

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.

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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.

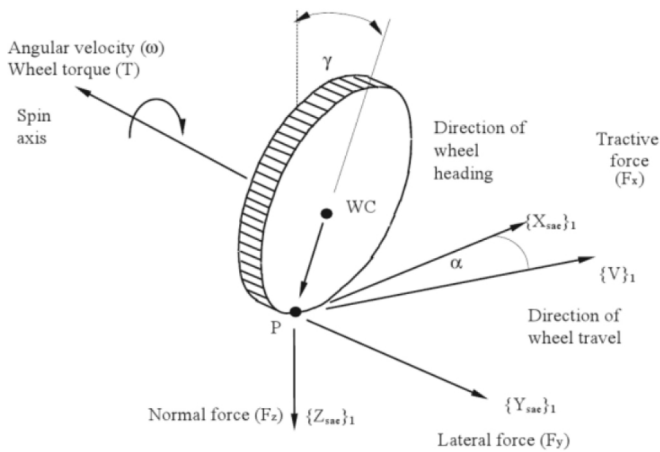


Figure 1. Tire axis frame, the SAE standard [6]

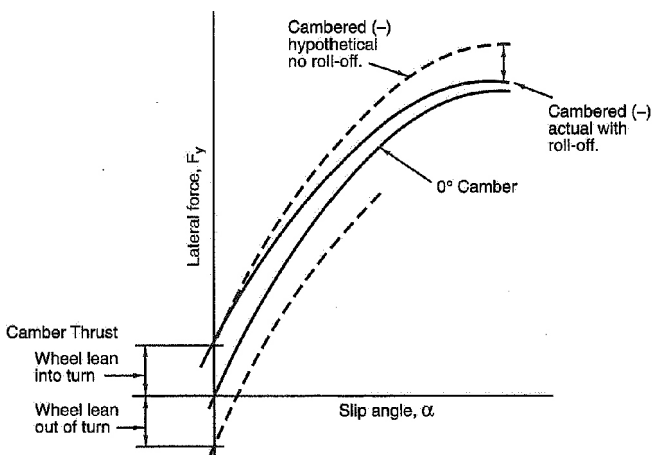


Figure 2. Camber thrust [4]

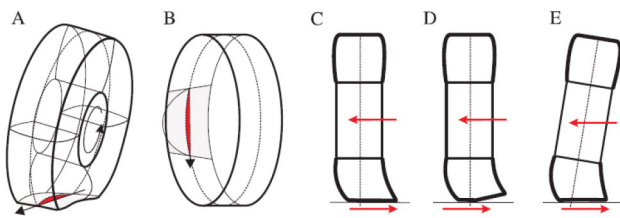


Figure 3. Tire deformation during cornering [7]

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:

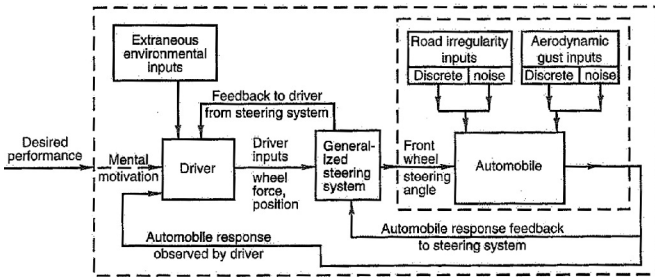


Figure 4. Driver-Vehicle relationship [4]

- Direct lateral acceleration

$$\gamma_{\text{active}} = a_y \cdot C_1$$

- Dead zone lateral acceleration

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

- Hyperbolic lateral acceleration

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

- Desired yaw rate,

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

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

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.

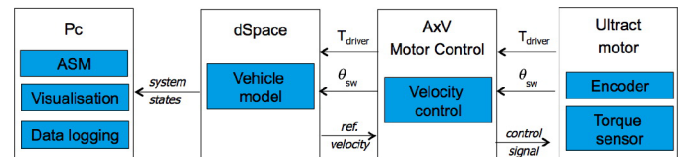


Figure 5. Simulator scheme

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]:

$$Y(x) = D \sin[C \tan^{-1}(BX - E(BX - \dots - \tan^{-1}(BX)))] + S_v, \quad (1)$$

$$X = x + S_h, \quad (2)$$

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

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

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

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

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. This diagram can be seen in Figure 7, the desired upper column dynamics are as given previously.