Development of Advanced Driving Simulator: Steering Wheel and Brake Pedal Feedback

Petr Bouchner, Stanislav Novotny

***Abstract*—** The paper presents a summary of the requirements on the system of active feedback on the steering wheel of the driving simulator in combination with feedback on the brake pedal. Those results were derived from the experience based on hundreds of experiments performed on faculty driving simulators. A functional design of an electronically controlled servo system which is used for experimental simulators is presented. The functions of the feedback described in the paper are derived from the measurements of "Car-Driver Interaction" in a real car on real roads. The procedure and some interesting results of data analysis from those experiments are presented in the paper, too. To be able to develop control algorithms for these feedback simulator subsystems, their functions had to be primarily simulated. The paper depicts, among others, the interconnection of the feedback system with the physical model of the car simulator.

***Keywords*—** Driving simulators, HMI research, motion cueing, driving simulation fidelity.

I. Introduction

Driving simulators at the Faculty of Transport Sciences have been widely used for research in the field of HMI for many years. During this period, measurements of several hundreds of experiments dealing mainly with different aspects of Driver-Car Interaction have been made (see for example [1,7]). These driving simulators are successfully used for problem solving not only for HMI, but also for problems of reliability in transportation ([8]) or ITS applications ([9,10,11]). Validity of results of performed experiments (or quality of the training) is tightly coupled with the fidelity of the simulation itself and also with the depth of immersion of the tested driver into the simulated scenes. Drivers in real cars on the road are exposed to full spectra of cues [3]. It is known that 80-90 percent of the perception of the driver is realized via the visual sense. On the other hand, the driver needs a certain kind of feedback so that he/she can correctly control the car, reacting adequately to the actual road conditions. The motion cueing supplying the driver with the information about car dynamics is usually provided by a combination of different kinds of movement of the motion platform supporting a car mockup but it can be also supplemented by feedback on the steering wheel. Since the laboratory works on both tasks - development of driving simulators and measurements of the experiments dealing with general aspects of driver behaviour – we can take advantage of experiences and already tested drivers' responses when developing car simulators.

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II. Perception cues

A development of simulation can be considered as a multidisciplinary task which encompasses a wide range of possible investigations. When analyzing needs and proposals for design of those modules, it is necessary to have knowledge of what kind of stimuli impacts on the driver and in which way it is done.

A. Visual cues

The driver from the observed virtual scenery gathers primary information about the shape and color of the surrounding objects (including the road), distance of the objects, self movement. From those primal cues he/she derives the secondary information about self (car) velocity in all directions, a limited range of self (car) accelerations in all directions, road condition, surrounding objects and traffic (obstacles) and their movement. In the next picture (Fig. 1) there is one of the simulators with fully surrounding projection.

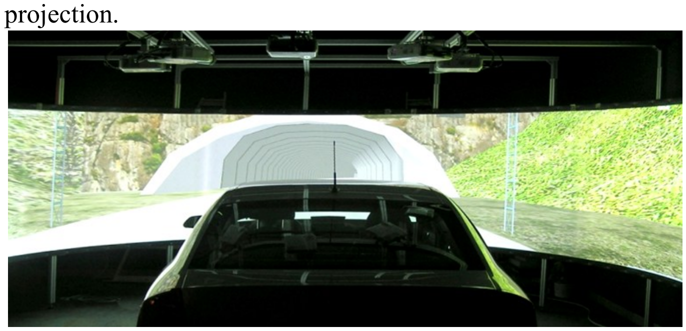

Fig. 1: Steady based full simulator with surrounding projection

B. Audio cues

Besides the visual information, the second most important one is the sound information. It accomplishes or substitutes the visual and other cues coming to the driver's senses. The driver can derive the information about a car velocity, engine velocity and its load, interaction with different types of road surfaces from a virtual sound, sound properties of surrounding environment (open road, tunnel, corridor, bridge, forest…), collisions etc.

C. Motion cues

Perceptions of motion (i.e. moving in all 3 main axes, yawing and rolling, vibration coming from various sources

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and directions) and perceptions of an arbitrary acceleration play a very important role in the process of car control. The driver gathers the information from these perceptions and reacts immediately. On the other hand, he/she gets the information about the car reactions as a feedback.

III. Steady Based Simulators

Majority of the experiments do not necessarily need full motion feedback. Since the motion base for the car simulators represents usually the most expensive part of the whole system, the steady based simulators are frequently used [4]. For those kinds of simulators, the steering wheel with correct realistic feedback can improve fidelity of the simulator significantly.

IV. Steering Wheel

The steering is the most direct way how the human driver interacts with a car. A driver is very sensitive to speed and correctness of the response of the steering. Realistic behaviour of steering wheel can increase significantly immersion in the driving. On the other hand, inadequate response of the steering wheel can disappoint the driver and downgrade the overall quality of the simulation.

Both of the frequently used simulators - the steady based or motion based - can be equipped with additional feedback devices. These can provide more realistic feelings during driving. The aim of their use is to stimulate mechanical feedback coming either from the car itself or from the environment (e.g. road, blasts of wind). From that reason, majority of steady based simulators are equipped with at least certain type of steering wheel feedback. There are several issues connected with the quality (or possible absence) of the steering wheel. The driver gathers a lot of information from responses of the steering wheel that helps him/her to control the car correctly. The most important ones are the actual deflection of steering wheel (derived from the resistance) and car velocity. The feedback should also respect typical phenomena of surface interaction like drain covers, ruts etc.

One of the typical situations which appear during the simulated driving is shown in the picture Fig.2. The drivers in the simulators can sharply turn at very high speeds the steering wheel without any fear (in reality this should lead to an accident) but front wheels skid and do not lead the car in required direction. The wheel skid is accompanied by skidding sound. Drivers assess the car behaviour as unrealistic. This problematic effect can be suppressed by the use of progressive limits of steering wheel angle movements proportional to car velocity.

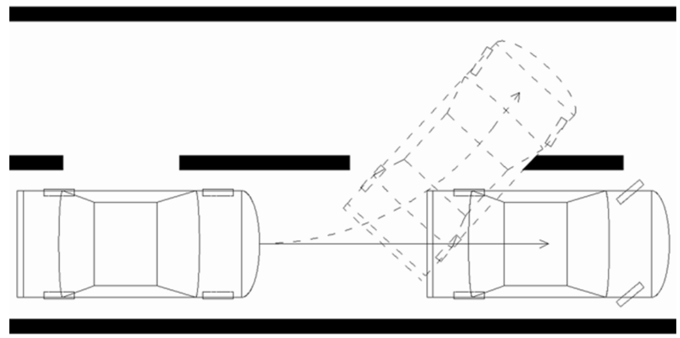

Fig. 2: Sharp turn of the steering wheel

V. Realization of the Steering Wheel Feedback

The feed back on the steering wheel can be performed in two ways with different degree of quality and adequate price [5]; a mechanical one and an electric one, usually based on the DC motor (either with or without a gearbox).

1. Mechanical feedback. The feedback is provided by certain kind of mechanical spring. Actually, the aim of this system is made to keep the wheel in the centre so that the forces maintaining the car in a straight direction are emulated. This approach is cheap to be implemented to any kind of the car simulator system but its behaviour is static and cannot take into account an actual physical behaviour of the car and/or any interaction with road surface.

2. Electric servo engine. Its behavior is in principle very similar to a mechanical spring but its main advantage is that it could be controlled and the force of the spring can be generated arbitrarily. From this point it is possible to create any kind of curve of the forces acting on the driver's hands. This overcomes the main drawback of the mechanical feedback – where the weakest force is generated at the zero position of the steering angle. In general the powered steering behaves in a more complex way, but it is possible to describe its function much more precisely since it is electronically driven. A torque generated by the electronically driven servo motor can be expressed basically by a following symbolic equation which does not necessarily need to take into account dynamics of the car physics. This algorithm is easy to implement and it works well (appears natural) within higher speed bands:

SW_Torque = TorqueSetValue + Friction + Damping + SpringStiffness

Some experiments require additional feedback on steering wheel originated from the road surface or different types or accidents (i.e. tire blow up). Those fast movements and vibrations should also be included into final behavior.

VI. Active Brake Pedal

Even the brake pedal feedback can be seen as passive (mostly mechanical) or active. There is no problem with weak feedback at zero zones like in the case steering wheel since there is only one direction of pedal depression and the brake pedal is naturally weakest at its zero position. From this reason, a simple mechanical spring or a spring and dumper set is used (we took advantage from the dumping effect of brake drum without any liquid). The active feedback on the brake can successively suppress negative influence of deceleration cues absence (in case of steady based simulators) or very limited range of deceleration produced by the moving platforms. Drivers of car simulators are often disappointed by inadequate car reaction in braking situation. In fact, the physical model can correctly compute all this processes but drivers cannot control the braking in the same way as they would in the real car. The reason is that they cannot obtain precise feedback from the car behaviour they are very sensitive to. The picture Fig.3 shows one of the possible improvements of car deceleration perception using the active brake feedback. The driver having no realistic feedback of a real progress of deceleration brakes too hard, so that he/she blocks the wheels and gets them slick. A slick sound is used in that moment, but this is not natural for common driving and drivers usually do not evaluate it correctly. Progressive resistance of the pedal and ABS pulses improve the situation significantly.

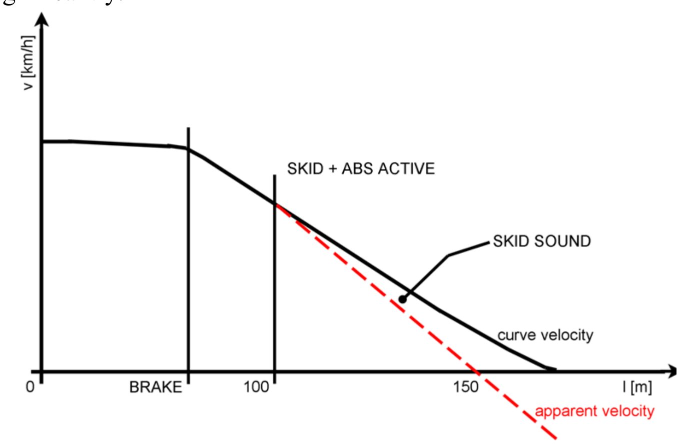

Fig. 3: Apparent and real deceleration of the car

VII. Real car experiments

To have enough knowledge about real behaviour of these active parts is essential for good simulation. Unfortunately these data are hardly available for public. The acquisition of the performance data from car driving used to be a very complex and expensive task. Fortunately, modern cars that are equipped with advanced electronic driving assistance devices utilize many different electronic sensors of physical quantities. Data from those sensors are digitized and transferred to the computational and controlling units via digital buses. It is possible to take advantage from this communication and scan and store the data without any serious intervention into the car itself and without any need of any external measuring devices [2].

VIII. Collected data

The measuring car was instrumented with measuring devices to obtain the quantities; Trajectory (path of the vehicle is obtained from GPS signal in 2D coordinates), car performance data (car velocity, vertical and longitudinal accelerations, engine revolutions, position of throttle pedal, depression of brake pedal, position of steering wheel and its velocity, the torque, by which the driver forces on the steering wheel and force developed by power steering) and camera recording. All the car performance data were collected via car CAN-bus protocol and CAN diagnostics protocol.

IX. Data analysis

The collected data were analyzed with main focus on steering wheel behaviour. In the pictures Fig. 4 and Fig. 5, it is possible to see the dependencies of the torque (by which the driver is forcing onto the steering wheel) on the instantaneous car velocity and actual deflection angle. First graph shows a complex 3d view and other pictures depict cuts in important speed bands. The blue points represent the torque produced when moving the steering wheel in the sense of deflection and green ones in the sense of restoration to zero position. In the field of very low speeds, we can see almost clear hysteretic loop with boundaries of +- 4 N/m and full deflection angle. Higher speeds exhibit narrowing of the hysteretic up to almost non hysteretic S shape curve. [7]

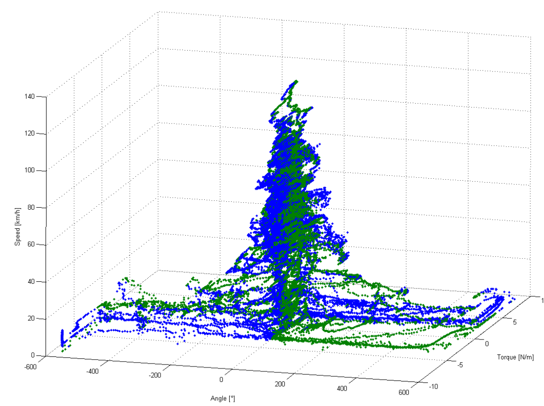

Fig. 4: 3d plot of velocity, steer angle, steer wheel force

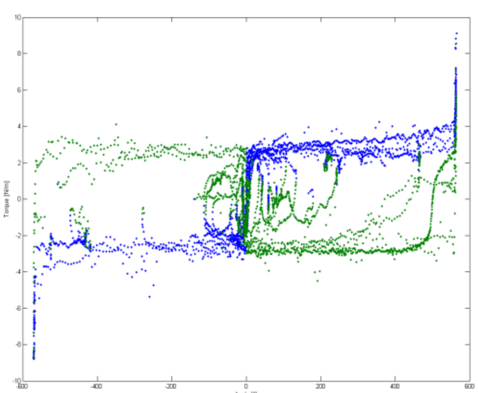

Fig. 5: 3d plot of velocity, steer angle, steer wheel force, cut at 0-5km/h

Also the range of steering wheel deflections is lowered non proportionally with the speed, over speeds 10km/h only values up to +- 50 o appear and in the highest speed range – over 80km/h -majority of the deflections are up to +- 25 o (Fig.7).

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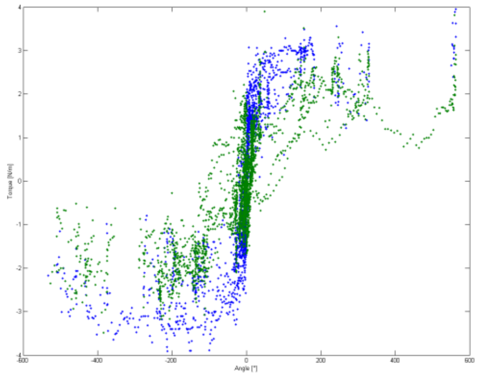

Fig. 6: Cut at 10-30 km/h

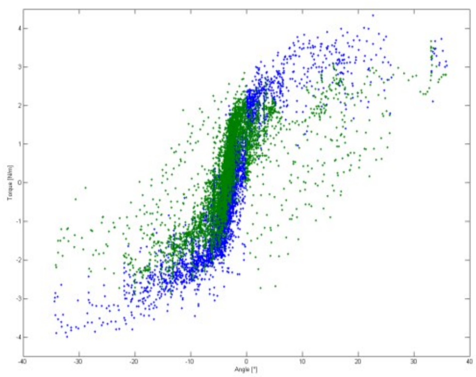

Fig. 7: cut at 80-140 km/h

X. Functional Design of the Active Steering Wheel and its Incorporation into the Simulation System

With the experience from plenty of experiments and real road experiments, it was possible to design functions of the active feedback of the devices. Generally, the most correct way would be to use the data coming from different parts of simulated physics or to use hardware in the loop approach. It is not very convenient for the driving simulators and as it was proposed in the beginning of the text, a straightforward copying of the real behaviour does not usually lead to convincing behaviour. The steering response curves are defined over three speed bands; speeds of 0-5 km/h full hysteretic loop, speeds < 80 km/h narrow hysteretic loop and for speeds > 80 km/h "S-curve" (see Fig.9). In the high speed band, in fact, the force is acting only against the movements of driver's hands towards central position. The block functional diagram is shown in the picture Fig.8. Note, that only the first quadrant is shown (steering to the right).

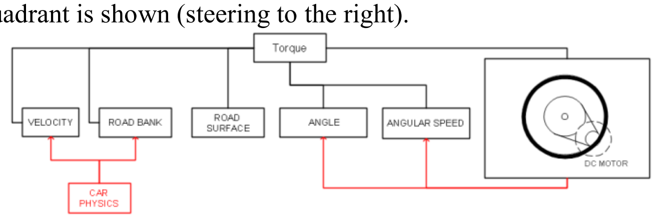

Fig. 8: Incorporation of active steering wheel into driving simulator

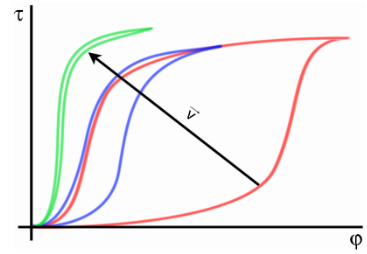

Fig. 9: torque feedback curve for different speed

XI. Functional Design of the Active Brake Pedal and its Incorporation into the Simulation System

The brake pedal is realized in a very similar way, composed of the DC engine and a transmitting belt strengthened by common spring which helps to generate enough torque in the limit positions of the pedal (since the human leg can produce very big forces in marginal situations). The block functional diagram is shown in the picture Fig.10.

The graphs in the picture Fig.11 show two feedback curves where the brake pedal acts against the driver's foot. Simple curve represents the case when the pedal is depressed while car is not moving ("hard pedal"). The second curve exhibits slight hysteretic properties and it is "softer" so that the driver can sensitively control braking manoeuver. The ABS feedback simulation is realized as simple addition (subtraction) of sine waveform of low amplitude to the actual force (not included in the graph). In future, also the contra feedback derived from the instantaneous deceleration will be incorporated so that it can enhance motion cueing of steady based simulators.

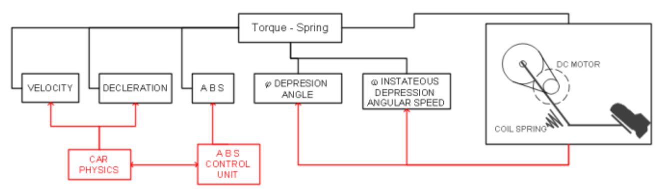

Fig. 10: Incorporation of active brake pedal into driving simulator

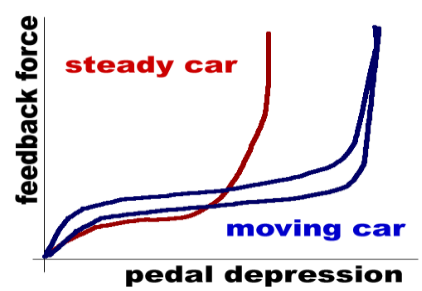

Fig. 11: Feedback force

XII. Summary

The topic of active feedback of steering wheel on driving simulators seems to be one of the most important within the scope of motion cueing. Motion based and mainly steady based driving simulators should be equipped with physically based steering wheel feedback (and brake pedal feedback as well) since those contribute to the overall fidelity of the simulation significantly. When dealing with steady based simulators, such a kind of feedback replaces missing motion cueing and it makes certain type of experiments feasible even on steady based simulators. The system of steering wheel and brake pedal feedback was designed in the laboratory of CTU which is connected just to the outputs of the physical engine of car simulator. Such enhancement of simulation system should significantly increase validity of experiments in which the driver misses for certain moment his visual contact with surroundings.

Unfortunately, the simulated driving has different properties form the real one and this depends mainly on the level of accommodation on the virtual environment of each particular driver. From the experiences, it is known that simple copying of the car behaviour into the simulator often does not bring good results. Some parameters should be emphasized and some (like vibration and vertical movements) supressed so that the drivers can feel them as real. To tune up the system, it will be necessary to measure a set of validation experiments with different kinds of experimental drivers. These experiments should not be focused only on the comparison of technical data coming from the real car and the simulator but mainly on a comparison of drivers' behaviour patterns in standardized situation and their subjective assessments. Also the brake pedal response needs real force measurements performed on different cars on different surfaces.

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