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Real driving at night – Predicting lane departures from physiological and subjective sleepiness☆

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ABSTRACT

Only limited information is available on how driving performance relates to physiological and subjective sleepiness on real roads. This relation was the focus of the present study. 33 volunteers drove for 90 min on a rural road during the afternoon and night in an instrumented car, while electroencephalography and electrooculography and lane departures were recorded continuously and subjective ratings of sleepiness were made every 5 min (Karolinska Sleepiness Scale – KSS). Data was analyzed using Bayesian multilevel modeling. Unintentional LDs increased during night driving, as did KSS and long blink durations(LBD). Lateral position moved to the left. LDs were predicted by self-reported sleepiness and LBDs across time and were significantly higher in individuals with high sleepiness. Removal of intentional LDs, enhanced the KSS/LD relation. It was concluded that LDs, KSS, and LBDs are strongly increased during night driving and that KSS predicts LDs.

1. Introduction

Driver sleepiness is a contributing factor to road crashes (Philip & Akerstedt, 2006). Most of the evidence, however, is based on retrospective self-reports of falling asleep events, or on the timing of the drive, or on prior sleep loss, that is, through inference. Very little is known about the details of physiological, behavioral and subjective changes in sleepiness leading up to a crash during real driving.

Simulator studies of night or early morning driving (after a night awake) show alpha/theta activity, slow eye movements or lateral variability to be increased before driving off the road (Anund, Kecklund, Peters, et al., 2008; Horne & Reyner, 1996; Lal & Graig, 2002; Otmani, Roge, & Muzet, 2005). However, there are no studies of real driving and sleepiness indicators that might predict crashes or other serious adverse events. The established knowledge about real driving and sleepiness indicators is that night driving leads to self-reported sleepiness (Åkerstedt et al., 2013; Sagaspe et al., 2008; Sandberg et al., 2011), and to inadvertent lane departures (Åkerstedt et al., 2013; Philip et al., 2005; Sagaspe et al., 2008). In addition, EEG alpha and theta activity, as well as blink duration are increased (Åkerstedt et al., 2013; Sandberg et al., 2011).

Studying physiological and subjective sleepiness indicators leading up to a real crash is obviously not feasible in a well-controlled study. However, studies of drivers in instrumented vehicles could link crashes to inattention/fatigue using video recordings of driver and road (Hanowski, Wierwille, & Dingus, 2003; Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). In a recent field experiment on 90 min of motorway driving it was shown that 40% of drivers during late night were taken off the road by the in-car driving inspector because of dangerous levels of sleepiness (Åkerstedt et al., 2013). This group of drivers also showed increased self-reported sleepiness and increased sleep intrusions in the EEG, compared to the control group.

An alternative approach is to study changes in sleepiness indicators leading up to lane departures, using the latter as a proxy for crash risk (Åkerstedt et al., 2013; Philip et al., 2005; Sagaspe et al., 2008), even if the validity of such an application is undocumented. Lane departures may be caused by many factors unrelated to sleepiness, however, like overtaking or avoidance maneuvers.

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These factors appear to have been removed in the existing studies (Åkerstedt et al., 2013; Philip et al., 2005; Sagaspe et al., 2008). Still, there might be other factors, for example, objects beside the road, the curvature of the road, or oncoming vehicles that the driver may slightly veer away from even if there is no objective risk of interference. These issues need to be addressed in order to arrive at a cleaner measure of sleep related *unintentional* lane departures. Prediction of lane departures is of interest for understanding the role of sleepiness in driving and perhaps for developing drowsiness monitoring systems. However the self-awareness of sleepiness is of particular interest with respect to the ability to refrain from sleepy driving, which is an issue of both legal and personal responsibility. It appears important to determine whether self-reported sleepiness predicts lane departures. This has not been studied in real driving, but simulator studies suggest such a link (Anund, Kecklund, Vadeby, et al., 2008; Reyner & Horne, 1998).

The purpose of the present study was to investigate the effect of night driving on unintentional lane departures and sleepiness indicators (EEG, EOG, self-reports), as well as to predict unintentional lane departures from such indicators. This also necessitated work to identify and remove different types of intentional lane departures.

2. Methods

2.1. Participants

43 subjects (21 females), aged 44 ± 8 years (mean ± sd) participated in the study. The participants were recruited by random selection of private vehicle owners (between 30 and 60 years) from the Swedish national vehicle register. The inclusion criteria included good self-reported health, absence of sleep disturbances, a minimum mileage of 5000 km/year, driving experience of more than five years, ability to abstain from caffeine and nicotine during the experiment, no medication, no glasses needed for driving, and a body mass index in the range of 18–27. No professional drivers or shift workers participated in the study. The subjects were compensated SEK3000 for their participation.

Before the experiment started, the subjects received written and verbal information about the study and signed an informed consent form. The study was approved by the Regional Ethical Committee in Linköping, Sweden (EPN 142-07 T34-09) and the use of public roads for experiments involving sleepy drivers was approved by the Swedish government (N2007/5326/TR).

2.2. Design

There were three time-of-day conditions: day (10.00–16.00), evening (16.30–23.00) and night (23.00–05.00). The order of the driving sessions was the same for all subjects, i.e. they arrived in the morning and completed all three sessions (day, evening and night) during the subsequent 24 h period. Each driving session was approximately 90 min long. Here, only the first and the last driving sessions have been analyzed.

2.3. Procedure

Three days before the experiment, the participants started to fill out a sleep/wake diary. The participants were instructed to sleep at least 7 h on each of the two nights before the experimental day and to go to bed no later than midnight and get up before 09:00. They were also asked not to drink any alcohol for 72 h before the experiment. On the experimental day the participants were asked to rise at 07:00. They were not allowed to drink any caffeine containing beverages after 07:00 until the end of the experiment. Before the drive the participants filled out a background questionnaire, informed consent form and a form acknowledging that they understood that they were responsible for the drive and that the test leader should be seen as a fall back in case of an emergency situation.

Three persons participated in the study each experimental day. They arrived one at a time. The first participant started his/her driving sessions approximately at 10:00, 16:30 and 11:00. The second and the third participant started their driving sessions about 2 and 4 h later, respectively.

When the participants arrived at the laboratory, they were (again) informed about the procedure, they were trained in the use of the KSS and they also had to take a breath alcohol test. The test leader then applied electrodes for EEG, EOG, EMG and ECG, which the participant had to carry during the entire experiment. The first driving session began as soon as the electrodes were applied. After the driving session the participant stayed in the laboratory while waiting for the two following driving sessions. Between the driving sessions they were allowed to read, watch TV, use the internet, take short walks in the building, etc. They were not allowed to sleep. The participants were served lunch, dinner and a light meal late at night. Fruits and caffeine-free beverages were available all the time. They were not allowed to eat sweets or drink soft drinks.

The participants were instructed to drive as they normally would do if they were alone in the car; however, they were also instructed not to exceed the speed limits. Before each driving session they were reminded about safety aspects, such as to use the main beam when appropriate. During the driving sessions, the participants were not allowed to drink, eat, use nicotine, listen to the radio, speak to the test leader or adjust the temperature or seat. They were allowed to stop for a short break if they felt it was necessary for their safety.

Before and after each driving session (and also during the driving sessions, see below), the participants rated their sleepiness on the Karolinska Sleepiness Scale (KSS). When the participants had completed all three driving sessions, they were sent home by taxi.

2.4. Instrumented car and test route

The vehicle used in the study was a Saab 9-3 Aero (model year 2008) which was instrumented with sensors and equipment for data logging. Driving data from the CAN network, such as speed, steering wheel angle, yaw rate, acceleration, etc. was continuously logged with a sampling frequency of 40 Hz. In addition, the vehicle was equipped with a GPS receiver, a camera based driver monitoring system (Smart Eye AntiSleep 3.2, Smart Eye AB, Sweden) and a lane tracker system (MobilEye N.V., The Netherlands) that provided lateral position data. The data acquisition system was monitored by a test leader, sitting in the backseat during the driving sessions. There was also a test leader in the front seat, who was prepared to take control of the vehicle in case the driver started losing control due to sleepiness. The vehicle was equipped with dual control brakes.

Physiological data (EEG, EOG, EMG and ECG) was acquired by a portable digital recording system (Vitaport 2, Temec Instruments BV, The Netherlands) that was synchronized with the vehicle's logging equipment by means of a common signal, logged in both systems.

Every five minutes, a small screen positioned on the dashboard to the right of the driver showed the text "Sleepy?" and the verbal descriptions for each stage of the Karolinska Sleepiness Scale. The driver then rated his/her average sleepiness for the past five minutes by saying the corresponding KSS value. The rating was registered by both test leaders (the test leader in the back seat registered the value directly into the computer data log).

The test route consisted of a two-lane rural road that was 9 m wide. The road was fairly straight and the traffic density varied from low (night) to moderate (afternoon). The posted speed limit was 90 km/h except for a few short road sections where the speed limit was lower (mostly 70 km/h but a few segments of 50 km/h were present, the latter also included passing through suburban areas). Subjects 1–21 drove 53 km before they turned and drove the same stretch of road in the opposite direction back to the starting point, while subjects 22–43 drove 62 km before they turned back. In total, the test routes were 106 and 124 km respectively, and took about 80–100 min to complete. It was always daylight during the day sessions and mainly dark during the night sessions (for some subjects it started getting light at the end of the night session). In the evening session, the lighting conditions varied, which was one of the reasons for excluding this session.

2.5. Measures

The participants rated their sleepiness using the modified version of the Karolinska Sleepiness Scale (KSS) with labels on all nine steps (Åkerstedt & Gillberg, 1990). The KSS scale ranges from 1 = extremely alert to 9 = very sleepy, effort staying awake, fighting sleep. Each rating refers to the preceding five-minute period.

Three EEG channels were recorded: Fz-A1, Cz-A2 and Oz-Pz. The EOG was recorded from both eyes, i.e. two vertical channels, and also one horizontal channel. The EMG electrodes were positioned on the lower cheekbone in order to capture muscle tensions (such as yawns) in the face. The ECG consisted of two electrodes on the trunk, i.e. one channel approximately corresponding to lead II. Silver cup electrodes were used for the EEG and disposable wet gel electrodes were used for all other signals. The sampling frequency was 256 Hz for the EEG, EMG and ECG, and 512 Hz for the EOG.

The EEG and EOG data were visually scored according to the Karolinska Drowsiness Score (KDS) procedure (Åkerstedt & Gillberg, 1990). The data were divided into 20-s epochs, which in turn were divided into 2 s periods. Each 2 s period was scored with regard to the presence of alpha (8–12 Hz) or theta (4–8 Hz) waves, or slow rolling eye movements. The number of 2 s periods containing sleep-related signs per epoch was converted to a percentage, i.e. if three 2 s periods within the same epoch showed sleep-related signs, the corresponding KDS value is 30%. In the analysis, the mean and maximum KDS values were used. EMG and ECG were not further analyzed.

Blink duration was extracted from one of the vertical EOG channels by using an automatic blink detection algorithm (Jammes, Sharabty, & Esteve, 2008). The algorithm low-pass filters the EOG data, calculates the derivative, and searches for sequences where the derived signal exceeds a threshold and falls below another threshold within a short time period. If the amplitude of the original, low-pass filtered EOG signal in such a sequence exceeds a subject specific threshold, the sequence is assumed to be a blink. To reduce problems with concurrence of eye movements and blinks, blink duration was calculated at half the amplitude of the upswing and the downswing of each blink and defined as the time elapsed between the two.

Driving variables included in the analysis are mean lateral position (LP_AVG), standard deviation of lateral position (LP_STD), lane departures (LD) and mean speed. Lateral position was defined as the distance from the left lane marking to the vehicle's center line.

A lane departure (right or left) was defined as the vehicle (partially or fully) leaving the designated driving lane by crossing over the driving lane boundaries. In order to remove all seemingly intentional lane departures from the analysis the videotapes of the drives were carefully scored for presumed causes of intentional lane departures.

First, all road segments containing curves were removed because of a clear tendency of taking short-cuts, resulting in lane departures. These intentional lane departures could not be separated from unintentional lane departures and therefore only data collected from straight road segments were retained for analysis. Furthermore, for analytical reasons only segments of at least 300 m and with a speed limit of at least 70 km/h were retained for the analyses. In total, 64 such segments were found. The length of the segments varied from 300 m to 1400 m, with an average of 670 m.

The contextual setting for each lane departure that occurred in the retained segments was scored as true or false with regards to the following categories: (1) overtaking another vehicle, (2) avoidance maneuver because of person/bicyclist/motor vehicle on the right side of the road, close to, or within the driving lane, (3) being overtaken, and (4) avoidance maneuver because of oncoming vehicle in the other lane being wide and/or driving close to the center of the road.

In total 1380 instances of potential lane departures were identified in the data (corresponding only to participants considered for the analyses, see below for details) by analyzing the lateral position signals. Of these, 515 were not actual lane departures but signal spikes due to noise, changes in driving lane markings, etc. Of the remaining 865 lane departures, 492 occurred in curves and were thus not included (for reasons described above). The final set of 373 lane departures (which occurred on straight segments) were retained for video analysis. Of these, 112 happened during the daytime driving session and the other 261 during the night-time session. The total number of intentional lane departures for the day and night drive was, respectively, 35 and 7 for oncoming vehicle, 29 and 9 for overtaking, 5 and 1 for being overtaken, and finally 8 and 0 for objects to the close right.

2.6. Data processing and statistical analysis

Out of the 43 participants, data from 31 were retained for the analyses. The reasons for exclusions were the following: 6 were excluded because of incomplete or erroneous data (e.g. didn't finish all driving sessions), another 5 were excluded because of poor video recordings (over-exposure mainly to strong sunshine) which made the video-based scoring of lane departures impossible.

The data were analyzed using Bayesian multilevel models, which were fitted to the data using Hamiltonian Monte Carlo sampling (Duane, Kennedy, Pendleton, & Roweth, 1987) by way of the No-U-Turn sampler (Hoffman & Gelman, 2014). The interpretation of the model predictors was carried out using 95% highest density intervals (HDI) in the posterior (Kruschke, 2011). The posterior distribution of each model was sampled using four Markov chains, each consisting of 50,000 iterations, of which the first 25,000 iterations were used for adaptation (warm-up) and, therefore, not included in the results below.

Three analyses were carried out: (1) effects of the overall design of the experiment (day–night, time on task), (2) the relationship between the observed indicators of sleepiness and lane departures and (3) the impact of removing (seemingly) intended lane departures from the data was investigated.

The first analysis was of the effects of the experiment design on the following output variables: KDS, blink duration, average lateral position and standard deviation of lateral position. The following model was used to this end:

$$y \sim N(\beta_{0i} + \beta_{it}\,\text{time} + \beta_2\,\text{session} + \beta_3\,\text{time} \times \text{session}, \sigma^2)$$

$$\beta_{0i} \sim N(\mu_{\beta 0}, \sigma^2_{\beta 0})$$

$$\beta_{i1} \sim N(\mu_{\beta 1}, \sigma^2_{\beta 1})$$

$$\text{for} \quad i = 1, \ldots, N_{\text{TS}}$$

Lane departures were modeled using the same inputs, but with a Poisson distribution and a logarithm link function. Furthermore, time spent on straight road segments (measured in minutes) were included as an *exposure* variable, i.e. on the log scale with a constant coefficient of one.

The purpose of the second analysis was to study the relationship between the observed indicators of sleepiness and lane departures. As a first step, the mean number of lane departures during each driving session was analyzed using the following model:

$$y \sim \text{Poisson}(\exp(\beta_{0i} + \beta_1 \overline{\text{kss}} + \beta_2 \overline{\text{blinkdur}} + \beta_3 \overline{\text{kds}} + \beta_4 \overline{\text{session}} + \log(\text{exposure})))$$

$$\beta_{0i} \sim N(\mu_{\beta 0}, \sigma^2_{\beta 0})$$

$$\text{for} \quad i = 1, \ldots, N_{\text{TS}}$$

Lane departures were also modeled longitudinally *within* driving sessions: The same predictors as above were used, but averaged over each five-minute interval instead of over whole driving sessions. Time-on-task was therefore also included as a predictor. The same analysis was also carried out using the KSS value from the *preceding* five-minute interval.

In order to describe the longitudinal relation between lane departures and high levels of subjective sleepiness, the test subjects were grouped according to their proportion of KSS ≥ 8 during a session. A *lowKSS* group was defined as the set of test subjects with estimations of KSS < 9 and a maximum of 10% of KSS estimations at KSS = 8 (N = 7, mean ± se = 5.92 ± .12). A *highKSS* group was defined as the set of test subjects with at least 60% at KSS ≥ 8 (N = 9, 8.0 ± .10). The intermediate group (not in analysis) contained 16 participants. Since the participants were pooled within each group, a standard (non-hierarchical) Poisson model was used. Only data from the night driving sessions were included in this analysis.

The purpose of the third analysis was to compare the relation of each of the different subsets of lane departures to the observed indicators of sleepiness. The subsets studied were: (1) all lane departures (but excluding lane departures filtered out due to erroneous signals), (2) only lane departures on straight segments, and (3) only unintentional lane departures on straight segments.

3. Results

With respect to session, the 95% HDI of the posterior probability distribution on session doesn't overlap with zero effect for blink duration, KSS, lane departures, and average LP. Thus KSS, lane deviations, and blink duration were significantly higher during the night session and LP showed a significant movement to the left. With respect to driving time only the KSS, had a 95% HDI non-overlapping zero effect (Table 1 and Fig. 1). KSS values increased significantly across time. According to the fitted model on lane departures, the probability of an unintentional lane departure during one minute of driving on a straight segment in the day session is 0.001, whereas during the night session it is 0.010.

The number of lane departures was predicted by: KSS: 0.56 (0.11–0.98) (mean and 95% HDI of the posterior probability distribution), blink duration: 5.85 (−1.22 to 12.5), KDS: −0.03 (−0.08 to 0.02), session: 0.54 (−0.69 to 1.79) and intercept: −9.53 (−11.8 to −7.47). Thus, KSS increased significantly with increasing number of lane departures. No other predictors were significant.

Since it might be of interest to know whether subjective sleepiness already at the start of a driving session would predict the number of lane departures during the drive, Kendall's tau correlation between KSS estimations five minutes into the drive and the number of lane departures during the drive was computed and found to be $r = 0.44$ ($p < .01$).

In the model of the longitudinal relationship of lane departures and indicators of sleepiness, the results became: KSS: 0.63 (0.84–0.41), blinkduration: 5.65 (10.04–1.26), KDS: −0.01 (0.01 to −0.04), time: −0.01 (0.01 to −0.02) and intercept: −8.59 (−6.92 to −10.25). The results mean that KSS and blink duration predicted lane departures longitudinally (their 95% HDI did not overlap zero). Both increased with increasing lane departures. For the same model, but with KSS estimates from the *preceding* interval the mean and 95% HDI for KSS were 0.27 (0.10–0.41), that is, a significant relationship with lane departures.

For the analysis of the high and low mean KSS groups, where a standard (non multilevel) Poisson regression model was used, the coefficients in the rate parameter $\theta_i = \mu_i e^{b_0 + b_g G_i}$, for the Poisson model, were found to be $b_0 = -1.56$ (±0.14) and $b_{\text{lowKSS}} = -1.62$ (±0.36), where μ_i is the offset for each observation, defined as the summed time on straight segments during the session. After entering the rate parameters into the Poisson regression model the expected number of unintended lane departures per minute of driving on a straight road segment were thus $\theta_{\text{L}} = e^{-1.56+(-1.62)} = 0.04$ for the low KSS group and $\theta_{\text{H}} = e^{-1.56+0} = 0.21$ for the high KSS group. In Fig. 2, the average *cumulative* LD per participant and KSS group is shown across driving time. The results show a much higher rate of accumulation for lane departures in high sleepiness individuals. The average number of total lane departures

Table 1
Mean and 95% HDI for each of the predictors and outcome variables in the first analysis. For LD a Poisson distribution was used, whereas for all other outcome variables the Gaussian distribution was used.

Variable	Intercept	Time	Session	Time × Session
Blink duration	0.23 (0.21 to 0.25)	−0.01 (−0.02 to 0.01)	**0.04 (0.03 to 0.05)**	0.01 (0.00 to 0.02)
KDS	1.06 (−3.23 to 5.25)	2.01 (−1.38 to 5.37)	1.55 (−0.32 to 3.40)	0.78 (−1.33 to 2.93)
KSS	0.88 (0.45 to 1.31)	**1.24 (0.85 to 1.63)**	**2.47 (2.26 to 2.69)**	0.19 (−0.05 to 0.44)
LD	−5.16 (−8.67 to −1.96)	1.86 (−1.18 to 5.05)	**2.90 (1.30 to 4.71)**	−0.56 (−2.19 to 1.02)
LP_AVG	−1.51 (−1.58 to −1.44)	−0.03 (−0.10 to 0.03)	**−0.26 (−0.29 to −0.22)**	0.03 (−0.02 to 0.07)
LP_STD	0.29 (0.22 to 0.35)	−0.03 (−0.10 to 0.04)	0.00 (−0.03 to 0.04)	0.02 (−0.02 to 0.07)
Speed	85.33 (82.44 to 88.20)	2.67 (−0.39 to 5.71)	0.71 (−0.99 to 2.40)	−1.93 (−3.84 to 0.02)

KDS, Karolinska Drowsiness Score; KSS, Karolinska Sleepiness Scale; LD, lane departures; LP, lateral position; AVG = average; STD, standard deviation. Bold indicates significant at $p < .05$.

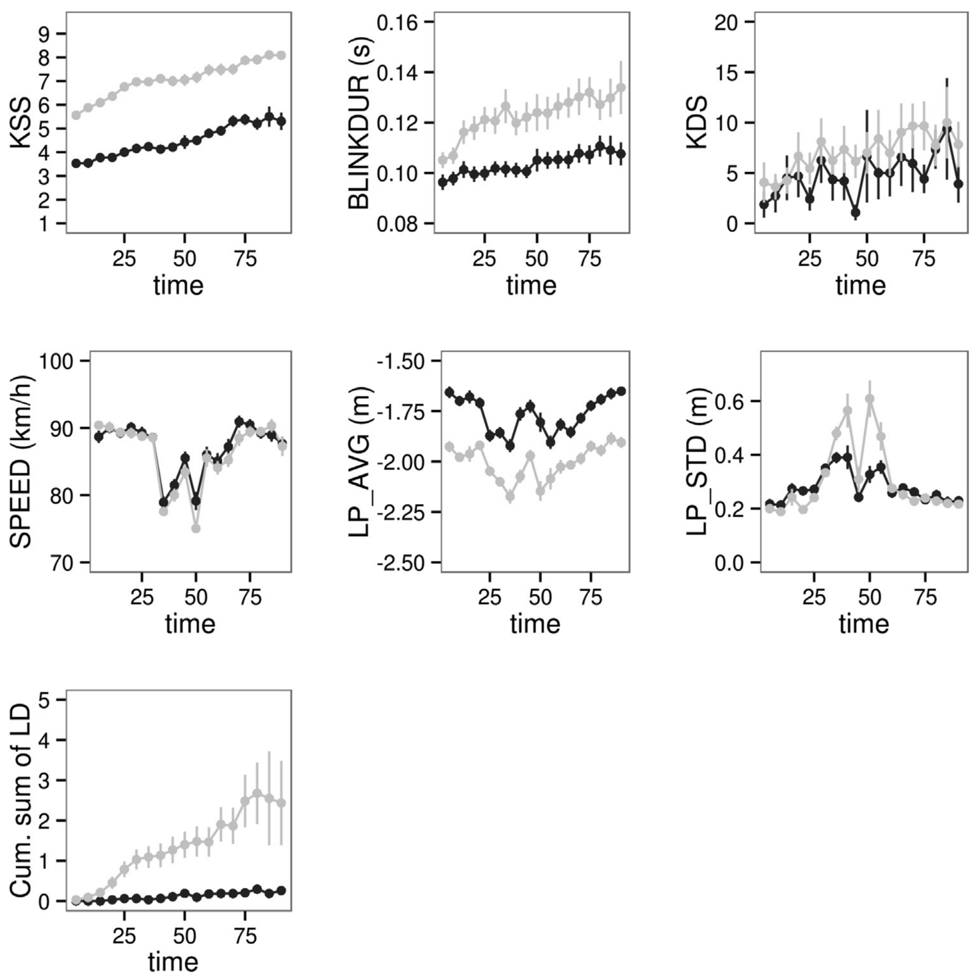

Fig. 1. Mean ± standard error (se) per minute for the day (black) and night (gray) driving sessions plotted across time (minutes) of driving. KSS, Karolinska Sleepiness Scale; blinkdur, blink duration; KDS, Karolinska Drowsiness Scale; LP_AVG, average lane position; LP_STD, standard deviation of lane position; Cum. sum of LD, cumulative sum of number of lane departures per minute.

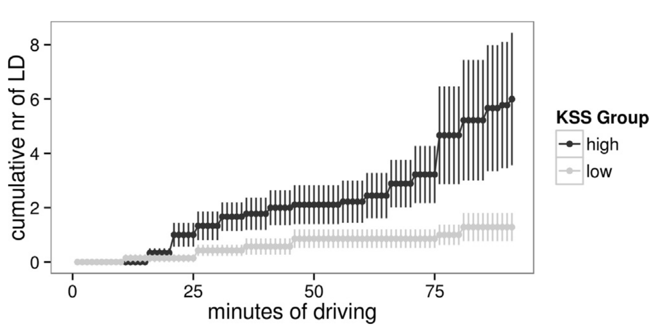

Fig. 2. Cumulation of lane departure in high and low KSS groups with confidence intervals.

per driving session in the sleepy group was 6.0 (standard deviation = ±2.4) whereas the average for the less sleepy group was 1.3 (±1.29).

Finally, in order to evaluate the effect of removing intentional lane departures before analysis, a comparison of the relation between KSS and lane departures was made for the two data sets. Fig. 3 shows that removing the curve segments led to an improvement in the relation between KSS and lane departures, but removing the remainder of the intentional lane departures had very modest effects. The complete removal of intentional lane departure (including curves) showed that particularly KSS values of 8 or 9 were associated with a considerable probability (0.35 for KSS = 9) of a lane departure.

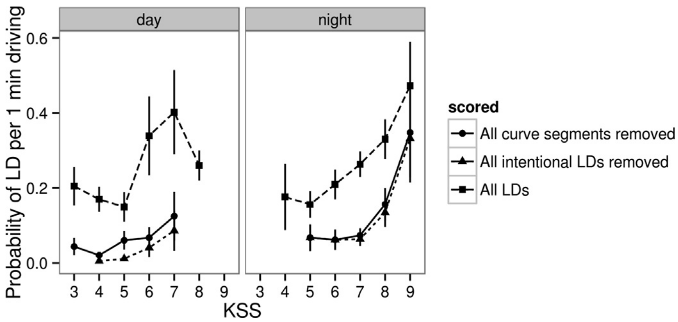

Fig. 3. Probability (mean ± se over individuals) of lane departures at different levels of KSS and with all lane departures, all straight segments (curved segments removed), and all remaining (intentional) intentional lane departures removed. Note KSS = 9 is not reached during day driving.

4. Discussion

The experimental design yielded clear effects of night driving on KSS, eye blink duration, lane departures and lateral position, while time on task was significant only for KSS (increased levels). Lane departures were predicted by KSS in the interindividual (cross sectional) analysis and by KSS and blinkduration in the intraindividual (longitudinal) analysis. Removal of "intentional" lane crossing made relations between the "unintentional" ones with KSS clearer.

The results on effects of session and time on task essentially support previous real road studies (Åkerstedt et al., 2013; Sandberg et al., 2011). The significant increase across time for KSS in the present study was significant in the previous real driving studies too (Åkerstedt et al., 2013; Sandberg et al., 2011), as was the effect of night driving (Åkerstedt et al., 2013; Sagaspe et al., 2008; Sandberg et al., 2011). Thus, self-rated sleepiness appears to show very consistent effects of night driving and time on task in real driving.

In the present study the KDS parameters did not show any effects of condition or time on task, while the previous studies showed effects for condition (Åkerstedt et al., 2013; Sandberg et al., 2011) and the latter did so also for time on task. The reason for the lack of response of KDS in the present study is not clear. Possibly, traffic density may have contributed, but there are no data to support this.

Blink duration was significantly increased in the present study as in the two previous studies (Åkerstedt et al., 2013; Sandberg et al., 2011). The effect was not significant for time on task, however, which probably is a somewhat weaker inducer of sleepiness than night driving.

Also lane departures was sensitive to both night driving and time on task, as in two previous studies (Åkerstedt et al., 2013; Sagaspe et al., 2008). However, as discussed below, it is important to remove "intentional" lane departures before analysis.

Lane departures was used as an indicator of driving performance and it was clearly related longitudinally to KSS levels, and to some extent to blink duration. To the best of our knowledge this ability of reported sleepiness to predict impaired driving has not been demonstrated before during real driving. It has been shown in studies using driving simulators (Anund, Kecklund, Vadeby, et al., 2008; Ingre, Åkerstedt, Peters, Anund, & Kecklund, 2006; Ingre, Åkerstedt, Peters, Anund, Kecklund, Pickles, 2006), however, which suggests that the present results are well supported. Interestingly, session (day/night) was not a significant predictor of lane departures when entered at the same time as KSS, despite the fact that the effect of day/night driving showed a highly significant relation to lane departures in the analysis of the effects of the experimental design. The reason may be that the sleepiness ratings may include more aspects of importance for sleepiness related driving performance than the effect of session (night driving) alone. Individual differences in response to night driving may be one such factor, as may individual differences in habitual sleepiness levels.

It should be emphasized that the KSS-values in the longitudinal analyses referred to the same interval as the lane departure value, although the rating was given the end of the interval. When KSS values were used to *predict* lane departures in the next interval the coefficient was lower, but still significant.

Another sleepiness/performance issue concerns whether the most subjectively sleepy group differs from the least sleepy group in terms of lane departures. The results indicate that individuals with high mean levels on KSS or a high number of ratings of KSS = 8 or 9 have a significantly higher propensity to have lane departures. This group difference is a new observation and suggests that sleepiness ratings may be comparable across individuals and possibly be interpreted in absolute terms. There does not seem to exist any comparable studies in the literature, except for simulator studies (Reyner & Horne, 1998).

It should be pointed out that the present links between reported sleepiness and lane departures were obtained despite the rather narrow range of KSS values during the night session. For example, no ratings below 6 were obtained for the night drive and very few values above 7 were obtained during the day drive (and very few lane departures). This suggests that the difference between for example, KSS values 6.5 and 8.5 is large in terms of driving performance. It has previously been demonstrated that the relation between KSS and lane departures is highly curvilinear (Ingre, Åkerstedt, Peters, Anund, Kecklund, Pickles, 2006), with ratings of 8 or 9 being necessary before any increase is seen in the dependent variable. In that study the probability of a lane departure at KSS = 9 was 0.50 and at KSS = 5 it was 0.02, with a pronounced exponential shape. In the present study (Fig. 3) the risk of a lane departure was 0.35 at KSS = 9 and 0.06 at KSS = 5, while the shape of the relation was exponential (for the night drive). The same curvilinear relationship also seems to hold for the appearance of sleep intrusions in the EEG or EOG (slow eye movements) (Åkerstedt & Gillberg, 1990). Furthermore, in the previous motorway study of night driving, drivers who were taken off the road because of dangerous sleepiness reached a level of 8.5 immediately before that event (Åkerstedt et al., 2013), and in a simulator study participants started to exit the road, hitting rumble strips at KSS levels of 8.1 (together with increased alpha/theta activity and long eye blinks) (Anund, Kecklund, Vadeby, et al., 2008). The observations above suggest that serious impairment in performance, mainly occurs at KSS levels of 8 and 9.

One purpose of the present study was to arrive at a measure of lane departures free from irrelevant (in a sleep loss context) events. Traditionally, lane departures due to overtaking, or to obstacles on the road, have been removed in the few real driving studies carried out (Åkerstedt et al., 2013; Sagaspe et al., 2008). Here we found that short-cuts across curves was a major contributor to lane departures. Some contribution during day driving also came from a car (or pedestrian) on the *side* of the road or from a large vehicle in the opposite lane. During night driving this effect was minute, possibly because of the lower traffic intensity. When the relation between KSS and lane departures was compared between "raw" and "cleaned" data the relation became more pronounced for the cleaned data. This indicates the importance of "cleaning" lane departure data in sleep related studies. In the present study the removal of intentional lane departures was made manually. Automatic removal will require advanced video-monitoring of the driving context, including quantification of critical road curvature. It should be emphasized that the present data were obtained on a road nine meter wide. The number of intentional lane excursions is likely to be considerably smaller on a motorway since it is wider, has less vehicles/objects interfering with driving, and has less sharp curves.

One may discuss to what extent lane departures represent unsafe driving. It seems likely that they do, and the measure has a high face value, but at present there is no data available on this issue. To resolve this problem seems to be an important future research effort. One might also consider if lane departures differ in seriousness depending on whether they occur to the left or right. In the present study too few lane departures occurred for analysis of this issue.

The present study also showed a movement toward the left, as in the previous real driving studies (Åkerstedt et al., 2013; Sandberg et al., 2011). The behavior may represent an attempt to avoid the dark, relatively diffuse, right edge of the road. The standard deviation of lateral position did not respond to night driving, similar to the results in the previous studies of real driving (Åkerstedt et al., 2013; Sandberg et al., 2011). This is in contrast to the observations in simulator studies in which this measure appears to be very sensitive (Anund, Kecklund, Peters, et al., 2008; Horne & Reyner, 1996; Lal & Graig, 2002; Otmani et al., 2005). The discrepancy may be due to properties of the steering system, or vehicle weight and speed may not permit the variability seen in simulated driving.

The speed reduction at night seen in the two previous studies (Åkerstedt et al., 2013; Sandberg et al., 2011) was not confirmed in the present one. The reason for this is unclear, but it is possible that differences in traffic density may have played a role. In addition, both speed and lane position showed unexpected variations during the middle of the drive. These seem to be due to segments with speed reductions to 70 km/h and reduced shoulder width.

One limitation with the present study is that day and night driving occurred in the same order for all individuals – for practical reasons. This may have induced habituation for the night drive, which may have affected the sleepiness levels during the night, including the lane departures. It would have been ideal to balance the order of sessions. On the other hand, it is unlikely that the lack of balancing would have affected the prediction of lane departures. Another limitation is that curves were removed from all the analyses because of measurement problems. Presumably, curves may be more conducive to lane departures and to real accidents. The strength of the study is the relatively large number of participants, the number of sleepiness indicators and the refined measure of lane departures.

In summary, the present study has demonstrated a strong effect of night driving on lane departures, subjective sleepiness ratings, blink durations and lateral position. It also showed a close link between subjective sleepiness and lane departures as well as a need for removal of intentional line departures in order to obtain result interpretable in terms of sleepiness.

Conflict of interest

No conflicts of interest have been reported.

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