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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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A B S T R A C T

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