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Drowsy drivers' under-performance in lateral control: How much is too much? Using an integrated measure of lateral control to quantify safe lateral driving

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ABSTRACT

Internationally, drowsy driving is associated with around 20% of all crashes. Despite the development of different detection methods, driver drowsiness remains a disconcerting public health issue. Detection methods can estimate drowsiness by directly measuring the physiology of the driver, or they can measure the effect that drowsiness has on the state of the vehicle due to the behavioural changes that drowsiness elicits in the driver. The latter has the benefit that it could measure the net effect that drowsiness has on driving performance which links to the actual safety risk. Fusing multiple sources of driving performance indicators like lane position and steering wheel metrics in order to detect drowsiness has recently gained increased attention. However, not much research has been conducted with regard to using integrated measures to detect increased drowsiness within an individual driver. Different levels of drowsiness are also rarely classified in terms of safe or unsafe. In the present study, we attempt to slowly induce drowsiness using a monotonous driving task in a simulator, and fuse lane position and steering wheel angle data into a single measure for lateral control performance. We argue that this measure is applicable in real-time detection systems, and quantitatively link it to different levels of drowsiness by validating it to two established drowsiness metrics (KSS and PERCLOS). Using level of drowsiness as a surrogate for safety we are then able to set simple criteria for safe and unsafe lateral control performance, based on individual driving behaviour.

1. Introduction

Sleepiness at the wheel, commonly referred to as driver drowsiness or drowsy driving, is a disconcerting public health issue. Although different sources quote different statistics, it is safe to say that internationally around 20% of all crashes are somehow related to drowsiness (AWAKE, 2002; MacLean et al., 2003; Klauer et al., 2006). As such, there is an extensive amount of literature addressing the issue of drowsiness detection. Different methods to detect drowsiness-induced impaired driving have been established, and many of them attempt to assess the level of drowsiness by monitoring the physiology of the driver. Self-reporting methods, such as the Karolinska Sleeping Scale (KSS; Åkerstedt and Gillberg, 1990), are widely used to subjectively assess driver drowsiness and produce reasonable results in drowsiness-related studies (Kaida et al., 2006). Another prominent and less intrusive method was based on the finding that drowsiness goes along with slow eye movements (Erwin et al., 1973) including slow eye closures (Skipper and Wierwille, 1986). This resulted in the development of the PERCLOS (percentage of eye closure) P80 measure which uses a vision system to quantify drowsiness as the proportion of time in a given interval that the eyelids are at least 80% closed (Wierwille et al., 1994; Wierwille and Ellsworth, 1994; Dinges and Grace, 1998). Another method to estimate driver drowsiness is using the effect that drowsiness has on the state of the vehicle due to the behavioural changes it elicits. This has the advantage that it directly measures the net effect of drowsiness on driver performance. Deriving from the amount of literature on this topic, two aspects of vehicle state are key in detecting driver drowsiness: lane position related (e.g., Hanowski et al., 2008) and steering wheel related (e.g., McDonald et al., 2012). In an attempt to investigate the impact of roadside monotony on crash causation, Thiffault and Bergeron (2003) conducted a driving simulator study and concluded that drowsiness causes drivers to respond slower to lane

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position deviations and with larger steering wheel movements. It so appears that drowsiness affects the driver's lateral control of the vehicle, and it has recently been argued that decreased lateral control performance can be used to not only detect imminent drowsiness, but also moderate levels of drowsiness (Forsman et al., 2013). This has the potential of using the level of drowsiness as a surrogate measure of safety to qualify lateral control performance as either safe or unsafe, because drowsiness measures like PERCLOS and KSS have known criteria (e.g., Hanowski et al., 2008; Sommer and Golz, 2010). However, as of yet no attempt has been made to do so on an individual level. In the present study, we use a high-fidelity driving simulator with a monotonous (night time) driving task in an attempt to fuse lane position and steering wheel measures into a single measure of individual lateral control performance, and set criteria for safe lateral control based on the PERCLOS and KSS drowsiness estimates. The result is a single vehicle-based real-time measure that quantitatively tells us if and how much lateral control performance degrades, independent of individual behavioural differences.

2. Methods

2.1. Participants

Seventeen participants (6 female and 11 male), age ranging between 28 and 56 years, participated in the experiment. Each participant was an experienced driver with at least eight years in possession of a driver's license and with a minimum mileage of 12,000 km per year. All participants were moderately to highly experienced with driving at night.

2.2. Driving simulator

The driving simulator used in this experiment was an modified vehicle mounted on a moving base, with a 180° view screen in front of the car, and displays placed behind the car in line with the rear-view mirrors (see Fig. 1). Many parameters including speed, pedal positions, lateral position, and steering wheel angle were recorded. The room was dark and the projection was adjusted to night-time driving with headlights visible (see Fig. 2). The road as well as the scenery were kept as monotonous as possible. Filters were added to the projectors in order to block blue light (470 nm), avoiding an excessive increased stimulation of the circadian mechanism (Brainard et al., 1988, 2001). A SmartEye eye-tracking system was installed in the simulator.

2.3. Roadway

A 9-km stretch of two-lane highway with various small radii curves as well as straight sections was repeated a number of times,

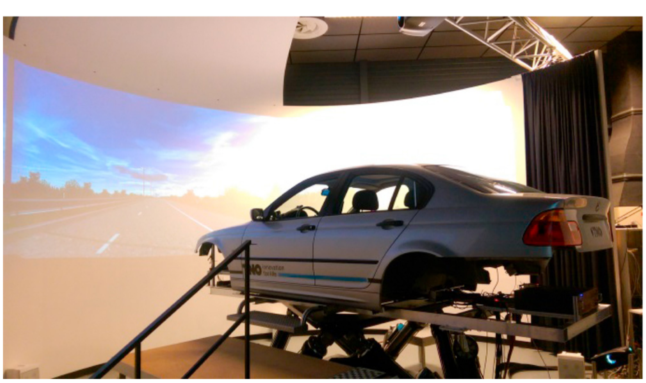

Fig. 1. Driving simulator.

Fig. 2. Night time driving task, front view with visible headlights.

such that the participant did not notice that he or she was driving the exact same road multiple times. The resulting road had no exits or on-ramps, no signs and there was no traffic present. A 2-km stretch of road was prepended for practice purposes.

2.4. Procedure

Participants were asked to abstain from drinking alcohol and caffeine 24 h prior to the experiment. The experiment took place during daytime. Before being seated in the simulator, a questionnaire was completed containing various questions to check for physical fitness, including the onset and duration of sleep the night before as well as the onset and duration of sleep on average. Participants who consumed caffeine or alcohol, or participants who had less sleep the night before than on average were excluded from participation. This way all participants started the experiment in relatively the same physical fitness, i.e., not fatigued. Participants were also familiarized with the KSS scale. After completing the questionnaire, the participant was seated in the driving simulator for the experiment to begin. Upon completion, the participant was brought to a bright room and was offered some water, and stayed there at least 15 min until he or she was recovered enough to safely drive home.

2.5. Task

Participants were instructed to drive 100 km/h and to stay in the right lane. Every 5 min, the KSS was queried using a pre-recorded monotonous and low-pitched voice. The participant was continuously monitored by the experimenter from the control room, which had an one-way intercom system from the simulator room, and answers to the KSS were recorded by the experimenter. After 1 h, the experimenter stopped the experiment. In case the participant was obviously extremely tired or felt asleep, the experimenter stopped the experiment before the 1-h mark.

2.6. Data analysis

For each session signals from the driving simulator like lateral position and steering wheel movements were extracted. Additional parameters were calculated, most significantly the iteration of the repeated road segment and type of road segment (curve left, curve right, straight). Using the data from the SmartEye system the eyes open ratio was calculated and blinks were removed. All data (driving simulator, eyes open ratio, and KSS) were synchronized and the data from the stretch of highway used for practice purposes was removed.