Optimized Haptical, Acoustical and Visual Tuning with Different Vehicle Dynamic Models for the BMW Driving Simulator

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Abstract Haptical, acoustical and visual feedback play an important role in creating the proper feel of operating a vehicle in a driving simulator. Flaws in the feedback may cause strain on the driver that can have adverse effects on the outcomes of the experiment. It is, therefore, essential to have accurate models of the vehicle comprising multi-body, driveline, steering system and tire dynamics.

1. INTRODUCTION

The prime objective of the BMW fixed base driving simulator [2] is to analyze and optimize the interaction between man and technology, i.e. the driver, the car and the driving environment. In a simulator environment new systems and components can be tested long before road tests are possible without posing any safety risks to the car's occupants or other road users. Recent simulator experiments comprise: navigation planning with different complexity of dialogs, development of adaptive cruise control, brake light intensity indication by means of different shape and intensity of lights, and adaptive headlight control. For Man-Machine Interface (MMI) [1, 2] studies it is of vital importance to give the driver optimal haptical, acoustical and visual feedback while accomplishing his/her task. The haptical feedback consists of the steering wheel aligning torque, pedal forces and resistance in operating controls. The visual feedback is obtained by image processing and is the source that provides a realistic display of the driving environment. Finally, the acoustic feedback, like driveline and wind noise, completes the pseudo-real driving ambiance. All three feedback sources have to be simulated in a driving simulator environment, and they obtain their main input sources from the vehicle dynamics model of the car (figure 1). If one of the three feedback sources is flawed or is missing, the results of the experiment become less meaningful.

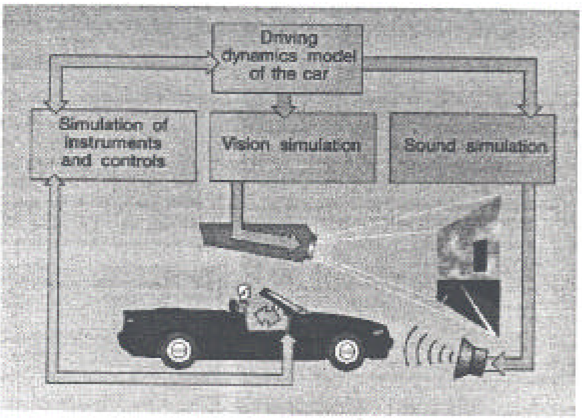

Figure 1. Structure of the BMW driving simulator.

In this paper the operation of each of the three feedback sources will be discussed in relation to the complexity of the vehicle dynamics model. The feedback consists of a hardware component (actuators such as steering wheel torque motor [7], loudspeakers, video projection) and software means to control the actuators. Both hard- and software issues will be explained in detail in sections 2 and 3.

2. THE DRIVING SIMULATOR HARDWARE

The heart of the driving simulator is comprised of several high-performance supercomputers operating in conjunction with software originating from aerospace simulators.

2.1 Computing power

A Silicon Graphics Onyx with a 2-pipe Infinite Reality Graphics Engine is used to generate a 4-channel imaging system with a 190 degree front view and a 60 degree mirrored back projection. The channels are visually combined using soft-edge blending to avoid sharp edges and are projected onto cylindrical, seamless screens. The Onyx is equipped with 8 R10000 RISC CPUs (200 MHz): 1 for calculating the vehicle dynamics, 1 CPU for processing surrounding traffic, 5 for displaying the graphics and 1 for the remaining functions such as sound, interface with the car, etc. The total memory available is 512 Mbytes. The graphical resolution is 1280x1024 pixels.

2.2 Sensors and actuators

In addition to a full-scale car, different mock-ups of vehicles, often equipped with a prototype interior lay-out containing new MMI features, can be driven in the simulator. Up to now no motion platform has been used. This implies that an acceleration feedback to the driver is missing while cornering and/or braking. Although the lack of feedback can be regarded as an extra handicap for the driver to stabilize the vehicle, valid results can be obtained with a fixed base solution in experiments that imply low dynamics of the vehicle. The vehicle driven in the simulator is equipped with several sensors that provide information for the simulation models and actuators that supply feedback to the driver. The sensors detect the steering wheel angular motion, accelerator and brake pedal position as well as hand brake, gear stick, light switch, turn signal and cruise control stalk positions. The haptic feedback is applied by means of actuators through the steering wheel (torque motor) [1] and accelerator and brake pedal.

3. THE DRIVING SIMULATOR SOFTWARE

3.1 Vehicle dynamics model

The vehicle dynamics model serves as an interface between the sensors and actuators in the simulator vehicle. The driver's actions (steering, braking/accelerating) will result in a motion of the vehicle (through the simulated vehicle dynamics) that determines the haptical feedback in the steering wheel and pedals, the acoustical feedback by means of driveline, wind and environment noises, and the visual feedback through displaying the driving environment. Flaws in the vehicle dynamics models will directly affect the quality of all three forms of feedback. A mismatch between input and output signals (such as a time delay between steering wheel rotation and torque), for example, will put extra strain on the driver. It is therefore essential to model all dynamics of importance to a level where the (subjective) feel is optimal.

vehicle model	**vehicle body**						**axles**	**wheels**
	longitudinal	lateral	vertical	roll	pitch	yaw	vertical (4x)	roll (4x)
7 DOF	●	●				●		●
8 DOF	●	●		●		●		●
9 DOF	●	●		●	●	●		●
14 DOF	●	●	●	●	●	●	●	●

Table 1. Overview of available vehicle models with different degrees of freedom (DOFs).

The vehicle dynamics model can be thought of as the following four subsystems:

- Multi-body (mass & inertia of vehicle main body, engine, axles, ...)
- Driveline (engine, torque converter, gearbox, differential, ...)
- Tires (force generators as a function of tire slip/load)
- Steering system (driver's input and torque feedback)

Currently, 4 vehicle dynamics models are available. Table 1 shows the degrees of freedom (DOF) described by each model.

At this point only the multi-body related degrees of freedom are considered. The driveline, steering system and dynamic tire models may add more degrees of freedom depending on their complexity of modeling. The 3 most simple vehicle models (7, 8 and 9 DOF) [10] do not contain suspension systems, meaning that kinematics as well dynamics involving axle motions are neglected. Consequently, these models can only be applied on flat roads. In situations with road undulations (elevation and superelevation) the orientation of the vehicle body (vertical, roll, pitch) will be adjusted according to the local roadway geometry (2½ dimensional). Additional roll and pitch of the vehicle body will occur due to cornering and/or braking forces. The equations of motion of the 3 simple vehicle dynamics models are generated by hand and the source code is available in C-language.

The more complex 14 DOF model contains suspension dynamics and kinematics. Special BMW software (figure 2) has been used to generate the equations of motion automatically.

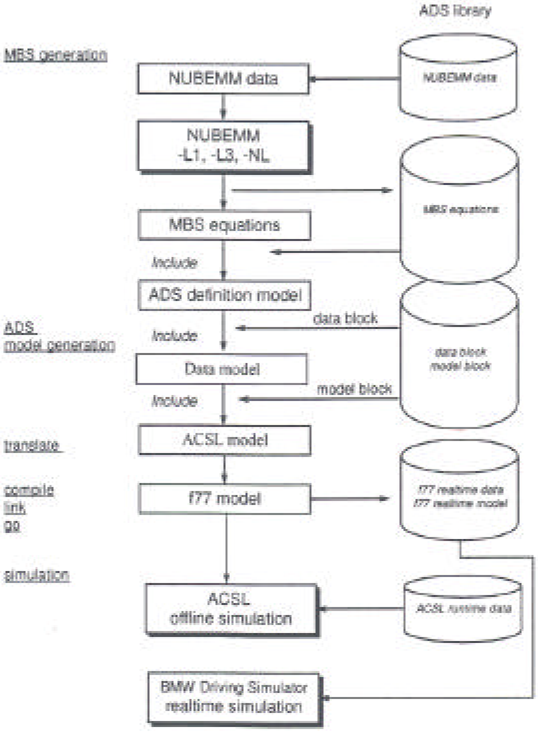

Figure 2. Structure of the 14 DOF vehicle model source code generation.

The ADS (Automobile-Dynamic-Simulation) [5,6] software is a modular library to calculate the vehicle dynamics and vehicle vibrations written in ACSL (Advanced Continuous Simulation Language) [4]. The ADS library is subdivided into different blocks: multi-body system (MBS) observer, environment, control, aerodynamics, tire, driveline, and vehicle mechanical MBS. A MBS program called NUBEMM (NUmerische BErechnung Mechanischer Mehrkörpersyteme) [8,9] is used to generate the equations of motion of the mechanical vehicle system. Figure 2 shows the program and test environment that generates an ACSL model for the off-line vehicle simulation and a real-time model for the BMW driving simulator. The first step in the simulation process is to generate the MBS equations with a NUBEMM data set containing the vehicle geometry, mass, inertia, joints, spring/damper elements, forces, etc.. The NUBEMM-L1 software calculates the linearized equations of motion in a moving reference frame. The next step is the ACSL code generation with an ADS definition model. This creates an ACSL model for the off-line vehicle simulation as well as an f77 source code model for the real-time simulation in the BMW driving simulator.

Driveline Model

The driveline model describes how traction and braking torques on the wheels are generated as a function of accelerator and brake pedal position. It contains a 3-dimensional look-up table of the engine torque as a function of engine speed and throttle position, engine inertia, torque converter characteristics (for automatic transmission), gearbox and differential ratios and a gear selection program for the automatic transmission.

Tire Model

The tire plays a crucial role in vehicle dynamics since it is the only contact medium transferring forces between the vehicle and the road. Table 2 provides an overview of steady state tire models used in the vehicle dynamics models at BMW. The tire model generates two forces (longitudinal F_x and lateral F_y) and one aligning moment M_z, all as a function of tire vertical load F_z, side slip angle α and longitudinal slip κ. The simple models are based on stiffnesses where the forces and moments depend linearly on the longitudinal and lateral slip. A more complex model uses stiffnesses that depend on the vertical tire load F_z. The well known Magic Formula (MF) tire model is based on an empirical model with coefficients that have physical meaning. The combined slip version of the MF describes the generation of forces in situations where cornering as well as braking/accelerating occur. In addition to the steady state tire models, a transient tire model based on the relaxation length has been used to avoid integration stability problems at low speed.

tire model	forces & moments		
	F_x	F_y	M_z
stiffness	$C_{F\kappa} \cdot \kappa$	$C_{F\alpha} \cdot \alpha$	$C_{M\alpha} \cdot \alpha$
stiffness $f(F_z)$	$C_{F\kappa}(F_z) \cdot \kappa$	$C_{F\alpha}(F_z) \cdot \alpha$	$C_{M\alpha}(F_z) \cdot \alpha$
Magic Formulae	$f(\kappa, F_z)$	$f(\alpha, F_z)$	$f(\alpha, F_z)$
Magic Formulae (combined slip)	$f(\alpha, \kappa, F_z)$	$f(\alpha, \kappa, F_z)$	$f(\alpha, \kappa, F_z)$
TM-Easy	$f(\alpha, \kappa, F_z, t)$	$f(\alpha, \kappa, F_z, t)$	$f(\alpha, \kappa, F_z, t)$

Table 2. Overview of available tire models.

Steering System

The steering system is the interface between the driver and the multi-body vehicle model. It not only serves as an input source for the driver's action but also provides important (torque) feedback to the driver. The haptic torque at the wheel is mainly determined by the front tire forces and aligning moments. Therefore the amount and quality of the haptic feedback strongly depends on the accuracy of the tire model. Figure 3 shows a layout of a simple steering system that can be used to calculated the feedback torque in the steering system. The front tire aligning moments M_z and side forces F_y, in combination with the mechanical trail t_m of the suspension (due to caster) and the steering system gear ratio i_{st}, determine the steering wheel torque M_{st} according to

$$M_{st} = \frac{M_{zL} + M_{zR} - \left(F_{yL} + F_{yR}\right)\cdot t_m}{i_{st}}$$

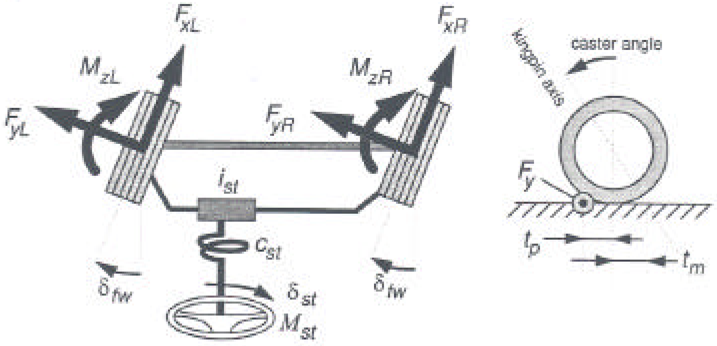

Figure 3. A simple steering system model for haptic feedback.

This simple model has been extended with a more detailed model of the power steering including friction and damping.

3.2 Vision model

The vision software contains a high quality database (based on MultiGen) containing 40 km of highway and country road including textures for trees, buildings, signs, and cars. The visibility range and light conditions can be varied throughout the course. The refresh rate with regard to displaying the images is of vital importance for a proper driving feel. If this rate is too low, the time lag will strain the driver because the feedback is not synchronized with the image. The delay may even lead to serious motion sickness of the driver resulting in an inability to drive the vehicle. The BMW driving simulator can be operated with a refresh rate of 60 Hz at a graphical resolution of 1280x1024 pixels.

3.3 Sound model

The sound module comprises starter noise, engine noises as a function of throttle and engine speed, tire squeal as a function of tire lateral and longitudinal slip, tire rolling noise, and wind noise. Furthermore, engine, tire, and wind noise of the surrounding vehicles can be heard when driving the simulator car. The sound model is based on the Paradigm AudioWorks II software/hardware solution.

4. FINDINGS

The haptic, acoustical and visual feedback for the driver have been perfected up to a level where non-experienced simulator drivers are able to drive a simulator car without great difficulty. Optimal feedback through all three sources ensures that the extra strain on the driver due to the simulated environment is minimized. Especially, the visual and haptic feedback should be generated in sync with the simulated vehicle motions. Flaws in the synchronization will strain the driver and can even lead to motion sickness. Only with high quality haptical, acoustical, and visual feedback will simulator experiments produce reliable outcomes that are valuable for developing, improving, and judging MMI concepts. The complexity of the vehicle dynamics model can be quite low depending on the application, and complicated suspension kinematics and dynamics can be omitted without adversely affecting the quality of the feedback to the driver. This only applies to MMI studies where the complexity of the vehicle model is of minor importance. For more serious vehicle dynamic studies, such as hardware-in-the-loop simulations, a more detailed vehicle model might be necessary. The tire model plays an important role in creating the right amount of haptic feedback. Simple linearized tire models do not suffice because they generate unrealistic vehicle motions and improper feedback from the steering wheel.

tire model	**steering feel**	
	9 DOF / SSM	**14 DOF / ASM**
stiffness	--	
stiffness $f(F_z)$	--	
Magic Formulae	+	
Magic Formulae (combined slip)	+	
Brush Tire		0
TM-Easy		++

Table 3. Subjective rating of steering feel with different tire models.

Table 3 shows a comparison of subjective judgment of the steering feel with different vehicle models in the BMW driving simulator. Two vehicle models (9 DOF and 14 DOF) are tested with different tire models in combination with either a Simple Steering Model (SSM) or a more Advanced Steering Model (ASM) as described in [1]. The advanced steering model takes the servo mechanism of the steering system into consideration. The subjective steering feel rating has been scaled from -- (poor) to ++ (very good). Besides steering feel at low speed (e.g. parking), the course of the haptic feedback in a steady-state turn as a function of vehicle speed, transitional behavior (lane change), and straight line stability have also determined the rating. Experimental tests have shown that the driver's behavior can be significantly influenced by different steering feedback torques. Simple tire models (such as those based on cornering stiffnesses) have no saturation of the tire side force and thus the steering wheel feedback torque keeps increasing linearly with the level of lateral acceleration. Furthermore, no influence of load transfer, and hence degradation of cornering ability, can be noticed. The more complex tire models exhibit a more realistic feel with torque saturation and appropriate feel at low vehicle speed (parking). The best haptic feedback has been obtained with the 9 DOF/Magic Formulae combination and the 14 DOF/TM Easy combination. With a proper feel, the driver can easily follow the driving simulator course and the vehicle exhibits a good straight line stability.

5. FUTURE DEVELOPMENTS

In the near future, BMW will increase the functionality of the driving simulator by installing a 6 DOF motion platform, a shaker system for the high frequency vibrations, and a 3-D real-time vehicle model for driving 3-D routes (like mountains). With these extensions, BMW will be able to develop, test, and optimize new components or systems for a car such as:

- Adaptive Light Control system (ALC) - the development and testing of the light distribution of head lamps. Movable head lamps are controlled as a function of path prediction based on the vehicle dynamics and route vectors coming from the GPS navigation system.
- Situation Adaptive Powertrain Management (SAM) with active accelerator and brake pedals in combination with an Adaptive Cruise Control system (ACC) - the aim of this project is to reduce fuel consumption by adapting the powertrain to the driving situation using information obtained from external and internal vehicle and traffic information sources.
- Analysis of the driver's behavior due to vehicle shuffle, vehicle vibration, and vehicle noise.
- Suspension simulation with an Automatic Stability Control system (ASC).

CONCLUSIONS

The haptical, acoustical, and visual feedback for the driver have been perfected up to a level where in experienced simulator drivers are able to drive a simulator car without great difficulty. Optimal feedback through all three sources ensures that the extra strain on the driver due to the simulated environment is minimized. Only with this high quality haptical, acoustical and visual feedback will simulator experiments produce reliable outcomes that are valuable for developing, improving, and judging MMI concepts.

The complexity of the vehicle dynamics model can be quite low depending on the application, and complicated suspension kinematics and dynamics can be omitted without adversely affecting the quality of the feedback to the driver. The tire model plays an important role in creating the right amount of haptic feedback, and thus, simple linearized tire models do not suffice because they generate unrealistic vehicle motions and improper feedback from the steering wheel.

With several vehicle models available, BMW has a powerful simulation tool to analyze, evaluate, and optimize man-machine interfaces by using simple vehicle dynamics models (without detailed suspension kinematics). Hardware in the loop tests for various components and advanced vehicle dynamics control can be carried out by using more sophisticated vehicle models [3]. The new, extended BMW driving simulator, therfore, has become a powerful tool allowing the development engineers to efficiently evaluate and optimize new and advanced future vehicle systems.

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