Motion Parameter Tuning and Evaluation for the DLR Automotive Simulator

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Abstract

The DLR dynamic driving simulator is a 6 DoF motion base with a range of 3 m in the horizontal plane and 2 m in the vertical direction. A real car is placed within the mounted cabin with a 270° field-of-view visualisation.

This paper describes the first evaluation tasks associated with the commissioning of a new motion-based driving simulator and presents a comprehensive strategy to prove its validity. After a short description of the laboratory environment, the classification according to a given validity definition and the prioritisation of the subsequent tasks are explained. Within a first phase, the parameters of the motion filter algorithm are optimised following an adapted tuning paradigm. Different manoeuvre specific tuned parameter sets are compared and evaluated during the main experiment consisting of two parts: a real world drive and a simulator test. Besides the objective criteria, i.e. comparison of steering behaviour or speed choice in the real and the virtual world, the subjective assessment of the motion cueing is introduced as an important contribution to the evaluation goals.

Introduction

New advanced driver assistance systems (ADAS) are being developed to increase comfort and safety of future cars. In order to ensure the acceptance of new systems by the drivers and to check the developed assistance functions and their effects on driving behaviour before bringing them into the mass market, experimental tests are necessary. As ethical considerations prohibit testing of ADAS in stressful or dangerous traffic situations simulator experiments are necessary. The major problem when using simulated scenarios for tests of this type is transferring the simulator results to reality. Hence, it has to be proven that drivers exhibit a similar behaviour within the simulation and in real traffic. Boer et al. [1] and Reymond et al. [2] showed the high importance of kinaesthetic cues* for this task and the problems that occur when using visual cues only. Thus motion-based simulators are necessary to get valid results from simulator experiments. However, it is well known that a motion-based simulator with a poorly tuned motion system can be worse than not having any motion cues at all. Simulator sickness and unrealistic driving behaviour are two unwanted effects of false motion cues. Only a thorough tuning of the motion system and evaluation of the simulator performance can guarantee the needed simulation quality.

**also called motion cues: To render the physical motion so that the driver perceives the motion in a virtual environment similar as in reality (see also* [3]*)*

Laboratory Environment

To provide a huge range of testing tools for ADAS research purposes as described above, several simulators with different levels of complexity have been installed at the Institute of Transportation Systems. Additionally a measurement vehicle called ViewCar was built up in order to observe driving behaviour in real traffic. The newest and most elaborate simulator is a 6 Degree-of-Freedom (DoF) motion base similar to a common Stewart platform but with the difference that the cabin is mounted below the platform. This enables the simulator to use a larger workspace because of the longer hydraulic arms. A real car is placed within this cabin. From the driver seat position a 240°x40° field-of-view visualisation is realised. Additionally there are three TFT monitors: two small ones which work as side mirrors and a huge one mounted on the backseats showing the rear-view scenery. The simulators physical limits are listed below. More details are given by Suikat [4].

Table 1: *Simulator position, velocity and acceleration limits*

	Position	**Acceleration**		**Position**	**Acceleration**
Surge	±1,5 m	±10 m/s²	**Roll**	-20 ° / +21 °	±250 °/s²
Sway	±1,4 m	±10 m/s²	**Pitch**	±21 °	±250 °/s²
Heave	±1,4 m	±10 m/s²	**Yaw**	±21 °	±250 °/s²

The measuring vehicle ViewCar enables the support of the ADAS development process by forming a base for the comparison of virtual and real driving behaviour. It is equipped with several sensors in order to record the physical vehicle state (via vehicle CAN, positioning system, lane detection) the driver behaviour (via gaze detection system, physiological data record) and the environment (optical cameras, laser scanner, radar). With obtained test drive data it is possible to gain knowledge about driver behaviour in real traffic, the demands on drivers and their reactions to certain traffic situations.

Figure 1: *DLR Dynamic simulator and ViewCar: virtual environment vs. real traffic driving behaviour*

Evaluation Strategy

As described in the introduction, the validation of the results obtained in a virtual environment is crucial and the motion cueing quality plays a central role for the validity of the results. The motion cueing validity is classified by Reymond and Kemeny [5] as follows:

- physical validity: comparing the rendered motion cues to the simulated vehicle dynamics
- perceptual validity: comparing the driver's multi-sensory perception of self-motion to a real situation
- relative behaviour validity: comparing the effect of some environmental parameter (e.g. road, vehicle, traffic conditions) on driving behaviour
- absolute behaviour validity: comparing the global driver behaviour to a real situation

They concluded that the physical validity is generally limited to the mid-frequency range of vehicle motion due to simulator physical limits. On the one hand, to achieve a large perceptual validity which is more important for the task of testing driver reactions, it may even be necessary to systematically deviate from physical validity beyond these limitations. On the other hand, perception is usually examined by means of questionnaires and thus may be distorted by the subjects' reports. So, especially for ADAS development tasks the behavioural validity becomes important. The first step in order to achieve this is to compare the influence of certain environmental factors on different aspects of driving behaviour during specific driving tasks. The overall goal is to extend these examinations until all different factors which influence driving are covered and a good absolute behavioural validity is achieved. However, this is not necessary for all research questions. Moreover, it may be necessary to do different kinds of tuning for different situations or manoeuvres.

The evaluation of the DLR driving simulators begins along this line of reasons. Subjective reactions and behaviour are recorded in real driving and a comparable virtual driving situation to evaluate the relative behaviour validity. With a pilot study it already has been shown that the driving behaviour in a virtual environment and in reality show similar effects even with a very simplified set-up [6]. Thus, using a tuned motion-based simulator promises a further augmentation of the validity. The essential prerequisite for this is a good parameter tuning before the actual experiments. In order to achieve large relative behaviour validity, the tuning begins with basic manoeuvres to spread to more complex ones. The approach used is described in the next section.

Motion Tuning

Due to the physical limits of the simulator, the simulated vehicle motion (specific forces and angular rates) can not be performed directly. Thus a filter algorithm, called washout filter is integrated to render the physical motion by scaling and filtering the vehicle motion. As flight simulators have a longer tradition than their automotive counterparts, the commonly used motion cueing algorithm was originally developed for aviation tasks. However, the demands of automotive tasks differ from those of flight simulations and there is no experience with a mechanical construction and the corresponding dynamics as applied in the new DLR dynamic driving simulator. So the motion algorithm parameters have to be varied (or tuned) in order to meet these new demands. This is a difficult task due to the numerous parameters and the necessity to take into account the simulator capabilities as well as the characteristics of human motion perception. Hence the overall goal of the tuning is to improve the perceived motion inside the simulator to resemble the feeling of driving a real car and to avoid simulator sickness at the same time. A helpful guideline for the motion tuning process is presented by Grant and Reid [7], who combined the knowledge gained in the field of flight simulation over the last decades to develop a tuning paradigm.

Washout Filter Algorithm

The motion algorithm included in the simulator motion system is a classical washout filter algorithm (see Figure 2) as comprehensively described in association with flight simulation [3, 8-11]. It mainly scales and filters the incoming vehicle dynamics data (specific forces and angular rates). Because of the physical limits of the simulator the low-frequency lateral and longitudinal forces (surge and sway) are represented via simulator tilt. This so called tilt coordination uses the imperfectness of the human perception and the gravity force vector to simulate low frequency acceleration cues. Only high frequency movements are directly rendered.

For gaining simulator experience with a preferably simple set-up, the existing filters which are already integrated in the simulator are used. Their translational (or specific force) high-pass filters are first order and not the recommended second or third order filter structures [9, 10]. The angular rate first order high-pass filter and the specific force second order low-pass filter, however, feature the recommended design.

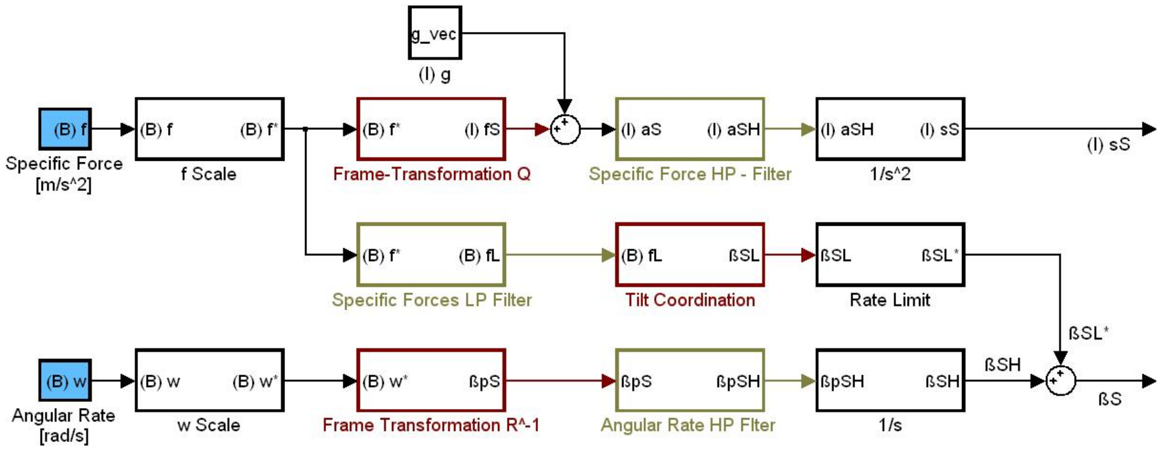

Figure 2: *Classical washout filter algorithm. Upper branch: Specific force high-pass filtering. Middle branch: Specific force low-pass filtering / tilt coordination. Lower branch: Angular rate high-pass filtering.*

Tuning Experiment

Initial values for the washout parameters (e.g. scale factors, filter frequencies, …) were selected as a trade-off between the first simulator behaviour insights and standard characteristic values [3, 9, 12]. The allowed coefficient values i.e. the initial ranges were selected the same way but with a higher permitted maximum value for the tilt coordination limits as discussed by Nordmark [13].

The driving manoeuvres for the two experiments done in the first step of the motion tuning are chosen based on Grant's advice to concentrate on manoeuvres with isolated individual DoF's [7]. Two basic manoeuvres fulfil this demand and are often used for several studies with motion-based simulators: Curve driving [1, 14, 15] (or steering [16]) which mainly addresses lateral acceleration and yaw and the central longitudinal manoeuvres accelerating and braking [1, 2, 14, 17, 18]. Consequently two virtual test tracks were created: one for each of the two chosen manoeuvres. The acceleration test track was composed of two parts. A long straight section is followed by alternating short straight sections and crossroads with stop signs, each with a different given speed limitation (Track *S3*). An overview of the second track (Track *S2*) which focuses on testing curve driving behaviour is given in Figure 3.

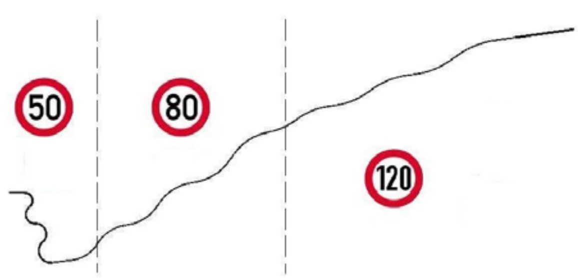

Figure 3: *Top view of the curve driving test track (Track S2) with given speed limits*

In the course of one test, the driver is instructed to carry out the particular manoeuvre with different vehicle speeds (given by speed limit signs along the track). In an iterative process of test runs, coefficient selection and coefficient adjustment, the motion parameters relating to the respective manoeuvres are systematically improved until the driver perceives the motion as realistic. Thus optimal tuned parameters for certain manoeuvres are obtained.

Evaluation Study

The evaluation main experiment consists of two parts: A real world drive with the ViewCar and a virtual world simulator run. Where the first part mainly provides the real world driving behaviour a focus of the simulator experiment is on the subjective assessment of the perceived motion. Both are systematically described in the following.

Part One - Real World Driving

The real world experiment track (Track *S1*) was chosen to be a 10 to 15 minutes drive. It comprises several curves with different degrees of curvature as well as sections forcing the driver to stop or to reduce speed (Figure 4). In this way both tuning manoeuvres will be found while driving this track.

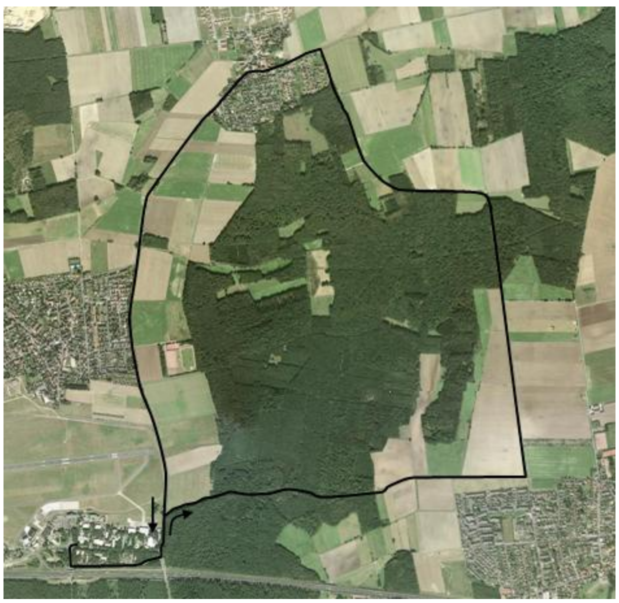

Figure 4: *Real world experiment track (Track S1) - aerial view*

Mainly the physical vehicle state will be recorded in order to obtain the real world driving behaviour of the test drivers, i.e. the steering behaviour (steering angle depending on time and vehicle position) and the speed choice (vehicle speed, throttle and brake depending on time and vehicle position). The test will be carried out with 16 subjects aged 25 to 50 years, half of them male and half female. Thus an at least moderate driving experience is guaranteed and driving effects of novice or old people can be excluded.

Part Two - Simulator Motion Assessment

The participation as a test driver in experiments in a virtual reality laboratory requires some experience with the used simulation environment to avoid the influence of learning effects and hence a great dispersion of the results [6, 15]. For the experiments within the laboratories of the Institute of Transportation Systems a simulator training based on the method of Hoffman et al. [19] was designed. Before starting the simulator experiment all subjects have to undergo this training in a fixed-based simulator. This reduces the chance of simulator sickness appearance and let the test drivers get used to driving in a virtual environment.

The motion assessment experiment is initiated by a short, unguided drive without any motion cues applied. This serves the re-acclimatisation to the virtual world as training and experiments are not undertaken on the same day. Furthermore, this initial drive provides a baseline for all following test segments. Next a test track consisting of three sections is driven three times, each run with a different parameter set. The first two sections are the curve driving track (*S2*) and the acceleration track (*S3*) from the tuning experiment followed by a virtual copy of the real world test track (*S1*). After every section, the driver is asked to report any symptoms of simulator sickness and to assess the motion under four different aspects:

- How realistic is the feeling of driving?
- How accurately can the car be handled?
- How well do the movements match reality?
- How safe did you feel?

On a two-level assessment scale, the drivers first conduct a verbal categorisation and then further differentiate between different levels within the selected category (Figure 5).

very poor			**poor**			**okay**			**good**			**very good**		
-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1

Figure 5: *Two-level assessment scale. Verbal categorisation and further differentiation.*

This procedure is repeated during the following two runs with changing parameter sets. The different sets are based on untuned initial parameter states and the manoeuvre-specific tuned values as described above (Figure 6). To exclude an effect of the parameter set sequence, the subsets are applied in varying order. Additionally the order of the first two tracks (*S2* and *S3*) is changed resulting in twelve different set-ups (Figure 7).

		parameter set		
		a	**b**	**c**
manoeuvre	**curve driving**	--	++	++
	acceleration	++	--	++

Figure 6*: Tuning states of the parameter sets (++ tuned / - - not tuned for the respective manoeuvre, e. g. set a is tuned for acceleration but not tuned regarding curve driving manoeuvres).*

		parameter-set order					
		a – b – c	**a – c – b**	**b – a – c**	**b – c – a**	**c – a – b**	**c – b – a**
track order	**S2 – S3 – S1**	I	II	III	IV	V	VI
	S3 – S2 – S1	VII	VIII	IX	X	XI	XII

Figure 7: *Sequence variation of the different parameter sets and the track order*

Conclusion

This paper describes an evaluation strategy and presents the structure of the first conducted experiments. Tuning the motion washout filter algorithm on different manoeuvre-specific test tracks results in manoeuvre-specific optimised parameter sets. A comparison of these sets reveals differences between the respective driver perception and effects regarding the manoeuvres. With the analysis of recorded physical values (e.g. steering angle, speed, etc.) of the real world drive and the motion-base simulator experiment, an objective comparison of the driving behaviour is performed. A further aspect which can rarely be found in motion-cueing related literature (except for Reid’s and Nahon’s work in 1986 [20]) is examined within this evaluation approach: a subjective assessment of the driver’s perception of self-motion. A comparison of individual assessments to the results of the driving behaviour analysis will show whether good achieved behaviour validity is identical to motion perceived as realistic. Hence the general possibility of achieving both tasks with one parameter set will be examined. Taking the driver’s opinions into account will help in gaining knowledge about how to avoid simulator sickness as well. Additional analysis will show which parameter set (related to the tuning manoeuvre and the experiment track section) obtains best ratings and if a combination of different tuning manoeuvres or an increase in the complexity of a single driving task is necessary to achieve a well tuned motion base. Subsuming, the experiments are designed to answer the questions what level of validity the DLR dynamic driving simulator has already reached and in which direction future tuning and evaluation should go. First results of this study will be presented at this conference and publication of the complete analysis will follow.

Acknowledgements

The presented research work is funded by the Ministry of Economics, Labor and Traffic of Niedersachsen (Project “Strategien für Fahrerassistenzsysteme”).

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