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Detecting lane departures from steering wheel signal

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ABSTRACT

Current lane departure warning systems are video-based and lose data when road- and weather conditions are bad. This study sought to develop a lane departure warning algorithm based on the signal drawn from the steering wheel. The rationale is that a car-based lane departure warning system should be robust regardless of road- and weather conditions. N = 34 professional driver students drove in a high-fidelity driving simulator at 80 km/h for 55 min every third hour during 36 h of sustained wakefulness. During each driving session we logged the steering wheel- and lane position signals at 60 Hz. To derive the lane position signal, we quantified the transfer function of the simulated vehicle and used it to derive the absolute lane position signal from the steering wheel signal. The Pearson correlation between the derived- and actual lane position signals was $r = 0.48$ (based on 12,000 km). Next we designed an algorithm that alerted, up to three seconds before they occurred, about upcoming lane deviations that exceeded 0.2 m. The sensitivity of the algorithm was 47% and the specificity was 71%. To our knowledge this exceeds the performance of the current video-based systems.

1. Introduction

Sleepiness at the wheel is common and a risk factor for traffic accidents. For instance, in the U.S., even 51% of the polled drivers have driven while sleepy (NSF, 2013) and 28% have nodded off at the wheel at least once (NSF, 2009). In 2013, 11% of all fatal crashes were pinned down to either sleepiness at the wheel or to failure to stay in the lane or on the road (NHTSA, 2013). However, because the role of sleepiness remains unknown in many crashes, this is probably a conservative estimate (Tefft, 2012). In the E.U., about 17% of the polled drivers have nodded off at the wheel at least once and of those 7% have been in an accident (Gonçalves et al., 2015). These numbers show that sleepiness at the wheel is still a topical safety issue (NTSB, 1999).

In drivers, sleepiness manifests as less frequent but large corrective steering wheel movements (Thiffault and Bergeron, 2003; Verwey and Zaidel, 1999), which increases the risk for lane drifting and running off the road (Philip et al., 2001; Sagaspe et al., 2008). While many accidents only involve one vehicle that departed from the road (Pack et al., 1996), they usually occur at highways where the speed is high and the consequences severe (Wang et al., 1996). Typically, the driver did not even attempt to avoid crashing (Wang et al., 1996). To combat these accidents, car-makers are developing technologies that warn the driver about imminent lane departures. So far these systems rely on dashboard-mounted forward-looking cameras that scan the road and algorithms that interpret whether the vehicle is in the lane or not. The sensitivity and specificity of these lane departure warning (LDW) systems has not been convincingly demonstrated (Dawson et al., 2014). The reason for this is probably that they are susceptible to road- and weather conditions and often suffer from data loss (Fröberg, 2007; Hillel et al., 2014). Consequently, there is a distinct need to develop non-video based LDW systems.

Signal processing research shows that one can use the signal from the steering wheel to compute the relative changes in lane position, if the vehicle's transfer function is known (Forsman et al., 2013). The rationale is that the steering movements that the driver makes translate to the wheels via the mechanics of the vehicle. Once the relative changes in lane position are known, one can compute metrics of global driving performance, like e.g. how much the vehicle is weaving in the lane (Åkerstedt et al., 2010). While such metrics are important and allow evaluating the drivers' general level of sleepiness (Åkerstedt et al., 2010), they do not allow evaluating immediate driving performance like imminent lane departures. Such ability requires that the absolute position in the lane is known.

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Fig. 1. Study protocol. Time of day progresses from left to right. Days progress from top to bottom. Black marks scheduled sleep at home. Grey marks scheduled wakefulness at the test site. Double asterisks denote 55-min driving sessions. Each driving session is preceded by a 15-min test battery including a 10-min psychomotor vigilance test. Double circles denote practice session.

In the work we present here, we set out to 1) derive the absolute lane position from the robust car-based steering wheel signal, and to 2) develop a non-video based algorithm that warns about upcoming lane departures up to three seconds before they occur.

2. Materials and methods

We used data from a laboratory-based, high-fidelity driving simulator study, where we monitored driver performance, sleepiness, and physiology during 36 h of sustained wakefulness.

2.1. Participants

N = 34 students at Työtehoseura's branch of logistics and vehicles participated in our study. N = 16 participants (mean age ± SD: 30 ± 12, range 18–55; all men) drove in a condition with nighttime scenarios only. N = 18 participants (mean age ± SD: 34 ± 11, range 19–52; two women) drove in a condition with daylight clear view only. The procedures were the same in both conditions, and therefore we describe them together.

Participant inclusion criteria were: good health, good sleep, and no medication affecting sleep or sleepiness (by questionnaire); ability to abstain from caffeine for 37 h; body mass index between 22 and 30; no problems with simulator sickness (by structured, supervised test driving of the simulator). The participants arrived and departed from the test site by taxi. They gave written informed consent, and we compensated them for their time. The University of Helsinki Institutional Review Board approved the study in June 2013.

2.2. Procedure

On Monday, the participants took a test session to practice the measurements (Fig. 1). To ensure that the participants arrived rested to the sleep deprivation experiment on Friday morning, we required ten hours time in bed per night (21:00–7:00, Mon-Fri), which we checked with at-home sleep diaries. The average wake up time was 06:38 (± 00:38) h, the average bed time was 20:58 (± 00:51) h, and the average time in bed was 9.75 h (± 41 min).

On Friday, the participants woke up at 7:00 and arrived at the test site by 8:30. We checked their compliance with our sleep-requirements and served them breakfast. At 9:45 the first test session started (Fig. 1). The sessions repeated every third hour until 20:15 on Saturday when the participants left for recovery sleep at home. Smokers (n = 12) could have a cigarette immediately after a test session (in a ventilated space at the test site). During the experiment we served 12 standardized meals (averaging 275 kcal, totaling 2200 kcal/24 h) immediately after each test session. No caffeine was allowed. Between the test sessions the participants had 90 min "own time" during which they could read, play cards and board games, watch movies, and converse with each other in the common room. The light level in the common room was 52 ± 4 lx and the temperature was 23 ± 1 °C. An experimenter monitored the participants continuously to ensure that they stayed awake.

Fig. 2. A rural road in daylight clear view in the high-fidelity driving simulator.

2.3. Measurements

Each test session included: a 10-min psychomotor vigilance test (PVT (Basner and Dinges, 2011)); a 55-min driving session in a high-fidelity driving simulator; and another 10-min PVT. Thus, each driving session was preceded and followed by an independent, established index of fatigue (Van Dongen et al., 2003). In addition to these tests, the participants rated their symptoms of sleepiness, and we recorded their eyelid movements and electrocardiograms. For the present data analyses we do not report on these results here.

The test site had two fixed-base high-fidelity driving simulators (Fig. 2), and hence we randomly assigned the participants to a certain simulator that he/she drove during the entire experiment. One simulator used hardware from a real truck and the other used hardware from a real bus (Team Simrac Finland Oy, Tampere, Finland). Both simulators used software (Eepsoft Oy, Tampere, Finland) to realistically simulate the mechanics and driving characteristics of a real truck. The simulated driving track comprised a network resembling Finnish uneventful rural roads with no other traffic. The track was 110 km long and included 21 straightaways that were 400 m or longer (Fig. 3). Because each driver completed 12 driving sessions, we defined 12 combinations of starting points and driving directions along the track and randomized their order to the driving sessions. The first 16 participants drove all 12 sessions in a nighttime scenario where the average illumination at the drivers' eye level was 0.9 lx (simulator 1) and 1.4 lx (simulator 2). The next 18 participants drove all sessions in daylight clear view where the average illumination at the drivers' eye level was 3.0 lx (simulator 1) and 4.9 lx (simulator 2). The condition on the road was full friction (i.e., dry, no ice). We instructed all participants to honor the 80 km/h speed limit, stay in lane, and keep their hands on the steering wheel, and to refrain from using cruise control and radio. The simulators sampled e.g. steering wheel angle θ, lateral lane position x, and driving speed v at a variable rate above 80 Hz, depending