled in the Appendix A. The point of actuation is of significant influence on the design, which limits the camber range and therefore the space requirements. An upper actuated mechanism has more displacement on the upper side of the wheel compared to the lower side, therefore it requires more space in the mudguard or it might collide with the damper on the other side. However a lower actuated mechanism has less displacement at the upper side of the wheel and therefore it can reach higher camber angles without major changes to the suspension and bodywork. The lower actuated mechanism has also more lateral displacement of the wheel over the road during actuation. This displacement causes friction and which eventually requires a more powerful actuator. The position of the actuator introduces other opportunities, such as control of active steering and active toe angle. The area of use is important to define the requirements of the mechanism. Sports vehicles tend to be lightweight and are usually not designed for durability. However an off-road vehicle drives in the most unknown circumstances and should be durable and reliable when driving in remote areas. Urban vehicles have varying requirements and that vary between the two ends of sports and off-road with more focus on cost.

These actuator concepts were divided into groups of five types and built in MSC.ADAMS/View [10]. This multi-body 3D software provides insight into the motion and limitations of the mechanism. That allowed us to analyze camber angles and actuator displacements which are listed in the Appendix A. Using the same parameters for each group we conducted a comparative study to present the differences in space requirements and actuator displacements.

CAMBER CONTROL SYSTEMS

The control system can be considered as the link between the driver and the camber mechanism. The driver is responsible for the path of the car, which means the driver should have a feeling of how the vehicle is behaving. A proper control system should assist the driver, but should always be under control by the driver. A general example is given in Figure 4. The driver has his own preferences and gets information from the environment, the steering wheel and the vehicle. Based on these inputs the driver gives an input to the steering system which will change the orientation of the wheels and this will change the vehicle motion. The common purpose of active camber control is to extend vehicle handling limits. However, driver's perception of such kind of extension can be crucial and change his/her steering feel and overall control of the vehicle. The camber control system should work in parallel with the steering system and receive information from the driver and the vehicle. Therefore, there are multiple possible control schemes to control the camber mechanism. The four different control schemes were designed aiming to: i) maximize lateral force and/or ii) achieve desired agile vehicle behavior. The difference between investigated control schemes are discussed in the section of experimental results. Four different control schemes were designed depending on:

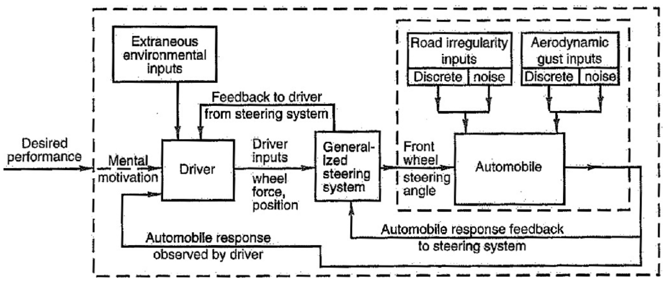

Figure 4. Driver-Vehicle relationship [4]

- Direct lateral acceleration

$$\gamma_{\text{active}} = a_{\text{y}} \cdot C_1$$

- Dead zone lateral acceleration

$$\gamma_{\text{active}} = \begin{cases} C_1 \cdot (|a_{\text{y}}| - C_{\text{offset}}) \cdot \text{sgn}(a_{\text{y}}) & |a_{\text{y}}| > C_{\text{offset}} \\ 0 & a_{\text{y}} \leq C_{\text{offset}} \end{cases}$$

- Hyperbolic lateral acceleration

$$\gamma_{\text{active}} = a_{\text{y}} \cdot C_1 \cdot \left(\frac{e^{C_2 \cdot a_{\text{y}}} - 1}{e^{C_2 \cdot a_{\text{y}}} + 1} + 1 \right)$$

- Desired yaw rate,

$$\dot{\Psi}_{\text{desired}} = \frac{V}{L} \cdot \delta$$
$$\gamma_{\text{active}} = \left(\dot{\Psi}_{\text{desired}} - \dot{\Psi}_{\text{real}} \right) \cdot C_1$$

with $C_1 = \frac{\max_{\text{camber angle}}}{\max_{\text{lateral acc}} - (\text{offset}_{\text{lateral acc}})}$

Newton's second law dictates that the force increases with the acceleration. Based on this linear relation all control schemes are designed to use the lateral acceleration as a control input. The camber angle is taken as the same angle for all four wheels and leans into the corner, which means a negative camber angle for the outer corner wheels and a positive camber angle for the inner corner wheels. This is to create maximum lateral force on all wheels and does not change other vehicle dynamics behaviour like under and over steer. The investigation on control mechanisms is mainly targeted to identify the influence of changing camber angles on the driver.

SIMULATOR SET-UP

The simulator in the Intelligent Automotive Systems (IAS) laboratory of the Delft University of Technology was used in a fixed-base configuration as shown in Figure 6 [11]. The system is equipped with steering actuator, dSpace [12] real-time hardware and the dSPACE Automotive Simulation Models (ASM) library based on Matlab/ Simulink. The ASM library includes a real-time vehicle simulation. This vehicle model pushes the parameters in real time to the visualization environment showing the motion of the vehicle in the virtual environment. This simulator set-up enables to create the desired track, visualization, vehicle dynamics, steer feedback and control. Therefore, tests with several controllers can be done by easily switching between them and all data can be saved regarding the vehicle dynamics response. The dSPACE work-flow schematic is presented in Figure 5.

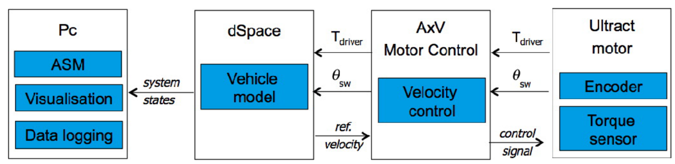

Figure 5. Simulator scheme

The track was first built to avoid any distractions, but this made it difficult to experience speed and safety. Therefore environmental effects (e.g. houses, etc) were introduced. The vehicle model was selected as the standard ASM mid-size car and its suspension model was modified to the active camber model. The Simulink model allows to integrate the four control schemes to the suspension model.

The limitations of the ASM software is the use of the magic tire formula version MF-Tire 6.0. This tire model is a single point contact model, so the tire shape does not influence the forces. The standard ASM car tire is a conventional car tire with a rectangle cross-section, but due to the limitations of the magic tire formula, this tire can be used. The magic tire formula is valid for up to 15degrees camber angles and beyond which it becomes less accurate. The magic tire formula can be represented as following [3]:

$$\begin{aligned} Y(x) &= D\sin[C\tan^{-1}(BX - E(BX - \ldots \\ &\quad - \tan^{-1}(BX)))] + S_v, \end{aligned} \tag{1}$$

$$X = x + S_h, \tag{2}$$

where B, C, D and E are factors for stiffness, shape, peak and curvature. The camber angle is in the horizontal shift factor S_h, which was already shown in Figure 2. This implies a larger camber angle would linearly increase the lateral forces, without roll-off characteristics. In this study the focus is on steering feel of the driver at changing camber angles and the shape of the tire graph is in the right order. The magic formula could be extended to a version which is more desirable for larger camber angles, but this would introduce even more unknown variables. The tire model should provide representable forces to create realistic feedback to the driver and guarantee sufficient realism of vehicle dynamics.

STEER FEEDBACK

Steering feel is important feedback for the driver during driving, it plays a significant role for the feeling of safety and comfort. Apart from that it's also something that contributes to the brand character, which separates the vehicle from other vehicles. Therefore steering behavior in a driving simulator is one of the most important elements to achieve a realistic driving environment. To reach realistic behavior, all components like vehicle modeling, proper visualization, motion cueing and others play a significant role [13]. Studies investigating the influence of motion cues on drivers have shown that having realistic steering feedback can partially compensate for the lack of motion cues [14].

The steering behavior in a simulator is determined by the used model and the hardware of the steering actuator. The steering model used in this study consists of a upper column with the steering wheel, a torque sensor and a rack-pinion unit. The assist characteristics are determined from look-up tables [12] which are based on the input torque and the vehicle velocity. The equations for the steering system used can be seen below and Table 1 shows a description for the parameters used.

Figure 6. Driving simulator set-up

$$J_{sw}\ddot{\theta}_{sw} = T_{driver} - T_{bar} - B_{sw}\dot{\theta}_{sw} \quad (3)$$

$$T_{bar} = B_{tb}(\dot{\theta}_{sw} - \frac{\dot{x}_r}{u_{rp}}) - K_{tb}(\theta_{sw} - \frac{x_r}{u_{rp}}) \quad (4)$$

$$m_{rack}\ddot{x}_r = \frac{T_{assist}}{u_{rp}} + \frac{T_{bar}}{u_{rp}} - B_{rack}\dot{x}_r - \ldots \\ -F_{rack} - F_{rackfric} \quad (5)$$

Table 1. Steering system parameters

Symbol	Description	Units
T_{driver}	Driver input torque	N/m
J_{sw}	Upper column assembly inertia	kgm^2
θ_{sw}	Steering wheel displacement	rad
B_{sw}	Upper column assembly damping	Nms/rad
T_{bar}	Torsion bar torque	N/m
B_{tb}	Torsion bar Damping	Nms/rad
K_{tb}	Torsion bar stiffness	Nm/rad
m_r	Rack-pinion assembly mass	kg
x_r	Rack displacement	m
u_{rp}	Rack to pinion ratio	m/rad
$F_{rackfric}$	Rack friction force	N
F_{rack}	Rack reaction force	N

The steering actuator used is a Phase Motion Ultract II AC motor, the specification can be seen in Table 2. This motor is directly connected to a steering wheel via it's shaft. Two sensors are used to control the motor, one of them is the torque sensor and the other one is an encoder for the steering wheel position.

In order to measure the driver's input torque strain gauges are glued onto the shaft in a way such that a Wheatstone bridge is formed. With the deformation on the shaft, the resistance of the wires changes, this then causes a voltage difference on the constructed Wheatstone bridge. This voltage difference correlates linearly to the torque applied on the shaft.

The encoder used is a SINCOS 5 channel encoder (2 absolute analogue tracks, 2 incremental analogue tracks, index track). The encoder signal is used by the motor's internal controller and it's provided as an input to the steering model used for force feedback.

Table 2. Motor specifications

Rated speed [rpm]	3000
Rated torque [Nm]	8.6
Rated current [A]	6.0
Rated power [kW]	2.7
Max. Torque [Nm]	42
Max Current [A]	33.8

Control of the motor is done using the Phase Motion AxV controller. This controller makes it possible to control the motor either using a reference position or velocity. For this study the choice has been made to use velocity control. An analog signal is used as a control signal, a certain reference velocity corresponds to a certain voltage. Velocity control is preferred because a reference velocity corresponds to a reference acceleration and this then corresponds to a torque, so actually torque control is achieved. The AxV control platform offers a bandwidth of 16 kHz for velocity control which makes it suitable for feedback simulation.

The driver experiences force feedback through the upper column, therefore the upper column dynamics should be simulated by the steering actuator. To do this, the velocity of the upper column dynamics should be supplied as a reference. A diagram can be seen in Figure 7, the desired upper column dynamics are as given previously.

The driver torque comes from the torque sensor and the reaction torque comes from the torsion bar, which is calculated using the steering wheel angle which comes from the encoder. To verify that the motor is able to deliver the desired upper column dynamics, verification is done by comparing the encoder output to the simulated output, an example of this can be seen in Figure 8.

TEST PROCEDURE

The participants were chosen to be young drivers in the age of 18-28 years and a driving experience of less than 100,000 km. The group was small which made it important to keep it within a limited range of driving experience and thus avoid the creation of too many dependencies.

The tests started with a proof of concept. The participants had to drive with a fixed camber angle on a straight line and enter a circle at a constant speed. This test was conducted to prove that camber angle was indeed increasing the lateral forces. Next to the objective data, it was already presenting results on steering feeling. The tests were then extended to a dynamic camber system and the circle was extended to a double circle with straight parts to connect them, as shown in Figure 9. The straight parts were introduced to have a smooth entrance into the next corner without the transient behaviour of the previous corner. The first corner is a large corner with a 75m radius and the second corner is a 62.5m radius. The radius of the second corner is smaller to create higher lateral forces and this is expected to show larger differences in controllers.

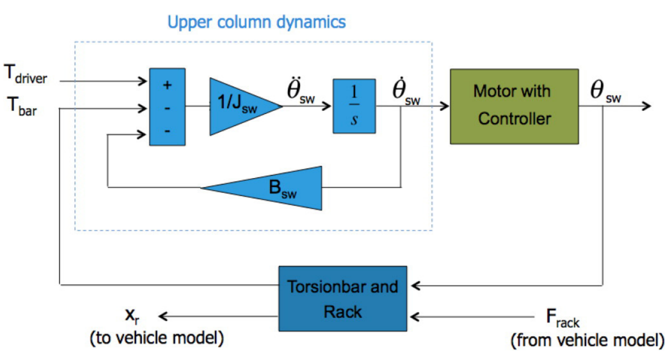

Figure 7. Feedback scheme

Each participant has one training drive on a lower speed of 50km/h to get familiar with the track and the simulator's vehicle model. After this training session the speed increases to 80km/h and the test begins with the four different controllers and a reference situation in a random order. The participants have to drive three times, the eight-shape track in each session. In the first eight-shape they can get familiar with the controller and the next two rounds they can focus on the controller experience.

Both objective and subjective data is recorded. All the vehicle data can be extracted from the ASM software, which provided information on the objective differences between the controllers. After each session the participants had to fill in the questionnaire which consists of six questions before they could continue with the next session. The questionnaire consisted of questions about how they experienced the vehicle control, vehicle response, steer effort, safety, speed and fun. The objective and subjective data was then be compared with each other to check for correlations.

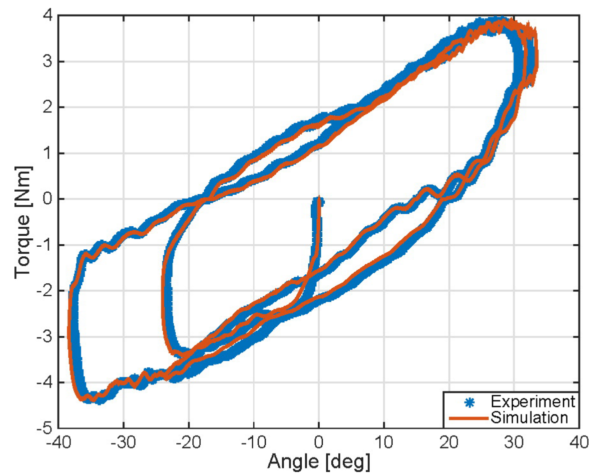

Figure 8. Motor output verification

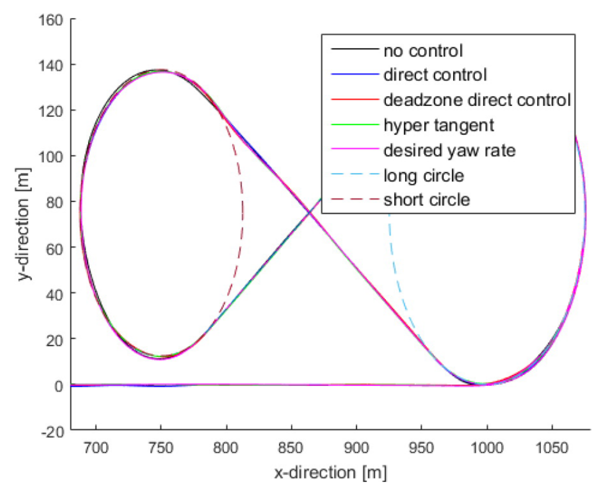

Figure 9. Trajectory test drive

EXPERIMENTAL RESULTS

The objective and subjective data of the participants were collected in the tests. The participants were asked to drive focused and were surrounded by curtains to not be distracted. Therefore the objective data was close to each other with slightly improved behavior for the active camber controls. The results are analyzed by first interpreting the tire behavior. Then the graphs of the yaw rate, lateral acceleration, steer wheel angle and lateral road position error of one test driver are discussed. This is followed by zooming out to get the overall picture of all participants combined. The data collection are concluded in Table 3 displaying the important variables. Finally, the questionnaire results are discussed and the final discussion of the results are presented.

The objective results are an effect of the tire forces and the steer input. The tire force with a camber angle would be expected as in Figure 2, which means a shift in the graph. But due to the controllers there is no lateral force at zero slip (thus also no added camber angle), while there is maximum lateral force at maximum slip (thus maximum camber angle). This results in the tire force graph of Figure 10. The figure shows that the normalized lateral tire forces $(\frac{F_y}{F_z})$ are still in their linear region while the reference situation reaches its maximum lateral force. A special case is the desired yaw rate. This control scheme is changing the camber angle based on the yaw rate error, therefore the line is making curly shapes.

The yaw rate in Figure 11 and lateral acceleration in Figure 12 are responses of the tire behavior, which results in the lateral position error in Figure 14. These figures shows the characteristics for only one driver. The driver steers the vehicle into the corner, but the tires reaches their maximal lateral forces and the vehicle cannot follow the track thus the driver keeps increasing the steer angle. Finally, the vehicle steers back to the track, therefore the yaw rate becomes too large and the driver has to correct for this, but this is a sensitive correction and again the vehicle loses the track. By looking at the graphs in Figures 11, 12 and 13 large overshoots are visible. This was the driver closest to the average which gave a good impression of the trend of all drivers. The box plots in Figures 15, 16 and 17 shows the results of all drivers combined. Figure 16 shows the steer angle, demonstrating a clear trend of smaller deviation and lower steer angle for the versions with control. Furthermore in Figure 15 a much higher error can be found for the reference configuration. The reference configuration has a large error with a large deviation, which can be marked as a hard to control vehicle.

The results of the questionnaire are shown in Figure 18. An overall view indicates that the controllers are all close to each other and the reference configuration mostly stands out. To find why the reference configuration stands out, the questionnaire results are compared with the vehicle data. The introduction of the control system shows a significant difference as seen in Figure 18. The drivers had less control without the active camber system but the control systems were difficult to distinguish individually. Drivers felt differences, but it was hard to grade them. So these were mostly graded between 3 and 4 on a scale from 1 to 5, which means sufficient or good behavior. Looking back to the graphs of steering angle in Figure 13, lots of overshoot and a massive settling time point at a difficult to control vehicle, while the controlled vehicles have smaller overshoots and a shorter settling time. This comes back in the yaw rate and lateral acceleration. The same is happening with the response time. Although the response time is the same for all systems, the reference configuration lacks lateral force which makes it feel like it responds later. The desired yaw rate controller response is the quickest, because it is dependent on the steering angle. This is an instantly controllable input, while the lateral acceleration first has to build up. The steer effort gives interesting results, because the question clearly asks about the force they have to apply on the steering wheel, which is lower in the case without control but still ends up on top. After asking the drivers they interpreted the effort they have to deliver to keep the vehicle on the track as effort and they had to deliver more work to keep it on the track. Comparing it to the steer torque it is a lower value without camber control. Figure 17 shows the differences in steer torque. The steer torque significantly increases for the controlled systems, but still it is experienced as less effort and a better feel of control. The experience of speed and safety are very similar compared to overall control, because if the controller is difficult and the lateral error is large the speed is most likely too high for that corner and does not feel safe to drive that track. This finally results in the fun to drive. If it is too difficult there is no fun, but if it is too easy as what happens with desired yaw rate the fun also drops.

Table 3. Vehicle data in the short corner

mean values	no control	direct control	deadzone direct control	hyperbolic	desired yaw rate
Lateral acceleration	$7.35 m/s^2$	$+5.21\%$	$+5.66\%$	$+5.41\%$	$+4.93\%$
Steering wheel angle	$93.87°$	-12.19%	-11.77%	-11.84%	-12.09%
Yaw rate	$19.95 rad/s$	$+0.85\%$	$+1.25\%$	$+1.03\%$	$+0.50\%$
Roll angle	$4.23°$	$+16.16\%$	$+16.83\%$	$+16.35\%$	$+15.27\%$
Longitudinal velocity	$76.99 km/h$	$+3.03\%$	$+3.01\%$	$+3.04\%$	$+2.90\%$
Lateral deviation	$0.48 m$	-41.61%	-45.38%	-41.34%	-37.60%
Steering wheel torque	$3.59 Nm$	$+28.10\%$	$+30.80\%$	$+29.52\%$	$+29.91\%$

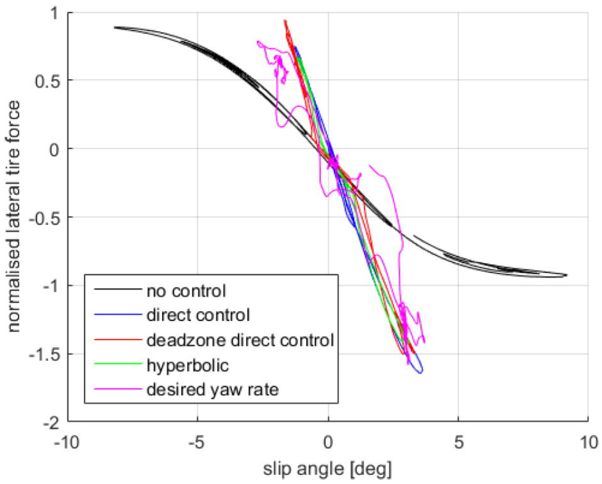

Figure 10. Tire forces (Front Right wheel)

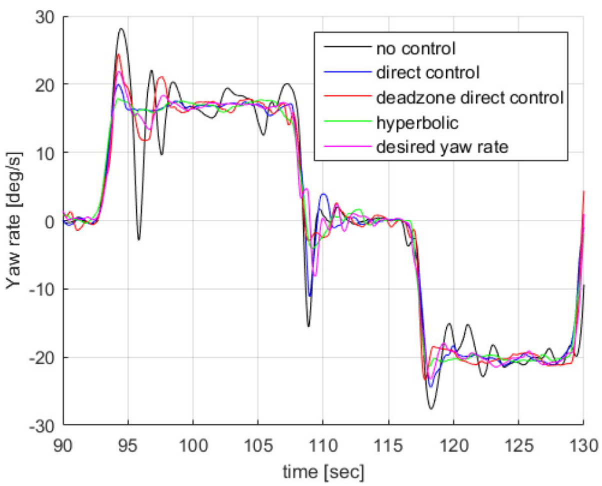

Figure 11. Yaw rate from a test driver

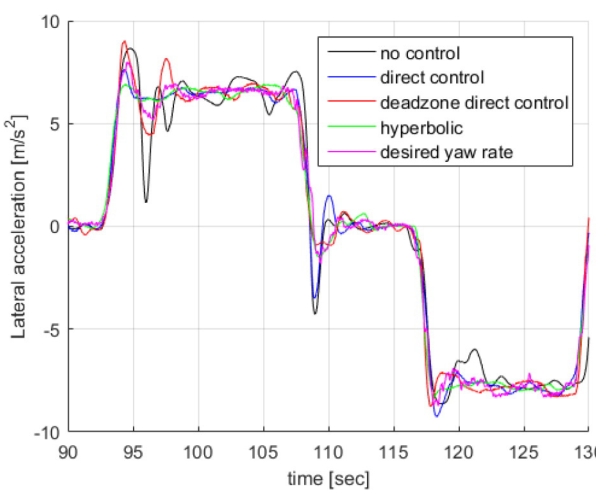

Figure 12. Lateral acceleration for long corner/straight part/short corner

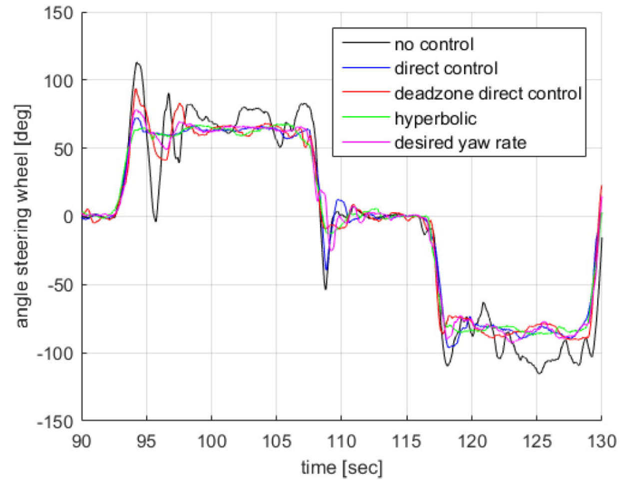

Figure 13. Steering wheel angle from a test driver

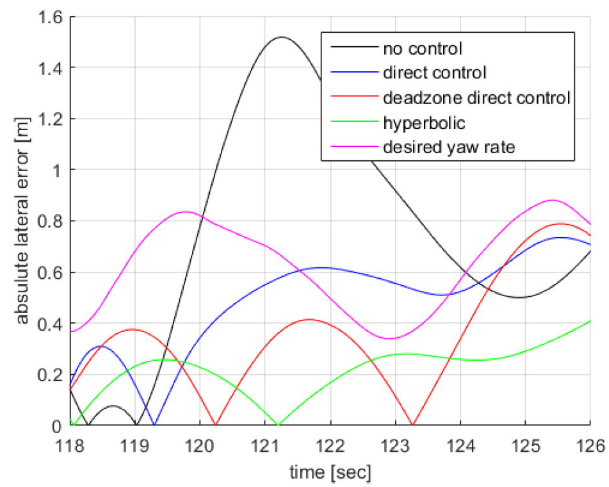

Figure 14. Absolute lateral position error of the short corner of one of the participants

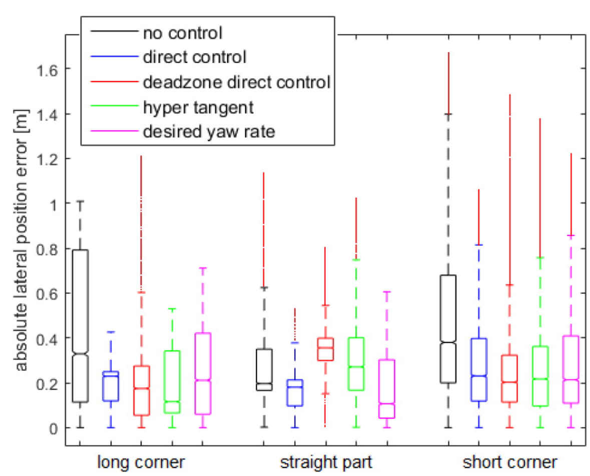

Figure 15. Boxplots absolute lateral position error long corner/straight/short corner

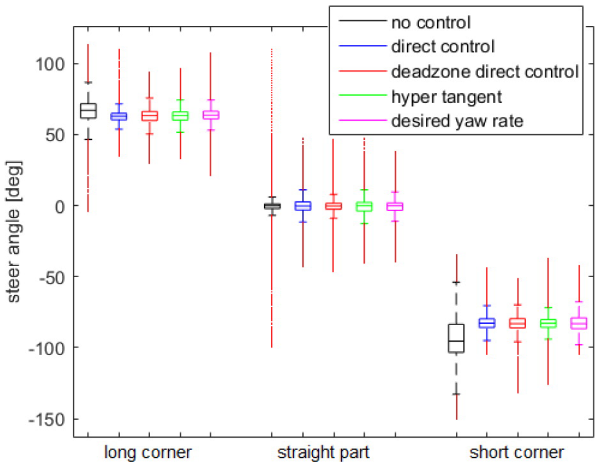

Figure 16. Steering wheel angle for long corner/straight part/short corner

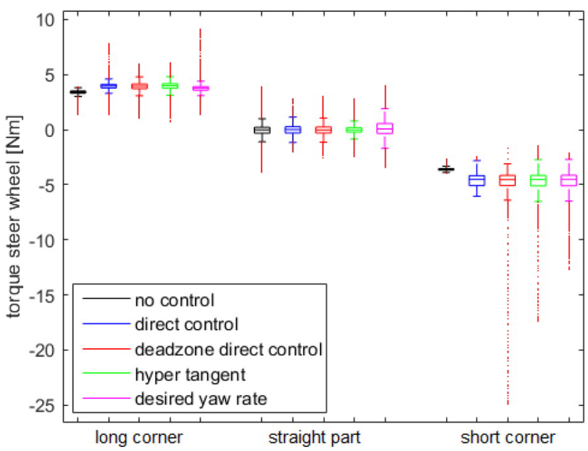

Figure 17. Torque on steering wheel for long corner/straight part/short corner

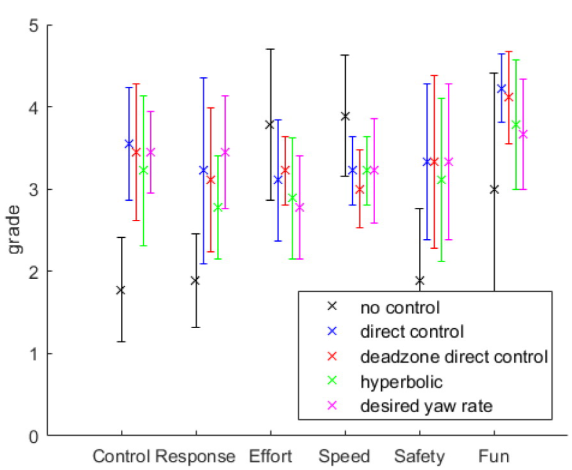

Figure 18. Results questionaire

A statistical analysis if performed for the questionnaire results to show the significance. The Wilcoxon ranksum test is used and the results of the reference configuration versus the controllers are presented in Figure 19. The overall control shows an unanimous " significant difference " for all controllers. There is no significant difference between the controllers.

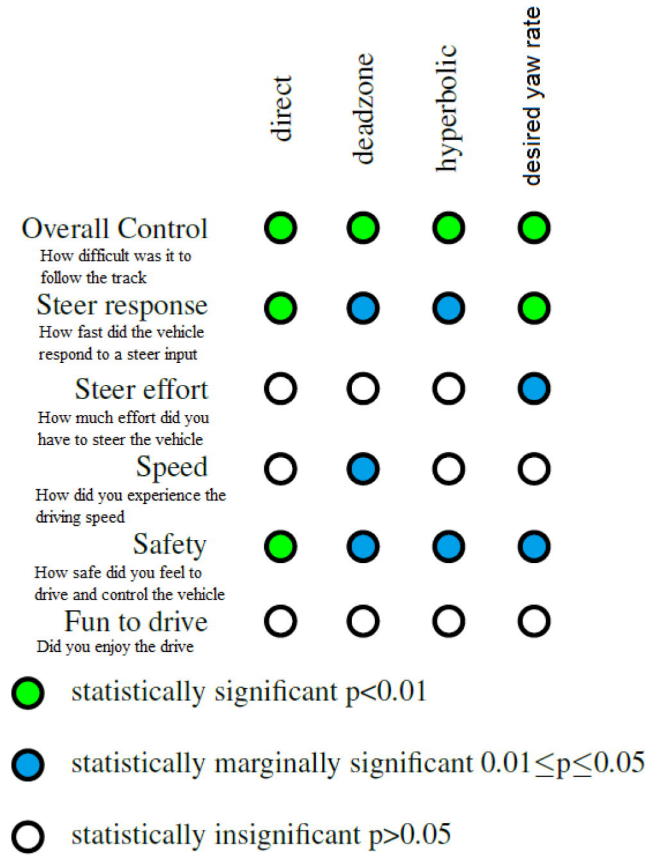

Figure 19. Subjective evaluation of experimental results

The experimental results further indicate for the participants with less driven kilometers, the active camber control assisted more with keeping the vehicle on track than for the more experienced drivers. The inexperienced drivers had more problems with filling in the questionnaire and had a hard time to distinguish the different controllers, while the more experienced drivers had less difference in vehicle data and more differences in the questionnaire data. Beginner drivers are most likely more concentrated on driving the vehicle, while more experienced drivers can think more about how the vehicle is responding and what they feel in the steering wheel. Furthermore experienced drivers were more capable of adjusting for the lack of lateral force. They did not try to drive on the desired line, but rather try to minimize the overall error by adapting their driving for vehicle performance.

The simulator is a software simulation of the reality, where the participants had the most comments about. Nevertheless, although the simulator lacked certain details in visualization and motion cues, the steering feedback was sufficient to keep the drivers focused and provide reliable answers.

CONCLUSIONS AND RECOMMENDATIONS

In this research we were looking for the influence of active camber control on steering feel. First a review was completed over the existing camber control mechanisms. In what follows, control schemes were investigated to be implemented in the real-time dSPACE hardware. Integrating the control algorithms within the simulation environments, a test scenario was designed, which consisted out of four different controllers and a reference configuration. Each participant had to drive three times on an eight figure track to test each controller. Finally, the tests with participants were conducted and the results were shown objective as subjective data. The objective results of with and without camber control were close to each other, because humans can adapt to changing situations and they automatically changed their steering behavior to minimize the lateral position error with the track. While the subjective data shows that the feel of control and feel of safety was significantly improved for the active controlled camber angle. Further analysis of the vehicle response shows that the vehicle without the camber control was driving on its maximum performance and the drivers had a hard time to control the vehicle, while for the controlled cases they still had leverage with the tires and the vehicle was much easier to control.

A simulator is the ideal setting for tests that require repeatability, which is crucial for comparative studies. However a considerable limitation is the used models inside. For example the tire model inside ASM is valid only up to 15 degrees. To get even more realistic feel the tire model can be extended to a more suitable one. The scope of this research was focused on steering feel, but if the roll and lateral acceleration were to be considered, further analysis on the motion cues and visual effects would have been required. Furthermore, the control schemes were focused on only camber controls for drive-ability and steering feel. However there are numerous other applications, such as emergency or evasive maneuvering for safety, that can be improved by more situation depended control strategies. The mechanisms are individual systems per wheel, which also gives the opportunity to change the camber angle per wheel and more precisely control the vehicle using systems such as ESP.

REFERENCES

1. Yoshino, T. and Nozaki, H., "About the Effect of Camber Control on Vehicle Dynamics," SAE Technical Paper 2014-01-2383, 2014, doi:10.4271/2014-01-2383.
2. Ramirez Ruiz, I., "Active Kinematics Suspension for a High Performance Sports Car," SAE Technical Paper 2013-01-0684, 2013, doi:10.4271/2013-01-0684.
3. Pacejka, H., "Tyre and Vehicle Dynamics," (Warrendale, SAE International, 2012), ISBN 978-0-0809-7016-5.
4. Milliken, W. and Milliken, D., "Race Car Vehicle Dynamics," (Warrendale, Society of Automotive Engineers, Inc., 1994), ISBN 978-1-56091-526-3.
5. Yoshino, T. and Nozaki, H., "Effect of Direct Yaw Moment Control Based on Steering Angle Velocity and Camber Angle Control," SAE Technical Paper 2014-01-2386, 2014, doi:10.4271/2014-01-2386.
6. Blundell, M. and Harty, D., "Multibody Systems Approach to Vehicle Dynamics," ISBN:978-0-08-099425-3.
7. Andreasson, J., "Generic road vehicle motion modelling and control," Thesis, Royal institute of Technology Vehicle Dynamics Stockholm, 2007.
8. Daimler AG, "The research vehicles of Mercedes-Benz," http://www.daimler.com, 2001.
9. Laws, S.M., "An Active Camber Concept for Extreme Maneuverability," Thesis, Stanfort University, 2010.
10. MSC ADAMS, www.mscsoftware.com.
11. Katzourakis, D.I., Abbink, D.A., Happee, R., Holweg, E., "Steering force feedback for human machine-interface automotive experiments," *IEEE Transactions on Instrumentation and Measurement*, 60(1):32-43,2011, doi:10.1109/TIM.2010.2065550.
12. dSPACE, www.dspace.com.
13. Shyrokau, B., Loof, J., Stroosma, O., Wang, M., "Effect of Steering Model Fidelity on Subjective Evaluation of Truck Steering Feel," *DSC EUROPE*, 2015.
14. Allen, R. and Rosenthal, T., "Requirements for Vehicle Dynamics Simulation Models," SAE Technical Paper 940175, 1994, doi:10.4271/940175.
15. Hirano, Y., "Integrated vehicle control of an inwheel-motor vehicle to optimize vehicle dynamics and energy consumption," *Intelligent Control and Automation (WCICA)* 2335 - 2339, 2013, doi:10.1109/WCICA.2012.6358264.
16. Zetterstrom, S., "Electromechanical steering, suspension, drive and brake modules," *Proceedings of Vehicular Technology Conference* 3:1856-1863, 2002, doi:10.1109/VETECF.2002.1040538.
17. Jazar, R.N., Subic, A. and Zhang, N., "Kinematics of a smart variable caster mechanism for a vehicle steerable wheel," *International Journal of Vehicle Mechanics and Mobility* 50(12):1861-1875, 2012, doi:10.1080/00423114.2012.699075.
18. Park, S., Sohn, J., "Effects of camber angle control of front suspension on vehicle dynamic behaviors," *Journal of Mechanical Science and Technology* 26(2):307-313, 2012, doi:10.1007/s12206-011-1206-1.
19. Iman, M., Esfahani, M., Mosayebi, M., Pourshams, M. et al., "Optimization of Double Wishbone Suspension System with Variable Camber Angle by Hydraulic Mechanism," *World Academy of Science, Engineering and Technology* 61:299-306, 2010, doi:10.1.1.193.1668.
20. Nemeth, B., Gaspar, P., "Control Design of Variable-Geometry Suspension Considering the Construction System," *IEEE Transactions on Vehicular Technology* 62(8):4104-4109, 2013, doi:10.1109/TVT.2013.2263156.
21. Mahmoodi-Kaleibar, M., Javanshir I., Asadi, K., Afkar, A. et al., "Optimization of suspension system of off-road vehicle for vehicle performance improvement," *Journal of Central South University* 20(4):902-910, 2013, doi:10.1007/s11771-013-1564-1.
22. Horiguchi, M., Mizuno, A., Jones, M., Futamura, K., "Active Camber Control," *Proceedings of the FISITA 2012 World Automotive Congress* 10:247-256, 2013, doi:10.1007.
23. Zachrison, A., Rösth, M., Andersson, J., and Werndin, R., "Evolve - A Vehicle Based Test Platform for Active Rear Axle Camber and Steering Control," SAE Technical Paper 2003-01-0581, 2003, doi:10.4271/2003-01-0581.
24. Schmid, W., "A Revolutionary Approach for Active Toe and Camber Regulation," *Aachener Kolloquium Fahrzeug- und Motorentechnik 2010* 19:1617-1636, 2010.
25. Siemens, "VDO Ecorner," http://www.autoblog.com/2006/08/10/siemens-vdo-announces-ecorner-motor-in-hub-concept, 2006.

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ACKNOWLEDGEMENTS

We would like to thank TASS International, The Netherlands, for their support and Delft-Tyre software. The research leading to these results has received funding from the European Union Horizon 2020 Framework Program, Marie Sklodowska-Curie actions, under grant agreement no. 645736.

ABBREVIATIONS

ASM - Automotive Simulation Models

IAS - Intelligent Automotive System

ESP - electronic stability program

APPENDIX

APPENDIX A

Table A.1. Benchmark table

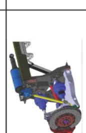
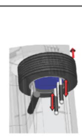
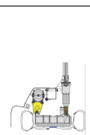
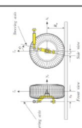
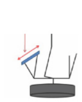
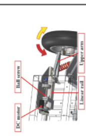
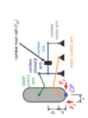
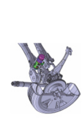
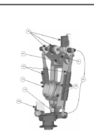
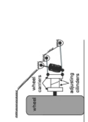
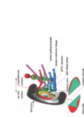
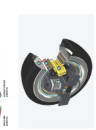
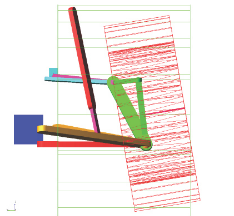
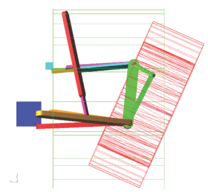
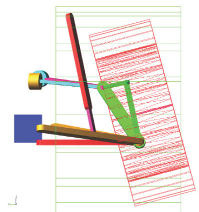
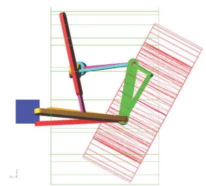
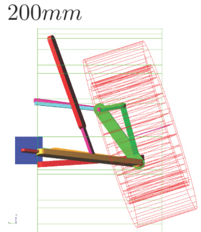
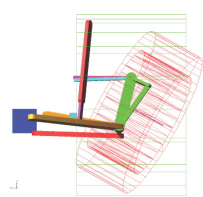
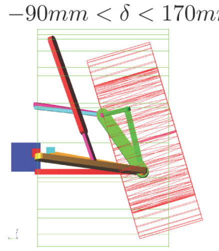
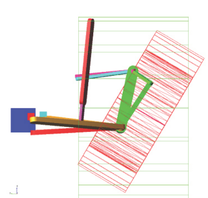
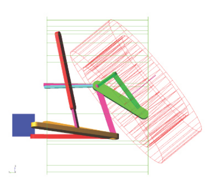
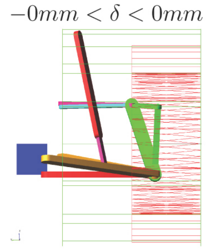
Actuation Mechanism	Figure	Max camber range	Point of actuation	Ready for active toe	Prototyped	Area of use	space requirements	additional unsprung mass weight
Ferrari [2]		$-6° < \gamma < -1.5°$	upper	yes	yes	sport	negligible	medium
Toyota [15]		$-5° < \gamma < 5°$	lower	yes	no	urban	negligible	high
Volvo [16]		$-5° < \gamma < 5°$	lower	yes	yes	urban	negligible	high
Caster angle [17]		$-12° < \gamma < 12°$	upper	no	no	road	medium	medium
UW longitudinal translation [18]		$-1° < \gamma < 1°$	upper	no	no	road	medium	negligible
UW lateral translation [1]		$-20° < \gamma < 20°$	upper	no	no	road	much	negligible
Stanford thesis [9]		$-45° < \gamma < 45°$	upper	no	yes	road	much	negligible
Crank bar upper wishbone [19] [20] [21] [22]		$-5.5° < \gamma < 5.5°$	upper	no	yes	(off-)road	negligible	negligible
Crank bar lower wishbone [23]		$-5.5° < \gamma < 5.5°$	lower	no	yes	urban	negligible	medium
Skew cylinders [24]		$-60° < \gamma < 60°$	middle	yes	yes	road	much	high
Mercedes [8]		$-30° < \gamma < 0°$	lower	no	yes	road/sport	much	high
Siemens [25]		$-4° < \gamma < 4°$	middle	yes	yes	urban	negligible	high

Table A.2. Benchmark table from MSC.ADAMS/View

Type	Workspace / Actuator displacement without vertical wheel travel	Workspace / Actuator displacement with a minimum of -100mm - 100 mm vertical wheel travel	Camber dependency while vertical wheel travel from -100mm to 100mm	Actuation power
Upper wishbone length of rods	$-19.5° < \gamma < 30°$ $-65mm < \delta < 130mm$ 	$-10° < \gamma < 25°$ $-35mm < \delta < 100mm$ 	$< 4.5°$	low
Upper wishbone position of joint	$-20° < \gamma < 35°$ $-70mm < \delta < 150mm$ 	$-15° < \gamma < 30°$ $-55mm < \delta < 120mm$ 	$< 5°$	low
Lower wishbone length of rods	$-30° < \gamma < 40°$ $-120mm < \delta < 200mm$ 	$-18° < \gamma < 30°$ $-75mm < \delta < 150mm$ 	$< 3.5°$	high
Lower wishbone position of joint	$-27.5° < \gamma < 40°$ $-90mm < \delta < 170mm$ 	$-16.5° < \gamma < 30°$ $-60mm < \delta < 130mm$ 	$< 3.5°$	high
On the knuckle	$-40° < \gamma < 0°$ $-0mm < \delta < 0mm$ 	$-30° < \gamma < 0°$ $-0mm < \delta < 0mm$ 	$< 5°$	high