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# The effect of steering-system linearity, simulator motion, and truck driving experience on steering of an articulated tractor-semitrailer combination

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## ABSTRACT

Steering systems of trucks consist of many linkages, which introduce nonlinearities that may negatively affect steering performance. Nowadays, it is possible to equip steering systems with actuators that provide artificial steering characteristics. However, before new steering systems are deployed in real vehicles, evaluation in a safe and controlled simulator environment is recommended. A much-debated question is whether experiments need to be performed in a motion-base simulator or whether a fixed-base simulator suffices. Furthermore, it is unknown whether simulator-based tests can be validly conducted with a convenience sample of university participants who have not driven a truck before. We investigated the effect of steering characteristic (i.e., nonlinear vs. linear) on drivers' subjective opinions about the ride and the steering system, and on their objective driving performance in an articulated tractor-semitrailer combination. Thirty-two participants (12 truck drivers and 20 university drivers) each completed eight 5.5-min drives in which the simulator's motion system was either turned on or off and the steering model either resembled a linear (i.e., artificial) or nonlinear (i.e., realistic) system. Per drive, participants performed a lane-keeping task, merged onto the highway, and completed four overtaking manoeuvers. Results showed that the linear steering system yielded less subjective and objective steering effort, and better lane-keeping performance, than the nonlinear system. Consistent with prior research, participants drove a wider path through curves when motion was on compared to when motion was off. Truck drivers exhibited higher steering activity than university drivers, but there were no significant differences between the two groups in lane keeping performance and steering effort. We conclude that for future truck steering systems, a linear system may be valuable for improving performance. Furthermore, the results suggest that on-centre evaluations of steering systems do not require a motion base, and should not be performed using a convenience sample of university students.

## 1. Introduction

About 1.25 million people lose their lives in traffic each year, and millions more are severely injured (World Health Organization, 2015). Heavy goods vehicles are involved in a high percentage of severe crashes, which is partly due to their large size and mass (Kharrazi and Thomson, 2008; NHTSA, 2017).

The steering system is a crucial part of any vehicle. The design of the steering system does not only have effects on subjective feel and comfort (Boller et al., 2017; Peppler et al., 1999; Pfeffer et al., 2008; Rothhämel, 2013; Tagesson, 2017), it also affects lane-keeping performance (Anand et al., 2013; Nagai and Koike, 1994; Shyrokau et al., 2015). In most current vehicles the steering system is a complex arrangement of mechanical linkages, leading to nonlinear steering characteristics due to friction, damping, and play between the steering components. In heavy goods vehicles, these nonlinearities are particularly strong due to the high loads involved. It would be of interest to develop steering systems that do not exhibit such nonlinearities.

Steering systems that provide synthetic force feedback have been found to yield improved driving comfort and lane-keeping performance (Sherwin and Williams, 2008; Williams, 2009). With the advent of torque overlay or steer-by-wire technology, even greater flexibility in

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the mapping between steering wheel angle, steering wheel torque, and the angle of the wheels becomes feasible (Huang and Pruckner, 2017; Müller, 2010). Because of the stringent safety requirements and high cost involved, steer-by-wire is still rare in series-production passenger cars (with Nissan's Direct Adaptive Steering being an exception; Miura, 2014), but it could be an attractive option for heavy goods vehicles. The last decade several researchers have investigated steer-by-wire systems for heavy goods vehicles (Koleszar et al., 2005; Weinfurter et al., 2006). With steer-by-wire, it becomes possible to eliminate nonlinearities and enhance stimulus-response compatibility (Amberkar et al., 2004).

Before deploying a new steering system on the road, a human factors evaluation is indispensable. Driving simulators are regarded as useful tools for the initial evaluation of steering systems, as simulators allow for accurate performance measurements in a safe and controlled environment (Knappe et al., 2007; Lee et al., 2013; Mohajer et al., 2015). However, simulators exhibit limited physical fidelity (e.g., in terms of tactile or vestibular stimuli), which may result in a lack of subjective presence and unrealistic driving performance (De Winter et al., 2012).

A hotly debated topic concerns the effect of simulator motion on driving performance. Each motion platform has dynamic and kinematic constraints, which means that it is impossible to provide perfectly realistic motion. After all, in order to provide sustained acceleration, sustained displacement is needed, whereas common hexapod-based platforms have a range of travel of about 1 m. Typically, motion scaling is used (Bellem et al., 2017; Berthoz et al., 2013) as well as washout and tilt coordination (Reymond and Kemeny, 2000; Savona et al., 2014; Takahiro et al., 2014) so that drivers may find the driving experience realistic despite the fact that the actual accelerations in the cabin do not correspond perfectly to the accelerations of the simulated vehicle. In flight simulation, it is well established that motion can result in enhanced tracking performance in disturbance-rejection tasks (Gundry, 1976; Hosman & Van der Vaart; 1981). For example, Martin (1986) found that in a roll-axis tracking simulator in which participants were required to keep their simulated plane ‘wings-level’ in the presence of unpredictable disturbances, accuracy improved threefold for a full motion condition as compared to a visual-only condition. Similar results, although with smaller effect sizes, have been found in driving simulator studies that compared motion on versus motion off conditions (Greenberg et al., 2003; Lakerveld et al., 2016; Repa et al., 1982; Siegler et al., 2001). Motion may be less important in manoeuvring tasks where the human himself initiates the motion (e.g., flying/driving through a curve; e.g., Colombet et al., 2008; Gundry, 1976; Michon, 1985) or if forces on the vehicle are small, such as when driving at constant speed or maintaining lane without severe lateral disturbances (i.e., on-centre handling) (cf. Damveld et al., 2012).

Apart from simulator motion, driving experience is a relevant moderator variable. It is known that experienced drivers visually scan the environment more efficiently (Underwood et al., 2011) and adopt a less risky driving style (De Winter and Kuipers, 2016) than young and inexperienced drivers. It may be argued that a human factors evaluation of steering systems should only be conducted among the target group (e.g., truck drivers) because the target group is better able to judge differences between a novel steering system and the steering system they are used to. However, experienced drivers may also yield a familiarity bias, because they may be habituated to their current non-computerized system and be less likely to embrace a novel steering concept (see Nilsson et al., 2009 for this phenomenon in a study on ship navigation). Novice drivers, who have never driven a truck before, might provide a less biased interpretation of differences between steering systems. Another, more practical, issue is that truck drivers are difficult to recruit; they have a busy professional schedule and may be unlikely to travel to a research institute to volunteer in an experiment. For pragmatic reasons, human-subject research is often performed using university students (Grether, 1949; Henrich et al., 2010), and truck manufacturers sometimes use novice or non-commercial truck drivers in their studies (e.g., DeWitt et al., 1999; Larsson, 2016; Markkula et al., 2014). An important question is therefore whether a convenience sample, without a truck driving license, can be used in preliminary experiments of steering feel in a driving simulator. Accordingly, it is worthwhile to investigate how the results of a convenience sample of novices differ from those of a target sample of experienced truck drivers.

This research investigated differences in lane-keeping performance, objectively recorded physical effort, and subjective assessment between a current nonlinear truck steering system and a truck steering system with a linear steering characteristic (which in real trucks may be achieved using torque overlay or steer-by-wire technology). Participants performed a highway merging and lane-keeping task with a tractor-semitrailer combination. The comparison was made in a driving simulator with the motion platform turned on, and the motion platform turned off, and among experienced truck drivers as well as among a university sample unexperienced in truck driving.

## 2. Methods

### 2.1. Participants

Two groups participated in the experiment. The experiment was conducted on nine different days between February 24 and March 5, 2016, with truck drivers and university drivers participating in alternating slots. The first group (truck drivers) consisted of 12 male licensed truck drivers with a mean age of 49.6 years ($SD = 14.2$). On average the truck drivers had their driver's license for 32.3 years ($SD = 11.8$), their average reported lifetime mileage was 1.60 million km ($SD = 1.73$ million km), and their average reported yearly mileage was 78,333 km (SD = 42,817 km). According to the UK Department for Transport (2017) and the Statistics Netherlands (2017), 99% and 97% of the drivers of heavy goods vehicles are male. Thus, the gender distribution of our sample is representative of the truck driver population.

The second group was recruited from the student and employee community of the Delft University of Technology and consisted of 20 male participants with a mean age of 25.3 years ($SD = 4.1$). On average they had their driver's license for 7.3 years ($SD = 3.7$), their average reported lifetime mileage was 67,525 km ($SD = 64,986$), and their average reported yearly mileage was 9898 km (SD = 11,090 km). Two university participants had limited experience in commercial vehicle driving. One truck driver and two university participants had prior experience with a moving-base simulator. Only males signed up for the experiment, consistent with the fact that males are overrepresented in human-subject research at technical universities (De Winter and Dodou, 2017).

The research was approved by the Human Research Ethics committee of the Delft University of Technology, and all participants provided written informed consent. It is noted that there was no a priori reason for the group size difference. The initial goal was to have 16 participants per group. Based on this, 32 experimental slots were fixed in advance. Four truck drivers did not show up or decided to cancel their participation at the last moment. They were replaced with university drivers, who were more easily recruitable.

### 2.2. Truck driving simulator

The experiment was performed in the 6 DOF SIMONA Research Simulator (Koekebakker, 2001; Stroosma et al., 2003). The SIMONA was equipped with a high-performance steering actuator and software representing a fully loaded tractor-semitrailer combination with a gross weight of 40 tonnes. The simulator software ran on a multi-node PC configuration using an in-house developed framework (Van Paassen et al., 2000).

The dynamics module included a 44 degrees-of-freedom model of an articulated vehicle, a steering system, and tire-road interaction, running at 500 Hz. This model was developed in MATLAB/SimMechanics and validated with measurements on a real tractor with a semi-trailer (Evers et al., 2009). The tires were modelled with a Magic Formula steady-state slip model describing nonlinear slip forces and moments (Pacejka, 2005). The tire model was verified with commercial software for tire modelling Delft-Tyre 6.1 (TNO Automotive, 2010) and provided almost identical results for longitudinal/lateral forces and self-aligning moments.

Steering wheel force feedback was provided by a steering actuator. The control loading hardware was a Yaskawa SGMCS-45M direct drive electric motor, and the control loading system was configured as an admittance display (see Adams and Hannaford, 2002). The maximum continuous torque of the actuator was 45 Nm and the peak torque was 135 Nm. The input/output interface of the actuator was running at a 2500 Hz update rate.

A 180 × 40 deg field of view was generated by three projectors through a collimating spherical mirror mounted on the front of the cabin. The resolution was 1920 × 1200 pixels per projector, and the frame rate was 60 Hz. The outside visuals, including the virtual traffic, were generated with STSoftware (Kappé et al., 2002). The visible part of the tractor cabin was rendered in such a way that the rendered window pillars lined up with the window pillars of the actual cockpit. The placement and views of the mirrors were tuned based on video recordings from a highway drive of a real heavy goods vehicle using a GoPro HD Hero3 + camera. Final tuning of the mirror angles was done using the feedback from a professional truck driver. Photos of the driving simulator are provided in Fig. 1.

### 2.3. Simulator motion

Motion cueing was provided by a classical washout algorithm (Stroosma et al., 2013). The parameters of the motion cueing algorithm, which were tuned using the feedback from a professional truck driver, allowed for rapid lane changes without exceeding the maximum lateral displacement of 1.1 m of the actuators. Only the steering task was investigated, and to harmonize conditions, the vehicle speed was kept constant throughout the experiment. This implied that the simulator cabin exhibited no vertical and longitudinal cabin motion, and no cabin pitch. The lateral acceleration of the simulator cabin was achieved by means of sway displacement (i.e., sideways movement of the platform) up to 0.20 m in either direction plus roll up to 3° in either direction.

An example of the motion of the driving simulator for one experimental session (participant #27, ride #6) is shown in Fig. 2. This figure shows the lateral g-force of the cabin of the virtual truck and the simulator cabin. The lateral g-force of the simulator cabin is achieved by rolling the cabin (causing a feeling of sustained acceleration due to gravity) and by means of sway (i.e., sideways movement) of the cabin. Up to about 23 s (Fig. 2), the truck drives in a right-hand curve, and the g-force of the truck cabin is positive according to the selected coordinate system. The simulator produces a sustained g-force to the right using cabin roll to the left (up to about 3 deg), with the more high-frequent peaks caused by sway (up to approximately 0.25 m). As can be seen, the accelerations of the simulator are downscaled with respect to the accelerations of the virtual truck with a factor of about 0.4, as is commonly done in driving simulators (Berthoz et al., 2013). However, the lateral accelerations of the simulator cabin still exceeded perceptual thresholds (cf. Kingma, 2005, who reported a threshold in lateral direction of 0.065 m/s$^2$).

### 2.4. Steering-system models

Two steering system models were tested in this experiment:

#### 2.4.1. Nonlinear steering model

The nonlinear steering model was a detailed model of a truck steering system (Loof et al., 2016). The model encompassed the dynamics of the steering wheel, steering column, the equivalent mass of the spindle, piston and sector-shaft, and the left wheel around the king-pin rotation axis. Two universal joints facilitated the height adjustment of the steering wheel and the packaging of the steering house. The friction torques represented friction in the bearings of the steering column, torsion-bar, spindle, king-pin, and friction caused by the seals in between the piston and the cylinder in the steering-house. The dynamics of hydraulic power steering were implemented using a Wheatstone bridge approximation. The model included kinematics of the pitman-arm, drag-link, and wheel lever to the left wheel. The kinematics of the tie-rod to steer the right wheel were also added. The steering model was validated with a laboratory test setup (Loof et al., 2016) and combined with the tractor-semitrailer model (Evers et al., 2009) to deliver accurate steering torques and vehicle motion.

#### 2.4.2. Linear steering model

The linear steering model was based on the nonlinear model, but nonlinearities caused by the compliance and friction in steering components between the steering wheel and the pitman arm, dynamics of hydraulic power steering, and free-play were removed. The pitman arm rotation was controlled according to the steering wheel angle movement via proportional torque control, taking into account a fixed ratio

**Fig. 1.** The truck driving simulator. Left = cabin view; Right = outside view.

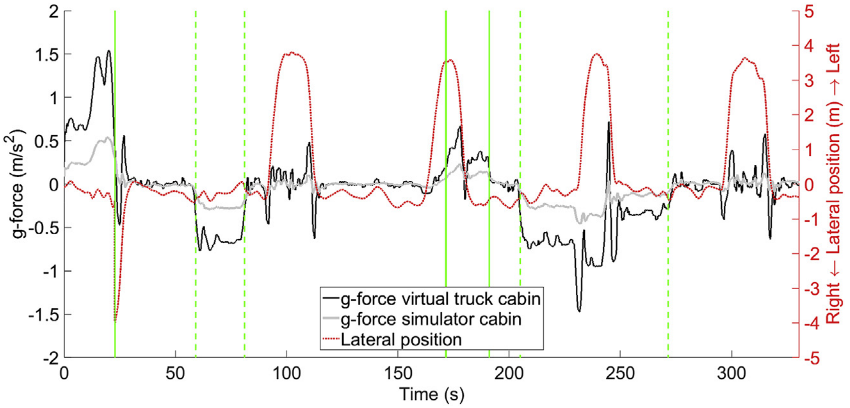

**Fig. 2.** Lateral g-force of the virtual truck cabin, lateral g-force of the simulator cabin, and lateral position on the truck on the road for one session with motion turned on. The solid vertical lines delineate right-hand curves, whereas dashed vertical lines delineate left-hand curves. The lateral position trace shows that there were four overtaking manoeuvres in the session. The jump in lateral position around 20 s is due to merging on a different driving lane.

of the steering mechanism. The steering feedback to the driver was generated by a linear stiffness-damper model. The parameters of the linear model were selected to provide the same amount of peak steering torque as in the nonlinear model, during a weave test manoeuvre at a steering frequency of 0.2 Hz corresponding to 1.5 m/s$^2$ of lateral acceleration according to ISO norm (11012:2009).

The relationships between steering torque, steering wheel angle, and lateral acceleration for both steering-system models are shown in Fig. 3 according to the above test manoeuvre. All characteristics were normalized from $-1$ to 1 because of confidentiality requirements. As can be observed, the linear steering model provides reduced hysteresis in the steering torque compared to the nonlinear model (Fig. 3, left). As evidenced by the relation between steering wheel angle and lateral acceleration, the vehicle response is hardly affected (Fig. 3, right).

### 2.5. Procedure

First, participants received a safety briefing and oral driving instructions, and completed an intake questionnaire. Next, participants completed a 6-min training session to get used to the driving simulator. Six minutes was regarded as sufficient for becoming accustomed to driving in a simulator (McGehee et al., 2004). During the training session, the participants drove the moving-base configuration with the nonlinear steering-system model.

Next, participants drove 5.5-min sessions for each of the following four conditions:

1. Fixed-base configuration with the linear steering-system model;
2. Fixed-base configuration with the nonlinear steering-system model;
3. Moving-base configuration with the linear steering-system model;
4. Moving-base configuration with the nonlinear steering-system model.

The participants drove each of the above-mentioned conditions two times. Thus, in total, eight sessions were driven by each participant in random order (Randomised Latin Square Method), with the restriction that the second run in a particular condition could not directly follow the first run in that condition. The selected steering system model and motion configuration were not disclosed to the participant. After each session, the drivers were asked to complete a questionnaire on their experiences during the past session.

### 2.6. Driving task

The driving route (Fig. 4) started with a highway ramp entering a 7.5 km long motorway. The lanes on the highway were dimensioned according to the guidelines from the Dutch Department of Public Works (Dienst Verkeerskunde, 1992). The width of the lanes was 3.5 m.

The vehicle speed was fixed at 80 km/h using cruise control; thus, participants did not use the pedals and did not change gears. This was done for two reasons. First, driving speed affects steering sensitivity and steering torques. The use of a constant speed via cruise control eliminates these confounds, and is in accordance with other research (Boller et al., 2017; DeWitt et al., 1999) and an ISO norm (11012:2009) on the evaluation of steering characteristics of heavy goods vehicles. Second, by keeping speed constant, we ensured that all participants experienced the same road and traffic conditions as a function of elapsed time, which, in turn, allowed us to perform synchronized analyses of lane keeping and overtaking as a function of elapsed time.

The task was to drive the vehicle within the right lane and, if necessary, overtake other trucks driving at a lower speed. Participants were told that the vehicle was a fully loaded tractor-semitrailer combination. Passenger cars on the left lane had sufficiently large gaps to allow for overtaking. Each participant completed four overtaking manoeuvres per session.

### 2.7. Data processing

#### 2.7.1. Objective measures

Data were recorded at a frequency of 25 Hz. The following objective

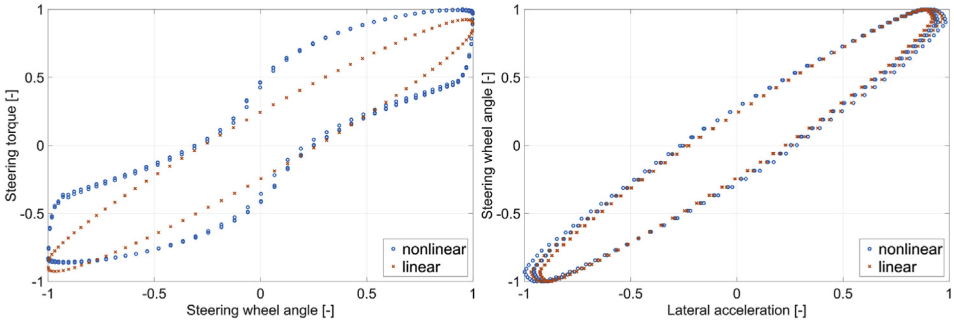

**Fig. 3.** The characteristics of the steering system models.

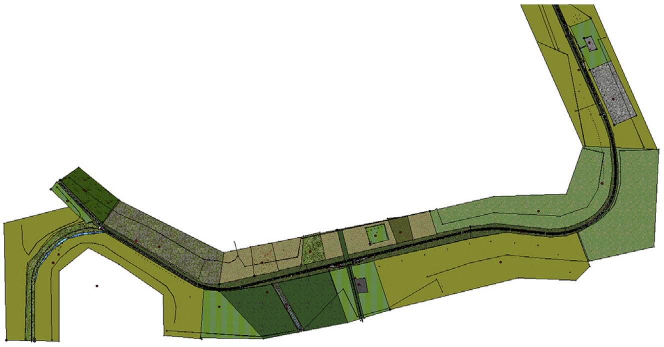

**Fig. 4.** Road design; the drive starts at the lower left at a single-lane merging onramp and continues along a two-lane highway stretch.

indicators were used to evaluate the steering and driving performance:

For the whole driving session (330 s of driving):

- Steering effort (Nm*deg), defined as the mean value of the product between the absolute steering wheel angle and the absolute steering wheel torque (Jaksch, 1979).
- Steering reversal rate (# per minute), a measure of steering activity (SAE J2944, Appendix F; see also Ranney et al., 2007). The raw steering wheel angle and steering velocity were filtered using a low-pass second-order Butterworth filter with a cut-off frequency of 0.6 Hz. The steering rate dead band was 3.0 deg/s, and the angular threshold was 3.0 deg.
- Steering wheel steadiness (% of time), another measure of steering activity. It is defined as “the percentage of the time the steering wheel's angular velocity was smaller than one degree per second” (Van Leeuwen et al., 2011). The raw steering wheel velocity was filtered using a low-pass second-order Butterworth filter with cut-off frequency of 0.6 Hz.

On straights:

- SDLP on straights (m). The standard deviation of the lateral position (m) is an indicator of lane-keeping performance (Dijksterhuis et al., 2011).
- MLP on straights (m, positive is to the left), the mean of the lateral position.

These two measures were calculated for a total of 66.12 s of driving on straights in which no overtaking manoeuvre occurred. This involved four separate segments of straight driving: (1) elapsed time: 40.00–59.12 s, travelled distance: 889–1314 m, (2) elapsed time: 122.00–141.00 s, travelled distance: 2711–3133 m, (3) elapsed time: 193.00–205.00 s, travelled distance: 4289–4556 m, (4) elapsed time: 260.00–276.00 s, travelled distance: 5778–6113 m.

In curves:

- MLP in curves (m, positive is to the outside of the curve). This is the mean of the lateral position in curves, where a sign reversal was applied to left curves. Thus, MLP in curves indicates whether the participant's lateral position was towards the outside or the inside of the curve. This measure was calculated for a selected 48.72 s of driving in curves in which no overtaking occurred. This involved (1) the on-ramp, a right hand curve with 600 m curve radius followed by a segment of 300 m curve radius (elapsed time: 0–22.84 s, travelled distance: 0–508 m), (2) a left-hand curve with a radius of 600 m (elapsed time: 59.12–69.00 s, travelled distance: 1314–1533 m), (3) another left-hand curve with a radius of 600 m (elapsed time: 205.00–221.00 s, travelled distance: 4556–4911 m).

For overtaking manoeuvres:

- Mean ‘changing to left lane’ time (s) across the four overtaking manoeuvers. ‘Changing to left lane’ started at the last moment when the lateral position with respect to the lane centre was smaller than 0.75 m, and ended when the lateral position first exceeded 2.75 m (Hegeman et al., 2005). Note that, because the lane width was 3.5 m, the lane markers between the left and right lanes were at a lateral position of 1.75 m.
- Mean ‘returning to right lane’ time (s) across the four overtaking manoeuvers. ‘Returning to right lane’ is defined analogously to ‘Changing to left lane’: It started at the last moment when the lateral position dropped below 2.75 m, and ended when the lateral position first dropped below 0.75 m.
- Mean time on left lane (s), averaged across the four overtaking manoeuvers. The time on the left lane is defined as the time between the first and last moment when the lateral position exceeded 2.75 m.

The measures MLP on straights, SDLP on straights, and MLP in curves were calculated across three or four time segments, as indicated above. That is, the lateral position data for the three or four separate time segments were combined into one vector, after which the standard deviation (SDLP) and the mean (MLP) were calculated. For MLP, our approach is equivalent to first calculating the mean lateral position per segment, and then calculating a time-weighted MLP. For SDLP, our approach gives slightly higher values than a time-weighted SDLP (Kircher and Ahlström, 2012; Verster and Roth, 2011).

Note that the segment 260–271 s involved a large-radius curve (1200 m, and increasing towards the end of the curve), where the mean absolute steering wheel angle was 6.5 deg, which was considerably lower than the mean absolute steering wheel angle in the other curve segments (13–32 deg). We therefore classified the segment 260–271 s as a straight instead of a curve.

### 2.7.2. *Subjective measures regarding the ride and the steering system*

A questionnaire was developed based on literature about steering feel evaluations (Harrer, 2006; Koide and Kawakami, 1988; Plantan et al., 1985) and using input from professional truck drivers. All questions were formulated in Dutch and only native speakers participated in the experiment. The total number of questions asked after each of the eight sessions was 38. The following questions are treated in the present paper:

- Motion sickness on a scale of 0 (*no problems*), 1 (*slightly uncomfortable, no specific symptoms*), 2 (*vague symptoms*), 3 (*slight symptoms*), 4 (*moderate symptoms*) … to 10 (*vomiting*).
- General experience of the ride on a 7-point scale with anchors at 0 (*none*) and 6 (*very much*), comprising the following questions:
  - o *Difficulty*: How difficult was the ride?
  - o *Risk*: How much risk did you experienced during this ride?
  - o *Mental effort*: How mentally strenuous was the ride for you?
  - o *Physical effort*: How physically strenuous was the ride for you?
- General opinion about the ride on a 7-point scale with anchors at −3 (*totally disagree*), −2 (*disagree*), −1 (*somewhat disagree*), 0 (*neither agree nor disagree*), 1 (*somewhat agree*), 2 (*agree*), and 3 (*totally agree*) covering the following statements. During this ride …
  - o *Safety*: I had the vehicle safely under control.
  - o *Realistic driving*: the control of the vehicle felt realistic.
  - o *Comfort*: I felt comfortable.
  - o *Realistic response*: the vehicle responded realistically to steering movements.
  - o *Easiness*: I found the vehicle easy to control.
  - o *Tight steering*: I found that the vehicle steered ‘tightly’.
  - o *Course stability*: I found the vehicle course stable.
- Acceptance score of the steering system, using a semantic differential scale in which participants had to select their position between two adjectives (Van der Laan et al., 1997). The mean usefulness score was determined across the following five items: 1.

useful–useless, 3. bad–good, 5. effective–superfluous, 7. assisting–worthless, and 9. raising alertness–sleep-inducing. The mean satisfaction score was determined from the following four items: 2. pleasant–unpleasant, 4. nice–annoying, 6. irritating–likeable, and 8. undesirable–desirable. All items were on a five-point scale from −2 to +2. Sign reversals were conducted for items 1, 2, 4, 5, 7, and 9, so that a higher score indicates higher usefulness/satisfaction.

- Steering feel assessment on a 7-point scale with anchors provided at −3 (*far too little*), −2 (*absolutely too little*), −1 (*a little too little*), 0 (*exactly right*), 1 (*a little too much*), 2 (*absolutely too much*), and 3 (*far too much*). The assessment included the following categories:
  - o Truck stability.
  - o *Play*: the play in the steering system.
  - o *Required torque*: the force needed to turn the wheel.
  - o *Uniformity*: whether the steering response was fluent versus shaky/shocking.
  - o *Sensitivity*: the sensitivity of the vehicle to small movements of the steering wheel.
  - o *Returnability*: the time that the wheel needs to turn back to the centre position.
  - o *Truck response*: the time that the vehicle needed to respond to steering movements.
- Realism assessment based on 8 items, on a 7-point scale, with anchors provided at 0 (*not realistic*) and 6 (*very realistic*). The realism assessment was performed only by the truck drivers.

### *2.8. Statistical analysis*

Statistical significance of the results was assessed using a mixed design analysis of variance (ANOVA) with either motion (on or off) or steering model (linear vs. nonlinear) as a within-subject factor, group (truck drivers vs. university participants) as a between-subjects factor, and a steering system × group interaction term. We performed the ANOVAs with only one within-subject factor for the sake of simplicity and interpretability (see Shyrokau et al., 2016 for an analysis with multiway ANOVAs). Partial eta squared ($\eta_p^2$) was used as effect size measure. Because of the large number of dependent variables, it was decided to adopt a conservative alpha level of 0.01.

We used a parametric test (ANOVA) because we expected all data to be approximately normally distributed across the participants. The subjective measures represent the aggregate of multiple survey items, which according to the central limit theorem implies that the data are approximately normally distributed. The objective measures are all measured on a ratio scale and should exhibit no floor or ceiling effects. As a robustness check, all ANOVAs were repeated after rank-transforming the results (Conover and Iman, 1981), see Supplementary materials (Tables S1–S4). Furthermore, the supplementary materials report the results of paired *t* tests of the steering system and motion condition for the truck drivers and university drivers separately (Tables S5–S8).

### *2.9. Principal component analysis*

To reduce the large number of subjective measures into a smaller number of indicators that represent the major sources of variation, a principal component analysis (PCA) was conducted. The following self-reports were submitted to PCA: general experience of the ride (4 items), general opinion about the ride (7 items), and steering feel assessment (7 items). Component loadings ('weights') were calculated from the 18 × 18 correlation matrix. Based on these loadings and the *z*-transformed scores on the items, we calculated component scores per participant and condition (No motion-Linear, No motion-Nonlinear, Motion-Linear, Motion-Nonlinear).

## 3. Results

All drivers completed their runs without collisions. Due to a problem with the simulator, one participant from the university sample completed only 4 of 8 runs, and one participant from the truck driver sample completed 7 of 8 runs. Because these participants drove with each of the four conditions, their results were retained in the analysis. Due to a data recording error, the objective measures of the truck drivers are based on 11 instead of 12 participants. From the 972 overtaking manoeuvres (243 sessions x 4 overtaking manoeuvres per session), there was one overtaking manoeuvre where a truck driver moved to the left lane very early, and one overtaking manoeuvre where a truck driver overtook via the right shoulder. These two overtaking manoeuvers were removed. Furthermore, from the total of 22.8 h of recorded data, we removed 55 s of data from two truck drivers, because these participants temporarily drove on the right shoulder.

No runs were stopped due to simulator sickness, and sickness was mostly reported to be 0 (i.e., no problems), with a mean of 0.35 ($SD = 0.65$, $n = 12$) for truck drivers and 0.25 ($SD = 0.72$, $n = 20$) for university drivers. An independent samples *t*-test showed no significant effect in simulator sickness between the two groups, $t(30) = 0.41$, $p = 0.685$.

The results of the principal component analysis of the self-reports are shown in Table 1. Based on inspection of the scree plot (i.e., percentage of variance explained), it was decided to retain one component. High loadings were obtained for safety, realism, comfort, and stability, whereas low loadings were obtained for difficulty, risk, and mental and physical effort. Accordingly, the first principal component may be interpreted as a generic indicator of driving experience ranging from 'negative' to 'positive'.

### *3.1. Effect of steering system on subjective measures for truck drivers and university drivers*

The results of the subjective assessments of the steering system are shown in Table 2. The linear steering system received higher scores of usefulness and driving experience (i.e., first principal component score) than the nonlinear system, although these differences were not statistically significant. A strong effect, however, was found for the item 'required torque': On the scale from −3 to 3, participants found the nonlinear system to require more steering torque (0.48 and 0.84 for truck drivers and university drivers, respectively) than the linear system

**Table 1**
Results of the principal component analysis on self-reports of the driving experience.

| Variable | First component loading |
|---|---|
| Difficulty | −0.80 |
| Risk | −0.76 |
| Mental effort | −0.72 |
| Physical effort | −0.69 |
| Safety | 0.89 |
| Realistic driving | 0.74 |
| Comfort | 0.91 |
| Realistic response | 0.84 |
| Easiness | 0.89 |
| Tight steering | 0.64 |
| Course stability | 0.75 |
| Truck stability | 0.64 |
| Play | 0.12 |
| Required torque | −0.20 |
| Uniformity | 0.20 |
| Sensitivity | −0.29 |
| Returnability | 0.22 |
| Truck response | 0.16 |
| **Eigenvalue** | **7.53** |
| **Variance explained (%)** | **41.8** |

**Table 2**

Results for subjective measures regarding the ride and the steering system (linear versus nonlinear steering system).

| | Truck drivers ($n = 12$) | | University drivers ($n = 20$) | | Effect of Steering system | | | Effect of Group | | | Interaction between Steering system and Group | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Linear | Nonlinear | Linear | Nonlinear | | | | | | | | | |
| | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | F(df1,df2) | $p$ | $\eta_p^2$ | F(df1,df2) | $p$ | $\eta_p^2$ | F(df1,df2) | $p$ | $\eta_p^2$ |
| First principal component score | −0.11 (0.94) | −0.30 (1.03) | 0.41 (0.67) | −0.16 (0.92) | 7.38 (1,30) | 0.011 | 0.197 | 1.29 (1,30) | 0.265 | 0.041 | 1.82 (1,30) | 0.188 | 0.057 |
| Satisfaction (−2 to 2) | 0.37 (0.43) | 0.39 (0.59) | 0.53 (0.55) | 0.22 (0.54) | 2.32 (1,30) | 0.138 | 0.072 | 0.00 (1,30) | 0.954 | 0.000 | 3.05 (1,30) | 0.091 | 0.092 |
| Usefulness (−2 to 2) | 0.12 (0.49) | 0.11 (0.81) | 0.64 (0.58) | 0.02 (0.63) | 6.22 (1,30) | 0.018 | 0.172 | 1.21 (1,30) | 0.280 | 0.039 | 6.01 (1,30) | 0.020 | 0.167 |
| Required torque (−3 to 3) | −0.07 (0.57) | 0.48 (0.46) | −0.14 (0.65) | 0.84 (0.69) | 30.9 (1,30) | < **0.001** | 0.508 | 0.68 (1,30) | 0.418 | 0.022 | 2.37 (1,30) | 0.134 | 0.073 |
| Realism score (0–6) | 3.47 (0.63) | 3.30 (0.87) | – | – | 0.82 (1,11) | 0.384 | 0.070 | – | – | | – | – | |

*Note.* Significant effects ($p < 0.01$) are denoted in boldface.

(−0.07 and −0.14 for truck drivers and university drivers, respectively). Furthermore, university drivers were particularly positive about the linear system, as indicated by the relatively high principal component score and usefulness (see Table S5 for the results for truck drivers and university drivers separately).

### 3.2. Effect of motion on subjective measures for truck drivers and university drivers

The effect of motion on the subjective measures was not statistically significant (Table 3, see also Table S6). There were also no significant differences between the ratings of truck drivers and university drivers (Tables 2 and 3).

### 3.3. Effect of steering system on objective measures for truck drivers and university drivers

Table 4 shows the effect of steering system on the objective measures. Consistent with the subjective results in Table 2, the nonlinear system required substantially more steering effort (M = 17.46 [SD = 0.65] and 17.26 [SD = 1.09] Nm*deg for truck and university drivers, respectively) than the linear system (12.75 [SD = 0.33] and 12.78 [SD = 0.70] Nm*deg for truck and university drivers, respectively). This effect is illustrated in Fig. 5, where it can be seen that the steering effort is higher for the nonlinear system than for the linear system, both in curves and on straight road segments.

The linear steering system resulted in a more precise lane-keeping performance on straights (i.e., lower SDLP) than the nonlinear system. The linear system also resulted in lower active steering (i.e., lower reversal rate, higher steadiness) than the nonlinear system, particularly for university drivers. Furthermore, the linear system resulted in slower lane changes than the nonlinear system. The effects of steering system on steering effort, SDLP on straights, and returning-to-right-lane time were statistically significant for both truck drivers and university drivers, whereas effects of steering activity were apparent only among the university drivers (Table S7).

The truck drivers had a higher steering reversal rate and lower steer steadiness than the university drivers. Furthermore, university drivers drove around 0.30 m more to the right on straights (i.e., MLP < 0 m) than truck drivers a strong effect (see Fig. 6, top, for an illustration). During lane changes, truck drivers spent more time on the left lane, and returned to the right lane in a larger amount of time, than did the university drivers.

### 3.4. Effect of motion on objective measures for truck drivers and university drivers

Table 5 shows that simulator motion resulted in less active steering (i.e., lower reversal rate, higher steadiness) among the truck drivers in particular, as compared to the no-motion condition (see also Table S8). Furthermore, a strong effect was observed for the MLP in curves: Both truck drivers and university drivers drove more to the outside of the curve when the motion was turned on than when the motion was off. This effect of motion, which was on average about 0.15 m, is illustrated in Fig. 6 (bottom). Near the end of the on-ramp (i.e., at an elapsed time of 15–21 s), where the curve radius was relatively small (300 m), the difference in MLP between motion on and motion off was relatively large (0.24–0.33 m). In other words, it seems that the effect of motion

**Table 3**

Results for subjective measures regarding the ride and the steering system (motion off versus motion on).

| | Truck drivers ($n = 12$) | | University drivers ($n = 20$) | | Effect of Motion | | | Effect of Group | | | Interaction between Motion condition and Group | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Motion Off | Motion On | Motion Off | Motion On | | | | | | | | | |
| | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | F(df1,df2) | $p$ | $\eta_p^2$ | F(df1,df2) | $p$ | $\eta_p^2$ | F(df1,df2) | $p$ | $\eta_p^2$ |
| First principal component score | −0.27 (0.94) | −0.14 (0.84) | 0.24 (0.61) | 0.01 (0.97) | 0.18 (1,30) | 0.672 | 0.006 | 1.29 (1,30) | 0.265 | 0.041 | 2.63 (1,30) | 0.115 | 0.081 |
| Satisfaction (−2 to 2) | 0.35 (0.46) | 0.42 (0.47) | 0.32 (0.48) | 0.42 (0.60) | 1.11 (1,30) | 0.300 | 0.036 | 0.00 (1,30) | 0.954 | 0.000 | 0.02 (1,30) | 0.890 | 0.001 |
| Usefulness (−2 to 2) | 0.05 (0.59) | 0.18 (0.57) | 0.25 (0.53) | 0.41 (0.70) | 1.79 (1,30) | 0.191 | 0.056 | 1.21 (1,30) | 0.280 | 0.039 | 0.01 (1,30) | 0.914 | 0.000 |
| Required torque (−3 to 3) | 0.28 (0.35) | 0.13 (0.46) | 0.46 (0.54) | 0.24 (0.66) | 5.16 (1,30) | 0.030 | 0.147 | 0.68 (1,30) | 0.418 | 0.022 | 0.17 (1,30) | 0.685 | 0.006 |
| Realism score (0–6) | 3.28 (0.75) | 3.49 (0.73) | – | – | 1.72 (1,11) | 0.217 | 0.135 | – | – | | – | – | |

*Note.* Significant effects ($p < 0.01$) are denoted in boldface.

**Table 4**
Results for objective measures of driving performance (linear versus nonlinear steering system).

| | Truck drivers ($n$ = 11) | | University drivers ($n$ = 20) | | Effect of Steering system | | | Effect of Group | | | Interaction between Steering system and Group | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Linear | Nonlinear | Linear | Nonlinear | | | | | | | | | |
| | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | $F$ | $p$ | $\eta_p^2$ | $F$ | $p$ | $\eta_p^2$ | $F$ | $p$ | $\eta_p^2$ |
| Steering effort for the whole session (Nm*deg) | 12.75 (0.33) | 17.46 (0.65) | 12.78 (0.70) | 17.26 (1.09) | 1621 | **< 0.001** | 0.982 | 0.10 | 0.759 | 0.003 | 1.03 | 0.317 | 0.034 |
| Steering reversal rate for the whole session ($\text{min}^{-1}$) | 10.51 (1.69) | 10.50 (1.34) | 7.37 (1.65) | 8.99 (1.67) | 9.68 | **0.004** | 0.250 | 18.0 | **< 0.001** | 0.383 | 9.95 | **0.004** | 0.255 |
| Steering wheel steadiness for the whole session (%) | 27.46 (5.55) | 24.86 (4.25) | 34.52 (6.33) | 28.57 (5.14) | 29.68 | **< 0.001** | 0.506 | 7.96 | **0.009** | 0.215 | 4.55 | 0.042 | 0.136 |
| SDLP on straights (m) | 0.18 (0.04) | 0.21 (0.05) | 0.18 (0.04) | 0.22 (0.06) | 22.07 | **< 0.001** | 0.432 | 0.23 | 0.635 | 0.008 | 1.47 | 0.235 | 0.048 |
| MLP on straights (m, positive = left) | 0.06 (0.11) | 0.04 (0.10) | −0.23 (0.17) | −0.26 (0.15) | 3.68 | 0.065 | 0.113 | 31.7 | **< 0.001** | 0.523 | 0.29 | 0.597 | 0.010 |
| MLP in curves (m, positive = outside) | −0.20 (0.11) | −0.16 (0.10) | −0.04 (0.11) | −0.07 (0.12) | 0.32 | 0.573 | 0.011 | 10.6 | **0.003** | 0.268 | 6.98 | 0.013 | 0.194 |
| Mean ‘Changing to left lane’ time (s) | 4.01 (0.44) | 3.49 (0.32) | 3.32 (0.77) | 3.17 (0.81) | 8.77 | **0.006** | 0.232 | 4.90 | 0.035 | 0.145 | 2.72 | 0.110 | 0.086 |
| Mean ‘Returning to right lane’ time (s) | 4.18 (0.69) | 3.61 (0.65) | 2.89 (0.71) | 2.55 (0.43) | 40.5 | **< 0.001** | 0.583 | 28.6 | **< 0.001** | 0.497 | 2.68 | 0.113 | 0.085 |
| Mean time on left lane (s) | 18.76 (1.78) | 19.62 (1.85) | 15.47 (2.52) | 15.50 (2.13) | 2.78 | 0.106 | 0.088 | 23.2 | **< 0.001** | 0.445 | 2.47 | 0.127 | 0.079 |

*Note*. Significant effects ($p < 0.01$) are denoted in boldface. Degrees of freedom = (1,29) for all reported tests.

on MLP is stronger if the curve is sharper. The presence of motion did not have statistically significant effects on participants' lane changing behaviour (Table 5), nor did it interact substantially with the steering system condition (see Tables S9 & S10).

## 4. Discussion

This study investigated the effects of steering-system model linearity of a heavy goods vehicle on subjective opinions about the ride and the steering system, and objective driving performance. The effects were tested with simulator motion on and off, and for truck drivers as well as university drivers.

### 4.1. Effects of steering system linearity

The nonlinear steering model involved considerably higher steering torques than the linear model, both in subjective (Table 2) and objective (Table 4) terms. The explanation for the substantial differences in steering torque between the linear and nonlinear system is that most of the driving time involved straight road segments and road segments with large curve radius, where steering angles were small. For such small steering angles, the nonlinear system required higher steering torques than the linear system (Fig. 3, left). The linear system also resulted in improved performance (i.e., lower SDLP) and a lower steering activity compared to the nonlinear system.

In summary, among both truck drivers and university drivers, the linear steering system required substantially less steering effort than the nonlinear system, while yielding an improved lane-keeping performance in terms of SDLP. Collectively, our findings suggest that for future truck steering systems, an artificial linear steering characteristic that eliminates nonlinear elements may be valuable.

### 4.2. Effects of simulator motion

Simulator motion did not significantly affect subjective ratings about the ride or ratings of overall realism (Table 3), which can be explained by the relatively limited cabin motion during highway driving. Indeed, visual cues provide a compelling and dominant illusion of motion (e.g., Kennedy et al., 1996), and the experimenters themselves could hardly notice the presence of physical motion versus no physical motion when trying the experimental setup.

In objective terms, there were apparent differences between motion on and off. In particular, with motion turned on, participants drove a wider path through curves (Table 5, Fig. 6). This finding is similar to Siegler et al. (2001) and Pretto et al. (2009) who compared driving with and without motion in a curve driving and slalom task, respectively. According to Pretto et al. (2009) the fact that participants drive a wider curve with motion compared to without motion is because motion makes driving physically more demanding due to the presence of inertial forces. We also found that motion caused the truck drivers to have a lower steering activity compared to without motion (Table 5, S8), which may be explained by the fact that truck drivers can use the motion cues to their benefit to steer smoothly. No substantial interactions were found between the steering and motion conditions (Tables S9 & S10), which suggests that on-centre steering characteristics can be evaluated in a fixed-base simulator.

### 4.3. Effects of truck driving experience

For safety and legal reasons, on-road experiments with trucks should always be conducted with licensed truck drivers. Considering that truck drivers are difficult to recruit, a legitimate empirical question is whether preliminary simulator-based tests of steering systems can be conducted with a convenience sample of drivers without a truck driving license.

Our results showed important differences between truck drivers and

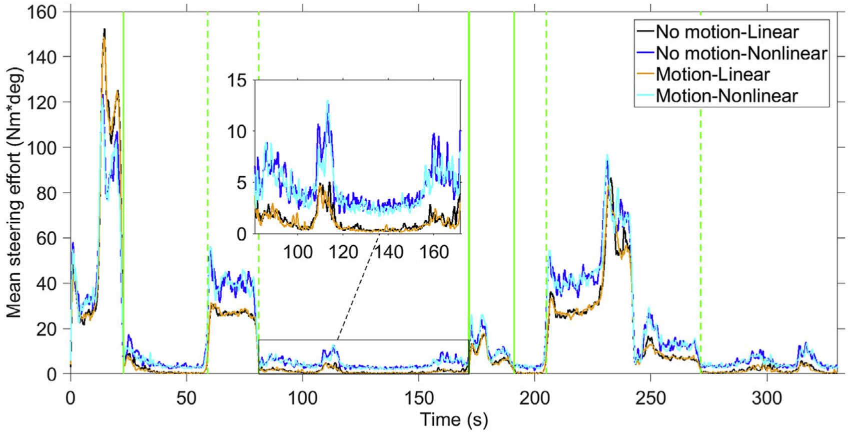

**Fig. 5.** Mean absolute steering effort across participants as a function of time in the session. The solid vertical lines delineate right-hand curves, whereas dashed vertical lines delineate left-hand curves.

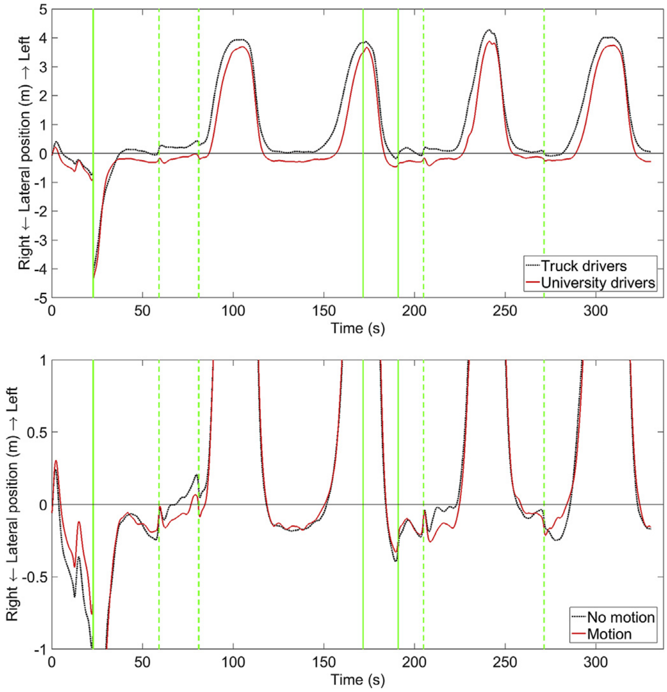

**Fig. 6.** Mean lateral position across participants as a function of time in the session. Top = effect of participant group. Bottom = effect of motion. The jump in lateral position around 23 s is due to merging on a different driving lane. The solid vertical lines delineate right-hand curves, whereas dashed vertical lines delineate left-hand curves.

university drivers. The truck drivers drove more to the left: they had an offset of about 0.05 m to the left of the lane, whereas university drivers had an offset of about 0.24 m to the right (see Tables 4 and 5). A possible explanation for these findings is that truck drivers have a better mental representation of their lateral position from the high viewpoint of the tractor cabin (e.g., using the mirrors) and are better able to position the articulated vehicle close to the lane centre. Furthermore, after overtaking, the truck drivers spent more time in the left lane and returned to the right lane more slowly than did the university drivers. This finding may also be explained by a superior mental model of the truck drivers: an articulated vehicle is longer and heavier than a passenger car, and it is important not to change back to the right lane too quickly as this could result in instability or a collision with the overtaken vehicle.

We observed various other differences between the driving styles of university students and truck drivers. The truck drivers had a substantially higher steering activity than the university drivers, whereas their SDLP was equivalent. Moreover, the university drivers in particular showed a lower steering activity for the linear steering system than for the nonlinear system (Table 4 and S7). Finally, the university drivers gave positive ratings to the linear system (Table 2 and S5), perhaps because they are not familiar with the conventional nonlinear system.

In summary, truck drivers exhibited a higher steering activity, a more leftward lateral position in the lane, and more gradual overtaking than university drivers. The effects of the steering system on SDLP on steering effort were found for both participants groups, but the effects on steering activity differed between university drivers and truck drivers. Accordingly, we recommend that university drivers should only be used for assessing basic physical effects of a steering system (e.g., how much physical effort it takes to steer), not for assessing *how* drivers steer (e.g., steering activity).

### 4.4. Limitations

Our study featured realistic vehicle dynamics and a realistic visual perspective on the road via the front view and the mirrors. However, due to space limitations of the simulator cabin, the steering wheel was more inclined than that of the steering column in a real commercial truck. The cabin itself (e.g., seats, dashboard) also differed from an actual truck.

Furthermore, the dynamic range of the motion-base simulator was not used to its full potential, as our experiment featured no vertical motion (to simulate bumpy roads and road rumble) while using downscaled lateral motion compared to real truck driving (Fig. 1). Simulator motion may interact with steering behaviour and driver's subjective ratings. For example, depending on the type of cabin suspension, friction near the steering wheel centre position may be beneficial to dampen out the transmission of road irregularities (cf. Brunner and Richardson, 1984, and see Tables S9 and S10 for our observed motion × steering interactions). Future research could use a large-excursion motion system (Schwarz et al., 2003; Nordmark et al., 2004) to simulate vertical motion and lane changes in a physically realistic manner.

Another limitation is that, for experimental control, the driving speed was fixed at 80 km/h, which is representative of highway driving. Future research could investigate the interaction between steering behaviour and longitudinal control, such as speeding up before merging or overtaking. Further research is also recommended into the effect of steering systems at vastly different speeds such as city driving, driving through sharp curves, or parking. Additionally, the present results

**Table 5**
Results for objective measures of driving performance (motion off versus motion on).

| | Truck drivers ($n$ = 11) | | University drivers ($n$ = 20) | | Effect of Motion | | | Effect of Group | | | Interaction between Motion condition and Group | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Motion Off | Motion On | Motion Off | Motion On | | | | | | | | | |
| | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | $F$ | $p$ | $\eta_p^2$ | $F$ | $p$ | $\eta_p^2$ | $F$ | $p$ | $\eta_p^2$ |
| Steering effort for the whole session (Nm*deg) | 15.21 (0.46) | 15.00 (0.43) | 15.06 (0.87) | 14.98 (0.89) | 4.93 | 0.034 | 0.145 | 0.10 | 0.759 | 0.003 | 0.81 | 0.375 | 0.027 |
| Steering reversal rate for the whole session ($\text{min}^{-1}$) | 11.24 (1.79) | 9.78 (0.99) | 8.18 (1.51) | 8.18 (1.60) | 21.7 | < **0.001** | 0.428 | 18.0 | < **0.001** | 0.383 | 21.5 | < **0.001** | 0.426 |
| Steering wheel steadiness for the whole session (%) | 24.87 (5.30) | 27.45 (3.71) | 31.41 (5.32) | 31.67 (5.67) | 9.11 | **0.005** | 0.239 | 7.96 | **0.009** | 0.215 | 6.11 | 0.020 | 0.174 |
| SDLP on straights (m) | 0.19 (0.05) | 0.19 (0.04) | 0.21 (0.05) | 0.19 (0.05) | 1.51 | 0.229 | 0.049 | 0.23 | 0.635 | 0.008 | 1.13 | 0.297 | 0.037 |
| MLP on straights (m, positive = left) | 0.06 (0.11) | 0.04 (0.11) | −0.26 (0.16) | −0.23 (0.15) | 0.03 | 0.853 | 0.001 | 31.7 | < **0.001** | 0.523 | 7.50 | 0.010 | 0.205 |
| MLP in curves (m, positive = outside) | −0.27 (0.12) | −0.10 (0.10) | −0.12 (0.11) | 0.00 (0.11) | 92.9 | < **0.001** | 0.762 | 10.6 | **0.003** | 0.268 | 3.70 | 0.064 | 0.113 |
| Mean ‘Changing to left lane’ time (s) | 3.82 (0.36) | 3.68 (0.38) | 3.28 (0.85) | 3.21 (0.65) | 1.52 | 0.228 | 0.050 | 4.90 | 0.035 | 0.145 | 0.19 | 0.668 | 0.006 |
| Mean ‘Returning to right lane’ time (s) | 3.90 (0.68) | 3.89 (0.67) | 2.63 (0.56) | 2.81 (0.56) | 2.30 | 0.140 | 0.074 | 28.6 | < **0.001** | 0.497 | 3.25 | 0.082 | 0.101 |
| Mean time on left lane (s) | 19.36 (1.48) | 19.02 (2.04) | 15.57 (2.75) | 15.40 (1.87) | 0.84 | 0.366 | 0.028 | 23.2 | < **0.001** | 0.445 | 0.10 | 0.758 | 0.003 |

*Note.* Significant effects ($p < 0.01$) are denoted in boldface. Degrees of freedom = (1,29) for all reported tests.

deserve to be compared with the results of an on-road study.

### 4.5. *Implications*

The past decades have seen an increase of support systems in vehicles, including adaptive cruise control, lane departure warning, and automated emergency braking (Bedinger et al., 2016; Bengler et al., 2014; Tideman et al., 2007). Many vehicle manufacturers are now developing automated driving systems that control the vehicle using sensors, computers, and actuators. However, it has been argued that it is unlikely that *fully* automated driving systems will be deployed at a large scale in the next few decades (Houtenbos et al., 2017; Shladover, 2016). Instead, the driver will likely remain in control of the steering wheel for a significant portion of the driving time, while automated steering may be activated or deactivated during different phases of a drive. For example, automated steering may be activated at the driver's convenience during lane keeping or lane changing (Banks and Stanton, 2016). A ‘linear’ steering system could be used in conjunction with such innovations, and offer greater flexibility in the trading of steering control between human and vehicle as compared to traditional steering systems that use mechanical linkages.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apergo.2018.03.018.

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