T.P. Witsenboer

Influence of Steering System Imperfections on Truck Steering Feel

a driving simulator study

TUDelft

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a driving simulator study

By

Drs. T.P. Witsenboer

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Supervisors:	Dr.ir. R. Happee Dr. B. Shyrokau Dr. C. Dijksterhuis
Thesis committee:	Prof.dr.ir. E.G.M. Holweg Dr.ir. D. Abbink

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Faculty of Mechanical, Maritime and Materials Engineering (3ME)
BioMechanical Engineering
Delft University of Technology
Mekelweg 2, 2628 CD Delft, The Netherlands

TU Delft Delft University of Technology

Master Thesis partners:

Project partners:

Abstract

Road safety is a prime concern in modern society. Statistics on traffic accidents show that articulated vehicles are overrepresented in fatal accidents. A third of all accidents happen during a vehicle maneuver with small lateral displacements: on-center handling. Stable guidance and handling behavior of the vehicle is mainly determined by its chassis, the vehicle dynamics and the steering system which needs to be reliable, predictable and to give the driver good steering feel. The function of a steering system is firstly to serve the steering wheel, which the driver uses to change the direction of the vehicle. Secondly it is an important source of information to the driver about the vehicle's operating status and response through the steering feedback caused by the front wheel tire forces, steering geometry and dynamics. Defining steering feel is difficult because it is a subjective matter, but it is clear that good steering feel is necessary for safe vehicle control and an important element to driver experience. Next to the steering system mechanism and architecture the steering system parameters are important for truck driver steering feel. Changing these parameters like steering ratio, friction, stiffness and play can improve the on-center feel of the articulated vehicle. Every mechanical system always possesses some imperfections, especially systems with transmissions, like steering systems. And even worse: every mechanical system will degrade over the life time of usage. Therefore steering system imperfections are defined as the steering system parameters that change over lifetime.

This study has been a first attempt to investigate the influence of the steering system imperfections on truck drivers steering feel. A simulation study is used as the experimental technique. There are many advantages to use driving simulation instead of real vehicle testing, like safety concerns, the convenience of changing vehicle parameters and reproduction of the exact test conditions, but the degree of replication of the real world (validity) of the driving simulator is critical in order to obtain useful results. The validation improvement process regarding the, in this study first time used, Mobile Truck Driving Simulator (MTDS) is done by using earlier research, interviewing truck drivers, recording truck rides from the view of the driver, measuring dimensions, using employment guides and let professional drivers run test drives on the simulator. The MTDS consists of a steering actuator (SensoDrive Sensowheel) with an original DAF steering wheel, pedals, three screens, a real-time system (DS1006) for real-time calculation of the used models, a driving simulation software package (StSoftware) and a desktop PC used for control and data storage. To mimic the different inclination angles of the steering wheel in a truck a dedicated construction is designed and produced.

The study started with an explorative research on six steering system parameters that show a large degree of degradation: column bearing friction, bevel box friction, hydraulic cylinder friction, king pin friction, free play in the system and the tie rod stiffness. Designation is done by using earlier described literature, interviews with maintenance engineers and putting questions on forums. The purpose of the explorative research is to find the (not yet revealed) minimum or maximum values of these steering system parameters within the boundaries of a realistic and stable steering system. Six professional truck drivers were asked to track the moment when the system does not show realistic steering feel anymore. During every test run one of the six steering system parameters is constantly changed using a predefined threshold tracking method resulting in general feedback and mean values of that particular parameter. The experiment resulted in three parameters to use in the main experiment: column friction, king pin friction and free play. Three different values for each of the parameters are applied: a baseline value (realistic model), a maximum value calculated from the average value plus the standard deviation (to increase significance level and a third value in between the other two).

The first objective of the main experiment was to find out how the three different steering system imperfections affect the steering feel of professional truck drivers. Steering feel is approached by a combination of four elements: general experience of handling, steering system, realism and steering system acceptance scale (SAS) based on the usefulness and satisfaction of the system. 18 Dutch professional truck drivers drove different test runs. Each time (only) one of the steering system parameters is changed and afterwards the subject completed a questionnaire. Evaluation of all drivers is used to find the following results:

- After increasing the column friction with the lowest amount (~1.6 Nm) drivers evaluated the ride regarding general experience as more difficult, more risky, demanded more mental and physical effort, less safe control, less comfort and less realistic steering feel and realistic response. Subjects also gave a lower score on the realism of the simulator. Regarding the steering system drivers evaluated only the force needed to turn the steering wheel as different compared to the baseline configuration (~0.1 Nm). The larger the increase of the column friction the larger is the decrease of the steering system acceptance. This is more because of a drop in satisfaction than in the usefulness score. A further increase to level two (~3.2 Nm) shows no different results.
- Increasing the king pin friction from the baseline value (50Nm) with one step (147Nm) is already evaluated as being more difficult, more risky, demanded more mental and physical effort and less safe. An increase to the second and largest level (244Nm) is evaluated as even more difficult and risky and steering as less realistic, less comfortable, less easy, less solid and less rate stable. Like with the increase of the column friction only one of the 7 items is rated different: the amount of force needed to turn the wheel. The variation of king pin friction also indicates a decrease of realism but only after increasing to level two. The scores for value one on system acceptance show a decrease of usefulness and satisfaction and decreases almost linearly with increased king pin friction to level two.
- Increasing the free play to the first level (0.81deg) is evaluated as more risky, less safe, with less realistic response, more difficult to control, less solid and less rate stable. An increase to the higher value two (1.53 deg) demanded more mental and physical effort and is less comfortable. The steering system was evaluated as being different regarding the amount of play in the system, where only the difference between value two and the baseline (0.1deg) is significant. The increase of free play in the system results in a decrease of realism. The increase in play show the smallest deviation regarding usefulness and satisfaction compared to the baseline and show the same linear relationship as the kingpin friction.

The second objective was to find out how the three steering system imperfections affect the objective driving indicators of professional truck drivers. The majority of objective indicators are directly related to data from the steering wheel. Due to possible lane change maneuvers driving performance is less straightforward. The results from 18x7 test runs:

- Increasing the column friction results in an proportional increase of steering effort and driver burden.
- An increase of king pin friction to the first value results in an increase of steering effort, driver burden and steer jerk; an increase to level two further increases steer jerk significantly. Level two also results in an increase of steering business, steer rate, steering steadiness and steering reversal rate.
- A first increase of free play only results in a different steering reversal rate, a further increase to the second level results in a increase of steering business, steer rate, steer jerk and steering steadiness.

This study shows the large impact of degradation of steering systems on driver experience and driver workload. No conclusion can be drawn on the driving performance regarding driving an articulated vehicle with a degraded steering system.

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1. Introduction

Driving a commercial vehicle is a complex task and involves many interactions between the driver and the vehicle through the various controls. Good performance depends on how well the truck is able to perform the driver's intentions, and how well differences between those intentions and the vehicle's responses can be assessed and corrected by the driver. Like braking, the throttle and gearshift lever, steering is an important mechanism used for navigation, guidance (track following) and stabilization (control) [1].

One of the most important factors to define a steering system is the vehicle's ability to communicate to the driver at all times what the vehicle is doing regarding its behavior. This communication comes largely from the steering wheel [2]. The driver not only exerts the steering wheel to give input to the vehicle, but also receives feedback about the state of the vehicle at that particular moment. This feedback consists of a haptic (force) feedback, which is largely responsible for the phenomenon of steering feel. In realizing steering feel mainly three systems are involved

1. The steering system involves the mechanical construction from steering wheel to the steered wheels.
2. The vehicle is the controlled system defining the performance of the steering task. The handling behavior of the vehicle is important to reach a good performance. Active steering systems are hypothesized to improve this performance but, up to the moment autonomous driving will be in charge, have to support the human driver as being the controller of the vehicle.
3. The human driver may be viewed as a complex system being highly adaptive when controlling a vehicle. For accurate feedback a human uses very precise senses. From this point of view it is important to understand the nature of steering feel, the components of steering feel and how it is evaluated by the driver.

The preferences of driver's steering feel are partly determined by the steering system characteristics Degradations in the steering system over lifetime the lifetime of the system, usually called steering system imperfections, are hypothesized to negatively affect steering feel and driver performance. Examples of imperfection are the steering wheel to road wheel stiffness, tie rod stiffness [3], damping and friction [4] of the steering system and steering play [5].

In the Netherlands road safety is a prime concern. During the period 1990-2012 the total number of fatal road injuries is more than halved, but still a major concern. At 11 percent of all casualties in 2012 an articulated vehicle was involved [6]. European statistics on vehicle accident causes show that 5% of truck involved accidents with at least one injury are due to technical failures, where a total of 85% is linked to human errors from road participants. From that share, a quarter of all participants are truck drivers [7].
From al accidents a third happen during a vehicle maneuver like a lane change and an overtaking maneuver. These maneuvers require small lateral accelerations and so the steering system plays an important role. Because there is no information available on the consequences and magnitude of

steering system degradations the malfunctioning of the steering system can be wrongly assigned to human error instead of technical failure.

Standardized tests and objective measures are available for research on steering system characteristics. These objective techniques make use of a steering robot, so no information is revealed on how the characteristics will work out with a specific driver. Steering feel is probed through subjective assessment because it relates to the human perception of the system. Subjective assessment can be done by deploying expert test and race drivers or using subjective tests from automotive magazines [8]. An important aspect of these tests is that they are all only performed on brand new trucks or during the design of these vehicles.

The conclusion that no dedicated standard is available to investigate steering system degradations and steering feel requires a different approach. There are different techniques available to collect human opinions in a straightforward way. One of the main involved methods to measure the opinion, beliefs and thoughts of the test driver is the use of dialog-based interaction (like interviews) or questionnaires. Questionnaires are usually viewed as a more objective research tool because of their structure: the participants respond to prompts by selecting from predetermined answers [9].

To implement steering system degradations in a heavy good vehicle involves a number of repetitions, control of experimental conditions and a safe experimental environment. For this reason, based on both existing [10] and new elements, a simulator set up is designed, improved by pilot drives, and used to assess the steering feel on professional truck drivers.

1.1 Research plan

The reason to launch a research on steering system imperfections is first the idea that it may be a hidden cause of a number of yearly fatal traffic accidents. Next to this dramatic consequence steering system imperfections can affect the steering feel of truck drivers.

There is the assumption that steering system imperfections deteriorates steering feel and driver performance, depending on driver feedback. But because these imperfections arise through the years of use it is difficult to test on real (new) vehicles.

Investigation of steering system degradations involves a number of repetitions, control of experimental conditions and a safe experimental environment. For this reason, based on both existing [9] and new elements, a simulator set up is designed, improved by pilot drives, and used to assess the steering feel on professional truck drivers.

Research objective:

To set up a human in the loop simulation study in order to investigate the consequences of critical changes of steering system parameters on the steering feel of truck drivers during on-center highway driving.

The research objective involves three research questions, in which the first has to be answered during an explorative research:

Research question 1:

What are the minimum or maximum values of the six designated steering system parameters within the boundaries of a realistic and stable steering system?

The outcome of this research question results in the investigation of the second research question:

Research question 2:

How do steering system imperfections affect steering feel of professional truck drivers?

Hypothesized is that steering imperfections degrades steering feel of the truck driver. This can be split into three different hypotheses.

Hypotheses:

I. *The increase of play in the steering system during the lifetime of the articulated vehicle degrades the steering feel of the truck driver*
II. *The increase of column friction in the steering system during the lifetime of the articulated vehicle degrades the steering feel of the truck driver*
III. *The increase of kingpin friction in the steering system during the lifetime of the articulated vehicle degrades steering feel of the truck driver*

Next to the evaluation of steering feel, the object indicators of driver performance are an important aspect that can be influenced by the steering system imperfections:

Research question 3:

How do steering system imperfections affect the objective indicators of driver performance of professional truck drivers?

Hypotheses:

I. *The increase of play in the steering system during the lifetime of the articulated vehicle negatively affect the objective indicators of driver performance of the truck driver*
II. *The increase of column friction in the steering system during the lifetime of the articulated vehicle negatively affects the objective indicators of driver performance of the truck driver*
III. *The increase of kingpin friction in the steering system during the lifetime of the articulated vehicle negatively affects the objective indicators of driver performance of the truck driver*

1.2 Report structure

To find an answer to the research question good understanding of the theoretical background is essential. Chapter 2 introduces the four main items involved in this research: the topic of steering feel, the vehicle and its steering system, simulation and the approach to the subjective assessment of steering feel. Chapter 3 describes the used apparatus regarding the simulation study. Because of the fact the mobile truck driving simulator (MTDS) is especially build for this purpose; the chapter also deals with the design and validation of the simulator. In finding a way to approximate the maximum levels of realistic steering feel first an explorative research is deducted and described in chapter 4. The purpose is to assign the main characteristics of steering system degradation and its value. Chapter 5 is about the main experiment and describes the used method, show the results and a discussion. Chapter 7 contains some general conclusions and recommendations about the overall research.

2. Theoretical Background

Driving a heavy good vehicle requires continuous steering actions from the driver. He or she will notice this correction generated by the interaction with the vehicle within the driving task of directional control. This interaction is sensed by the driver through different feedback cues, mainly via visual feedback but also via the steering wheel. Different human sensors are involved in perceiving the vehicle response and steering wheel feedback. Figure 2-1 shows the driver-vehicle control loop block diagram. The four colored blocks in the diagram are the main aspects involved in the experimental research of steering feel: the truck driver and its steering feel, the handling of the vehicle by actuating the steering system, simulation as the used research tool and subjective assessment of steering feel by using a questionnaire. These aspects form the theoretical background of this thesis and will be further described in the next four sections.

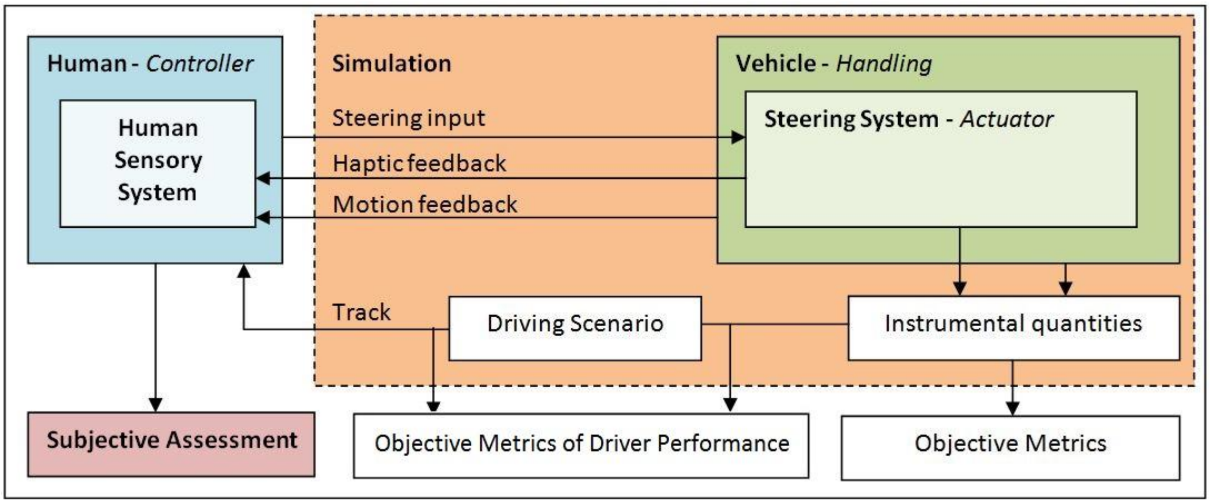

Figure 2-1 Driver-vehicle control loop block diagram (adapted from [11])

2.1 Truck Driver Steering Feel

Steering Feel

Early research stated that steering feel cannot be defined, but only described since it is not traceable back to anything [12]. This reasoning comes from the fact that the description of steering feel is a subjective matter and thus defined by the personal experience. Some highlighted that steering feel is a myth, because it is a single perception and concentrates on the feeling of the wheel-road contact [13].

This non holistic approach is far from complete, because perception is necessarily the resultant of many different properties and forces on and by the steering wheel. In following a track the driver generates an input torque by rotating the steering wheel. Because of the tire-road contact this results in a change in lateral direction. The moment generated in the contact between tire and road is the main feedback signal to the driver via the steering wheel. Having steering torque feedback results in better curve negotiation and skid recovery by the driver [14]. Without steering feedback, drivers become disorientated in tight turns [15]. This all means that a proper steering feedback is an important element to driver experience.

Next to the tire-road contact, every driver will feel the road through the mechanical linkages in the steering system to the wheels. Vibrations of the wheels will be transferred to the steering wheel via this mechanical connection. Next to this, the linkage provides a certain feel when the driver will turn his or her steering wheel. This part of the road feel plays also a prominent role in driving experience [14] and the driver's control strategy. Lack of damping, non-linearity and lash in the steering system can reduce the driver's ability to precisely place the vehicle on a desired path [16].

The characteristics of steering feel are not only important with regard to driving experience, but also a matter of safety. A loss of steering control results in many accidents. Good steering feel means that the vehicle requires minimal steering correction and the ability to follow the driver's intention accurately. Next to the quality of steering feel, steering confidence by the driver is closely connected to safety. Predictability of steering feel and an ample amount of precise feedback about the magnitude of the steering input to the driver is important. Next to the quality itself, steering feel can be used in the providing of information to the driver on how to change their control strategy [17]. Steering feel characteristics rated as poor, like vague steering and ambiguous vehicle response, lead to exhaustive driving loads and decrease the driver's ability to focus on the main driving demands [18].

Steering feel can be defined as a function of three vehicular characteristics: steering activity, steering effort and vehicle response: [19]

- The source of steering activity is from the combination of inputs like steering wheel angles, steering wheel torques and their derivatives over time with changing lateral accelerations around the center position [20]. The felt steering wheel torques by the driver, dependent on where the driver holds the steer, consists of: [21]
  - Moments about the kingpin axis due to: longitudinal tire forces, lateral tire forces, vertical tire forces and tire self-aligning torques
  - Moments due to damping and inertia in the steering system
  - Power assistant torque
- Steering effort requires measurements of steering friction, torque dead-band and steering stiffness.
- Time lags in vehicle responses to a given input of the steering wheel have proven to be much related to steering feel [22].

A method to describe steering feel is proposed arranging descriptive words in nine dimensions: stability, response, play, resistance, ratio, road feel, jerk, comfort and steering wheel return [23].

Human Factors

Steering feel is greatly affected by the vehicle dynamics and steering system, which will be described in the next section, but also by the human in the loop. Human beings introduce additional dynamics, through grip dynamics, intrinsic inertia, damping and stiffness properties of the muscles [24]. Although driving comfort is closely related to human vibration, it contains a mental and an environmental aspect as well as physiological effects [25]: all the mental and physical variability within and between humans, like skills, experience, fatigue, emotions, workload, distraction and alertness. Drivers have personal preferences and steering feel has an elementary influence on this. Even though the same values of objectively approached steering feel are obtained from a measuring device, different subjective perceptions of each driver may occur. These individual differences make finding the optimal steering feel, or rather steering characteristics a difficulty [26].

The human body has two inputs for motion perception: environmental motion with respect to the body and the inertial stimulants on the body, from the gravitational force and external forces and moments on the body [27]. The prominent sense of environmental motion is obtained through the visual system and also through the acoustic system [28]. The inertial haptic stimulants are acquired by:

- *Vestibular system:* the vestibular system, located in the inner ear (left and right), is the prominent sense that provides the perceptual system with information about linear and angular inertial accelerations of the body. Psychophysical studies have revealed an important contribution of vestibular cues in distance perception and steering [29].
- *Tactile system*: forces perceived by the human by touching the surface [30]. Sensor cells in the skin deliver information about pressure and local velocity in the skin.
- *Proprioceptive perception:* sensor cells provide awareness of movement or activity in muscles and joints, which delivers information about the position and forces of parts of the body to each other.

The haptic perception of steering feel is a complex subjective experience in which all of the human senses are addressed [31].

2.2 Vehicle handling and the steering system

Vehicle handling

The steering system on itself is not the only dependent characteristic for good steering feel. Arguably the chassis plays a major role in the overall steering feel of a vehicle [32] and also the vehicle dynamics affect the steering behavior of the vehicle:

- Longitudinal mass distribution of the trailer changes the rear axle load of the tractor which affect the articulated vehicle's understeer/oversteer behavior [33]
- Roll motion of the vehicle like suspensions roll stiffness and chassis torsional stiffness [34]
- Front suspension kinematics such as camber angle and kingpin inclination angle [35]

Steering feel is of particular interest in evaluating on-center handling [36]. On center is the region of low lateral acceleration in freeway driving [37] and of great importance to truck driving. At first since many trucks will spend most of their time driving on a highway. Second also because most truck drivers die in single-vehicle run-off accidents during on center handling. Main used objective boundary to define on-center behavior is a lateral acceleration of 2 m/s^2 [38]. The importance of on-center handling on steering feel means that even in the on-center driving area, the driver is informed of the operating status via forces at the steering wheel. On-center feel can be improved by changing the parameters of the steering system however the effectiveness of this system is limited by the true center position varying with road camber and side winds [39].

Steering System

The function of the steering system is dual: firstly it serves the steering wheel, which the driver uses to change the direction of the vehicle. The ability of the vehicle to respond to course changes is called the guidance behavior of the vehicle. Secondly it is an important source of information for the driver about the vehicle's operating status and response [40]. As mentioned in the steering feel part, the steering wheel torques are normally caused by the front wheel tire-forces, but also by the steering systems geometry [41] and dynamics.

DAF Steering System

Figure 2-2a shows the DAF hydraulic power steering (HPS) assisted steering system. At the right a more detailed overview of the components involved in this HPS assisted recirculating steering mechanism (figure 2-2b). By turning the steering wheel (δ_{SW}), the driver applies a torque (M_{SW}) to the steering gear input shaft (I). The torsion bar (II) is on one end pinned to this input shaft and exerts a moment to the spindle (III) pinned on the other end. In response to this moment, the spindle tries to axially move the cylinder (IV) because of the recirculating ball mechanism (V). This movement is resisted by its engagement to the sector shaft (VI) which is connected to the steered wheel via the pitman arm (VII), draglink (VIII), wheel hub lever (IX) and kingpin (X) .This resistance actuate the control valve (XI) which directs pressurized oil to one of the chambers, depending on the direction of motion of the input shaft. The tie rod (XII) links the steered left wheel with the right wheel, also called the Ackermann linkage.

During low speed driving, the power steering system reduces the steering torque required to steer. When driving at high speeds, less power is needed, to provide stability at higher on-center speeds. The hydraulic pressure is adapted to the driver's input steering torque using the power steering pressure characteristic.

Future technologies

State of the art in truck driving steering systems is the partial application of electric power steering (EPS) hardware. The high torques and forces required to steer the heavy axles make the power density of hydraulics, up to now, a necessary actuation technology for commercial vehicles. The electric motor is used to modify the torque feedback to the driver, and the adjustable hydraulic

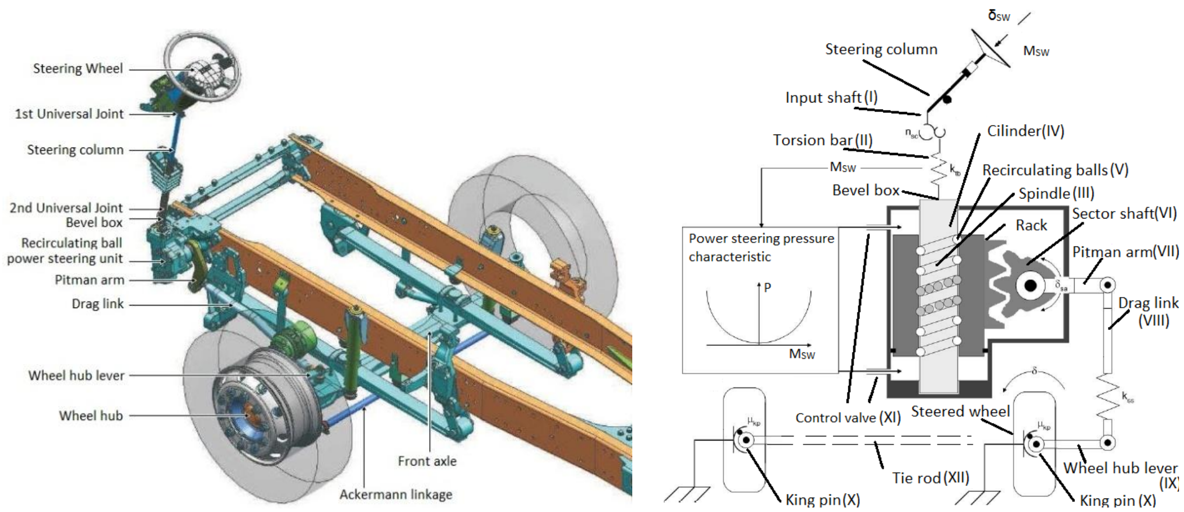

Figure 2-2 **a)** DAF steering system (adapted from [24]) **b)** the recirculating ball steering mechanism with HPS in detail (adapted from [42])

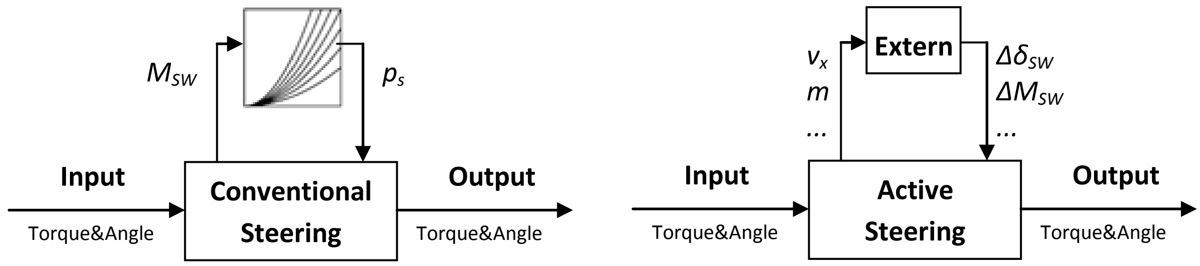

Figure 2-3 **a)** Passive Steering System **b)** Active Steering System [46].

gearbox does the work required to steer the heavy axle [43]. This means that the use of EHPS in commercial vehicles directly raises the need to step from a passive system to an active system (AS).

From a passive EPS steering system, active steering systems (AS) are developed with electrically variable gear ratio systems. In passive systems the output of the steering system is only dependent on the input and the power steering characteristics. The output of an active steering system is dependent on the input and any chosen external parameter (figure 2-3) AS is used as a promising technology with the ability to control the front wheel angels, which improves the steering performance and handling stability of vehicle. However it has a serious problem of unexpected reaction hand wheel torque caused by the intervened steering angle [44]. In passive steering systems the feedback by means of steering wheel torque and the vehicle response to the steering wheel angle are to be optimized in order to find optimum performance. In active steering systems, some of these limitations may be eliminated, thus opening up for new areas of steering feel [45].

Steering system imperfections

Next to the steering systems mechanism and architecture the steering system parameters are important for truck driver steering feel. These parameters include steering ratio, friction, damping, inertia, stiffness and servo characteristics [46]. Steering system imperfections are defined as steering system parameters that change over lifetime.

Steering system imperfections can have a large influence on steering feel:

- Steering play is a contributing factor that degrades steering feel [6]
- Steering column non-uniformity results in lower steering torques, especially for large steering angles.
- Friction, stiffness and damping in the steering system have a masking on force feedback [47]. Previous research [24] has shown that steering torque is most affected by friction, substantially by stiffness due to steering wheel mass eccentricity and least by damping.

Steering system imperfections do not directly result in bad steering performance. Play badly increases shimmy steering wheel behavior, but also prevents the driver from unwanted steering input. Damping and friction dissipates external disturbances, but makes the response less predictable. Lower stiffness decreases the steering effort, but provides a less predictable torque response [24]. Next to this two-way reasoning, humans show a wide range of adaptation to changes in the vehicle steering characteristics [48]. Some other conclusions from earlier research on steering system parameters [21],[49]:

1. Low returnability and linearity helped to emulate the familiar 'lighter' and highly assisted steering feel of modern power steering vehicles
2. A middle of the range on-center feel ensured comfortable centering properties during nominal highway driving, while the appropriate stiffness ensured comfortable centering properties at low speeds.
3. A higher stiffness than the given range exploited the inherent benefit of a steering system in reducing conventional steering lag, resulting in a highly responsive driving experience.
4. A lower overall steering ratio, a stiffer torsion bar and a higher tire cornering stiffness can improve centre feel and steering response from the middle, and vice versa.
5. A higher trail generates a highly improved centre feel at the expense of the steering response.
6. Increased steering friction at the rack reduces the steering response from the middle and an increased column friction diminishes the centre feel.

From the components characteristics in the steering system, some are essential to research the effect of steering system imperfections to steering feel:

- Kinematic parameters
  – Steering play
  – Steering column non-uniformity
- Dynamics parameters
  – Stiffness
  – Damping
  – Friction

By running tests with a steering robot objective metrics exist to approach the play, stiffness and friction using so-called Lissajous curves. These curves are created by plotting steering characteristic quantities against each other, like steering wheel torque against steering wheel angle (figure 2-4a) to plot stiffness (#1) and friction (#3) and lateral acceleration against steering wheel angle (figure 2-4b) to plot the free play (#4). More details on objective measures can be found in the literature study report [50].

Using new steering systems, recent developments are for example park assistance, side wind compensation, course correction and disturbance compensation can result in poor steering feel, called artificial and less communicative to the driver [51]. Many auditory Lane Departure Warning Systems (LDWS) designed to prevent situations where a truck is drifting from its lane is labeled by drivers as "annoying" and turned off, with associated consequences [52]. Haptic guidance (force feedback) on the steering wheel is a promising alternative [53]. Using objective and subjective assessments the optimal balance in terms of stiffness, damping and friction can be found such that the haptic support system provides improved natural steering feel.

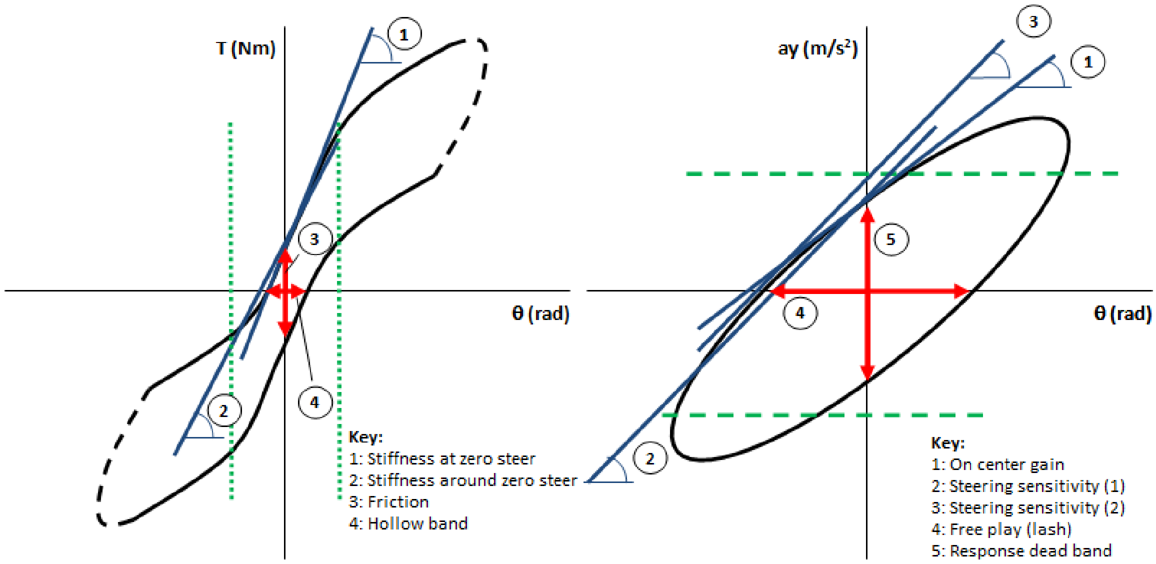

Figure 2-4a) Lissajous curve of steering wheel torque against steering wheel angle **b)** Lissajous curve of lateral acceleration against steering wheel angle

To investigate the effect of the imperfections on steering feel a simulation study can provide both objective and subjective measurements. This is first needed because there are still no standardized objective ways on how to measure what drivers feel. The second reason to provide both is to check the reliability of the subjects and the third is it can be very useful to find new correlations between objective and subjective measures. To increase the chance of finding these correlations requires good understanding on how to design and use subjective assessment during a simulation study.

2.3 Driving simulator studies

One of the common used laboratory experiment techniques is a simulation study. Based on a mathematical model of the system in the real world they present the experiments are conducted by computer simulation or human in the loop (HuIL) simulation. In this research a fixed based HuIL driving simulation (DS) is used as the representation of driving a real vehicle.

The history of simulators starts before WWII with the flight simulators used for training purposes [8]. The reason to introduce simulators over the use of actual equipment is the idea to reduce operational costs. In design two main approaches are used: high fidelity and low-cost without compromising training effectiveness. Driving simulators are developed in the late 1950's, not only for training but also for research purposes. Next to the driver performance, also the need to improve our understanding of driving behavior in traffic situations became important. Nowadays driving simulators are used in three main fields of expertise: investigating human factors and behavior, investigating and evaluating new appliances for new vehicles and use as an educational instrument for learning and continuing education [54].

Advantages and disadvantages of simulation

The applicability of a simulation study depends on the objectives and characteristics of the experiment. Next to the scope it also demands insight in the advantages and disadvantages. In literature many pros and cons are available and the most important ones regarding a fixed based driving simulation are shown in table 2-1. It is important to find a way to deal with the disadvantages and minimize the consequences.

Driving simulator validity

The motion system is one of the main used characteristics in classifying driving simulators. This motion system can be from fixed based up to more than six degrees of freedom (DoF): three rotational and three translational. Four examples of driving simulators are shown in figure 2-5: fixed - based, 3 DoF (roll, pitch and heave), 6 DoF and a double motion based 7 DoF driving simulator. Motion simulation is all about the earlier described psychophysical perception of inertial stimulants on the body and environmental motions with respect to the body [28]. The motion system plays an important role regarding the fidelity of the simulator system

The degree of replication of the real world in a driving simulator is called validity which consists of physical validity (fidelity) and behavioral validity (predictive validity). Fidelity in human factor studies is mainly based on the sensory realism of driving simulator. Using larger screens with a higher screen resolutions and a better night-time visibility can be used to provide better speed and position estimation from visual information. But the absence of vestibular cues in distance perception and steering has reported increased steering reaction times [55] and a decrease of safety margins in control of lateral acceleration [56] in both simulator studies and real driving experiment [57].

Advantages	Source	Disadvantages	Source
Convenience to change vehicle parameters	[58]	Simulated crashes do not have the same consequence as a real crash and may affect subsequent behavior	[62]
Reproduction of exact test conditions	[59]	Fidelity: the real world will never be replicated in all its complexity	[61]
Convenience to record many parameters	[60]	The important combinations of real-world information and feedback that are important to driving are not completely known	[62]
Not dangerous to drivers and equipment	[61]	High-end simulators require considerable hardware and software development, where low-cost simulators can be imprecise and inflexible	[62]
Many confounding variables that occur in road-driving can be controlled (weather, traffic, road condition, other drivers' behavior)	[62]	Drivers seems to have different judgments in a DS: large underestimation of the distance, higher speed levels and bigger and faster steer inputs	[63]
Simulators offer cost savings through flexible configurability	[62]	The longitudinal and lateral control of the driving simulator seems to be faster	[61]
Driving simulation is compelling and elicits emotional reactions from drivers that are similar to those of actual driving	[62]	Simulator sickness because of visual-vestibular conflict	[64]

Table 2-1 An overview of advantages and disadvantages of driving simulators.

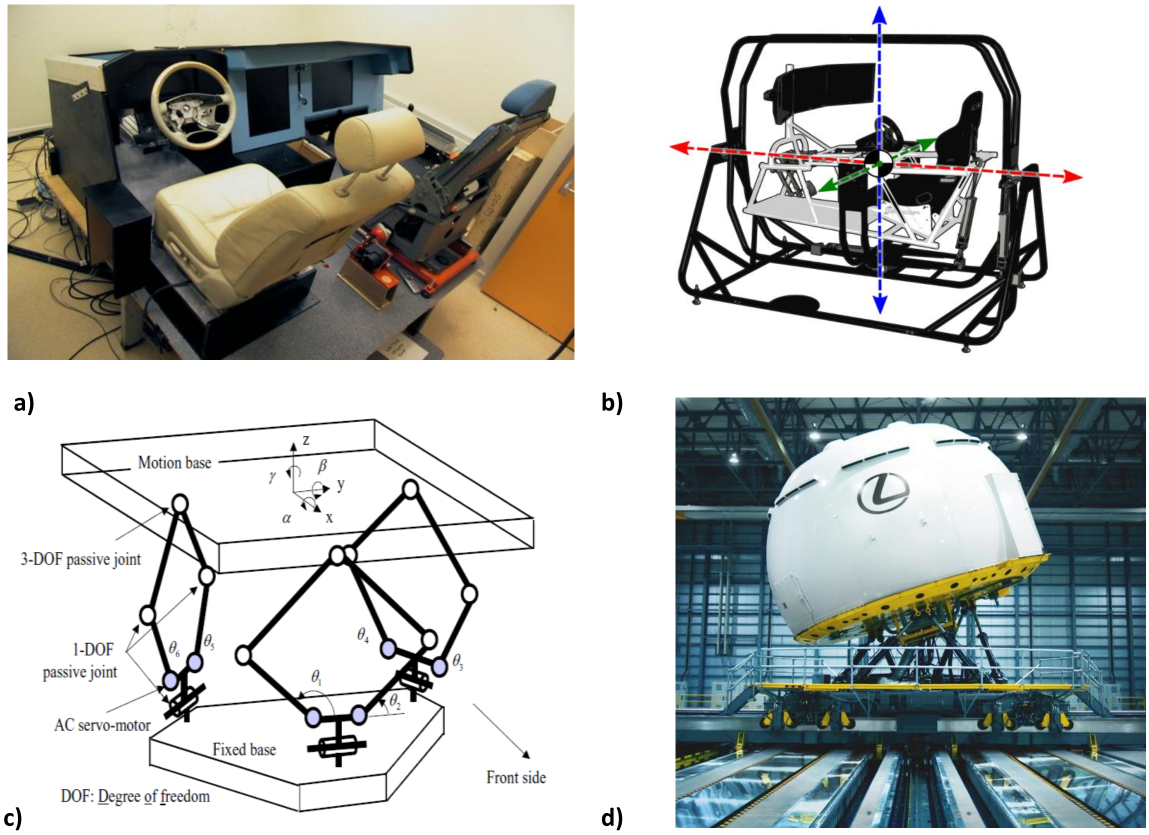

Figure 2-5 Four types of driving simulators :

a) Fixed based platform **b)** 3 DoF platform;

c) 6 DoF platform **d)** >6 DoF platform (Lexus): double motion base [65]

Vestibular cues can be generated by using a moving base in the driving simulator. Next to improving the fidelity a moving base can be the first step in the prevention of a major problem in the use of simulators: the visual-vestibular conflict called simulator sickness [66], i.e., information that is signaled by the human retina or vestibular apparatus which is in conflict with expected values based on past experience [67]. This includes lags in the response variables [68], and discrepancies between the visual and physical motion cues. Lags in the visual system are on the order of the sum of the frame rate, the integration time step, and networking delays. Although fidelity of a driving simulator is important, often too much importance is placed on it. Although this applies to both validity dimensions, in human factors research no level of physical validity is useful if behavioral validity cannot be generated. The behavioral validity for DS research deals with the appropriate reproduction of driving response as it will occur on the road.

Real time simulation

The realism of simulation thus depends on the basic fidelity of the cuing, the relationship between the operator's control responses and the response of the cuing devices. Recent technological developments have brought high fidelity vehicle dynamics simulation into a new realm, that of real time simulation [69]: high speed microprocessors, parallel processor computers and recursive vehicle dynamics formulations which are a key enabling technology in a high fidelity driving simulator. Given the driver of the simulator control over the steering wheel, brake pedal, throttle, and gear shift lever, vehicle dynamics predicts all information required by the motion system, visual system and audio system in real-time [70]. Simulation of machines with operator in the loop functionality demands for real time simulation (RTS) to realistically mimic real life operation of the machinery [71].

A system is said to be a real-time simulation (RTS) system if the correctness of the system responses depends on both the accuracy and timeliness of the computation [72]. The processing of actuator signals, the model calculations themselves, and the output of sensor signals have to be performed in one simulation step [73]. The response generated by the simulation after each time step is considered useful for RTS only if the computation time for each time step remains below or equal to the actual time being simulated [74]. The accuracy of these computations and how well they are implemented in the simulation model mainly determines the validity of the human-in-the-loop real time simulator [75].

2.4 Subjective assessment tool: a questionnaire

As mentioned in the introduction there are objective tests available using steering robots to measure steering system characteristics. Human in the loop requires subjective tests which are available from automotive magazines and opinions from expert test and race drivers. Between pure objective tests and the opinions presents a gap [7]. This gap mainly exists because of the difficulties of subjective assessments:

- Difficulty to describe steering feel
- Deficiencies in reliability of the results [59]
- Deficiencies in reproducibility of the experiments
- Redundancy in measurements [54]
- Different perceptions and assessments of each subject [76]

The lack of sources on how to obtain the evaluation of steering feel from professional truck drivers on different system configurations requires the design of a dedicated assessment tool. Several guiding principles are used in the design of subjective assessments: [77]

- Experienced test drivers would be used
- The test drivers must be intimately involved in the design of the questionnaire and the language to describe handling features
- The evaluation methodology would be at the discretion of the driver
- The rating scheme would concentrate on using comparative rather than absolute judgments
- A preliminary pilot study would be used to test the methodology prior to the main experiments.

Data collection

Important in research is how to gather useful information during the experiment. In a vehicle handling assessment using a simulator both the objective parameters and subjective ratings need to be collected.

Before starting to collect data from the subject in the experiment it is useful to obtain predictor and outcome data on pilot subjects to make sure that any technical problems (like simulator program bugs, video projection failure, inappropriate audio levels and incomplete data capture) or procedural problems (like unexpected driver fatigue and ask confusion) are resolved. Clear and well-developed

	Advantages	Disadvantages
Surveys and questionnaires	* Administration is comparatively inexpensive and easy even when gathering data from large numbers of people spread over wide geographic area * Reduces chance of evaluator bias because the same questions are asked of all respondents * Many people are familiar with surveys * Some people feel more comfortable responding to a survey than participating in an interview * Tabulation of closed-ended response is easy and straightforward process	* Survey respondent may not complete the survey resulting in low response rates * Items may not have the same meaning to all respondents * Size and diversity of sample will be limited by people's ability to read * Unable to probe for additional details * Good survey questions are hard to write and they take considerable time to develop and hone.

Table 2-2 (Dis)advantages of surveys and questionnaires as used data collection method.

standard operating procedures are crucial to increase the precision and decrease the chance of confounding biases in the data collection process. Pilot testing can reveal a range of questions that participants are likely to have before and during the drive [78]. To collect correct data the different variables need to be defined: the dependent (or outcome) variables like driver and experimenter rating [79] and the independent (or explanatory) variables from the scenario: the steering system imperfections. In choosing the variables it is important to recognize the risk of confounding variables and effect modification [80], which can be accounted for during the statistical analysis.

A questionnaire is a written, online or verbal tool for easily collecting data from many individuals or groups that can be analyzed using qualitative and quantitative techniques [81]. Often wrongly argued as easy, the design of a valid and reliable questionnaire is a complex process that involves many sometimes conflicting considerations [82]. This section will describe the considerations and procedures to develop the questionnaire used during the experimental phase.

Questionnaire design

Before setting up questions to ask to the subjects it is first important to a review the available sources that deals with the design of a questionnaire. Questionnaire design often starts at the level of specific principles [83], which implies that the greatest weakness in questionnaire design is the lack of theory [84]. General principles are:

- The subject defines what you can do
- Find out what is in the subjects minds
- Let the subject tell you what he or she means
- A questionnaire consists of four integrated layers: objectives, questions, words and lay-outs
- Without clear objective you cannot begin to formulate questions and worry about wording

If the objective of the project is clear different procedures for planning and developing a questionnaire are available and can be followed and adapted to the objective [81], [85], [86]. After completing the questionnaire a checklist can be useful to check the completeness of the questionnaire (figure 2-6a). The next step in designing a survey study is to conduct a check of quality of the questionnaire [87]:

- Check on face validity
- Control of the routing in the questionnaire

- Prediction of quality of the questions with some instrument
- Use a pilot study to test the questionnaire

Question design

The core of a questionnaire is the pool of questions. To develop a good questionnaire it is important to ask good questions. To design good questions some decisions have to be made: [87]

- Subject and dimension: a researcher has to choose the subject and dimension on which to evaluate the subject of the question
- Formulation of the question: different formulations of the same question are possible
- The response categories: choosing an appropriate response scale (see section 5.5)
- Additional text: besides the question and answer categories it is also possible to add an introduction, definitions, instruction and a motivation to answer.

Next to the kind of information and the type of question structure, the wording used in a questions and responses are of great importance. Researchers strive for objectivity in surveys and must be careful not to lead the respondent into giving a desired answer. Many investigators have confirmed that slight changes in the way questions are worded can have a significant impact on how people respond. Several authors have reported that minor changes in question wording can produce 25% difference in people's opinions. Adjectives and adverbs are subject to having highly variable

General questionnaire guidelines		
Questionnaire has:		
	an introduction	☐
	an appropriate first question	☐
	an opening set of questions that are easy to answer	☐
	a meaningful order to the questions	☐
	a clear section separation	☐
Self-completion questionnaire format guidelines		
Questions have:		
	a number	☐
	a common format	☐
	clear completion instructions	☐
	clear routing instructions	☐
	appropriate space for 'write in' answers	☐
	a format that distinguishes *Don't know*, *No opinion* and *Not applicable* options from lists of scale answer options	☐
Questions are not:		
	split across pages	☐
Questionnaire has at the end:		
	a thank you statement	☐
	instructions on how to return the completed form	☐

General question guidelines		
Questions do not include:		
	ambiguous terms or phrasing	☐
	technical terms	☐
	unnecessary negative phrasing	☐
	overly long lists of answer options	☐
	any ambiguity with reference to *you* as a singular or a collective	☐
Questions do not require:		
	respondents to do mental arithmetic	☐
Questions are not:		
	leading	☐
	overly long	☐
Questions do not ask:		
	more than one question at a time	☐
	the respondent about someone else or someone else's opinions	☐
Questions provide:		
	exhaustive answer options	☐
	an appropriate frame of reference for the respondent	☐
	appropriate *Don't know*, *No opinion* and *Not applicable* answer options	☐
Factual question guidelines		
Questions include:		
	definitions for unfamiliar concepts	☐
	answer option lists when recall is difficult	☐
Questions do not:		
	make unreasonable assumptions that behaviour or events are regular	☐
	require unrealistic factual recall	☐
Non-factual question guidelines		
Questions include:		
	extreme or strong agree/disagree statements	☐
	both positive and negative agree/disagree statements	☐
Questions do not:		
	require ranking that excessively increases the survey burden	☐
	ask about hypothetical situations	☐
Sensitive question guidelines		
Questions are:		
	preceded by a reminder of confidentiality	☐
	preceded by a reminder of the purpose of the research	☐
	located towards the end of the survey	☐

Figure 2-6 **a)** Questionnaire check-list **b)** Question check-list [88]

meanings and should be avoided in surveys [89]. Next to wording of the question itself, wording of technical terms is extremely important to get understandable questions. This deserves a dedicated section and is further described in the next two sections.

What makes a question a good question: [85]

- Asks for only one answer on only one dimension
- Can accommodate all possible answers
- Has mutually exclusive options
- Produces variability in response
- Follows comfortably from the previous question (see next part about ordering)

Just like in the design of the questionnaire a checklist exists to support checking the quality of the questions (figure 2-6b).

Word pool to describe steering feel

As mentioned as an important part of asking good questions, is to describe technical terms in such a way all subjects will understand. In literature a considerable debate of the right recipe for great steering feel exists. A variety of different criteria are used to define steering feel. Table 2-3 shows an overview of these evaluation items. For proper use of the items, two different mappings are used to categorize the items in different groups, based on the steering activity:

1) Straight ahead driving[a], ***driving stability***[b] and ride ***comfort***[c] [40]

2) First impression[d], maneuvering[e], straight ahead driving[f] and cornering[g] [90]

The difference between objective measures and subjective assessment evaluation items is the way of expressing. Where objective measures are characteristic values, subjective assessments results in subjects expressing feelings and perceptions in sentences and words. Nevertheless this big difference both uses dimensions to describe a system by using coordinates in pre-defined dimensions. The method of finding (multiple) dimensions of human perception regarding steering feel is based on the structure model called circumplex. It is a circle around a Cartesian coordinate system describing two dimensions of emotion [91]. In figure 2-7 the two dimensions are the pleasure-displeasure dimension (horizontal axis) and the arousal-sleep dimension (vertical axis). The remaining four variables do not form independent dimensions, but help to define the quadrants of space. The method is used to find the variables (words), the number of dimensions and their relation to each other which is declared by the words' position on the circle resulting in a word pool of 36 words, which could be expressed as nine dimensions (table 2-4). In subjective assessment these words can be used to ask the questions to derive the dimensions. Comparing the results of the research with the items describing steering feel:

- 4 dimensions are equal to one of the items: road feel, steering ratio, returnability and response
- 2 dimensions are equal to one of the item groups: comfort and stability
- 1 dimension is used as description for an item: resistance (friction)
- 1 dimension is not used as item, but comes close to hysteresis: play

Subjective item	Description	Source	Category
Effort and progression (cornering feel)	The magnitude of steering wheel torque and the progression of steering effort build up with increasing lateral acceleration	[16],[76],[92],[93],[59],[90],[18],[94]	c,d,e,f
Steering response	The vehicle dynamic behavior towards a steering wheel input	[18],[94],[90]	a,d,g
Steering torque feedback	The steering wheel torsional gain and frequency characteristics in response to changes in tire lateral force and aligning torque	[16],[90]	a,c,d,f,g
Returnability	The restoring torque felt when the driver is returning to the straight ahead position; closely linked with effort and hysteresis	[16],[90]	a,e,g
Initial steering torque	Force which is perceived at the steering wheel in the first instant when turning into a corner	[59]	
Steering precision	The ability of the steering system to precisely follow the track intended by the driver	[40],[59]	b
Friction	The ***resistance*** in the steering system to follow a driver's command	[59],[95],[90]	d
Damping	The gradual reduction of the gain of steering input	[95]	
Stiffness	Whether the steering stiffness over the whole steering angle range is appropriate.	[95],[92],[90]	d
Linearity of steering torque (gradient)	Whether steering torque change with respect to steering angle smoothly. Whether steering angle is foreseeable as steering torque is increased gradually	[92],[95]	b
Steering velocity	The velocity of the steering wheel to turn	[40]	b
Steering ratio / steering demand	The ratio between steering input and wheel turn	[125]	
Modulation	Easy learning of the steering systems characteristics	[9]	f,g
Hysteresis feel	The differences in steering torque required when steering away from versus returning to center	[19]	
Transient torque feel	How quickly steering effort changes during transient steering maneuvers: phase between steering effort and steering angle	[19]	b
Solid feel	Whether it is easy to keep the steering wheel at a fixed angle with appropriate friction	[171],[77]	
Centering feel	Whether it is possible to feel the center position of the steering wheel according to the reaction torque	[171],[77]	a
Sticky feel	Whether the steering wheel feels sticky when turning the wheel quickly from one direction to the other	[30]	a
Road feel	Whether the driver can feel the road; the impression imparted to the driver by the wheels of the vehicle in motion	[30],[95]	b,c
Smoothness	The steering system follows the natural response of the vehicle	[95]	
Roll reaction	The effect of the rolling action of the vehicle body to the steering system	[95],[90]	f,g
Roll reaction time lag	The time between the steering action and the rolling action of the vehicle body	[95]	
Correction demand after cornering	The extra input needed to correct a steering action after the maneuver.	[95]	
Steering torque drop-off before limit	The loss of steering torque around the limits of the vehicle.	[95]	
Overall evaluation	Whether the overall steering feel of this characteristics suits to drivers' preference	[92],[93]	

Table 2-3 Evaluation items for subjective steering assessment

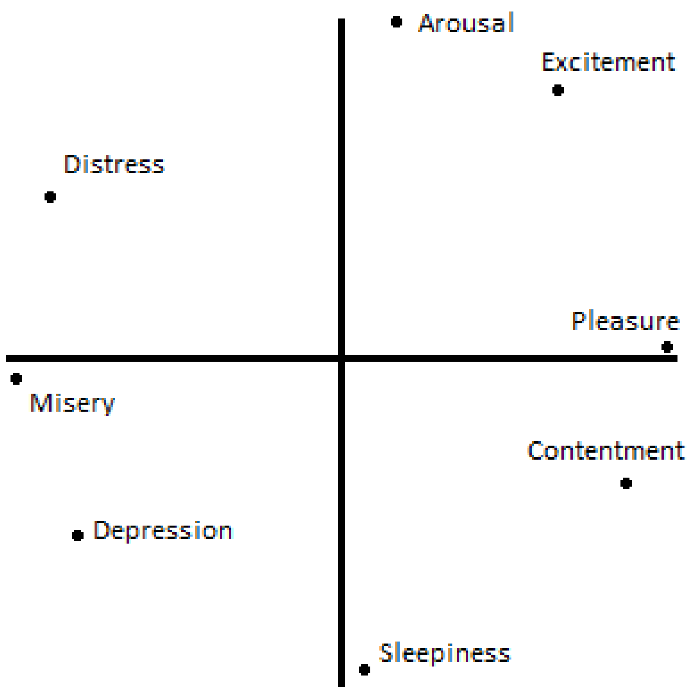

Figure 2-7 Eight affect concepts in a circular order.

Some words still difficult to understand, even in context. It is therefore useful to ask feedback from respondents at the end of a pilot test. The difficulty in finding the optimal steering characteristics, or rather steering feel, is found in the different subjective perceptions and assessments of each driver [76]. The need for a thorough definition of a vocabulary for subjective ratings that is understood by all test drivers can be assessed as well during the pilot test.

Concepts to assess control systems

Next to finding new ways to assess steering feel by designing new questions using a word pool, which results in a (not yet) validated questionnaire, steering feel can also be seen as a resultant characteristic of the steering system. From this point of view existing and validated questions and scales can be used from literature:

Dimension	Related words	Dimension	Related words
Stability	(un)Stable Directionally stable Rate-stable Sensitive to lane-grooves Wobbly	Resistance	Heavy-easy Inertial Light as a feather Force-requiring
Response	Controlled, Delayed, (in)direct, Distinct, Erratic Obedient, Quick, Reactive Precise, (in)Exact, Slippery, Sensitive	Jerk (comfort)	Jerky, Pulsing Stabbing, Shaky Steering wheel jerk Vibrating
Road feel	Road feel Road contact	Ratio	Large / small steering wheel angle required
Play	Play	Steering wheel return	Steering wheel return

Table 2-4 Dimensions of steering feel and related words [23]

System Usability Scale (SUS)

Usability is not a quality that exists in any real or absolute sense. Perhaps it can be best summed up as being a general quality of the appropriateness to a purpose of any particular arte fact [96]. The usability is a combination of: (figure 2-8a)

- Effectiveness: the ability of users to complete tasks using the system, and the quality of the output of those tasks
- Efficiency: the level of resource consumed in performing tasks
- Satisfaction: users' subjective reactions to using the system

System Acceptance Scale (SAS)

The idea of standardized tool is to measure driver acceptance of new technology [97]. The tool assesses system acceptance on two dimensions by nine 5-point scale items: (figure 2-8b)

- Usefulness of the system
- User satisfaction of the system

Rating scale methods

When people express their opinion they will use a library of expressive words instead of numbers. So the measuring results will have that character too. By using rating scales this results can be translated into numbers [7]. Different rating scales exist and it mainly depends on the research objective, the questions and the expert level of the subjects which method to use. Main characteristics of the different methods:

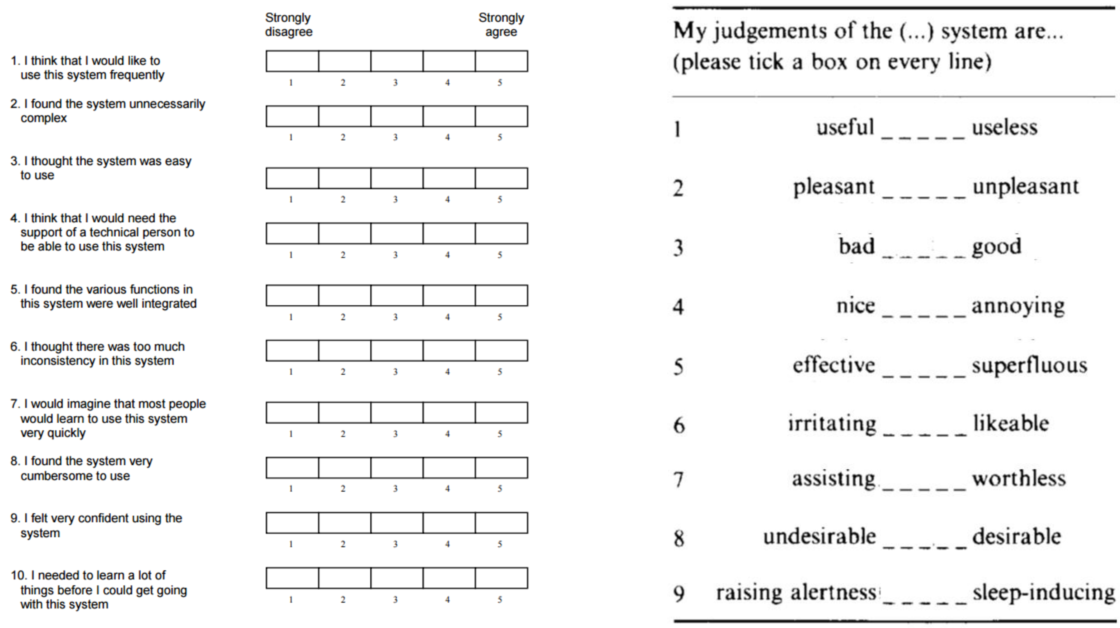

Figure 2-8 **a)** System Usability Scale (SUS) **b)** System Acceptance Scale (SAS)

- Symmetric vs. non-symmetric
- Number of points
- Continuous versus non-continuous
- Number of polars (uni-, bi-, tri,- etc.)
- Number of levels (one, two, three etc.)

The described SUS and SAS both use a 5 point Likert scale, but SAS uses a bipolar scale: from -2 to 2. The choice of the bi-polar evaluation scale has the advantage that the deviation from the optimum must be explained by the subject. By using different antonyms it is important to randomize the poles so that negative and positive connotations do not consistently fall on the same site [98]

Other dedicated scales to assess steering feel characteristics are shown in figure 2-9

- Improved SAE standard: 10 point quasi bipolar [99]
- Two level 10 point -1/+1 bipolar scale [31]
- Combination of two-level -4/+4 bipolar scale, two-level 6 point scale and 9 point scale [49]

2.5 Discussion

The objectives introduced in the first chapter will be used for a broad discussion about the strengths and weaknesses of the used terminology, approaches and methods and to find any conflicts or gaps which can be used in further research.

Appreciated steering feel is important with regard to driving experience and safety and depends on the quality (requires minimal steering correction and follow driver's intention accurately), predictability and informativity.

The steering system parameters play a role in defining steering feel, and so steering feel performance, as a function of three vehicular characteristics:

- Damping, inertia and non-uniformity in the steering system: steering activity
- Friction, stiffness and play in the steering systems: steering effort
- Impedance in the steering systems: vehicle response

Steering system parameters that change over lifetime are called steering system imperfections and can result in steering feel degradation. Earlier research on steering system parameters gave insight in the most important parameters: **play, stiffness and friction** [24].

1	2	3	4	5	6	7	8	9	10
UNACCEPTABLE				BORDER LINE	ACCEPTABLE				
CONDITION NOTED BY									
ALL OBSERVERS		MOST OBSERVERS		SOME OBSERVERS	CRITICAL OBSERVERS		TRAINED OBSERVERS		NOT OBSERVED
INTOLERABLE	SEVERE	VERY POOR	POOR	MARGINAL	BARELY ACCEPTABLE	FAIR	GOOD	VERY GOOD	EXCELLENT
1	2	3	4	5	6	7	8	9	10

Vehicle X

1 Parking Steering Torque too low [ ][ ][x] too high +7

Optimum = [ ]

Vehicle Y

1 Parking Steering Torque too low [x][ ][ ] too high -7

Steering Effort

Unacceptable (too light)			Acceptable			Unacceptable (too heavy)		
Extremely light	Quite light	Relatively light	Slightly light	Appropriate	Slightly heavy	Relatively heavy	Quite heavy	Extremely heavy
-4	-3	-2	-1	0	1	2	3	4

Steering Stiffness

Unacceptable(too small)			Acceptable			Unacceptable (too big)		
Extremely small	Quite small	Relatively small	Slightly small	Appropriate	Slightly big	Relatively big	Quite big	Extremely big
-4	-3	-2	-1	0	1	2	3	4

Linearity of Steering Torque

Unacceptable (linearity is bad)			Acceptable (linearity is good)		
Extremely bad	Quite bad	Relatively bad	Relatively good	Quite good	Extremely good
0	1	2	3	4	5

Solid Feel

Unacceptable (feel elastic)			Acceptable			Unacceptable (feel viscous)		
Extremely elastic	Quite elastic	Relatively elastic	Slightly elastic	Appropriate	Slightly viscous	Relatively viscous	Quite viscous	Extremely viscous
-4	-3	-2	-1	0	1	2	3	4

Steering Aligning Torque

Unacceptable (too weak)			Acceptable			Unacceptable (too fierce)		
Extremely weak	Quite weak	Relatively weak	Slightly weak	Appropriate	Slightly fierce	Relatively fierce	Quite fierce	Extremely fierce
-4	-3	-2	-1	0	1	2	3	4

Centering Feel

Unacceptable (too fuzzy)			Acceptable			Unacceptable (too sharp)		
Extremely fuzzy	Quite fuzzy	Relatively fuzzy	Slightly fuzzy	Appropriate	Slightly sharp	Relatively sharp	Quite sharp	Extremely sharp
-4	-3	-2	-1	0	1	2	3	4

Overall Evaluation

Bad			Middle			Good		
Extremely bad	Quite bad	Relatively bad	Slightly bad	Moderate	Slightly good	Relatively good	Quite good	Extremely good
1	2	3	4	5	6	7	8	9

Figure 2-9 Three examples of dedicated rating scales

Main advantages of using a simulator on the topic of steering system imperfections influencing steering feel:

- Convenience to quickly change steering system parameters
- Simulators are good at assessing driver performance

One main issue is the simulator sickness at low fidelity driving simulators. If desired this can be considered during subjective assessment by adding a simulator sickness questionnaire. A motion based simulation has many advantages over fixed based because of the earlier described psychophysical perception. Although the physical validity is important, behavioral validity as being the reproduction of driving response is mostly important. For this reason a fixed based simulator can still be very useful in human factors research.

Obtaining parameters for the steering system is a challenge, collecting steering system imperfection parameters even more. In the set up of the driving simulator scenarios it is important to have some insight in the direction and magnitude of the steering system imperfections.

To describe steering feel a large variety of subjective items exists. Before using one or more of these items in a questionnaire it is important to be sure that the subjects will understand what the meaning of a specific item is and that the subjects are able to assess this item. **Stiffness** and **friction** are difficult to be distinguished by non-professional drivers and maybe have to be combined to resistance or force needed to turn the steering wheel. The dimension of play is easily understood by all experienced drivers.

Important recommendations regarding the design project:

- Intimately involve test drivers during all phases to end up with a powerful research method.
- Using pilot tests can reveal a range of questions that participants are likely to have before and during the experiment.

In summary the following research gaps exist:

- Steering system imperfections are assumed to degrade steering feel, but this is still hypothesized
- Steering system imperfections do not necessarily result in bad steering performance
- In the set up of the driving simulator scenarios it is important to have some insight in the direction and magnitude of the steering system imperfections. This insight is not available
- Regarding the influence of steering system imperfections on steering feel no questionnaires exist

The first and second research gap points towards a new research opportunity, where the third and fourth gap needs to be incorporated in their experimental design.

3. Apparatus

In simulation studies human subjects must have the impression that they truly drive a vehicle to give an accurate judgment about their steering preferences. Cues that remind subjects that they are driving a simulator have the potential to ruin the perception of the steering feedback, regardless of how accurate the steering feedback [100]. The common theme is that simulators designed for human subject testing lack steering feedback realism. Beyond realistic steering feel, the steering has to be highly adjustable and provide environments that simulate typical driving situations.

To investigate the influence of steering system imperfections on truck driving steering feel a fixed based mobile truck driving simulator (MTDS) is used. Figure 3-1 shows the MTDS which consists of different hardware and software applications and is a dedicated research tool specially developed for the research purpose. This chapter will give an overview of the used components to design the simulator and discusses validation issues regarding the first use of this MTDS.

3.1 Hardware

The representation of a 40 tons DAF XF euro 6 truck-trailer combination is done by combining different components. This includes a steering wheel and pedals as control devices, but also other hardware like a driver seat and screens to visualize the environment the truck is driving in. Not included important controls are a gear shift lever, because of the automatic transmission and a direction indicator.

Steering actuator

The steering wheel is the main input for the driver to follow a track. The used device to represent the steering system is a Sensodrive Senso-Wheel SD-LC force-feedback-system (figure 3-2a) which has

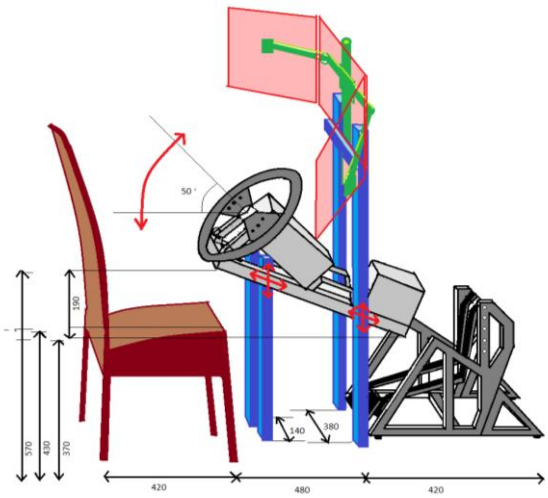

Figure 3-1a) Draft of the MTDS **b)** Final set-up of the MTDS

been developed for usage in driving simulators. This device not only processes the driver's input, but also provides realistic steering perception by applying sensitive force-feedback torques at the dynamics of the drive. The in the steering model calculated torques are transferred to the steering wheel. Using a customized adapter, the Sensodrive steering wheel is replaced by an original DAF truck steering wheel (figure 3-2b). The maximum torque is 16.58 Nm with a resolution of 0.03 Nm, the angle resolution is 0.009 degrees incremental, the gear ratio is a direct drive and cycle time is 1ms.

Pedals

Additional Sensodrive Senso-Wheel Pedals is used to enable the driver to control the speed of the articulated vehicle (figure 3-2c). The pedal system consists of a throttle, brake and clutch pedal. The clutch pedal is not used because of the automatic transmission of the truck. Using the pedals conveys a realistic driving experience.

Screens

The surroundings of the truck are visualized on three Dell P2214H IPS 22-Inch Screen LED-Lit Monitors which are mounted on an Arctic Cooling Z3 Pro triple monitor arm. The left and right screens are inclined around the driver position to provide of horizontal view of around 150 degrees. The resolution is 1920 x 1080 pixels at a refresh rate of 60 Hz max.

3.2 Computing components

The simulation of the handling behavior of the articulated vehicle is operated by a dSPACE Real-Time (RT) system incorporating a DS1006 Quad Core AMD Opteron™ processor board which operates an up to 50 DOF multi-body model of the truck with semitrailer [101].

Figure 3-2a) Senso-wheel **b)** DAF steering wheel **c)** Senso-wheel pedals
[a) and c) from:www.sensodrive.de b) from www.DAF.com/genuine-daf-options]

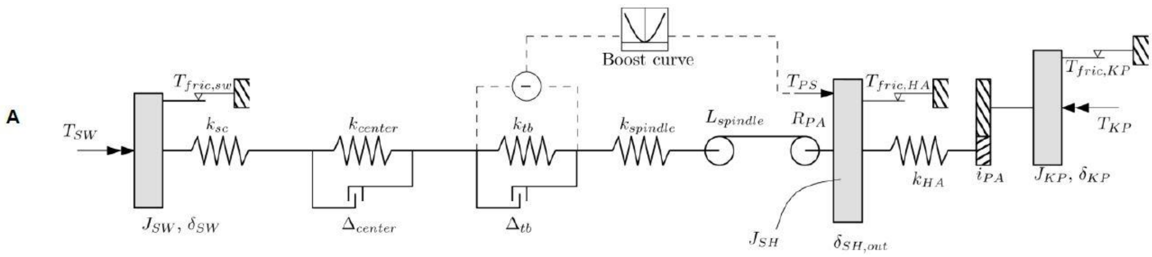

Figure 3-3 Steering model [102]

The steering model is a full non-linear multi-body model (figure 3-3) including:

- Friction on the input, the hydraulic cylinder, the bevel box and the kingpin.
- Play on the center, torsion bar and shaft.
- Dynamics on steering wheel, spindle, pitman-arm, drag-link and torsion bar

The tire model is based on Pacejka's non-linear tire model with relaxation behavior. An IO interface relates the Senso-wheel wheel and pedal components to the dSPACE.

One desktop PC is used to connect the three used processor boards (DS2002, DS2102 and DS4001) linked via a fiber-optic connection. An UDP connection is used to transfer data from the simulation software program to the dSPACE RT system.

3.3 Software

Next to the computation, the desktop PC runs the software used before, during and after the simulation. Matlab/Simulink runs on this PC where the models and control algorithms are adopted and enhanced. The animation data is transmitted from the desktop PC over one HDMI connection, with an active 1-to-4 HDMI splitter in between to the three monitors. To run the simulations two more software programs are used.

dSPACE Controldesk

Controldesk is dSPACE's universal experiment software for electronic control unit (ECU) development. It performs the needed tasks by uniting functionalities and provides a single working environment during the complete experimentation cycle. In the MTDS Controldesk is used to:

- Set experimental variables
- Start and stop the simulator
- Showing real time measures
- Collect the data during the simulation run
- Export the data to Matlab

ST Software

The MTDS is programmed with the use of ST Software, a program specially developed by experts in the field of DS technology and driving behavior research. ST Software package contains three categories of modules: design of simulation tasks, the runtime simulation and for the data storage. Figure 3-4 shows a functional overview of the driving simulator.

Two important modules in the design phase are first *stRoaddesign*, which a graphical designer tool to build a virtual road environment with roads, intersections, buildings, landscapes, trees and other objects. The road design used in this research consists of a more or less thirteen kilometers long realistic motorway section with a couple of exits and entries. This 2D design will be converted into a full 3D environment. Second important module is stScenario, which is used to write the scenarios defining the traffic participants, traffic conditions and data storage scripts used for the UDP transfer of data to the dSpace system. A group of modules form the real-time simulation environment, with first stControl as the graphical user interface (GUI) of the simulator. The main functionalities and measures are copied into the Controldesk GUI. Second stRender is used as the

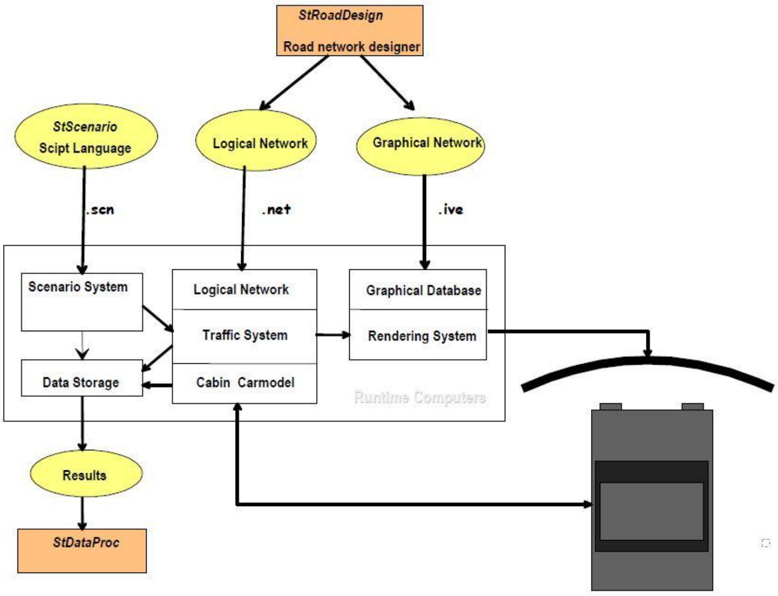

Figure 3-4 Functional overview of the DS. From: www.stsoftware.nl/data/doc/StScenario

graphical rendering module ensuring real time visualization from the truck cabin (figure 3-5). Next to rotation around the vertical axis (yaw), rotation around the longitudinal axis (roll) and rotation around the lateral axis (pitch) are included in the visualization.

Despite the laboriousness of the scenario design and the medium quality of visualization the advantages of ST Software are the natural driving behavior of other road users and the realistic traffic environment, securing the validity of the experiments.

3.4 Validation

This research was the first time that the MTDS has been used and so the different components had to be checked on validity. Most of them were validated during earlier research [10], like the vehicle model, the steering model (figure 3-6), the simulation software and the Sensodrive Senso-wheel and Pedals. Some components still had to be identified, checked and adapted to reach a high fidelity standard.

Figure 3-5 Visualization from the cabin (compressed in width to fit to paper)

The identification was done by interviewing truck drivers, recording truck rides from the view of the driver and monitoring the driver's viewing habits, measuring dimensions, using employment guidelines and let professional drivers run test drives on the simulator. Items to check were the correct replacement of the original steering wheel for the DAF steering wheel, the view from the driver and the dimensions of the configuration of the hardware.

Steering wheel torques

The consequence of the replacement of the original Senso-wheel for a DAF steering wheel can be an incorrect torque measurement by the internal measurement device, because of the different inertia of the steering wheels. The applied torques were therefore measured with an external Senso-wheel Steering Torque Sensor (LMS) and compared with the measurement of the Senso-wheel system. Only a very small deviation was detected, and not significantly more than the normal measurement difference between the two measurement devices.

View driver

To monitor the view from the driver, during a couple of rides a professional truck driver was recorded using two GoPro HD Hero3+ Silver Edition action cameras: one mounted on the forehead of the driver, the other pointed at the driver. The obtained knowledge from the rides: frequent use of the mirrors for lane keeping purposes, the view in the mirrors and the fact that there is not that much rotation during on-center handling.

Next to these recordings, a professional truck driver made different test drives in the fixed based simulator (figure 3-7) [9]. Next to continuous adjustments on view and mirrors the main feedback issue is the incorrect orientation of the steering wheel and steering column.

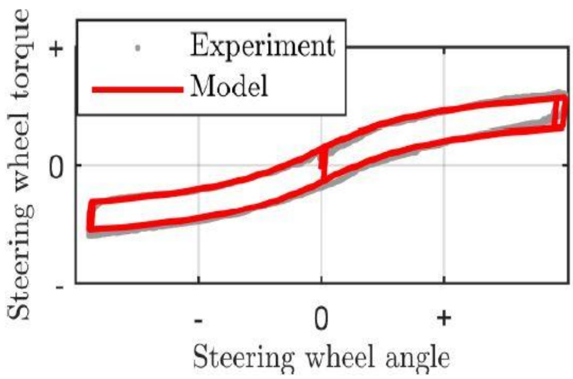

Figure 3-6 Validation of the steering model (no axis-labels due to confidentiality) [102]

Figure 3-7 Test run on fixed based simulator

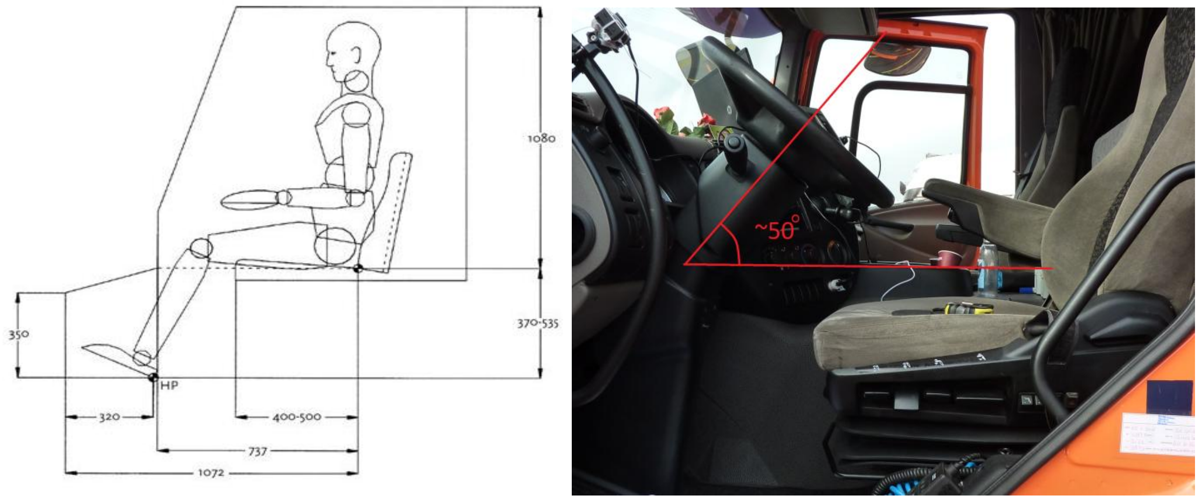

Figure 3-8a) Employment requirements Of truck cabin dimensions [103] **b)** Steering wheel inclination angle of a Truck Steering System

Dimensions of the configuration

The remark on the incorrect orientation of the steering wheel is added to the employment guidelines regarding the dimension requirements of the truck driver cabin (figure 3-8).

In order to meet the requirements a construction of 40x40 aluminum profiles was designed (figure 3-9a) and fabricated by ITEM (figure 3-9b;3-9c), which enables the flexible adaptation of the MTDS dimensions irrespectively the driver and the inclination angle. The Senso-wheel (figure 3-2a) was mounted on two carriers which can rotate to meet the inclination angle. Within the construction the Senso-wheel can also freely move in three directions to meet the employment requirements. The monitor arm was also mounted to the stable construction.

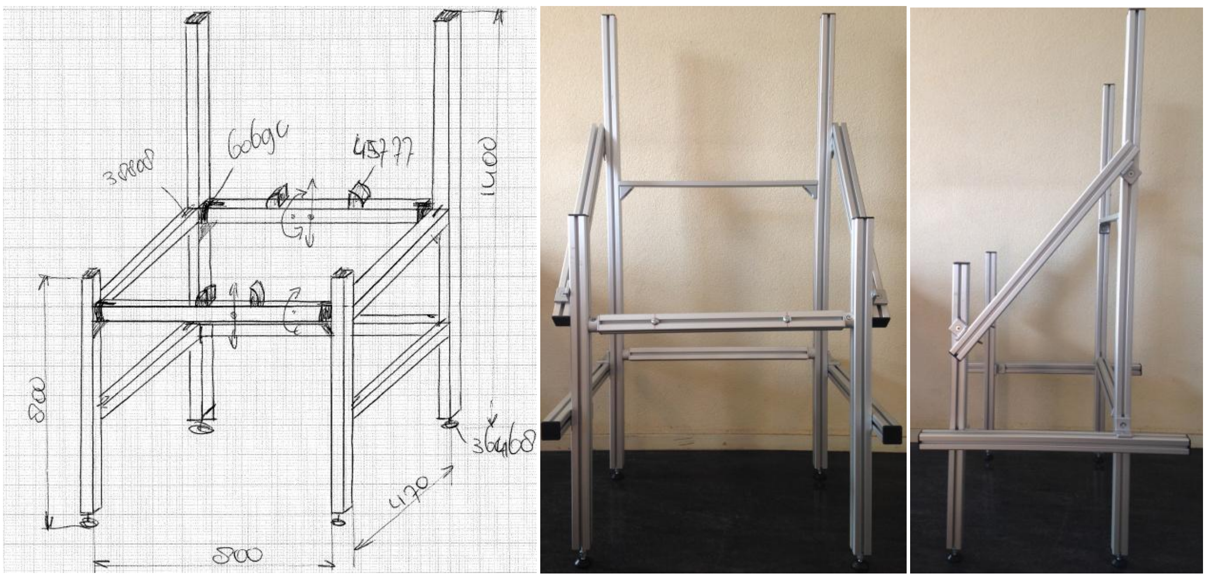

Figure 3-9 **a)** Design of construction **b)** Final product front **c)** Final product side

4. Explorative Research

In chapter one road safety is introduced as an important concern of the federal government. The difficulty of assigning the main causes of accidents can result in overestimating the number of accidents caused by human errors. As described in the steering system section (Chapter 2.2) over the lifetime of an articulated vehicle the steering system degrades. These so-called steering system imperfections are quantified by its steering system parameters. In literature no dedicated information is given about the location and values of these imperfections. Designating the components and involved coefficients is done by using the earlier described literature, interviews with a maintenance engineer, putting questions on forums. In total six steering system parameters are selected (figure 4-1) and investigated during the pilot experiment.

1. Column bearing friction
2. Bevel box friction
3. Hydraulic cylinder friction
4. King pin friction
5. Free play in the system
6. Tie rod stiffness

The six steering system imperfection parameters need to be given a thought-out value to find the influence of steering system imperfections on steering feel. The purpose of this pilot study is to find out to what extent the values of the parameters are still acceptable to professional truck drivers driving a truck. The important condition is that using this property value keeps the steering system stable. This forms the first research questions of this thesis:

RQ1: What are the minimum or maximum values of the six designated steering system parameters within the boundaries of a realistic and stable steering system?

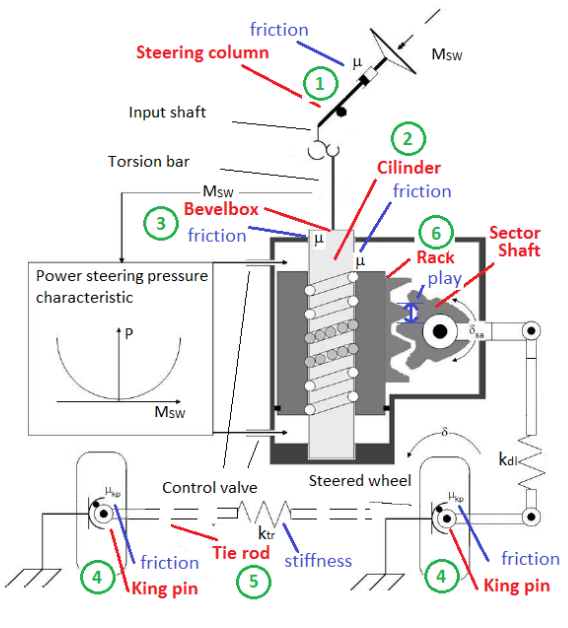

Figure 4-1 The six steering system imperfections: component and dynamic coefficient

4.1 Method

To find the extreme values the simulator apparatus as described in chapter 3 is used. During the truck driving simulator study this search can be approached by applying a threshold tracking method (figure 4-2). The idea of this method is to present subjects with a sequence of stimuli, where the next stimuli is defined by the subject, based on the last answer of the polar question/assertion (yes/no; correct/incorrect; agree/disagree). The algorithm in the figure can be characterized by:

- Threshold method: minimum
- Initial value: 6
- Time step: 1 second
- Step size: 1
- Number of identical answers before making a step: 2
- Duration: 46 steps

The threshold method differs between the six parameters: for play and friction the method is used to find maximum threshold value and in case of stiffness it is used to find a minimum threshold value. The idea is to find this value during a fixed time period. This asks for an algorithm with a predefined time step, a certain step size up/down, a number of steps down/up after a negative answer and, if desired, the possibility to change the step size. The algorithm is implemented in the GUI of dSPACE ControlDesk including the controls to run the pilot study (figure 4-3).

Participants

The test group consisted of 6 Dutch male drivers with an average age of 43.7 years (SD = 16.4). They all had a full European standard CE driving license for on average 25.5 years (SD = 17.0). On average they drove a total distance of 1.3 million kilometers (SD = 0.87m) with on average a yearly distance over the past three years of 52.500 kilometers (SD 29.111 km).

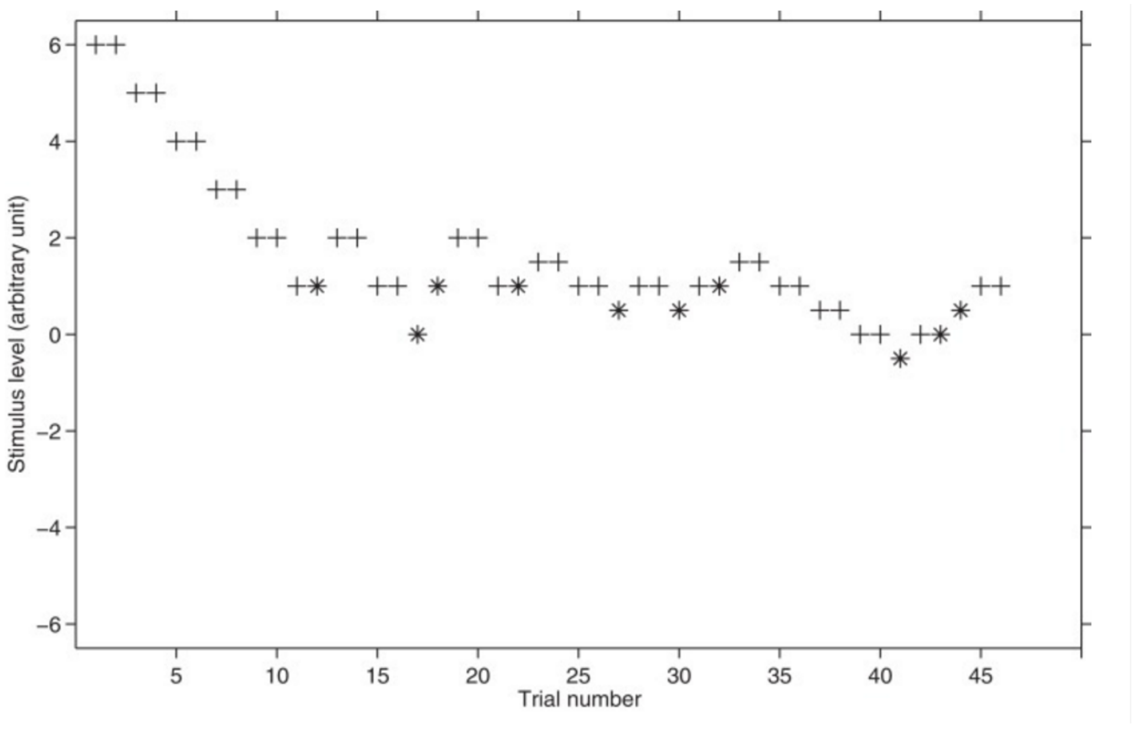

Figure 4-2 Threshold tracking method [104]

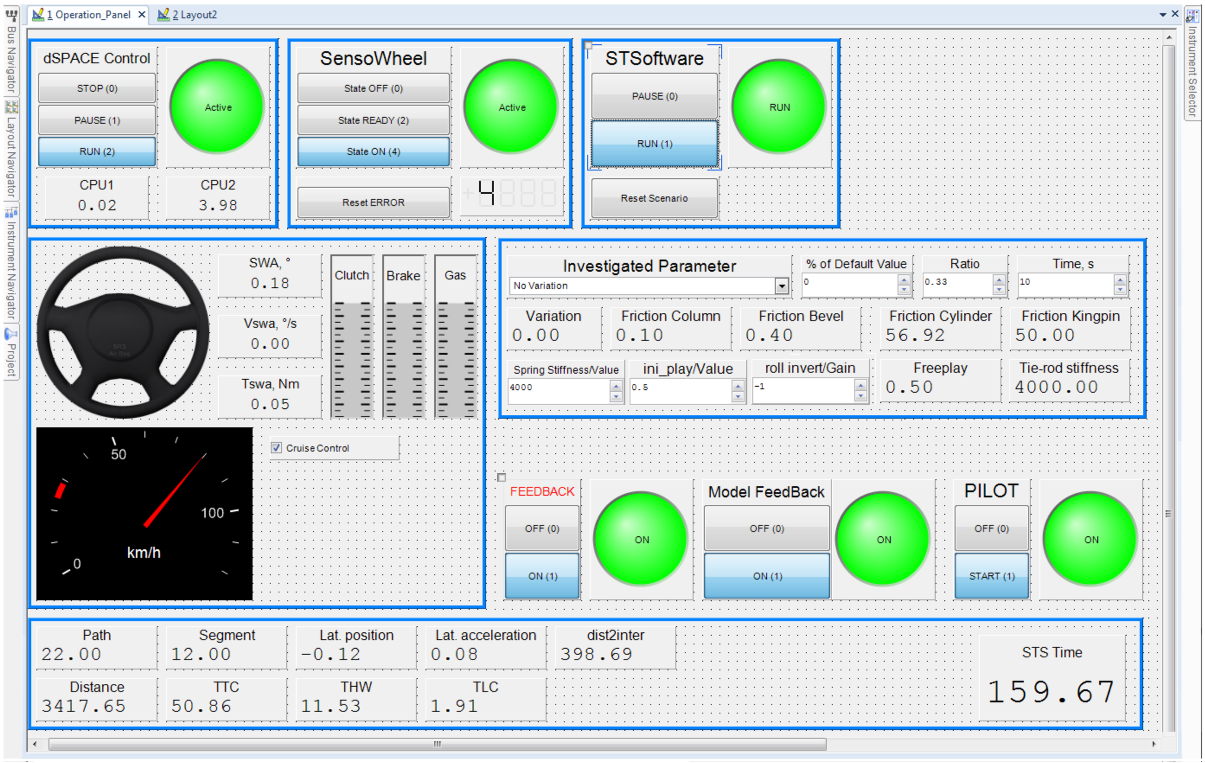

Figure 4-3 Controldesk GUI of pilot experiment (running mode)

In general all participants drove on daily basis different truck brands (4x MAN, 2x Scania, 2x DAF, 2x Volvo, 1x Renault) and with different configurations: no trailer, semi-trailer and trailer.

Experimental design

During the experiment the participants are asked to continually drive the same route starting with a 1.5 kilometer long highway ramp entering a 12 kilometer long motorway (figure 4-4). The road environment is a realistic reconstruction with three motorway exits and entries and includes the necessary traffic signs. The lanes on the highway are dimensioned by the guidelines from the Dutch Department of Public Works [105]. The variety of curves with different angles and radii all generate less than 2 m/s^2 lateral acceleration with a calculation speed of 95 km/h, which corresponds to on-center handling.

Subjects were instructed to keep driving on the motorway and show the driving behavior they are expected to show, obeying the normal traffic rules, taking into account the fellow road users and overtaking slow traffic if needed. The initial vehicle speed was set 10 km/h above the maximum allowed speed of 80 km/h for two reasons. First this was because of the experimental start up time and second to provide the subjects with some time to familiarize with the mode of the system.

The experiment consists of six rides, whereby in each case one of the six steering system parameters is adjusted. Because the different rides will not be compared with each other, the same sequence is applied to all subjects equal to the used numbers in figure 3-1. During the ride the magnitude of the property will be constantly changed. The task of the driver is *to track the moment when the steering system does not show realistic steering feel anymore*. If this is the case the driver is asked to press the clutch pedal, which will be followed by a short beep sound to inform the driver he hit the clutch.

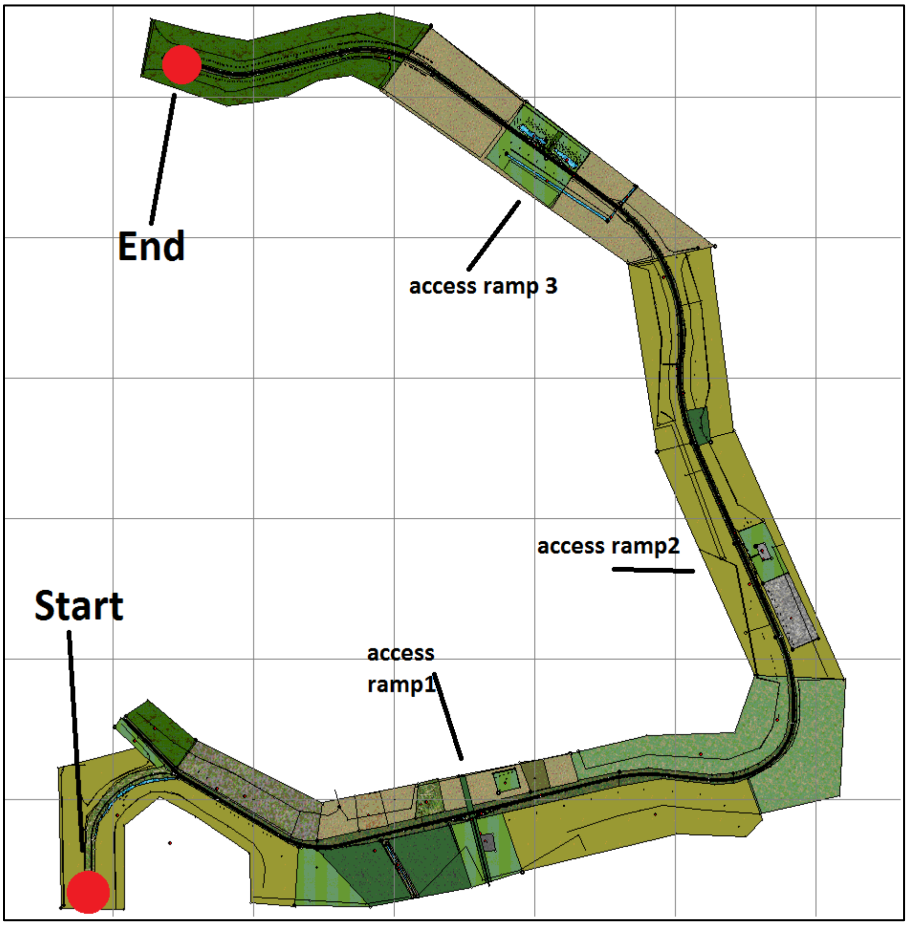

Figure 4-4 Overview of the track with grid = 1x1 km.

From this point the property will change back in the direction of the initial value. The duration of the experiment is 10 minutes.

Procedure

Using the mobile property of the simulator, the researchers visited the location preferred by the participants. The first participant visited the TU Delft laboratory, two participants were examined at their home address and three others at their company address. When they arrived at the experimental room they received a consent form including instructions about the goal and content of the experiment. After signing the consent form the participant had to fill in a questionnaire A (see Appendix A-1) to provide some background information about age and experience in truck driving.

Next the participant toke place in the simulator and the configuration was adapted to the driver's preference and habit. In order to get accustomed with the simulator all participants drove a 10 minutes training session on the same described motorway track with the realistic steering model (all six parameters at initial value). After the training session the participants had to drive the six rides with the main task to press the clutch pedal at the moment of unrealistic steering feel. After each trial the participant was asked if a break is needed, if not the next trial is started. To minimize the risks of making any mistakes during the reconfiguration, run and recording of the different test runs the researcher made use of a checklist (Appendix B-1).

Defining the algorithm values

The threshold tracking method uses a predefined algorithm to find the extremes of the steering system parameters. This algorithm is based on:

- Initial value
- Time in between steps
- Initial step size
- Number of steps back
- Final step size

The initial values follow directly from the validated steering model, the other are predefined by the researchers and defined by running an explorative experiment using the first participant.

Figure 4-5 shows the result of this test run. The blue are the applied values during the tracking method, the green line indicated a press on the clutch as executed by the subject. Using the results of the test the final algorithm values are chosen (table 4-1). The nominal values are chosen before the test run and can be freely changed using a percentage of this value. Time step for all six trials is set to 5 seconds and only the tie rod stiffness uses a smaller step size after the first clutch hit. The limit value of the algorithm is based on safety, actuator properties and the computational power of steering model.

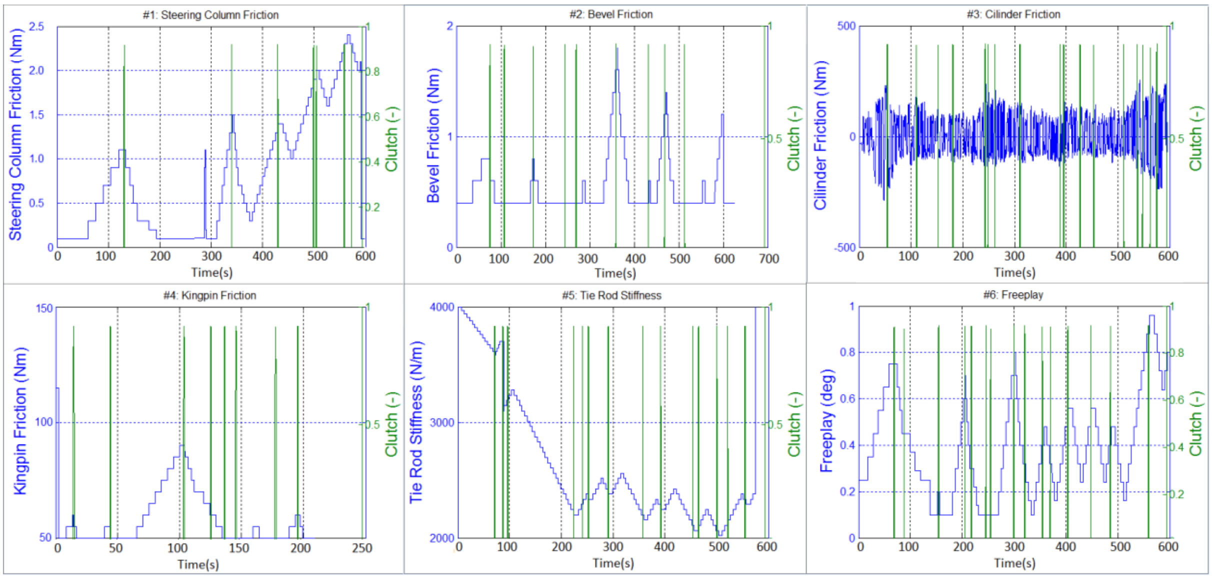

Figure 4-5 Results of test to define algorithm settings

#	Steering System Parameter	Initial value	Nominal value	Defined Initial step	Percentage	Time	Ratio 2nd step size	Limit value
1	Column friction (Nm)	0.1	0.4	0.1	25%	5	1	3.1
2	Bevel friction (Nm)	0.4	0.4	0.4	12.5%	5	1	2.8
3	Cylinder friction (Nm)	0	100	10	10%	5	1	1100
4	King pin friction (Nm)	50	50	10	20%	5	1	400
5	Tie rod stiffness (N/m)	4000	300	90	30%	5	0.5	100
6	Free play (deg)	0.1	1	0.04	4%	5	1	n/a

Table 4-1 Final chosen algorithm values to run pilot experiment

Data processing

During the experiments 69 different measures are recorded, including motion states, steering system state data, driver input and the orientation of the truck. Because driver performance is not part of the task description most data is just recorded for descriptive reasons. Important recorded data are:

- Runtime
- Values of the steering system parameters over time
- Moment of hitting the clutch

The data will be recorded from the start of running the scenario at a frequency of 50 Hz. The pilot study algorithm will be started within 10 seconds.

To analyze the recorded data for each of the parameters a plot is generated combining all five subjects. A box plot together with a representation of the mean is used to find the extreme values of the six steering system parameters. Next to this objective data registration, the participants are asked to provide feedback of how realistic the imperfections felt to them. This will help to find the most realistic parameters to further investigate.

4.2 Results

The results of the pilot experiment for each of the five participants (#1-#5) regarding the six steering system parameters are respectively plot in six graphs (figure 4-6). Box plots (figure 4-7) give an overview of the total results for each of the parameters. For more comprehension the mean value is added to the plots, clearly marked by an ‘x’.

Steering column friction

The results show that all subjects get adapted to an increasing steering column friction, clearly indicated by all reaching the maximum value of 3.1 Nm. There is a big difference between the subjects. The participant (#5) not depressing the clutch pedal indicated that, although he disliked the increased magnitude of friction, to him it still feels realistic due to his experience driving outdated trucks. Participant #1 clearly stated that due to the malfunctioning of the HPS system in his truck the past months he is used to high resistances. And although participant #3 is more used to later truck steering systems he also get used to the higher friction, resulting in not indicating that the steering system does not feel realistic anymore. The mean threshold value was therefore a lot higher than the first opinions of the drivers.

Bevel friction

The change in the amount of bevel friction was more often observed by the participants. Around a magnitude of 1Nm the steering wheel showed lots of vibration which did not feel realistic to the drivers. This is confirmed by the box plot showing little deviation.

Cylinder friction

Because the magnitude of the cylinder friction is steering rate dependent, the plot shows the tuning signal for better comprehension. Different than the steering column friction, participant #1 indicated that the change in cylinder friction felt very unrealistic to him. Also other participants did not reach the maximum level and stayed around the same threshold value. The box plot shows that this value

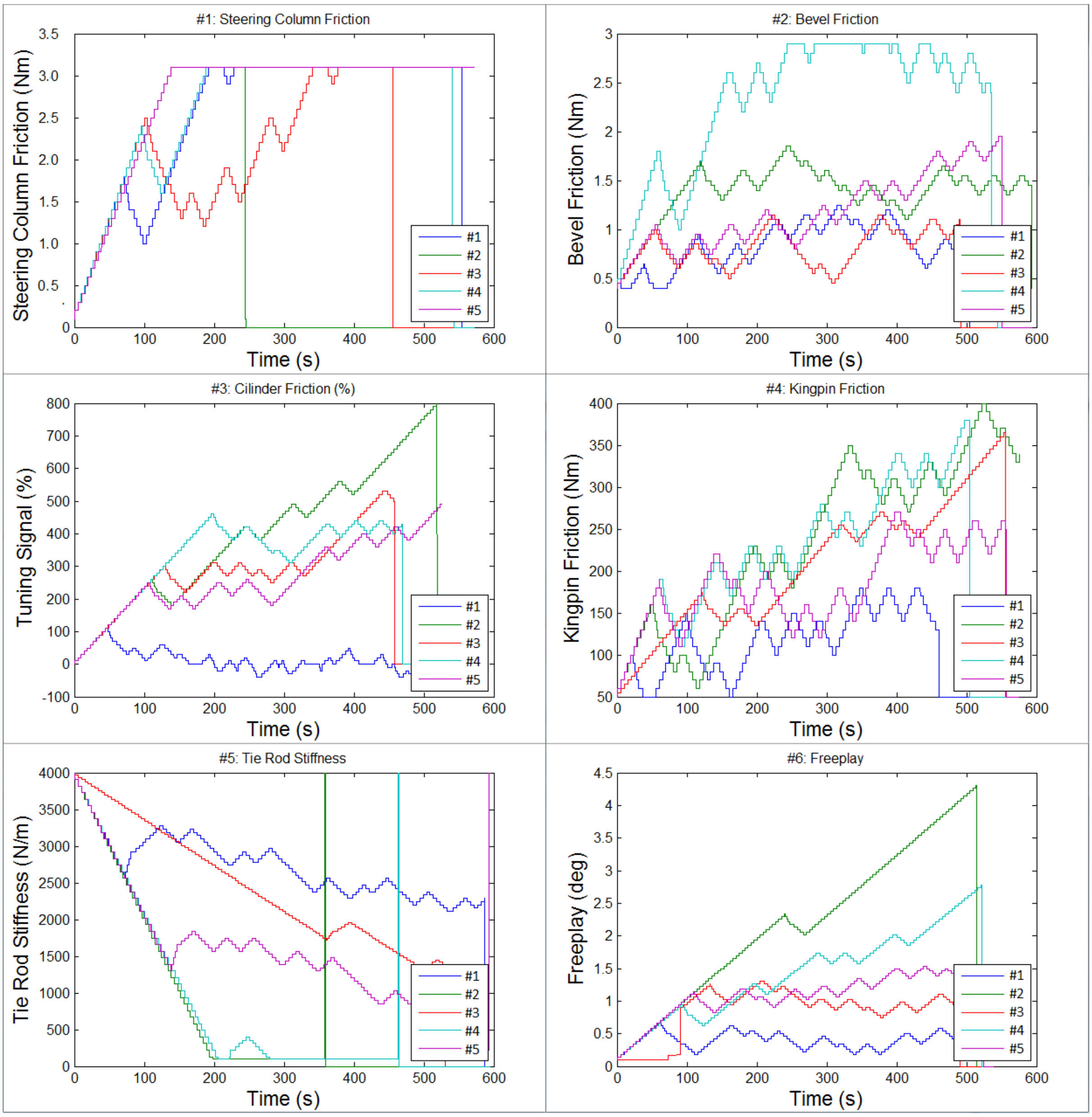

Figure 4-6 Results of the pilot experiments for the six steering system parameters

was different for each of the participants due to the deviation. Participant #2 reported clearly that he did not like the idea of depressing the clutch too much.

Kingpin friction

The change of the next tested parameter was clearly felt by the drivers, resulting in a high number of clutch hits. The fact that the change was deep into the system did not show any problems. Participant #5 stated that it felt to him that the wheels were kind of stuck. The box pot shows not much scatter and equal around the mean value.

Tie rod stiffness

The decrease of tie rod stiffness, resulting in turning the truck by only the left wheel was not felt by two drivers; even if the right wheel was not controlled anymore by the driver. Other participants indicated less reality at a certain moment. Participant #3 followed a different, and thus incorrect,

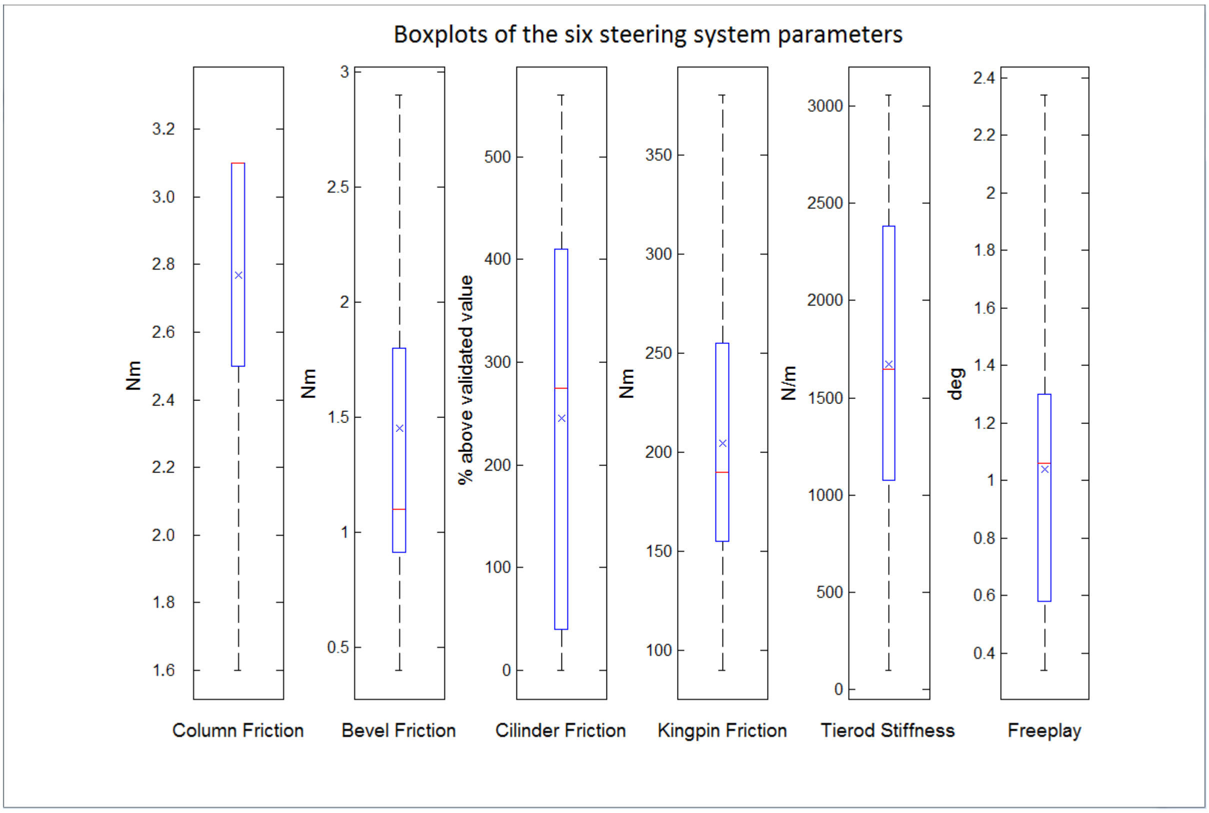

Figure 4-7 Box plots of the six steering system parameters: red = median value (IQR); lower Whisker = 1st quartile, blue box = 2nd + 3rd quartile, upper whisker = 4th quartile blue box. No outliers (>1.5*IQR). Blue 'x' is the mean value.

algorithm than the others and has been deleted. Confronting the drivers with the imperfection afterwards, resulted in a similar opinion. The mean value is already at a magnitude that the right wheel is not controlled anymore

Free play

Most of the drivers had clearly an opinion about the increase of free play. Only participant #4 did not share the idea of a less realistic steering system. Confronting the participant again resulted in not willing to follow the task description. His opinion increased the mean value, but still the deviation is acceptable.

4.3 Discussion

From the results section, and also earlier indicated, it became clear that the task description was too laborious to participant #2. For this reason this participant was deleted from the results. The steering system parameters not suitable to further investigate are:

1. Bevel box friction

The vibration in the steering wheel felt unrealistic to the drivers and can be due to numerical instabilities of the steering model at certain values of friction. Without further testing of arising instabilities the bevel box friction is not investigated in the final experiment.

2. Cylinder friction

The cylinder friction was highly different evaluated by the drivers. This can be because the amount of friction is steering rate dependent and therefore difficult to assess by experienced but still non-expert test drivers. This is the reason also the cylinder friction will no longer be part of the experiment

3. Tie rod stiffness

The tie rod stiffness was felt by the drivers, but feedback afterwards showed the need of cabin motion. When the tie rod is less stiff or even broken, the cabin will show lots of vibration at the right hand side. Three drivers indicated they had experienced a malfunctioning tie rod before. This reasoning let to also not taking the tie rod stiffness into consideration.

Independent variables and values

The removal of one participant and three parameters resulted in the three steering parameters to test in the final experiment: the column friction, the kingpin friction and the free play. The idea is to test the participants during the final experiment on seven different steering system set ups. This will be further described in the next chapter.

The values to consider during the experiment are next to the baseline, two values for each of the three parameters:

- Baseline value: from validated steering model
- Value 2: mean value + 1 time the standard deviation (to increase the significance level)
- Value 1: in between the baseline value and value 2

The final data used to calculate the means and standard deviation is the minimum number of clutch (m) hits by all four participants regarding the column friction (m=3), king pin friction (m=6) and free play (m=6). Table 4-2 gives an overview of the experimental values.

Property	Column Friction (Nm)	Kingpin Friction (Nm)	Free play (deg)
Mean	2.642	189	1.1
Standard deviation	0.620	55	0.43
Baseline value	0.1	50	0.1
Value 1: in between baseline and value 2	1.681	147	0.81
Value 2: from pilot experiment	3.262	244	1.53

Table 4-2 Experimental values

5. Main Experiment

The pilot experiment on the main steering system imperfections resulted in finding an answer on the first research question. First by assigning three steering system parameters to further investigate during a driving simulator study: column friction, kingpin friction and free play. Degradation of the steering system is a result of the increase of the dynamic coefficient of these parameters during the lifetime of the steering system. Secondly by defining the maximum increase of the values for each of the parameters at which the degradations still result in a realistic steering system.

In chapter 2 the definition, dimensions and assessment of steering feel are introduced. The objective of the research is to investigate the consequences of the critical changes of the steering system parameters on the steering feel of truck drivers during on-center highway driving. To reach the objective results in a second research question:

RQ2: How do steering system imperfections affect steering feel of professional truck drivers?

Hypothesized is that steering imperfections degrades steering feel of the truck driver. This can be split into three different hypotheses.

I. *The increase of play in the steering system during the lifetime of the articulated vehicle degrades the steering feel of the truck driver*
II. *The increase of column friction in the steering system during the lifetime of the articulated vehicle degrades the steering feel of the truck driver*
III. *The increase of kingpin friction in the steering system during the lifetime of the articulated vehicle degrades steering feel of the truck driver*

Important in any driving simulation study is the driver performance. The variation of the steering system parameters can have an influence on the objective metrics of driver performance.

RQ3: How do steering system imperfections affect the objective indicators of driver performance of professional truck drivers?

I. *The increase of play in the steering system during the lifetime of the articulated vehicle negatively affects the objective indicators of driver performance of the truck driver*
II. *The increase of column friction in the steering system during the lifetime of the articulated vehicle negatively affects the objective indicators of driver performance of the truck driver*
III. *The increase of kingpin friction in the steering system during the lifetime of the articulated vehicle negatively affects the objective indicators of driver performance of the truck driver*

The driving simulator experiment is designed in such a way that for each of the three steering system parameters both research questions are clearly defined by using the influences on steering feel as the main aspect of this research.

5.1 Method

To evaluate the influence of steering system imperfections on truck driver steering feel the simulator apparatus as described in chapter 3 is used. The participants were tested during several runs, but different than during the explorative research the steering system was unchanged during the run.

Participants

In order to obtain valid and useful subjective results it is important to select the right persons to participate in the experiment. The objective of the research asks for skilled and experienced drivers. Because skill is based on the (unknown) qualification of the driver, subjects were selected on level of experience, based on:

- Drove a high lifetime mileage (>250,000km) or highly yearly mileage (>32,500km) [6]
- Used to drive with a truck-(semi)trailer combination
- Years of having driving license (>5 years)
- One out of 17 is normally a female driver [6]
- Active driver

Reasons to use experienced drivers are that the mental state and environmental conditions will vary between experiments [106] and that they show smaller levels of stress needed in a simulation study where subjects are conscious that they cannot be exposed to risks as they usually are on the real road [107]. The result from one subject is deleted after running the experiment because of the selection criteria.

The test group consisted of 18 male Dutch drivers with an average age of 43.9 years (SD = 12.4). They all had a full European standard CE driving license for on average 24.2 years (SD = 14.2). On average they drove a total distance of 1.8 million kilometers (SD = 1.43m) with on average a yearly distance over the past three years of 79,167 kilometers (SD 35,282 km). In general all participants drove on daily basis different truck brands (9x DAF, 6x Scania, 4x MAN, 2x Volvo, 2x Mercedes-Benz, 1x Renault) and with different configurations: semi-trailer (14x), trailer (9x) and no trailer (2x). Divers which have several more driving hours per week than an average driver are considered as highly experienced drivers [79]. Based on this definition 15 participants are identified as highly experienced drivers (>65,000km yearly).

Experimental design

During the experiment the similar route is used as during the explorative research: The participants are asked to continually drive the same route starting with a 1.5 kilometer long highway ramp entering the 12 kilometer long motorway. The road environment is a realistic reconstruction with three motorway exits and entries and includes the necessary traffic signs. The lanes on the highway are dimensioned by the guidelines from the Dutch Department of Public Works [105]. The variety of curves with different angles and radii all generate less than 2 m/s^2 lateral acceleration with a calculation speed of 95 km/h, which corresponds to on-center handling.

Subjects are instructed to maintain driving on the motorway and showing normal driving behavior, obeying the normal traffic rules, taking into account the fellow road users and overtaking slow traffic if needed. The initial vehicle speed was set 10 km/h above the maximum allowed speed of 80 km/h for two reasons. First this was because of the experimental start up time and second to provide the subjects with some time to familiarize with the mode of the system. The repeated-measures within subjects experiment consists of seven rides including a baseline run without modification of the steering system. During each ride, compared to the baseline configuration, only one of the steering system parameters is changed to its desired value to modify the steering system (table 5-1). In contrast with the explorative research, the steering system model will be unchanged during the ride. To provide the participants with enough time to evaluate the system, the duration of the experiment is set to 5 minutes.

Procedure

Using the mobile property of the simulator, the researchers visited the location preferred by the participants. In total four locations are visited to run the experiments, 11 participants were examined at two home addresses and seven participants at their company address. When they arrived at the experimental room they received a consent form including instructions about the goal and content of the experiment. After signing the consent form the participant had to fill in questionnaire A (Appendix A-1) to provide some background information about age and experience in truck driving.

Next the participant takes place in the simulator and the configuration is adapted to the driver's preference and habits. In order to get accustomed with the simulator all participants drove a 5 minutes training session on the same described motorway track with the realistic steering model (baseline setup u from table 5-1). During the training session the participant can ask any questions regarding the simulator set-up. After the training session the participants had to drive the seven rides (table 5-1) with the main task to evaluate the steering system. After running the experiment for 5 minutes, the simulation is aborted by the researcher and the subject is asked to fill in a questionnaire. This questionnaire (see Appendix A-2) will be further described in the next part of this section. After each trial the participant is asked if a break is needed, if not the next trial is started. To minimize the risks of any mistakes during the reconfiguration, run and recording of the simulator the researcher makes use of a checklist (Appendix B-1).

Randomization

In a simulation study it is important to consider the issue of learning. Familiarization of the experimental setting by learning has an influence on what drivers likes and which system setting leads to higher objective and subjective scores. To deal with learning effects first familiarization of the simulator is needed, therefore the training session is included. Next to training the second way is to randomize the order of the repeated-measures study. For this purpose a Latin square design is used, which is an m-by-n array with m subjects and n repeated measures. In the array each experimental value occurs only once in each n rows and each n columns (table 5-2).

Experimental setup	Column Friction (Nm)	Kingpin Friction (Nm)	Free play (deg)
1: Baseline	0.1	50	0.1
2: Column friction value 1	1.681	50	50
3: Column friction value 2	3.262	50	50
4: Kingpin friction value 1	0.1	147	50
5: Kingpin friction value 2	0.1	244	50
6: Free play value 1	0.1	50	0.81
7: Free play value 2	0.1	50	1.53

Table 5-1 Experimental conditions

Experiment:/subject:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
#1	1	3	7	7	6	4	4	2	5	3	2	6	6	5	1	7	3	1	4	5	2
#2	6	6	3	5	4	7	2	5	3	4	3	2	7	6	2	1	1	4	5	1	7
#3	3	7	4	2	1	1	6	6	7	7	6	3	3	2	5	4	5	5	1	2	4
#4	4	1	5	3	2	2	7	7	1	5	4	4	1	7	3	2	6	6	6	3	5
#5	5	2	6	4	3	3	1	1	2	1	7	5	4	3	6	5	7	7	2	4	6
#6	2	4	1	1	7	5	5	3	6	2	1	7	5	4	7	6	4	2	3	6	3
#7	7	5	2	6	5	6	3	4	4	6	5	1	2	1	4	3	2	3	7	7	1

Table 5-2 Randomization by Latin square design (red = withdrawn from the experiment).

Data processing

During the experiment 65 different measures are recorded, including motion states, steering system state data and driver input. Because driver performance is not the main task of the participants the use of driver performance measures is limited and has to be assessed with restraint. The evaluation of the steering system by the driver is assessed with a questionnaire. To evaluate the driver performance different objective indicators are calculated.

Subjective Assessment

The questionnaire used to assess the consequences of the experimental modification of the steering system on the truck drivers steering feel is designed by using multiple sources. First by making use of the literature from chapter 2, second by interviewing professional truck drivers, third use the experience of subjective evaluation and last by continuous improvement using the reviews from professional truck drivers. The evaluation is approached by a combination of four elements: general experience, steering system settings, steering system acceptance scale (SAS) and the realism: the quality of being realistic. These subjectively assessed elements, each with a dedicated rating scale, will be further described. The complete questionnaire can be found in Appendix A-2.

General experience and vehicle handling

The experience of the drive is separated in two parts: workload and vehicle handling. The workload is approached by four items: the difficulty of the ride, the risk level during the ride, the level of mental and level of physical effort. The 7 point scale is from 0 [not at all] to 6 [very (much)]. The handling characteristic of the ride is included in the questionnaire by asking to indicate to which extent the subject agrees (7 point scale from 1 [strongly disagree] to 7 [strongly agree]) on seven statements:

- I controlled the vehicle in a safe way
- Steering the vehicle felt realistic to me
- I felt comfortable
- The response of the truck regarding my steering input felt realistic
- Controlling the truck was an easy task for me
- The vehicle steered 'solid'
- The vehicle was rate stable

System Acceptance Scale (SAS)

The system acceptance scale is used to evaluate the consequence of steering system imperfections on the subjective assessment of the usefulness and satisfying of the system. The scale is described in chapter 2 and without any adaptation used in the questionnaire.

Steering system

This part of the questionnaire typically deals with the steering system and is the main part regarding steering feel. From the theoretical background in chapter 2 the dimensions of steering feel are used to assess the different steering system set ups: stability, amount of play, amount of force needed to turn the wheel, the steering wheel jerk, the steering sensitivity, the steering wheel return and the steering response. Instead of grading the dimensions, the dimensions are evaluated by using a bipolar scale from -3 [way too little] to +3 [way too much] with as extra indication that between -1 and 1 this acceptable and below -1 and above +1 this degree of this dimension is unacceptable.

Realism

The final part of the questionnaire is on the realism of the simulation. The same seven dimensions as in the part on the steering system are used, including an extra dimension about the movements of the vehicle. A 7 point scale is used from 0 [not realistic at all] to 6 [very realistic]. The reason to add this part to the questionnaire is twofold: first to evaluate if the steering system imperfection felt by the driver is realistic in normal truck driving and second if the MTDS itself is evaluated as being a realistic interpretation of real truck driving and useful in further truck driving simulator research.

Objective indicators

The driver performance is assessed with the objective metrics shown in table 5-3. The majority of the indicators is directly related to the data from the steering wheel and is used to indicate driver task demand.

Recorded data is first synchronized by starting at 200 meters from the original start to deal with start-up issues. Because of the random lane changes during highway motion, including entering the highway, the original data need to be filtered. Figure 5-1 shows five random runs with different lateral behavior resulting in a shorter data set with varying data length. This is the reason only one course following performance measure can be used: the road departure index (table 5-3).

5.2 Results

After running all experiment, measuring all performance indicators and completing all questionnaires statistical tests are used to interpret the results between:

- Baseline – Column friction value1 – Column friction value2
- Baseline – Kingpin friction value1 – Kingpin friction value2
- Baseline – Free play value1 – Free play value2

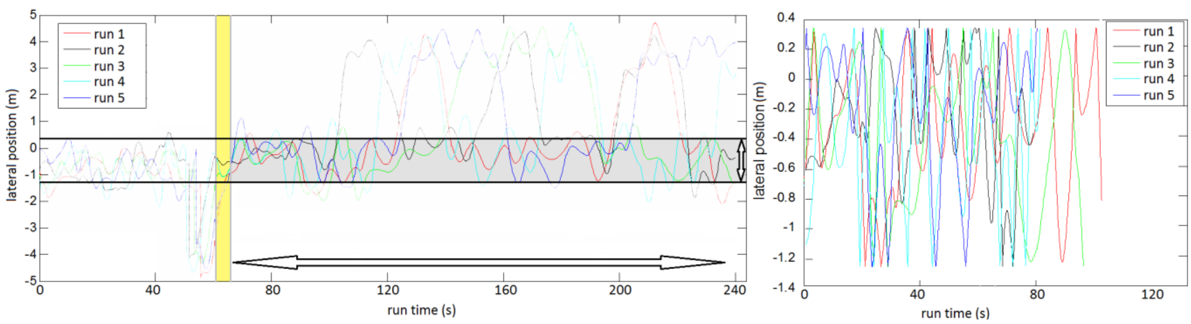

Figure 5-1 Filtered data based on lateral position. Left=original data from 200 meter; right = filtered data

Driver task demand measure		Calculation / Description	Entity	Source	Remarks
I	Index of steering business(A)	$\int_0^{t_n} \left[\frac{dSWA}{dSWA^{\wedge}}\right]^2 dt$	-	[108]	^ = normalized threshold of dSWA
II	Index of steering effort (B)	$\int_0^{t_n} \left[\frac{SWT}{SWT^{\wedge}}\right]^2 dt$	-	[108]	^ = normalized threshold of SWT
III	Comprehensive index of driver burden	$\sqrt{\frac{(\mathbf{A})^2 + (\mathbf{B})^2}{2}}$	-	[108]	-
IV	Steering reversal rate (SRR)	# steering wheel angle corrections over time	/m	[63]	-
V	Steer rate	RMS (dSWA)	rad/s	[111]	
VI	Steer jerk	RMS(d^2SWA)	rad/s^2	[111]	
VII	Steering steadiness	% of dSWA around zero	-	-	
VIII	Zero crossings dSWA	# steering rate corrections over time	/m	[63]	
Course following performance		**Calculation / Description**	**Entity**	**Source**	**Remarks**
IX	Road departure index	# of line crossings right	-	-	

Table 5-3 Objective indicators of driver performance

Each of the four parts is separately analyzed in the same order starting first with descriptive analysis to check data mistakes, distributions and assessing the direction and rough size of the outcomes. Next if desired a reliability analysis is done and finally an analysis of variance technique is used to assess differences between different group means. For a repeated measures within subject design and depending on the data this can be a parametric one-way ANOVA with repeated measures or a non-parametric Friedman test with a post-hoc Wilcoxon signed-rank test. What test to use depends on a number of assumptions that have to be met (table 5-4).

Subjective Assessment

First follows an overview of the results on the subjective indicators. In the next section the results of the objective metrics are given.

General experience and vehicle handling

The subjective indicators are plotted using box plots, including Whisker bars to show the upper and lower quartile. Outliers are more than 1.5 times different than the median value (IQR). The graphs on general experience (part A) are shown in figure 5-2, the graphs on vehicle handling (part B) in figure 5-3. The statistical significance of the subjective part is assessed by using the non-parametric Friedman test (table 5-5). This is because the Shapiro-Wilk null-hypothesis on normality is rejected ($p<0.05$). The complete analysis results on statistically significance can be found in Appendix C-1.

Assumption	Repeated measures ANOVA	Friedman Test	Wilcoxon Signed-Rank Test
#1	Dependent variable at continuous level	One group is measure on >3 different occasions	Independent variable consist of at least two related groups
#2	Independent variable consist of at least two related groups	Group is a random sample from the population	Dependent variable at least ordinal level
#3	No significant outliers in the related groups	Dependent variable at least ordinal level	
#4	Dependent variable is approximately normally distributed	No need to be normally distributed	
#5	Sphericity: equal variances of the differences (Mauchley's)		

Table 5-4 Assumptions to check before using a test technique [112]

		Test	Column friction 1-2-3		Kingpin friction 1-4-5		Free play 1-6-7	
#	Assessment Item	Fr or AN	χ^2 or F	p-value	χ^2 or F	p-value	χ^2 or F	P-value
A1	In general, how difficult was this ride?	Fr	14.33	**0.001**	17.45	**0.000**	9.48	**0.001**
A2	In general, did you feel you were at risk during this ride?	Fr	9.41	**0.009**	23.83	**0.000**	13.24	**0.001**
A3	In general, how mentally strenuous was the ride to you?	Fr	16.17	**0.000**	19.28	**0.000**	10.39	**0.006**
A4	In general, how physically strenuous was the ride to you?	Fr	23.02	**0.000**	16.62	**0.000**	11.45	**0.003**
B1	… I controlled the vehicle in a safe way	Fr	16.88	**0.000**	16.17	**0.000**	14.51	**0.001**
B2	… steering the truck felt realistic to me	Fr	15.03	**0.001**	13.37	**0.001**	17.23	**0.000**
B3	… I felt comfortable	Fr	19.28	**0.000**	15.62	**0.000**	12.28	**0.002**
B4	... the response of the truck felt realistic	Fr	7.86	**0.020**	14.35	**0.001**	8.82	**0.012**
B5	… controlling the truck was an easy task for me	Fr	22.92	**0.000**	22.09	**0.000**	12.88	**0.002**
B6	… The truck steered ‘solid’	Fr	3.52	0.172	13.12	**0.001**	9.50	**0.009**
B7	… The truck was rate stable	Fr	7.44	0.024*	14.72	**0.001**	6.54	**0.038**
C1	Usefulness of the system	AN	9.55	**0.001**	11.64	**0.000**	5.28	**0.010**
C2	Satisfaction of the system	AN	14.06	**0.000**	15.12	**0.000**	8.32	**0.001**
D1	The stability of the truck	Fr	0.48	0.786	6.58	**0.037**	0.36	0.836
D2	The amount of play in the steering system	Fr	1.39	0.517	3.88	0.144	13.51	**0.001**
D3	Amount of force you need to turn the wheel	Fr	22.45	**0.000**	13.22	**0.001**	3.06	0.216
D4	The steering wheel jerk	Fr	0.48	0.786	1.82	0.404	1.76	0.416
D5	Sensitivity of the vehicle response to SW movements	Fr	2.98	0.225	2.17	0.338	2.98	0.225
D6	The steering wheel return	Fr	0.59	0.746	1.22	0.543	0.93	0.629
D7	The response of the vehicle	Fr	0.933	0.627	0.74	0.692	1.85	0.397
E	Realism	AN	9.24	**0.001**	10.20	**0.000**	5.89	**0.006**

Table 5-5 Results of Friedman (Fr) and ANOVA (AN) test on subjective indicators
*not significant due to Bonferroni correction

Column friction

After increasing the column friction with the two different values, the drivers evaluated the four general questions as statistically different from the baseline configuration. The ride is rated as more difficult, more risky and demanded more mental and physical effort on both values. The evaluation between the two column frictions did not show any differences.

The questions on vehicle handling show a significant decrease on both values regarding safe control, realistic steering feel, comfort, realistic response and again difficulty. Solid steering and rate stability did not show any significant difference.

Kingpin friction

The variation of the kingpin friction also shows a significant difference for all values on the four general questions: more difficult, more risky and demanded more mental and physical effort. The post-hoc Wilcoxon signed-rank test shows also that a further increase of the kingpin friction from value1 to value2 is evaluated as more difficult (Z=-3.42,p=0.001) and more risky (Z=-2.63,p=0.009).

Following the post-hoc rank test are the questions on vehicle handling significantly lower evaluated for both values on safety and only for value two on all other items: less realistic steering, less comfortable, less realistic response, less easy, less solid and less rate stable.

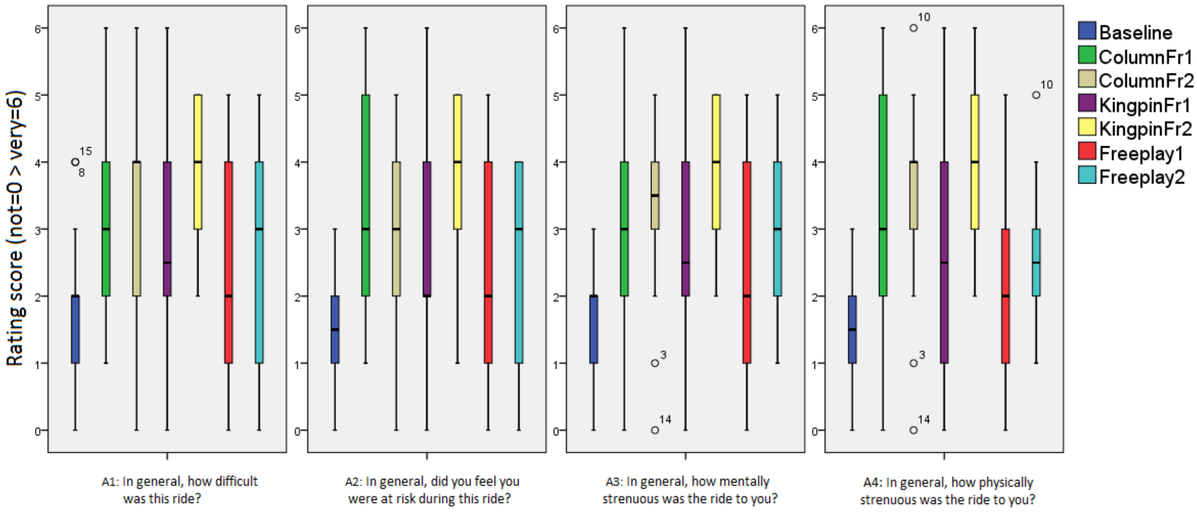

Figure 5-2 Subjective indicators questionnaire part A : general question

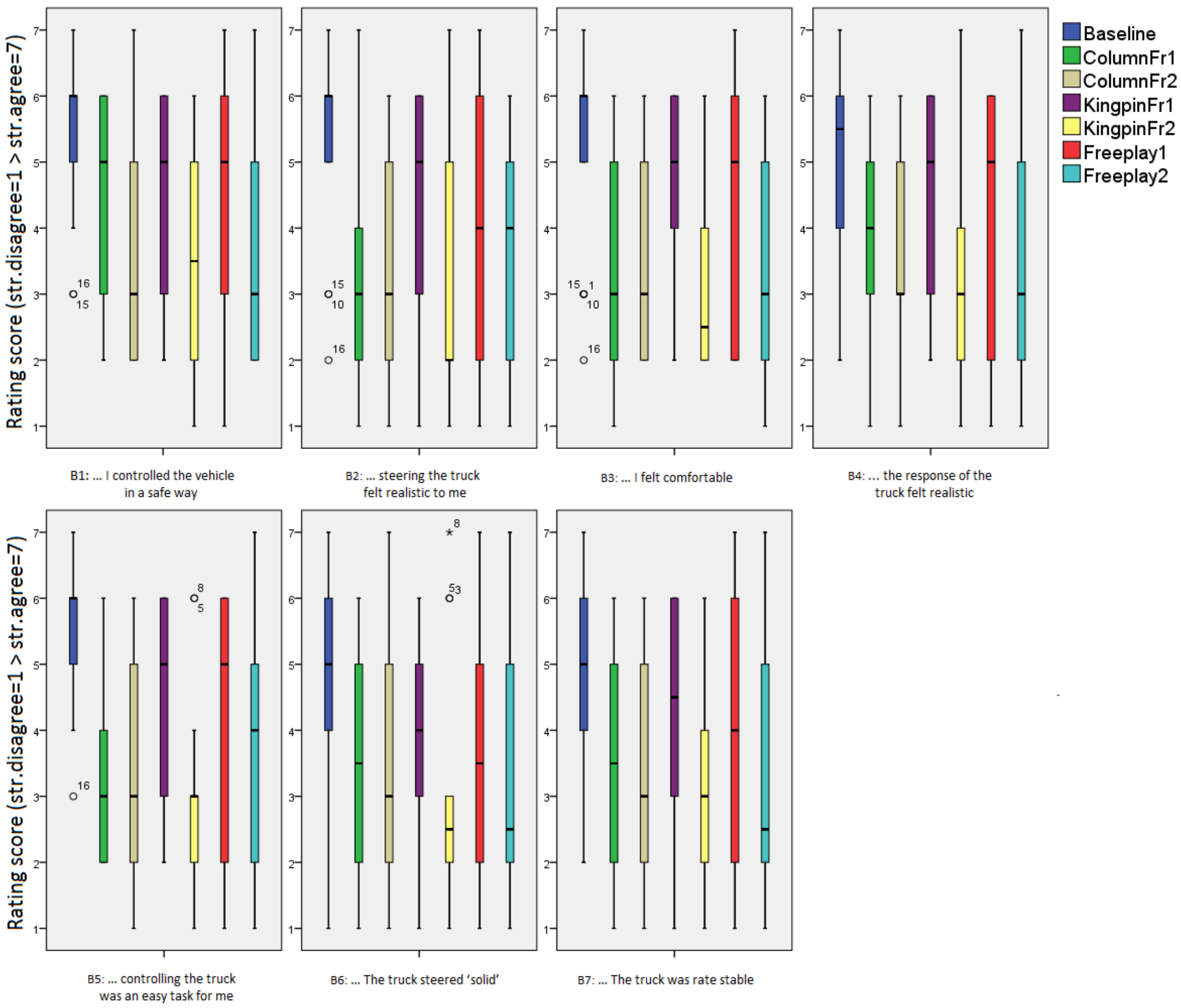

Figure 5-3 Subjective indicators questionnaire part B : vehicle handling

Free play

The third configuration is the increase of free play in the system. Again the general questions are evaluated as more difficult (only value2), more risky (both values) and demanded more mental and physical effort (both only value2). Post-hoc analysis showed that a further increase itself did not show any further increase. The evaluation on vehicle handling show statistical difference with the baseline on all indicators for all values, except comfort (only value2). Post-hoc analysis further showed that an increase of steering play from value1 to value2 showed no difference on any of the items.

System acceptance

The result of the acceptance of the different steering system setting is separated in two subscales: the scores on acceptance and the scores on satisfaction. Figure 5-4 shows the means of the two subscales including the deviation of 95% CI interval. As the scores indicate the usefulness and satisfaction of the system are rated as equal.

Column friction

Compared with the realistic baseline configuration, the increase in column friction to value1 shows a clear difference in rating. The usefulness decreases and the satisfaction decreases even more. A further increase of the column friction to value2 does not show a clear difference.

Kingpin friction

The scores on the increase of the kingpin friction in the system also show a decrease in usefulness and satisfaction, but in this case the usefulness and satisfaction almost linearly deteriorates when increasing from the baseline, to value1 and subsequently value2.

Free play

The configuration with more play in the steering system show the smallest deviation regarding usefulness and satisfaction compared with the baseline. The increase in free play shows the same approximately linear relationship between baseline, free play value1 and free play value2.

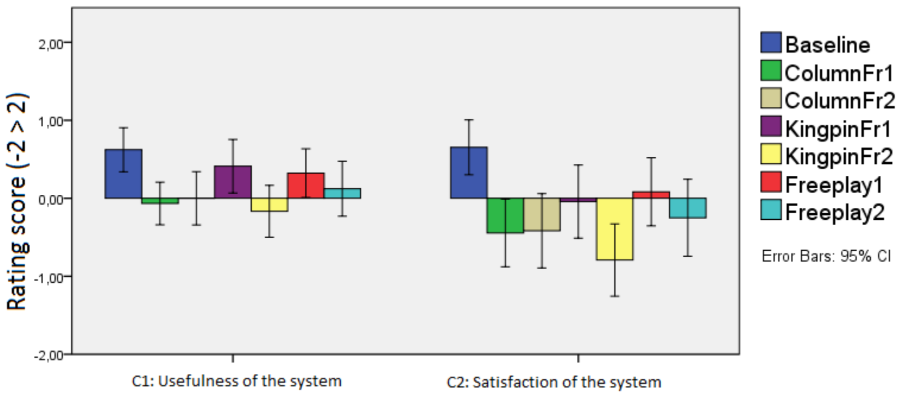

Figure 5-4 Subjective indicators questionnaire part C : system acceptance scores

Steering system

The subjective evaluation of the steering system properties are plotted using box plots (figure 5-5), including Whisker bars to show the upper and lower quartile. Outliers are more than 1.5 times different than the median value (IQR). During the descriptive analysis the possibility of adding the subjective indicators to one evaluable dimension has been viewed. The reliability was tested using Cronbach's alpha. Although a good score on reliability (0.671), adding the scores resulted in unwanted results because of sign differences between the items. Therefore the items are analyzed separately. The statistical significance of the subjective part is assessed by using the non-parametric Fiedman test (table 5-5). This is because the Shapiro- Wilk null-hypothesis on normality is rejected ($p<0.05$). The complete analysis results on statistically significance can be found in Appendix C-1.

Column friction

After increasing the column friction with the two different values, the drivers evaluated only the force needed to turn the steering wheel as different as the baseline configuration for both values of the steering column friction (table 5-5). Increasing the friction from value1 to value2 did not show any difference on the participants.

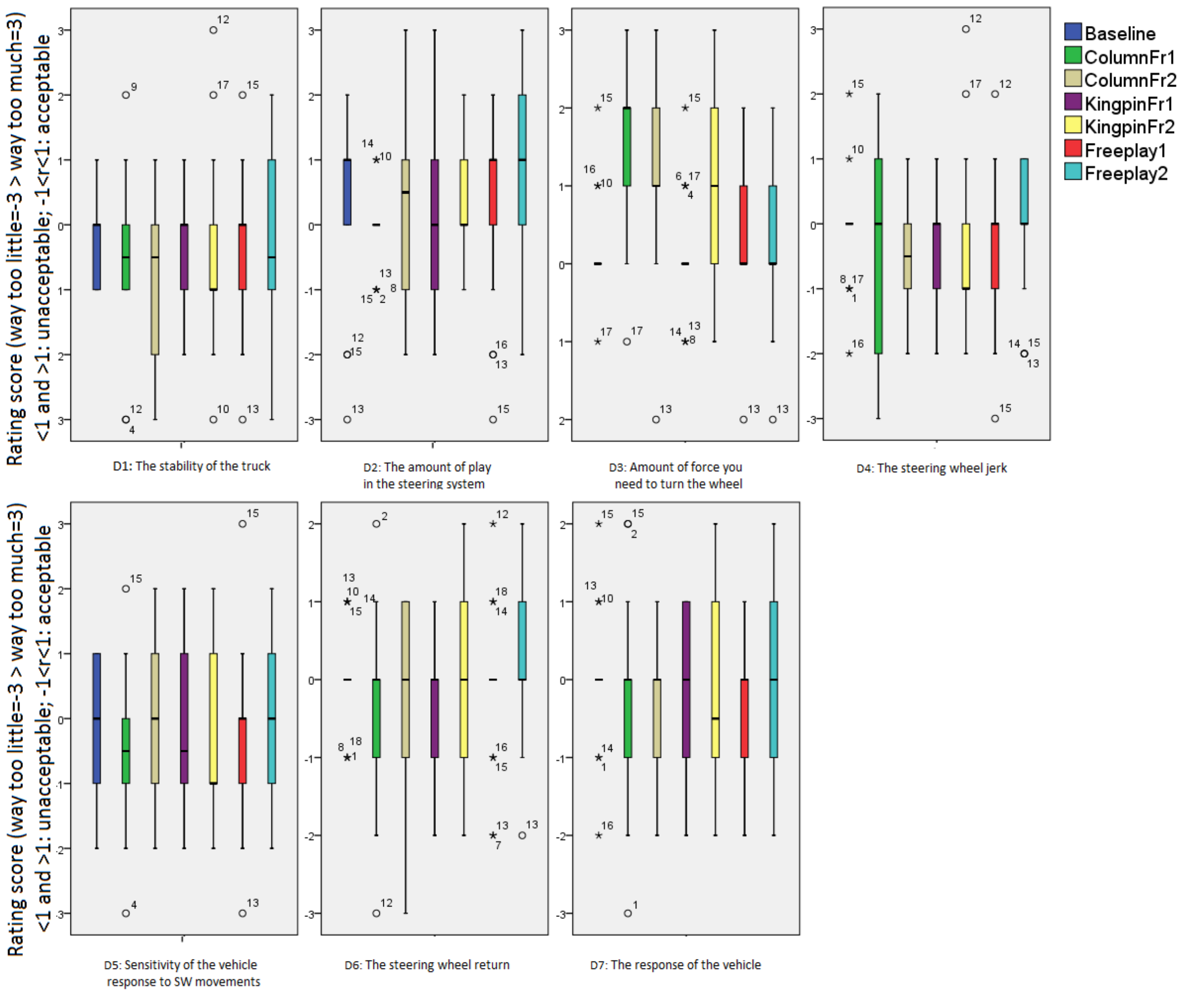

Figure 5-5 Subjective indicators questionnaire part D: steering system properties

Kingpin Friction

The variation of the kingpin friction showed a significant difference on two indicators: the stability of the truck and the amount of force needed to turn the wheel. Post-hoc testing showed that the difference on the stability is rejected and the amount of force is different with value2 (Z=-2.810, p=0.005).

Free play

Third configuration is the increase of free play in the system. This change only results in a different evaluation of the amount of free play in the system. Post-hoc tests show that only the difference between value2 and the baseline is significant (Z=-3.513,p=0.000).

Realism

The evaluation of the realism is done with subjective indicators from the last part of the questionnaire. During the descriptive analysis the possibility of adding the subjective indicators to one evaluable dimension has been viewed. The reliability was tested using Cronbach's alpha. The excellent score on Cronbach's alpha (0.945), including the fact the alpha cannot be increased by deleting one of the items, results in the merge of the eight items to one dimension: realism (figure 5-6). The statistical significance of the subjective part is assessed by analysis of variance (ANOVA) and results are shown in table 5-5. Although the Shapiro-Wilk null-hypothesis normality is slightly rejected for 1 out of the 8 items (0.033 < p <0.58), the symmetry of the data assumes the ANOVA to be robust enough to compensate for the violation of normality. Sphericity can be assumed using Mauchly's test (p>0.05). The complete analysis results on statistically significance can be found in Appendix C-1.

Column friction

After increasing the column friction with the two different values, the drivers evaluated the steering system configuration as less realistic (F=9.239,p=0.001). Post-hoc tests using the Bonferroni correction revealed that this is true for both values. The increase from value1 to value2 does not show any difference.

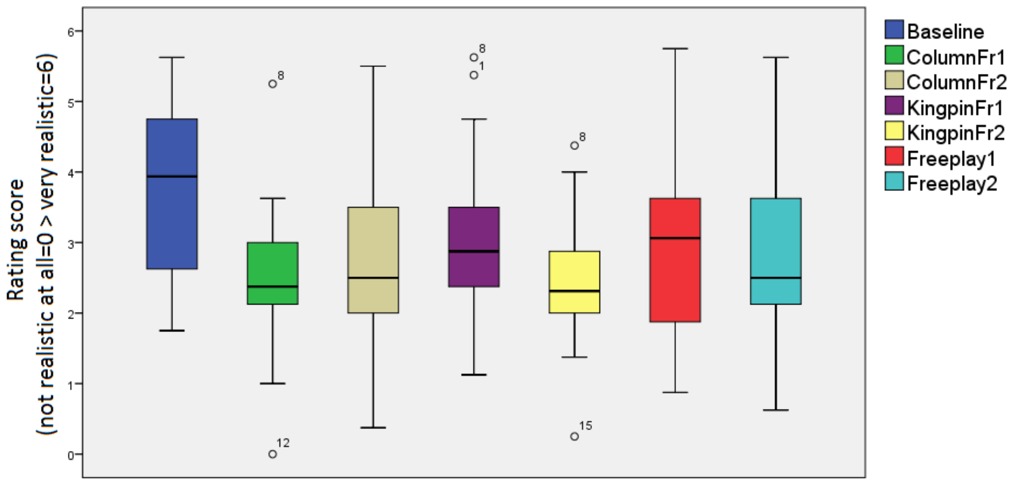

Figure 5-6 Subjective evaluation of questionnaire part E: realism

Kingpin friction

The variation of the kingpin friction also indicate a decrease of realism (F=10.201,p=0.000), but depending on the post-hoc test only after the increase to value2 (diff=1.313,p=0.001).

Free play

The increase of free play in the steering system results in a lower, but still highly significant, decrease of realism (F=5.894,p=0.006) for both values. An increase from value1 to value2 does not reveal a difference.

Objective Metrics

The significance of the objective part is assessed using analysis of variance (ANOVA). The results of the test are shown in table 5-6. The complete analysis results on statistically significance of the objective metrics can be found in Appendix C-2. The box plots of the results from the nine indicators are shown in figure 5-7.

Column friction

Comparing the baseline condition and the index of driver effort (II) indicates a significant difference for both column friction values. Pair wise comparison show a further increase from value1 to value2. The same result exists for the index of drive burden (III). The other objective metrics does not show any significant difference between the baseline and conditions including more column friction.

King pin friction

The increase of kingpin friction clearly results in a difference between a large number of objective measures. The index of steering business (I) is only significant at the highest value of king pin friction, the other two indexes on both values. Pair wise comparison indicates also an increase of steering effort (II) and driver burden (III) from king pin friction value1 to value2. Two other indicators that differ between the baseline and the king pin friction levels are the steer rate (V) for only value2 and steer jerk (VI) for both values. Pair wise comparison shows that steer jerk further increases from kingpin friction value1 to the highest friction value. The last two indicators that differ for only the second value are the steering steadiness (VII) en steering rate reversal rate (VIII).

		Column friction 1-2-3		**Kingpin friction 1-4-5**		**Free play 1-6-7**	
I	Index of steering business	1.91	0.175	14.29	**0.000**	10.63	**0.001**
II	Index of steering effort	30.16	**0.000**	48.40	**0.000**	2.38	0.108
III	Comprehensive index of driver burden	27.19	**0.000**	47.32	**0.000**	2.61	0.089
IV	Steering reversal rate (SRR)	1.54	0.229	0.69	0.509	2.11	0.137
V	Steer rate	2.19	0.127	17.20	**0.000**	11.20	**0.000**
VI	Steer jerk	1.79	0.196	20.69	**0.001**	12.87	**0.000**
VII	Steering steadiness	1.96	0.156	13.56	**0.000**	7.56	**0.002**
VIII	Zero crossings dSWA	0.65	0.529	3.76	**0.000**	6.17	0.005*
IX	Road departure index	1.93	0.160	2.35	0.110	0.70	0.502

Table 5-6 Results of ANOVA test on objective indicators

*not significant due to Bonferroni correction

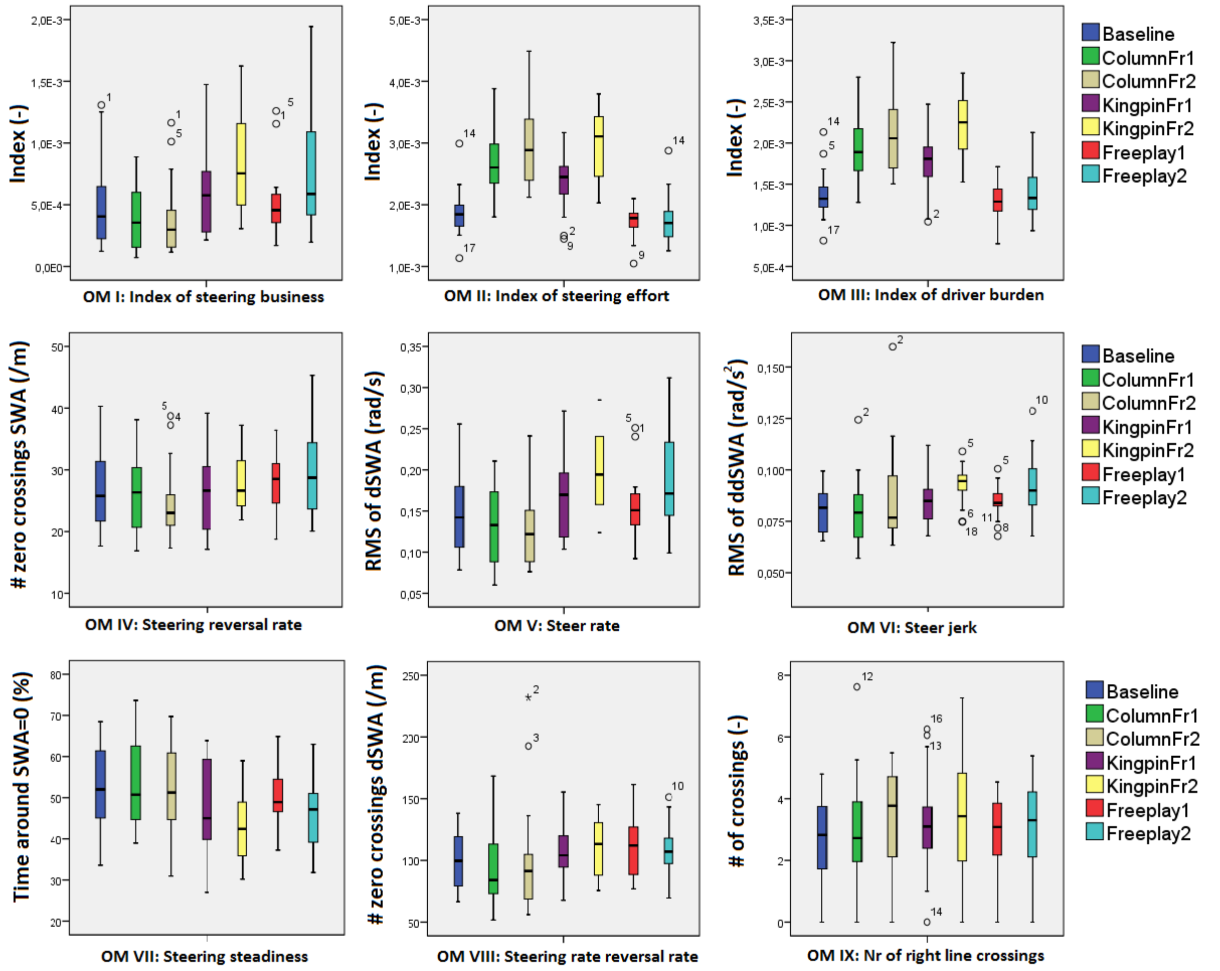

Figure 5-7 Boxplots of the objective metrics (OM) I to IX including upper and lower Whisker. Outliers are >1.5 times the median (IQR) and extremes more than 3 times the median (IQR).

Free play

The experiments with free play result in a different index of steering business (I) for only free play value2, indicating more rotation of the steering wheel. Other measures with a difference at the second value compared to the baseline are the steer rate (V), steer jerk (VI) and steering steadiness (VII). The steering rate reversal rate is only different at the first value of free play.

5.3 Discussion

The experiment shows that the mobile truck driving simulator (MTDS) can be a useful research tool in the investigation of truck driver steering feel. Regarding the fact that even expert drivers have difficulties to focus on steering feel only and ratings are normally influenced by overall impression of the test vehicle it is promising that the main steering system characteristics are assessed and so evaluated by the drivers.

Subjective Assessment

Using a dedicated questionnaire the influence of steering system imperfections on the steering feel of professional truck drivers is approached. Participants are asked to assess the steering system configuration on in total 35 different items during a 5 minutes drive. General opinion is that steering system imperfections increase the workload of the on-center handling of a truck-trailer combination. For all the three parameters this is already the case by an increase to value1, the lower of the two experimental values. On the other hand an increase from the first to the larger value2 of the imperfection does not further increase the evaluation of the workload. This indicates that a small deviation from the optimal value can already have a harmful effect.

The rating of the items on on-center vehicle handling is significant lower. Participants indicated that the ride was less safe, less realistic and less comfortable. Regarding kingpin friction and free play the truck steered less solid and less rate stable. Also the validation of the first confirmation question regarding more difficult (A1) is equal to less easy (B5) underline the level of expertise of the subjects. The subjective rating of vehicle handling decreased, but the course following performance did not show a significant reduction. This shows that professional truck drivers can deal with the imperfections, but they feel them, recognize them and this can result in negative user satisfaction.

Without having the natural skills to assess all steering system properties it became clear that with the increase of both frictions and play the usefulness and satisfactions decreases. Also the baseline configuration is clearly indicated by the majority of drivers. The SAS shows that steering system imperfections have a larger influence on satisfaction of the steering system than on the usefulness of the system. Degradations keep the system useful (you are still able to steer) but deteriorate driver satisfaction.

As mentioned the subjects had to assess the system on 35 items. Earlier research [113] already stated that human test subjects can only asses two or three items at a time. Therefore it is good that the subjects indicated:

- The increase of force to steer the wheel when one of the friction levels increased.
- The increase of play when the level of free play was increased.

A little more difficult to assess:

- The influence of the increase of play on the kingpin friction, because of its non-linear stick-slip behavior was indicated by some drivers, but did not show a significant result.
- The jerk of the steering wheel, clearly visible during the test run when the king pin friction was increased, was not recognized. The participants did feel the instability of the system, but did not mention the jerky behavior.

Objective measures

The objective indicators did show some statistical difference between the different configurations: first an increase of one of both frictions increased the effort needed by the driver controlling its vehicle. Second an increase of kingpin friction and play also lead to a change of other indicators like steering rate, steering jerk and steering steadiness. Third an increase of play influences the steering business instead of the effort needed to turn the steering wheel.

Next to this expected results, the only driving performance measure indicates no difference. Reason of this can be:

- The on-center driving task: limited radius of the curves.

- Other geometrical/environmental causes like lane width (3.50m) and number of other road users.
- Skills of the drivers: used to drive different brands and so different configurations.
- Main task of the participant is the evaluation of steering feel, not on driver performance.
- Driver gets accustomed to the route.
- Duration of the drive: only recorded for 5 minutes.
- Number of participants (n=18).
- Data logging resolution of the ST Software simulation software program.

The last item being assessed by the participants is the realism of the simulation. This dimension consists of in total 8 items. One remark during the experiment is the twofold explanation of realism. Is it the realism on how the imperfection is simulated or the realism of the imperfection itself? The difference between the baseline and the experimental setups was clearly significant, but be careful with drawing conclusions

6. Conclusion and recommendation

In this chapter conclusions are drawn based on both the explorative research and the main experiment. From the conclusions some recommendations are given regarding further research.

6.1 Conclusion

The objective of this research has been to set up a human in the loop simulation study in order to investigate the consequences of critical changes of steering system parameters on the steering feel of truck drivers during on-center highway driving. The literature review in chapter two attempted to give more details on the different aspects involved in the objective.

From the theoretical background it can be concluded that truck driver steering feel is hard to define. It is an attempt to describe a multidimensional feeling of the steering input from the human and the feedback via different perceptional cues from the steering wheel, the vehicle and its handling in contact with a specific driving environment. Because the steering system is involved in the combination of steering activity, steering effort and vehicle response, the parameters of the system play an important role in defining the quality of steering feel.

The degradation of a mechanical system during the lifetime of a product is an inevitable fact which also applies to the different components of the steering system. Which parts degrade most and the involved levels of degradation are hard to find in literature and therefore an explorative research designated six different parameters, including the threshold values of realistic steering feel. The used mobile truck driving simulator (MTDS) is recently developed and required continuous validation. On several occasions a professional truck driver is invited to provide feedback on the progress. From the six designated imperfections, three are finally evaluated during a pilot experiment as showing realistic behavior in the truck driver simulator.

- Column friction
- Kingpin friction
- Free play

The influence of steering system imperfections on steering feel is investigated by separately increasing the values of these three parameters during a truck driving simulator study. In total 18 subjects rated the steering feel of the different settings by finishing seven 5 minute on-center highway rides: one baseline configuration and 6 degraded configurations. Using a questionnaire a first attempt is made to approach steering feel from multiple perspective: as a combination of driver experience, handling characteristics, system acceptance, the steering system properties and the realism of steering feel.

Main results of the experiments depending on the driver's evaluation on experience and handling:

- All configurations different than the ideal situation (baseline) show an increase of the driver workload regarding difficulty, risk taking, physical effort and mental effort.
- All configurations different than the ideal situation showed lower agreement on handling qualities of the vehicle and its steering system (safety, realism, realistic steering and response, ease and comfort
- An increase of kingpin friction and free play lowered the rating of 'solid' steering and rate stability of the truck.

The assessment of the steering system properties resulted in a correct evaluation of the changed parameter: more force is needed if one of the two friction levels increased and more play is recognized by the drivers if the free play is increased. The apparent lack of ability to correctly assess the changes in the steering system is in line with earlier research and confirms the difficulty of multi-sensing.

To validate the use of the brand-new MTDS the drivers graded the dimension realism of the MTDS on eight items. The realism decreased significantly when imperfections are introduced in the steering system and the general feedback from truck drivers regarding the realism of the steering feel in the MTDS was promising. On a 7 point scale (0 = not realistic at all, 6 = very realistic) the baseline configuration was on average graded with a 4.

Another way of approaching good steering feel is done by measuring the acceptance of the system as a combination of usefulness and satisfaction of the different system settings. Conclusions:

- Increase of column friction to level1 led to a decrease of usefulness and satisfaction. A further increase to level2 did not result in any further change
- Increase of king pin friction and free play to level1 leads to decrease of acceptance and an increase to level2 led to a linearly decrease of the acceptance level
- The impact of steering system imperfections on driver satisfaction was clearly larger than the impact on the usefulness.
- Comparing the three imperfections showed that free play at the boundaries of realistic steering feel showed the highest acceptance level and king pin friction the lowest acceptance level.

During the experiments instrumental quantities are recorded. From this data a variety of driver performance measures on mainly driver task demand and course following performance are calculated. The workload measures showed to be in line with the changes of the steering system parameters, with the main difference between frictions and play that friction influences effort and play business.

The course following performance did not show a difference. This directly indicates the risk of steering degradations: human can adapt to systems without a deterioration of their performance, but the steering feel is clearly evaluated to be affected by the steering system imperfections.

6.2 Recommendation

The MTDS showed to be a good instrument to do research on professional truck drivers:

- The feedback from the truck drivers regarding the set up and the realism of especially the direct feel at the steering wheel was promising.
- The portability of the MTDS is very supportive regarding the recruitment of specific participants like experienced professional truck drivers

Regarding next experiments on a MTDS it is recommended to:

- Increase the duration of the ride for on-center handling, especially if performance measures are important
- Feedback from professional truck drivers on steering system imperfections showed that imperfections are not only sensible in the steering wheel, but also because of vibrations of the cabin. Therefore using a moving based platform when testing on imperfections will be recommendable.
- A total experiment time of 60-90 minutes is the maximum for professional truck drivers.

The attempt to get more insight in the role of steering system imperfection parameters on steering feel is a good first step, but more emphasis can be put on finding more details about the influence of each of the steering system parameters on steering feel and steering performance. The focus can then be not only on imperfections, but also on finding optimal steering feel taking into account the different motion states.

Next to the first use of the MTDS, a new questionnaire was designed for ongoing and future research purposes. Recommended is to validate the questionnaire by continuously improvement so it can be used in all future research with the MTDS involved.

The coming years new advanced driving assistance systems (ADAS) will be designed to partly take over the steering task of the driver. Research of driving behavior on this shared control of the steering wheel needs an experimental tool which represents realistic steering feel. The MTDS has shown the potential to be used for this purpose.

Some final recommendations on the possible improvements of this MTDS:

- Find a way for safer transport of the MTDS from location to location; especially protective cases would be beneficial.
- Extent the MTDS with an original truck drivers seat.

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A-1: Questionnaire part A

(This questionnaire is a translation of the original questionnaire in Dutch)

V1. What is your age?

____

V2. In what year did you receive your first truck driving license?

____

V3. In total how many kilometers did you drive in a truck?

____

V4. How many kilometers per year do you drive in a truck?
Please estimate your mileage based on the past three years.

____

V5. What is the brand of the truck you normally drive?
You can select more than one option.

□ DAF
□ Renault
□ Mercedes Benz
□ Volvo
□ MAN
□ Scania
□ Else, namely:____

V6. What kind of truck configuration do you normally drive ?
You can select more than one option

□ Truck without (semi-)trailer
□ Truck + trailer
□ Tractor + Semi-trailer
□ Else, namely:____

A-2: Questionnaire part B

After ride # (to decide)

Regarding the just experienced ride: Please indicate to which extent the following terms apply? Whereby: 0 = not at all and 6= very/very much

		0	1	2	3	4	5	6	
In general, how difficult was this ride?	Not at all	o	o	o	o	o	o	o	Very
In general, did you feel that you were at risk during this ride	Not at all	o	o	o	o	o	o	o	Very much
In general, how mentally strenuous was the ride to you	Not at all	o	o	o	o	o	o	o	Very
In general, how physically strenuous was the ride to you?	Not at all	o	o	o	o	o	o	o	Very

Regarding the just driven set-up, can you please indicate to which extent you agree with the following statements?

In general, during this ride:

	Strongly disagree	Dis-agree	Some-what disagree	Neither agree or disagree	Somew hat agree	Agree	Strongly agree
… I controlled the vehicle in a safe way	o	o	o	o	o	o	o
… steering the truck felt realistic to me	o	o	o	o	o	o	o
… I felt comfortable	o	o	o	o	o	o	o
… the response of the truck regarding my steering input felt realistic	o	o	o	o	o	o	o
… controlling the truck was an easy task for me	o	o	o	o	o	o	o
…. The truck steered 'solid'	o	o	o	o	o	o	o
… The truck was rate stable	o	o	o	o	o	o	o

Please fill in the scale below. The center position indicates ‘neutral’.

In my opinion the steering system was

useful	o	o	o	o	o	useless
pleasant	o	o	o	o	o	unpleasant
bad	o	o	o	o	o	good
nice	o	o	o	o	o	annoying
effective	o	o	o	o	o	superfluous
irritating	o	o	o	o	o	likeable
assisting	o	o	o	o	o	worthless
undesirable	o	o	o	o	o	desirable
raising alertness	o	o	o	o	o	sleep-inducing

The next questions relate to the specific properties of the steering wheel and how the truck responds to the steering wheel movements you made during the last drive.

Please indicate to which extent you experienced the following terms during the last drive. Whereby -3 = Way too little, 0 = exactly good, +3 = way too much. Furthermore, a score of more than 2 points left or right from zero indicates that you would find this degree unacceptable in driving a truck.

	Unacceptable		**Acceptable**			**Onacceptable**	
	Way too little	**Too little**	**Shortly too little**	**Exactly good**	**Shortly too much**	**Too much**	**Way too much**
Score	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**
The stability of the truck	o	o	o	o	o	o	o
The amount of play in the steering system	o	o	o	o	o	o	o
The amount of force you need to apply to turn the wheel	o	o	o	o	o	o	o
De steering wheel jerk (did the steer react fluently, or on the contrary vibrating, pulsing, stabbing and/or shaky)	o	o	o	o	o	o	o
The sensitivity of the vehicle response to steering wheel movements	o	o	o	o	o	o	o
The steering wheel return	o	o	o	o	o	o	o
The response of the vehicle	o	o	o	o	o	o	o

Please indicate to which extent you experienced the following terms as *realistic* during the last drive. Whereby 0 = not at all and 6= very

		0	1	2	3	4	5	6	
The stability of the truck	Not realistic at all	o	o	o	o	o	o	o	Very realistic
The amount of play in the steering system	Not realistic at all	o	o	o	o	o	o	o	Very realistic
The amount of force you need to apply to turn the wheel	Not realistic at all	o	o	o	o	o	o	o	Very realistic
De steering wheel jerk (did the steer react fluently, or on the contrary vibrating, pulsing, stabbing and/or shaky)	Not realistic at all	o	o	o	o	o	o	o	Very realistic
The sensitivity of the vehicle response to steering wheel movements	Not realistic at all	o	o	o	o	o	o	o	Very realistic
The steering wheel return	Not realistic at all	o	o	o	o	o	o	o	Very realistic
The response of the vehicle	Not realistic at all	o	o	o	o	o	o	o	Very realistic
De movements of the truck	Not realistic at all	o	o	o	o	o	o	o	Very realistic

B-1: Checklist Experiment

Checklist:

Task / Experiment	ini	1	2	3	4	5	6	7	Task / Experiment
Switch on dSpace									Switch on dSpace
Switch on Sensowheel									Switch on Sensowheel
Open dSpace									Open dSpace
Go Online									Go Online
Uncheck cruise control									**Uncheck cruise control**
Set Record file to id#									**Set Record file to id#**
Set roll to 1									**Set roll to 1**
Set freeplay to 0.1									**Set freeplay to 0.1**
Open St software									Open St software
Open Simulation									Open Simulation
Go Online									Go Online
Start dSpace									Start dSpace
Start Sensowheel									Start Sensowheel
Run+Pause ST software									Run+Pause ST software
Start Model Feedback									Start Model Feedback
Start Feedback									Start Feedback
Set Parameters:		#1	#2	#3	#4	#5	#6	#7	**Set Parameters:**
Set column friction	100	1	1681	3262	100	100	100	100	**Set column friction**
Set kingpin friction	50	50	50	50	147	244	50	50	**Set kingpin friction**
Set freeplay	0,1	0,10	0,10	0,10	0,10	0,10	0,81	1,53	**Set freeplay**
Start Measuring									**Start Measuring**
Run ST Software									Run ST Software
Start Triggered									**Start Triggered**
Stop Recording									**Stop Recording**
Stop Measuring									**Stop Measuring**
Stop All Programs									Stop All Programs
Go Offline									Go Offline
Close St Software									Close St Software

B-2: m.files DP Measures

```
%% Used to synchronize data on start position and length

clear all

a = 67; %nr of variables in Y
c = 2; %nr of varables in X
e = 12000; %nr of timesteps

%% load all files
load('Driver11_001.mat')
load('Driver11_002.mat')
load('Driver11_003.mat')
load('Driver11_004.mat')
load('Driver11_005.mat')
load('Driver11_006.mat')
load('Driver11_007.mat')
load('Driver11_008.mat')

Driver01_000 = Driver11_001;
Driver01_001 = Driver11_002;
Driver01_002 = Driver11_003;
Driver01_003 = Driver11_004;
Driver01_004 = Driver11_005;
Driver01_005 = Driver11_006;
Driver01_006 = Driver11_007;
Driver01_007 = Driver11_008;

%% set beginvalues 200 meter from start
b1 = 385;
b2 = 352;
b3 = 361;
b4 = 393;
b5 = 374;
b6 = 401;
b7 = 354;
b8 = 373;
d1 = e+b1;
d2 = e+b2;
d3 = e+b3;
d4 = e+b4;
d5 = e+b5;
d6 = e+b6;
d7 = e+b7;
d8 = e+b8;

%% reset datasheets and latin square randomization
for i = 1:a
Driver01_000.Z(i).Data = Driver11_001.Y(i).Data(:,b1:d1);
Driver01_001.Z(i).Data = Driver11_002.Y(i).Data(:,b2:d2);
Driver01_002.Z(i).Data = Driver11_007.Y(i).Data(:,b7:d7);
Driver01_003.Z(i).Data = Driver11_004.Y(i).Data(:,b4:d4);
Driver01_004.Z(i).Data = Driver11_005.Y(i).Data(:,b5:d5);
Driver01_005.Z(i).Data = Driver11_006.Y(i).Data(:,b6:d6);
Driver01_006.Z(i).Data = Driver11_003.Y(i).Data(:,b3:d3);
Driver01_007.Z(i).Data = Driver11_008.Y(i).Data(:,b8:d8);
end
% set time to zero
for j = 1:c
Driver01_000.W(j).Data = Driver11_001.X(j).Data(:,b1:d1)-Driver11_001.X(j).Data(1,b1);
Driver01_001.W(j).Data = Driver11_002.X(j).Data(:,b2:d2)-Driver11_002.X(j).Data(1,b2);
Driver01_002.W(j).Data = Driver11_007.X(j).Data(:,b7:d7)-Driver11_007.X(j).Data(1,b7);
Driver01_003.W(j).Data = Driver11_004.X(j).Data(:,b4:d4)-Driver11_004.X(j).Data(1,b4);
Driver01_004.W(j).Data = Driver11_005.X(j).Data(:,b5:d5)-Driver11_005.X(j).Data(1,b5);
Driver01_005.W(j).Data = Driver11_006.X(j).Data(:,b6:d6)-Driver11_006.X(j).Data(1,b6);
Driver01_006.W(j).Data = Driver11_003.X(j).Data(:,b3:d3)-Driver11_003.X(j).Data(1,b3);
Driver01_007.W(j).Data = Driver11_008.X(j).Data(:,b8:d8)-Driver11_008.X(j).Data(1,b8);
end

%clear original files
clear vars Driver11_001
clear vars Driver11_002
```

```
clear vars Driver11_003
clear vars Driver11_004
clear vars Driver11_005
clear vars Driver11_006
clear vars Driver11_007
clear vars Driver11_008

%save to new file
save('Driver1.mat')

%% change matrices because of overtaking and startposition
% use lateral position to skip parts

clear all
load('Driver1.mat')
lowlimit = -1.25;
uplimit = 0.35;

%% for #1 (this script runs also for other 6 conditions.

for i = 1:67
    Driver01_001.V(i).Data = Driver01_001.Z(i).Data;
end

NrColumns = 12001;
teller = 0;
data = zeros(1,12001);
Minus1 = 0;

for teller1 = 1:NrColumns

   size1 = size(data);
   sizecolumns1 = size1(1,2);
   check1 = teller1 - Minus1;

   if check1 > sizecolumns1

   else %check what needs to be deleted because lateral position is outside boundarie
        if Driver01_001.V(23).Data(1,check1) < lowlimit || Driver01_001.V(23).Data(1,check1) > 
uplimit
                % if last in array do something else
            size2 = size(data);
            endofarray = size2(1,2);

            if check1 == endofarray %take out last column of all STS data in Y
                data = data(1,1:check1-1);
                for q = 1:67
                        Driver01_001.V(q).Data = Driver01_001.V(q).Data(1,1:check1-1);
                end

            else %take out column
            Minus1 = Minus1+1;
                data = data(1,[1:check1-1,check1+1:end]);
                for q = 1:67
                    Driver01_001.V(q).Data = Driver01_001.V(q).Data(1,[1:check1-
1,check1+1:end]);
                end

            end
        end

    end

end


size2 = size(data);
NrColumns1 = size2(1,2);
Minus2 = 0;

    for teller2 = 1:NrColumns1
        check2 = teller2-Minus2;

        if Driver01_001.V(28).Data(1,check2) == 4 && teller == 0
            data = data(1,check2:end); %take out column of all STS data in Y
            teller = 1;
            Minus2 = teller2;
```

```
            for q = 1:67
                Driver01_001.V(q).Data = Driver01_001.V(q).Data(1,check2:end);
            end

        end

    end


save('Driver1.mat')


%% load .mat files and save one item for each set up in one matrix
% then in total 21*7 lines with 12000 columns. Array 'columnwidth' recalls
% number of data per run.

clear all
t = 18;
datasheet = zeros(147,12001);
columnwidth = [];

% Driver1
load('Driver1.mat')
A = size (Driver01_001.V(t).Data(1,:));
B = A(1,2);
columnwidth(1,:) = B;
datasheet(1,1:B) = Driver01_001.V(t).Data(1,:);
A = size (Driver01_002.V(t).Data(1,:));
B = A(1,2);
columnwidth(2,:) = B;
datasheet(2,1:B) = Driver01_002.V(t).Data(1,:);
A = size (Driver01_003.V(t).Data(1,:));
B = A(1,2);
columnwidth(3,:) = B;
datasheet(3,1:B) = Driver01_003.V(t).Data(1,:);
A = size (Driver01_004.V(t).Data(1,:));
B = A(1,2);
columnwidth(4,:) = B;
datasheet(4,1:B) = Driver01_004.V(t).Data(1,:);
A = size (Driver01_005.V(t).Data(1,:));
B = A(1,2);
columnwidth(5,:) = B;
datasheet(5,1:B) = Driver01_005.V(t).Data(1,:);
A = size (Driver01_006.V(t).Data(1,:));
B = A(1,2);
columnwidth(6,:) = B;
datasheet(6,1:B) = Driver01_006.V(t).Data(1,:);
A = size (Driver01_007.V(t).Data(1,:));
B = A(1,2);
columnwidth(7,:) = B;
datasheet(7,1:B) = Driver01_007.V(t).Data(1,:);
clearvars -except datasheet columnwidth t

%% Calculate performance measures

%% OM1: Steering Reversal rate (SWA = 0) t=35 and t=time
% see seperate function reversal_rate
clear all
t=35;
load('datasheet35.mat')
load('columnwidth35.mat')
SWAp = datasheet.*(360/(2*pi));

for i = 1:147
last = columnwidth(i,1);
filter_order = 2; %order of a low-pass Butterworth filter
cutoff_frequency = 0.6; %filter cut-off frequency (Hz), 0.6 Hz according to SAE J2944
data_frequency = 50; %data sampling frequency  (Hz)
threshold = 3; %minimum gap size (deg), 3 according to SAE J2944
time = 1:0.02:(columnwidth(i,1)+49)/50; %dataset of time
SWA = (SWAp(i,1:last)).';

[SRR(i,1), Nr(i,1), Nd(i,1)] = reversal_rate(time, SWA, filter_order, cutoff_frequency,
data_frequency, threshold);

end
```

```
save('OM01_SRR');


%% OM2: Index of steering business (t=36)
clear all;
t = 36;
load('datasheet36.mat')
load('columnwidth36.mat')
for i = 1:147
    SWAth = 1;
    sdatasheet = (datasheet/SWAth).^2;
    dt = 0.02;
    sdtdatasheet = sdatasheet.*dt;
    last = columnwidth(i,1);
    ISBS(i,1) = sum(sdtdatasheet(i,1:last));
    ISBM(i,1) = (1/last).*ISBS(i,1);
end

clearvars -except datasheet sdatasheet sdtdatasheet ISBS ISBM max t
% save as table with 21*7 experiments rows
save('OM02_IndexStBusiness.mat')
%

%% OM 3: Index of steering effort (t=40)
clear all;
t = 40;
load('datasheet40.mat')
load('columnwidth40.mat')
for i = 1:147
    SWTth = 8;
    sdatasheet = (datasheet/SWTth).^2;
    dt = 0.02;
    sdtdatasheet = sdatasheet.*dt;
    last = columnwidth(i,1);
    ISES(i,1) = sum(sdtdatasheet(i,1:last));
    ISEM(i,1) = (1/last).*ISES(i,1);
end

clearvars -except datasheet sdatasheet sdtdatasheet ISES ISEM last t
% save as table with 21*7 experiments rows
save('OM03_IndexStEffort.mat')

%% OM 4: Index of driver burden
clear all
load('IndexStBusiness.mat')
load('IndexStEffort.mat')
IDBS = ((ISES.^2+ISBS.^2)/2).^(1/2);
IDBM = ((ISEM.^2+ISBM.^2)/2).^(1/2);
save('OM04_IndexDriverBurden')

%% OM 5: RMS(T*SWA)
clear all
t1 = 35;
t2 = 40;

load('datasheet35.mat')
load('columnwidth35.mat')
datasheetSWA = datasheet;
clearvars -except t1 t2 datasheetSWA
load('datasheet40.mat')
load('columnwidth40.mat')
datasheetSWT = datasheet;


for i = 1:147
last = columnwidth(i,1);
SWASWT(i,1:last) = datasheetSWA(i,1:last) .* datasheetSWT(i,1:last);
rmsSWASWT(i,1) = (mean((SWASWT(i,1:last)).^2)).^(1/2);

end
clearvars -except rmsSWASWT datasheetSWA datasheetSWT
save('OM05_rmsSWASWT')

%% OM 6: Steer rate (t=36)

clear all
```

```
load('datasheet36.mat')

for i = 1:147
    last = columnwidth(i,1);
    meandSWA(i,1) = (mean((datasheet(i,1:last)).^2)).^(1/2);
end
clearvars -except datasheet meandSWA
% save as table with 21*7 experiments rows with 4*1 minute + 1*total
% columns
save('OM06_meandSWA.mat')

%% OM 7: Steer jerk (t=36) = mean ddSWA

clear all
load('datasheet36.mat')
d_datasheet= diff(datasheet,1,2);

for i = 1:147
    last = columnwidth(i,1);
    meanddSWA1 = (mean((d_datasheet(i,1:last)).^2)).^(1/2); %mean(d_datasheet(i,1:12000));
    meanddSWA(i,1) = meanddSWA1;
end
clearvars -except datasheet meanddSWA d_datasheet
% save as table with 21*7 experiments rows with 4*1 minute + 1*total
% columns
save('OM07_meanddSWA.mat')

%% OM 8: High frequency steering
%see seperate function high frequency steering
clear all
t=35;
load('datasheet35.mat')
SWAp = datasheet.*(360/(2*pi));

for i = 1:147
last = columnwidth(i,1);
data_frequency = 50; %data sampling frequency  (Hz)
SWA = (SWAp(i,1:last)).';
filter_order = 2;
low_cutoff_frequency = 0.1;
high_cutoff_frequency = 1;
HFC(i,1)= high_frequency_steering (SWA, filter_order, low_cutoff_frequency,
high_cutoff_frequency, data_frequency );

end

save('OM08_HFS')

%% OM 9: Steering steadiness
%see seperate function steering steadiness
clear all
t=36;
load('datasheet36.mat')
VSWAp = datasheet.*(360/(2*pi));

for i = 1:147
time0 = 1:0.02:(columnwidth(i,1)+49)/50; %dataset of time
time = time0.';
last = columnwidth(i,1);
VSWA = (VSWAp(i,1:last)).';
SWS(i,1)= steering_wheel_steadiness( time, VSWA );
end

save('OM09_StSt')

%% OM 10: # of line crossings right line (t=19) >> divide by time (minutes)
clear all
load('datasheet19')

for i = 1:147

%first get rid of pseudo zero crossings
last = columnwidth(i,1);

    for j = 2: last
        if sign(datasheet(i,j)) == 0
        datasheet(i,j) = sign(datasheet(i,j-1));
```

```
        end
    end

num = find([0 diff(sign(datasheet(i,1:last)))]<0);
LCR(i,1) = sum(num(:) > 1);

time = last/3000;
LCR_pm(i,1) = LCR(i,1)/time;

end
clearvars -except datasheet LCR num LCR_pm
% save as table with 21*7 experiments with 4*1 minute
save('OM10_LaneCrossingRight.mat')

%% OM11: # zero crossing dSWA  (t=36)
clear all
load('datasheet36')

for i = 1:147

%first get rid of pseudo zero crossings
last = columnwidth(i,1);

    for j = 2:last
        if sign(datasheet(i,j)) == 0
        datasheet(i,j) = sign(datasheet(i,j-1));
        end
    end

dSRR = find([0 diff(sign(datasheet(i,:)))]~=0);
zeroCrossing(i,1) = sum(dSRR(:) < last);
time = last/3000;
dSWA_zeroCrossing(i,1) = zeroCrossing(i,1)/time;

end
clearvars -except datasheet dSWA_zeroCrossing dSRR
% save as table with 21*7 experiments with 4*1 minute
save('OM11_dSWA_ZeroCrossing.mat')

%% OM 12: Steering Entropy
%see seperate function steering_entropy

clear all
t=35;
load('datasheet35.mat')
load('columnwidth35.mat')
SWAp = datasheet.*(360/(2*pi));

for i = 1:147
last = columnwidth(i,1);
data_frequency = 50; %data sampling frequency  (Hz)
SWA = (SWAp(i,1:last)).';
[alfa(i,1), S_SE(i,1)] = steering_entropy (SWA, data_frequency);
end

save('OM12_SE')

%% OM 13: TTC (t=32)
clear all
load('datasheet32')

yminall = zeros(147,20);
for i = 1:147

     x = 1:columnwidth(i,1);
     y = datasheet(i,:);
     [ymax,imax,ymin,imin] = extrema(y);

     %figure(1)
     %plot(x,y,x(imax),ymax,'g.',x(imin),ymin,'r.')
     %ylim([0 100]);
     %xlim([0 columnwidth(i,1)-1]);

     size3 = size(datasheet(i,:));
     sizecolumns3 = size3(1,2);

     size1 = size(imin);
```

```
    sizecolumns1 = size1(1,2);
    minus = 0;

    for j = 1:sizecolumns1

        size2 = size(imin);
        sizecolumns2 = size2(1,2);

        icolumn = j-minus;
        if icolumn > sizecolumns2

        else

        id = imin(1,icolumn);

           if id == sizecolumns3
               if icolumn == 1
               imin = imin(2:end);
               ymin = ymin(2:end);
               else
                   if icolumn == sizecolumns2
                    imin = imin(1:icolumn-1);
                    ymin = ymin(1:icolumn-1);
                   else
                    imin = imin(1,[1:icolumn-1, icolumn+1:end]);
                    ymin = ymin(1,[1:icolumn-1, icolumn+1:end]);
                   end
               end
           else

           if y(1,id+1)< 9999 || id == sizecolumns3
               minus = minus+1;

               if icolumn == 1
               imin = imin(2:end);
               ymin = ymin(2:end);
               else
                   if icolumn == sizecolumns2
                    imin = imin(1:icolumn-1);
                    ymin = ymin(1:icolumn-1);
                   else
                    imin = imin(1,[1:icolumn-1, icolumn+1:end]);
                    ymin = ymin(1,[1:icolumn-1, icolumn+1:end]);
                   end
               end
           end

           end
        end

    end


    breed = size(imin);
    breed1 = breed(1,2);

    yminall(i,1:breed1) = ymin;
    iminall(i,1:breed1) = imin;
end
% calculate mean TTC
for k = 1:147

    meanyminall(k,:) = mean(nonzeros(yminall(k,:)));

end

clearvars -except datasheet meanyminall yminall iminall
% save as table with 21*7 experiments rows with 4*1 minute + 1*total
% columns
save('OM13_meanTTC.mat')

%% OM14: SD of Lat pos (t=23) >> problem: different data length
clear all
load('datasheet23')

for i = 1:147
    last = columnwidth(i,1);
```

```
    sdlatpos(i,1) = std(datasheet(i,1:last));

end
clearvars -except datasheet sdlatpos
% save as table with 21*7 experiments with 4*1 minute
save('OM14_sdlateralposition.mat')

%% OM 15: SD of SWA t=35 >> problem: different data length
clear all
load('datasheet35')

for i = 1:147
    last = columnwidth(i,1);
    sdSWA(i,1) = std(datasheet(i,1:last));

end

clearvars -except datasheet sdSWA
% save as table with 21*7 experiments with 4*1 minute
save('OM15_sdSWA.mat')

%% OM 16: # of line crossings left line (t=18) >> divide by time (minutes)
clear all
load('datasheet18')

for i = 1:147

%first get rid of pseudo zero crossings
last = columnwidth(i,1);

    for j = 2: last
        if sign(datasheet(i,j)) == 0
        datasheet(i,j) = sign(datasheet(i,j-1));
        end
    end

num = find([0 diff(sign(datasheet(i:1:last)))]<0);
LCL(i,1) = sum(num(:) > 1);

time = last/3000;
LCL_pm(i,1) = LCL(i,1)/time;

end
clearvars -except datasheet LCL num LCL_pm
% save as table with 21*7 experiments with 4*1 minute
save('OM16_LaneCrossingRight.mat')
```

C-1: Analysis Results

Statistical tests on subjective assessment

- 1: Non-parametric test: (a-b-c) Friedman and post-hoc (a-b) Wilcoxon: A+B+D
- 2: Repeated measures within subject analysis of variance (1-way ANOVA): C+E

Question	Value	1-2-3	1-2	1-3	2-3	1-4-5	1-4	1-5	4-5	1-6-7	1-6	1-7	6-7
A1	χ²(a-b-c) or Z (a-b	14.333	-3.08	-2.787	-0.566	17.452	-2.595	-3.419	-.2443	9.480	-2.354	-2.843	-1.393
	p value	**0.001**	**0.002**	**0.005**	0.571	**0.000**	**0.009**	**0.001**	**0.015**	**0.001**	0.019*	**0.004**	0.163
A2	χ²(a-b-c) or Z (a-b	9.406	-2.888	-2.778	-0.266	23.831	-2.837	-3.539	-2.625	13.236	-2.811	-2.765	-0.575
	p value	**0.009**	**0.004**	**0.005**	0.79	**0.000**	**0.005**	**0.000**	**0.009**	**0.001**	**0.005**	**0.006**	0.565
A3	χ²(a-b-c) or Z (a-b	16.172	-2.917	-3.311	-0.081	19.279	-2.719	-3.539	-1.983	10.393	-2.506	-2.710	-0.984
	p value	**0.000**	**0.004**	**0.001**	0.935	**0.000**	**0.007**	**0.000**	0.47	**0.006**	0.12	**0.007**	0.325
A4	χ²(a-b-c) or Z (a-b	23.017	-3.447	-3.475	-0.566	16.623	-2.583	-3.437	-2.065	11.451	-1.653	-2.923	-1.904
	p value	**0.000**	**0.001**	**0.001**	0.571	**0.000**	**0.010**	**0.001**	0.039*	**0.003**	0.098	**0.003**	0.057
B1	χ²(a-b-c) or Z (a-b	16.877	-2.971	-3.221	-1.178	16.172	-2.676	-3.395	-2.129	14.509	-2.729	-3.320	-1.901
	p value	**0.000**	**0.003**	**0.001**	0.239	**0.000**	**0.007**	**0.001**	0.033*	**0.001**	**0.006**	**0.001**	0.057
B2	χ²(a-b-c) or Z (a-b	15.031	-3.067	-3.258	-0.029	13.368	-1.849	-3.283	-2.465	17.231	-2.972	-3.220	-0.549
	p value	**0.001**	**0.002**	**0.001**	0.977	**0.001**	0.065	**0.001**	**0.014**	**0.000**	**0.003**	**0.001**	0.583
B3	χ²(a-b-c) or Z (a-b	19.283	-3.330	-2.908	-0.426	15.621	-1.085	-3.260	-2.948	12.275	-1.778	-3.091	-1.901
	p value	**0.000**	**0.001**	**0.004**	0.670	**0.000**	0.278*	**0.001**	**0.003**	**0.002**	0.075	**0.002**	0.057
B4	χ²(a-b-c) or Z (a-b	7.862	-1.959	-2.785	-0.970	14.351	-0.852	-3.097	-2.437	8.821	-2.490	-2.896	-0.670
	p value	**0.020**	0.050	**0.005**	0.332	**0.001**	0.394*	**0.002**	**0.015**	**0.012**	**0.013**	**0.004**	0.503
B5	χ²(a-b-c) or Z (a-b	22.915	-3.442	-3.539	-0.212	22.091	-2.363	-3.667	-2.496	12.877	-2.708	-3.288	-0.516
	p value	**0.000**	**0.001**	**0.000**	0.832	**0.000**	0.018*	**0.000**	**0.013**	**0.002**	**0.007**	**0.001**	0.606
B6	χ²(a-b-c) or Z (a-b	3.516	-1.973	-2.396	0.000	13.115	-1.726	-3.201	-2.231	9.500	-2.852	-3.027	-0.690
	p value	0.172	0.049*	0.017*	1	**0.001**	0.084	**0.001**	0.026*	**0.009**	**0.004**	**0.002**	0.490
B7	χ²(a-b-c) or Z (a-b	7.444	-2.243	-2.642	-0.688	14.724	-1.887	-3.234	-2.026	6.542	-2.595	-2.838	-0.953
	p value	**0.024**	0.02*	0.02*	1	**0.001**	0.053	**0.001**	0.02*	**0.038**	**0.005**	**0.002**	0.118
C_Usefulness	ANOVA F or Diff	9.545	0.689	0.622	-0.067	11.641	0.211	0.789	0.578	5.276	0.300	0.500	0.200
	p value	**0.001**	**0.006**	**0.010**	1.000	**0.000**	0.675	**0.001**	**0.006**	**0.010**	0.174	**0.026**	0.577
C_Satisfaction	ANOVA F or Diff	14.062	1.097	1069	-0.028	15.115	0.694	1.444	0.750	8.319	0.569	0.903	0.333
	p value	**0.000**	**0.001**	**0.002**	1	**0.000**	**0.046**	**0.000**	0.057	**0.001**	**0.041**	**0.003**	0.539
D1	χ²(a-b-c) or Z (a-b	0.481	*-0.778*	*-1.490*	*-0.292*	6.577	-0.632	-1.377	-0.912	0.359	*-0.879*	*-0.105*	*-0.258*
	p value	0.786	*0.436*	*0.136*	*0.770*	**0.037**	0.527	0.169	0.362	0.836	*0.380*	*0.917*	*0.796*
D2	χ²(a-b-c) or Z (a-b	1.319	*-1.565*	*-0.690*	*-0.778*	3.875	-2.124	-1.047	-0.082	13.508	-1.541	-3.136	-1.760
	p value	0.517	*0.118*	*0.490*	*0.436*	0.144	0.034	0.295	0.934	**0.001**	0.123	**0.002**	0.078
D3	χ²(a-b-c) or Z (a-b	22.448	-3.493	-2.932	-1.165	13.217	-3.02	-2.801	-2.812	3.063	*-1.318*	*-0.730*	*-0.333*
	p value	**0.000**	**0.000**	**0.003**	0.244	**0.001**	0.763	**0.005**	**0.005**	0.216	*0.187*	*0.465*	*0.739*
D4	χ²(a-b-c) or Z (a-b	0.481	*-0.637*	*-0.842*	*-0.090*	1.815	*-0.165*	*-0.969*	*-0.821*	1.756	*-0.121*	*-0.136*	*-0.749*
	p value	0.786	*0.524*	*0.400*	*0.928*	0.404	*0.869*	*0.332*	*0.412*	0.416	*0.904*	*0.891*	*0.454*
D5	χ²(a-b-c) or Z (a-b	2.980	*-0.999*	*-0.500*	*-0.815*	2.167	*-0.917*	*-0.869*	*-0.184*	2.980	*-0.871*	*-0.135*	*-1.309*
	p value	0.225	*0.318*	*0.617*	*0.415*	0.338	*0.359*	*0.385*	*0.854*	0.225	*0.384*	*0.892*	*0.191*
D6	χ²(a-b-c) or Z (a-b	0.585	*-0.850*	*-1.165*	*-0.723*	1.220	*-1.706*	*-0.291*	*-0.879*	0.927	*-0.543*	*-0.577*	*-1.027*
	p value	0.746	*0.301*	*0.144*	*0.416*	0.543	*0.064*	*0.456*	*0.604*	0.629	*0.499*	*0.71*	*0.371*
D7	χ²(a-b-c) or Z (a-b	0.933	*-0.933*	*-1.393*	*-0.589*	0.737	*-0.042*	*-0.468*	*-0.351*	1.850	*-1.697*	*-0.242*	*-1.724*
	p value	0.627	*0.351*	*0.164*	*0.556*	0.692	*0.967*	*0.640*	*0.726*	0.397	*0.090*	*0.809*	*0.085*
E_sum	ANOVA F or Diff	9.239	1.354	1.111	-0.243	10.201	0.569	1.313	0.743	5.894	0.667	0.910	0.243
	p value	**0.001**	**0.012**	**0.006**	1	**0.000**	0.266	**0.001**	**0.040**	**0.006**	0.177	**0.010**	0.828

df = 2
N = 18

bold = significant
* not significant because of Bonferroni

grey = no post-test
blue = parametric test (ANOVA)

Statistical tests on the objective metrics

- Parametric test : repeated measures within subjects (1-way ANOVA)

Driving performance measure	Value			1-2-3	1-2	1-3	2-3		1-4-5	1-4	1-5	4-5		1-6-7	1-6	1-7	6-7
Thesis																	
I	ANOVA F or Diff	Normality	Mauchly	1,913	6,90E-05	9,00E-05	2,03E-05	Mauchly	14.293	0.000	0.000	0.000	Mauchly	10.633	-3,46E-05	0.000	0.000
	p value	4 of 7 rej	**0.044**	0.175	0.69	**0.035**	1	0.326	**0.000**	0.158	**0.001**	**0.005**	**0.029**	**0.001**	1	**0.003**	**0.020**
II	ANOVA F or Diff	Normality	Mauchly	30,156	0.001	0.001	0.000	Mauchly	48.399	0.000	-0.001	-0.001	Mauchly	2.377	0.000	0.000	0.000
	p value	1 of 7 rej	0.141	**0.000**	**0.000**	**0.000**	**0.000**	0.687	**0.000**	**0.001**	**0.000**	**0.000**	0,368	0.108	0.132	0.416	1
III	ANOVA F or Diff	Normality	Mauchly	27.192	0.001	0.001	0.000	Mauchly	47.319	0.000	-0.001	0.000	Mauchly	2.605	0.000	-2,09E-06	0.000
	p value	1 of 7 rej	0.263	**0.000**	**0.000**	**0.000**	**0.000**	0.563	**0.000**	**0.001**	**0.000**	**0.000**	0.275	0.089	0.181	1	0.315
IV	ANOVA F or Diff	Normality	Mauchly	1.540	1.964	0.452	-1.512	Mauchly	0.689	0.438	-1.050	-1.488	Mauchly	2.108	-1.441	-2.724	-1.283
	p value	no reject	0.643	0.229	0.290	1	1	0.118	0.509	1	1	0.402	0.882	0.137	0.891	0.200	0.955
V	ANOVA F or Diff	Normality	Mauchly	2.193	0.011	0.015	0.004	Mauchly	17.198	-0.022	-0.055	-0.033	Mauchly	11.203	-0.009	-0.039	-0.030
	p value	1 of 7 rej	0.243	0.127	0.536	0.057	1	0.215	**0.000**	0.090	**0.000**	**0.001**	0.379	**0.000**	0.670	**0.001**	**0.023**
VI	ANOVA F or Diff	Normality	Mauchly	1.793	0.000	-0.006	-0.006	Mauchly	20.690	-0.005	-0.012	-0.007	Mauchly	12.868	-0.004	-0.010	-0.007
	p value	1 of 7 rej	0.001	0.196	1	0.751	0.101	0.830	**0.000**	**0.048**	**0.000**	**0.03**	0.025	**0.000**	0.057	**0.000**	0.056
VII	ANOVA F or Diff	Normality	Mauchly	1.964	-3,33E-05	-3,90E-05	-5,65E-05	Mauchly	13.555	4.149	**9.643**	**5.493**	Mauchly	7.555	2.260	5.790	3.530
	p value	no reject	0.051	0.156	0.647	0.250	1	0.244	**0.000**	0.154	**0.001**	**0.004**	0.911	**0.002**	0.421	**0.003**	0.118
VIII	ANOVA F or Diff	Normality	Mauchly	0.649	7.018	-1.152	-8.170	Mauchly	3.763	-5.894	-10.445	-4.551	Mauchly	6.172	-10.627	-7.417	3.211
	p value	1 of 7 rej	**0,001**	0.529	0.98	1	0.422	0.676	**0.033**	0.370	**0.028**	0.885	0.076	**0.005**	**0.000**	0.151	1
IX	ANOVA F or Diff	Normality	Mauchly	1.933	-0.521	-0.790	-0.270	Mauchly	2.354	-0.577	-0.894	-0.317	Mauchly	0.704	-0.261	-0.420	-0.159
	p value	no reject	0.884	0.160	0.706	0.163	1	0,226	0.110	0.560	0.250	0.570	0.409	0.502	1	0.943	1

df = 2 **bold = significant**

N = 18