Online Steering Dynamics in the BMW Driving Simulator

Franz M. Reich
Research Engineer
University of Technology of Vienna
&
Jost H. Bernasch, Jan P. Löwenau
Research Engineers
BMW AG Research Center

Abstract

An advanced steering wheel system for the BMW driving simulator has been developed and integrated in the vehicle dynamics model. The steering wheel system reacts to the driver with a realistic steering wheel torque, which depends on speed, steering angle, steering angular velocity and lateral acceleration. The steering model's parameters are adjustable in order to reflect real steering properties and to map the special steering hardware. The complete technical arrangement was implemented and tested intensivly. The results are compared with driving test data and found to be in good coincidence.

By means of experiment's it could be demonstrated that test persons had got a very improved steering behaviour compared with a prior solution generating torque with a left and right sided spring-damper element. A much more stable behaviour in standardized driving manoeuvres with appropriate speed could be achieved. The driver's workload to keep the vehicle in lane is reduced. Additionally, the dynamic steering torque is comparable with the torque measured in similar test rides on the BMW test track.

Notation

Symbol	Dimens.	Property
a_y	m/s^2	lateral acceleration
l	m	wheelbase ($l = l_v + l_h$)
m	kg	vehicle mass
v	m/s	vehicle velocity
i		steering gear ratio
M_{a_y}	Nm	steering aligning torque a_y
M_B	Nm	vertical distortion torque
M_D	Nm	damping torque
M_L	Nm	steering aligning torque
β	rad	sideslip angle
$\dot{\beta}$	rad/s	sideslip velocity
δ_L	rad	steering angle
$\dot{\delta}_L$	rad/s	steering angular velocity
ψ	rad	yaw angle
$\dot{\psi}$	rad/s	yaw rate
$\ddot{\psi}$	rad/s^2	yaw acceleration
τ	rad	vertical distort. damping
Θ	kgm^2	vehicle yaw inertia

Presented at the **1996 IMAGE Conference**
Scottsdale, Arizona 23-28 June 1996

Introduction

In a driving simulator like the BMW driving simulator it is important to simulate drivers inputs as known from real driving. For a straight line stability and to react properly it is necessary to have a realistic steering aligning torque. In the past, detailed experimental and theoretical investigations in modelling steering behaviour have been performed by (Braess, 1970; Roenitz, 1977; Koziara, 1994; Roos, 1995; Gipser, 1995). Until now, a closed description of steering dynamic contributions to the steering aligning torque in a simulator, like the steering torque due to lateral acceleration, vertical distortion torque as well as the damping torque does not exit. A first step to this goal to consider a better understanding of the closed-loop simulations of steering wheel torques in a simulator has been taken by (Schumann, 1995).

In this paper some important features of an advanced steering system from the low to the high velocity range and the entire steering range will be presented. The steering torque due to lateral acceleration, the vertical tyre distortion torque that results from the pneumatic trail as well as the steering damping torque are consistently incorporated in closed-loop simulations. It will be shown that the obtained realistic steering aligning torque in the BMW driving simulator can be described in a very good agreement with experimental results by using of the developed steering model.

Description of BMW Driving Simulator

A 2-pipe Silicon Graphics Onyx is used to generate a 4-channel imaging system each 1280x1024 pixel with 190 degrees front view (left, middle, right) and 60 degree mirrored back projection. A high quality database with 40 km highway and country road allowing standard driving maneouvres (braking, lane change etc.) as well as overtaking, U-turns and right-of-way traffic by using the rear view mirror. Up to now a motion animation platform is not used, therefore no feedback of acceleration is given. Especially in this case vehicles in a driving simulator should have a realistic steering wheel torque for an optimal straight ahead stability.

Fig. 1 shows a BMW 325i convertible in the BMW driving simulator equipped with sensors for steering wheel motion, accelerator pedal, brake pedal, hand brake, gear shift position (automatic), light and cruise control stick. Also, other cars from the production line equipped with appropriate sensors are integrated in the simulator easily, as e.g. a type 7-series limousine. Additionally, different mock-ups are already in use in the simulator. These prototype cars have got electrical and electronical equipment such as the above-mentioned sensors as well as with the new developed advanced steering system.

Different experimental investigations have already been demonstrated successfully by (Haller, 1994; Naab, 1994; Schumann, 1995; Bernasch, 1995): 1) navigation planning with different complexity of dialogs using the board monitor; 2) parking lot reservation using the board monitor and different input devices; 3) development of an adaptive cruise control system with driver identification via fuzzy control; 4) and a study on the influence of indicated brake intensity by means of different shape of lights and different intensity of lights.

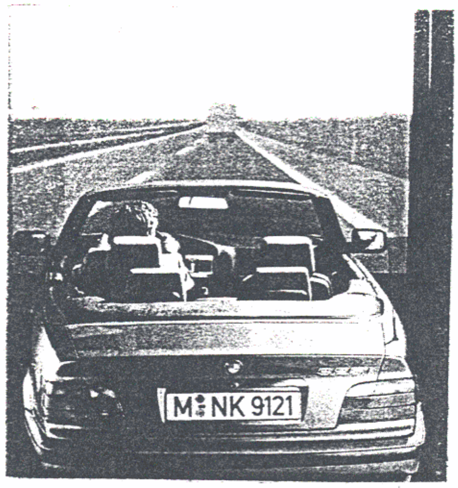

Fig. 1: BMW driving simulator.

Steering Wheel System

Steering Properties

In the first version of the simulator the steering torque was generated with a left and right sided spring-damper element. As the steering torque could not deliver a realistic tactile feedback, most of the unexperienced drivers overcompensated with wrong steering corrections. This lead to an unstable driving state, in particular under high lateral accelerations. In those cases the driver lost control.

The new steering wheel system provides the driver with a realistic steering wheel torque, which depends on speed, steering angle, steering angular velocity and lateral acceleration. The steering model's parameters are adjustable in order to reflect real steering properties and to map the special steering hardware.

Mechanical Hardware

The mechanical solution of the driving simulator steering system is based on an electrical torque motor integrated in the steering line as shown in Fig. 2. This steering system applies a torque on the steering wheel to support the driver in the simulator with a realistic steering wheel feedback.

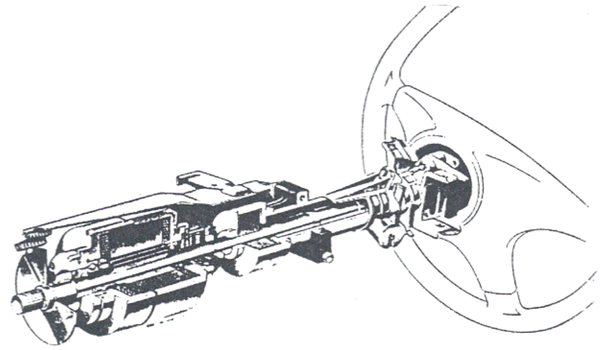

Fig. 2: Torque motor of the simulator vehicles.

Steering Wheel Dynamics

In addition to the description of the vehicle driving dynamics that is used to determine the dynamic state of the simulated vehicle, the calculation of the steering wheel equations are based on the well known linear single track model according to Fig. 3 (Mitschke, 1992; Roppenecker, 1994).

The differential equations for side slip velocity $\dot{\beta}$ and yaw rate acceleration $\ddot{\psi}$ are given by

$$\begin{aligned} \dot{\beta} &= a_{11}\beta + a_{12}\dot{\psi} + b_1\delta_L/i \\ \ddot{\psi} &= a_{21}\beta + a_{22}\dot{\psi} + b_2\delta_L/i. \end{aligned} \quad (1)$$

The coefficients a_{kj} and b_k $(k, j = 1,2)$ depend on the vehicle mass, vehicle inertia θ, position l_v, l_h of the center of gravity and the cornering stiffness parameters c_v, c_h of the front and rear tires. β represents the sideslip angle and δ_L the steering angle, $\dot{\psi}$ is the the yaw rate.

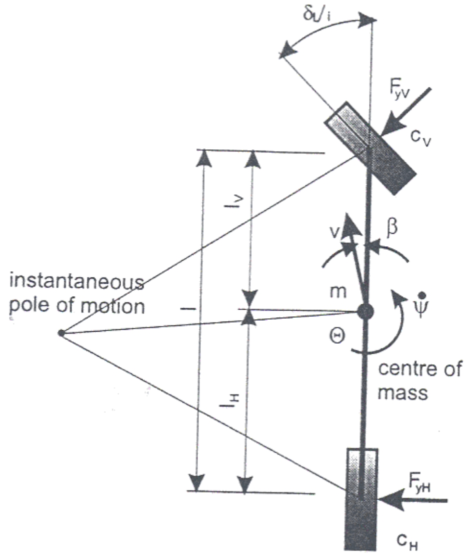

Fig. 3: Single track model.

The steady state solution of Eq.1 is given by:

$$\delta_L = const. \quad \ddot{\beta} = 0 \quad \dot{\beta} = 0 \quad \ddot{\psi} = 0, \quad (2)$$

where the yaw rate is written as

$$\dot{\psi} = \frac{K_1}{K_2\, v^2 + K_3}\; v\, \frac{\delta_L}{i}\,. \quad (3)$$

Here v denotes the vehicle velocity and i the steering ratio. The coefficients K_1, K_2 and K_3 are given by

$$\begin{aligned} K_1 &= c_v\, c_h\, (l_v + l_h) \\ K_2 &= m\, (c_h\, l_h - c_v\, l_v) \\ K_3 &= c_v\, c_h (2\, l_v\, l_h + (l_v^2 + l_h^2)). \end{aligned} \quad (4)$$

With the steady state solution of the yaw rate (Eq. 3) the lateral acceleration can be approximated by:

$$a_y \approx \dot{\psi}\, v. \quad (5)$$

This approximation will be used to determine the steering aligning torque in the steering system model. The yaw rate $\dot{\psi}$ is given by (Eq. 3) and the velocity v is available directly from the vehicle dynamic's model of the driving simulator. This approximation describes the coupling between the steering model and the driving simulator dynamics.

Steering System Model

The steering aligning torque may be described by three torque functions given by M_{a_y} associated with the lateral acceleration a_y, the vertical distortion torque M_B and the damping torque M_D. The first part that is caused by the lateral acceleration a_y reads:

$$M_{a_y} = k_1 \arctan(k_2\, a_y) \qquad (6)$$

The lateral acceleration a_y is described by Eq. 5. The steering shape fitting parameters for the steering torque are given by k_1 and k_2. For practical purposes the arctan function has been used because it describes the behavior between the road, tire, wheel and steering system very well and it reflects the behaviour of the steering aligning torque (Paceijka, 1995).

The second part of the steering aligning torque (the vertical distortion torque due to the pneumatic trail) is modelled by the line shape function

$$M_B = k_B \left(\frac{-\tau}{\pi(\dot{\delta}_L^{\,2} + \tau^2)} - y_B \right) \exp\left(-|v| k_v\right) \qquad (7)$$

This function describes the steering torque which results from the velocities including the case $v = 0$. k_B and k_v are fitting parameters, τ is the vertical distortion damping and $\dot{\delta}_L$ is the steering angular velocity. By the line shape analysis for the vertical distortion the shift factor y_B has been introduced. The distortion torque decreases exponentially with increasing velocities in order to describe a realistic steering torque at low velocities. The damping M_D, which is the third component of the steering aligning torque, is modelled for the closed-loop simulation of the steering system. From the damping shape analysis the following equation is used:

$$M_D = \frac{d_{ger}}{1 + d_{abst}\delta_L} \exp\left(|\dot{\delta}_L| k_{pot}\right) \qquad (8)$$

Here d_{ger} is the damping parameter for driving in a straight line, d_{abst} is a weighting factor, δ_L is the steering angle and k_{pot} is a weighting factor for the velocity. The weighting function $\exp(|\dot{\delta}_L| k_{pot})$ scales approximately the damping model to the steering hardware of the simulator vehicle. Finally, the total steering aligning torque M_L can be combined in the following way:

$$M_L = M_{a_y} + M_B + M_D \qquad (9)$$

Fig. 4 shows the calculated steering aligning torque as a function of vehicle velocity and steering angle at constant steering rate $\dot{\delta}_L = 4\ deg/s$. For the closed-loop simulation of the steering system the steering aligning torque M_L is online applied to in the driving simulator's dynamics (rate 100Hz).

It can be seen, that at velocity $v = 0$ the vertical distortion torque is described properly. At increasing velocities the vertical distortion torque decreases immediately and the steering torque depends strongly on the lateral acceleration.

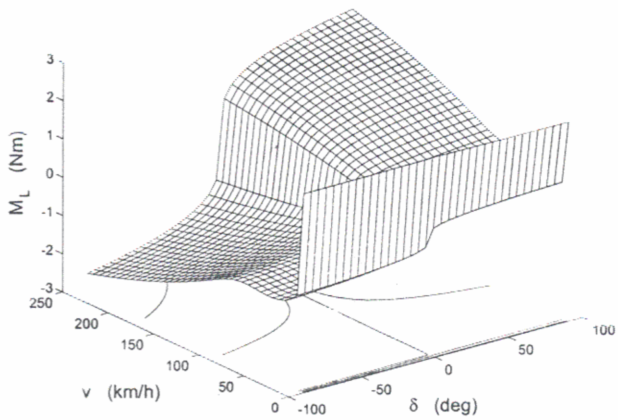

Fig. 4: Simulated steering aligning torque.

It could be observed that almost all the people were able to drive the simulator for the first time in a stable manner without loosing control. They drove comfortably under proper straight line stability. The model is choosen in order to reflect real steering properties and to map the different vehicle models on the steering hardware.

Experiments, Results and Discussion

To achieve a good realistic feeling of driving in the simulator, verifications on the BMW test track have been conducted. The vehicle dynamics signals and steering wheel forces resulting from different test maneouvres on the real test track and from the approximately identical test track modelled in the animated environment in the driving simulator have been compared.

About a dozen test persons have been involved in comparing maneouvres using the whole steering system within the complete velocity range.

Test environment

In order to exclude the influence of other traffic, measurements were carried out on the BMW test track near Munich, Bavaria. Fig. 5 shows an example of recorded data. The measurements are valid for driving through a curve with a radius of 110 m.

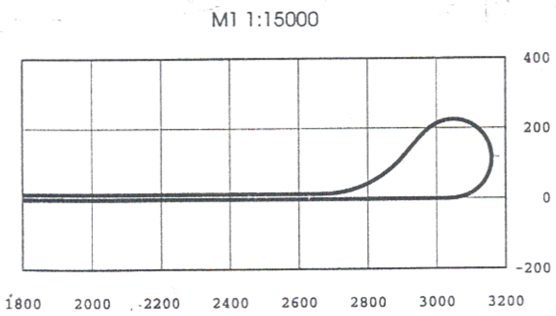

Fig. 5: Test curve on the BMW test track.

Testing data acquisition. In order to get a realistic driving feeling and a straight line stability in the simulator experimental and simulation data have been compared. For the whole steering and the complete velocity range, the measurements on the test track have been recorded with a 7-series vehicle. The following signals have been recorded:

Symbol	Dimens.	Property
a_y	m/s^2	lateral acceleration
M_L	Nm	steering wheel torque
v	m/s	vehicle speed
$\dot{\beta}$	rad	side slip angle
δ_L	rad	steering wheel angle
$\dot{\psi}$	rad/s	yaw rate

A representative drive in a 180^0 curve with radius $110m$ (see Fig. 5) with a speed ranging from 85 to 125km/h has been selected and the signals of interest are shown in Fig. 6.

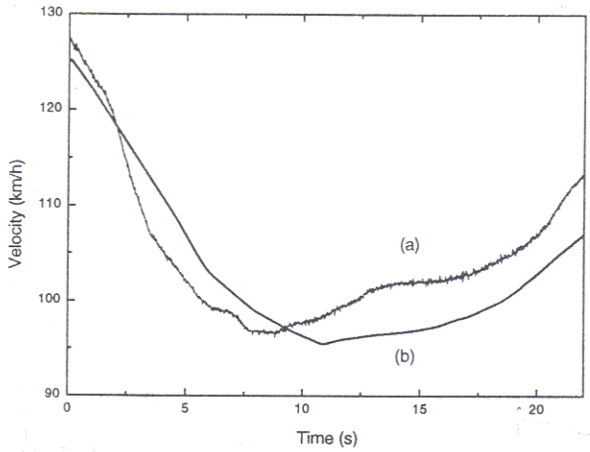

Fig. 6: Velocity measurement test track (a) and simulator (b).

Further curves of all vehicle dynamic related signals and steering wheel forces have got a very similiar shape. For example, in Fig. 7 the measured and the simulated steering wheel angle based on the advanced steering model are compared. The result illustrates the quality of modelling of the test track in the simulated environment. Especially the vehicle dynamics and the steering wheel angle generated in the simulator are in good agreement with the data from the real driving experiment.

Subjective results with test persons. Beside the comparision of the objective data several test rides in the simulator with experienced and unexperienced drivers have been carried out. With the new hardware for the steering wheel torque with a realistic tactile feedback the number of people getting into an unstable driving state has decreased dramatically.

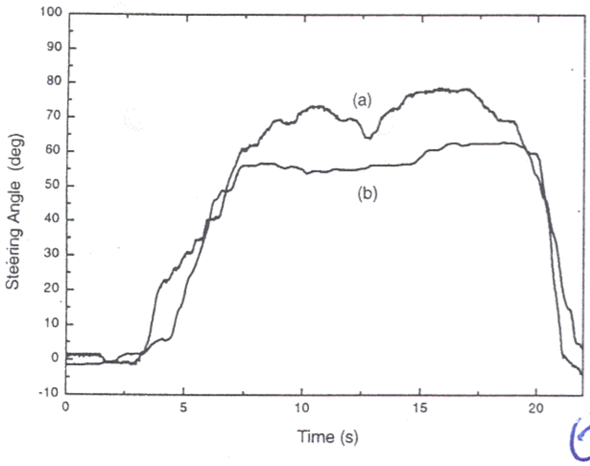

Fig. 7: Steering angle measurement test track (a) and simulator (b).

Torque properties and workload. Tests indicate also that the behaviour of the driver as the driver can significantly be influenced by different steering aligning torques. Fig. 8 shows a group of curves for the measured (a), optimized (b), low (c) and high (d) steering aligning torque. With a low (c) and high (d) steering aligning torque drivers lost control of the vehicle's straight line driving due to the nonrealistic steering response. Additionally, while doing additional complicated tasks, drivers in the driving simulator often loose control of the vehicle and as a consequence they could not fulfill the experimental tasks.

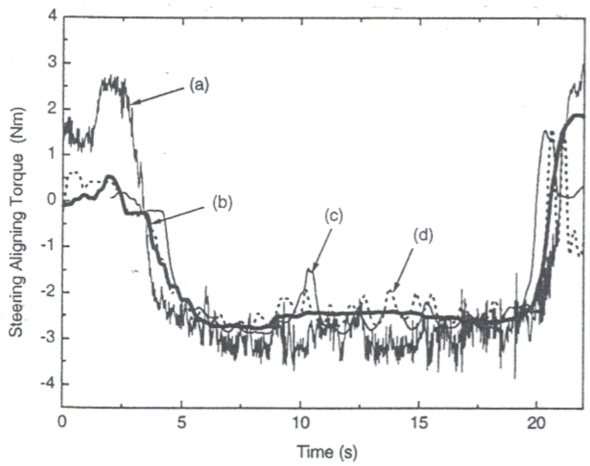

Fig. 8: Steering aligning torque measurement test track (a) and driving simulator optimized (b), low (c), high (d).

The measured (a) and optimized (b) curves coincide very well. The drivers can follow very easily the prescribed driving simulator course and the vehicle has a good straight ahead driving stability. The steering system supports the driver in keeping the vehicle lateral position in the lane while he keeps full control about the vehicle. Furthermore, the curves show once more very clearly the importance of proper steering wheel forces as a feedback source for safe driving. To fulfill the task of stable driving in the simulator the workload of the driver is reduced (see curve (b)) compared to the curves (c) and (d). As a consequence a wide range of demanding experiments for ergonomical studies are possible and recommendable.

Conclusion

A quantitative analysis of an advanced steering wheel system for the BMW driving simulator could be demonstrated. The discussed simple steering model describes the experimental findings of the steering aligning torque. It is sufficient for the entire practical velocity and steering range, and is, in this respect, an extension of results presented in (Bernasch, 1995).

The steering system for the BMW driving simulator as discussed in this paper represents the major step towards a comprehensive concept for an online steering systems including the whole multibody structure and the servo mechanism. The increase of functionality of the BMW driving simulator and the integration of the online steering system combined with the planned motion platform into an overall driving simulator concept are important topics for future extentions.

References

Braess, H. -H. (1970). Theoretische Untersuchung des Lenkverhaltens von Kraftfahrzeugen. XIII FISITA Congress, International Automobile Safety Conference, Bruxelles, Paper 17.1.B, p.1-28.

Bernasch, J., Haenel, S. (1995). The BMW driving simulator used for the develop ment of a driverbiased adaptive cruise control, Proc. of the Driving Simulator Conference, DSC'95, Sophia Antipolis, France, 12-13 Sept, p.157-174.

Gipser, M. (1995). High Performance Simula tion of Tire, Suspension and Steering for System Dynamics, VDI-Berichte, Baden-Baden, p.293-309.

Haller, R. (1995). EMMIS-Review, Evaluation of Results, Drive II Project V2006, Commision of the European Communities.

Koziara, B., Fauser, J. (1994). Optimization of the dynamic response of steering systems by coupling numerical simulations with tests and test benches, VDI-Bericht Nr. 1153, VDI-Verlag Düsseldorf.

Mitschke, M. (1992). Dynamik der Kraftfahr zeuge, Band C: Fahrverhalten, Springer-Verlag, Berlin, Heidelberg

Naab, K., Reichart, G. (1994). Driver assistance systems for lateral and longitudinal vehicle guidance, Proc. Int. Symp. on Advanced Vehicle Control. Tsukuba, Japan, p.449-45

Paceijka, H.B. (1995). Tyre Dynamic Properties, Smart Vehicles, (Pauwelussen & Paceijka, eds), Swets & Zeitlinger Publishers, Lisse, Netherlands, p.55-68

Roos, G. (1995). Numerical Design of Vehicles with Optimal Straight Line Stability on Undulating Road Surfaces, Thesis, Technische Universiteit Eindhoven, Netherlands

Roenitz, R., Braess, H. -H., Zomotor, A. (1977). Verfahren und Kriterien zur Bewertung des Fahrverhaltens von Personenkraftwagen, Automobil-Industrie (1/77 Teil 1; 3/77 Teil 2), p.29-39;39-46

Roppenecker, G. (1994). Fahrzeugdynamik: Grundlagen der Modellierung und Regelung, at-Automatisierungstechnik 42, p.429-441.

Schumann, J., Löwenau, J. P., Naab, K. (1995). Vision in Vehicles (5), (A.E. Gale ed), The active steering wheel as continuous support for the driver's lateral control task, Amsterdam, North Holland.