Do repeated rumble strip hits improve driver alertness?

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Abstract

Driving while sleepy is associated with increased crash risk. Rumble strips are designed to alert a sleepy or inattentive driver when they deviate outside their driving lane. The current study sought to examine the effects of repeated rumble strip hits on levels of physiological and subjective sleepiness as well as simulated driving performance. In total, 36 regular shift workers drove a high-fidelity moving base simulator on a simulated road with rumble strips installed at the shoulder and centre line after a working a full night shift. The results show that on average, the first rumble strip occurred after 20 minutes of driving, with subsequent hits occurring 10 minutes later, with the last three occurring approximately every 5 minutes thereafter. Specifically, it was found that the first rumble strip hit reduced physiological sleepiness; however, subsequent hits did not increase alertness. Moreover, the results also demonstrate that increased subjective sleepiness levels, via the Karolinska Sleepiness Scale, were associated with a greater probability of hitting a rumble strip. The present results suggest that sleepiness is very resilient to even strongly arousing stimuli, with physiological and subjective sleepiness increasing over the duration of the drive, despite the interference by rumble strips.

Keywords: Rumble strip, audible edge line, sleepiness, arousal, physiological sleepiness, subjective sleepiness, driver performance

1. Introduction

It is estimated from case-control studies that the effect from sleepiness contributes to approximately 19% of all fatal and severe road crashes (Connor et al., 2002). Driving while sleepy is associated with increases of alpha and theta activity in the electroencephalogram (Kecklund and Åkerstedt, 1993) as well as increases of subjective sleepiness (Åkerstedt et al., 2014). Sleepiness also impairs driver performance levels, such as increased variability of lateral position and regulation of a constant driving speed (Campagne et al., 2004, Åkerstedt et al., 2005).

A common consequence of driving when highly sleepy is veering outside of the driving lane and potentially running off the road (Radun and Summala, 2004, Hallvig et al., 2014). Road treatments such as the addition of rumble strips seek to alert the driver when they deviate outside the driving lane. When a moving vehicle hits a rumble strip, audio-tactile vibrations are produced and the driver can re-orientate the vehicle and their own attention back to driving.

Rumble strips are an effective road-based countermeasure for driver sleepiness (Hatfield et al., 2009). Self-reported data suggests that approximately three-quarters of drivers report they became more alert and corrected their vehicle trajectory after a rumble strip hit with 7% reporting awakening from sleep (Marvin and Clark, 2003). Driving simulators studies also demonstrate the alerting effects of hitting a rumble strip. Significant reductions in physiological sleepiness indices and reduced variability of lateral position occur after hitting a rumble strip (Merat and Jamson, 2013, Anund et al., 2008). However, the alerting effect from hitting a rumble strip appears to be transient (i.e., 3-4 minutes) in its duration (Anund et al., 2008). Considered together, these studies demonstrate the alerting effect of hitting a rumble strip, but the duration of the effect appears transient.

An aspect of the effectiveness of rumble strips that has not previously been examined is the stability of the alerting effect. That is, previous research has demonstrated the immediate effect that hitting a single rumble strip can have (e.g., Anund et al., 2008, Merat and Jamson, 2013); however, it is unknown what the effect is of repeated rumble strip hits. The study by Anund et al., (2008) suggests that the mechanism does not involve a reduction of sleep pressure; an alternative explanation is that hitting a rumble strip results in increased arousal which masks the underlying level of sleepiness. Moreover, self-report studies suggest that sleepy drivers might prolong their driving due to the presence of rumble strips acting as safeguard (Vadeby et al., 2013, Hatfield et al., 2008). As such, examining the stability effect of repeated rumble strip hits is a pertinent issue for road safety.

The current study sought to examine the effects of repeated rumble strip hits on physiological and subjective sleepiness as well as simulated driving performance with a reanalysis of previously collected data (i.e., Anund et al., 2008). Specifically, three research questions were posed: (i) what effect does repeated rumble strips hits have on driver's physiological and subjective sleepiness as well as driving performance; (ii) what are the overall trends with the physiological and subjective sleepiness and driving performance data during the simulated drive with repeated rumble strips hits; and (iii) what is the probability of hitting a rumble strip and the associated level of subjective sleepiness. Subjective sleepiness is the main indicator drivers have to gauge their level of sleepiness. Karolinska Sleepiness Scale (KSS) ratings are exponentially related to physiological sleepiness indicators – demonstrated as a steep increase in physiological sleepiness when KSS levels 8 and 9 appear (Åkerstedt et al, 2014). Thus, it was expected that a similar pattern would be found for the relationship between KSS and probability of hitting a rumble strip.

2. Method

2.1 Participants

In total, 36 participants (19 females and 17 males) whom were all shift workers took part in the study and had a mean age of 36 years (SD = 8.18; range = 23-56). Participants reported an average vehicle licensure of 17 years (*SD* = 8.83; range = 2-38) and drove on average 193 529.41 km/year (*SD* = 124,921.36). An advertisement in the local newspapers invited participants into the study. The exclusion criteria for the study included: not being a night shift worker; being a professional driver; being younger than 25 or older than 65 years of age; driving less than 5000 km/year; travelling through three time zones in the two weeks or less prior to the study; use of sleeping medications; experiencing any sleep-related issues; and having any significant health problems. Each participant received a monetary compensation of approximately €160.

2.2 Measures

2.2.1 Physiological sleepiness

The physiological signals of the participants (i.e., EEG, EOG, and EMG) were recorded with the portable Vitaport II system (Temec Instruments BV, Amsterdam, Netherlands). The EEG was recorded from three bipolar derivations positioned at Fz-A1, Cz-A2 and Oz–Pz which were sampled at 256 Hz with Ag-AgCl electrodes. The EOG recordings used a vertical pairing for each eye (placed centrally in line with the pupil) and a horizontal pairing (placed laterally of the canthus and in line with the pupil). The EMG recording location was a submental placement. The EOG and EMG signals were recorded with disposable electrodes and were sampled at 512 Hz.

The EEG and EOG data was manually scored using criteria from the Karolinska Drowsiness Score (KDS) by an experienced polysomnographer. The KDS is scored utilising 20 second epochs whereby each 2 second burst of alpha (8-12 Hz) or theta (4-8 Hz) activity, slow rolling eye movements greater than one second in duration, or a long eye blink that has a duration greater than 0.5 of a second are each assigned a score of 10%. For example, a 20 second epoch that contains five instances of any of these signs of sleepiness would be assigned a score of 50% (Gillberg et al., 1996). The KDS score was then averaged into one minute time bins to produce the mean KDS and the maximum KDS variables. The EOG data was also analysed to assess the participants' blink duration which was calculated at half the amplitude of the upswing and downswing of each blink and defined as the time elapsed between the two. Blink durations were averaged across one minute time bins.

2.2.2 Subjective Sleepiness

Subjective sleepiness was assessed using the Karolinska Sleepiness scale (KSS: Åkerstedt and Gillberg, 1990). The KSS is a self-report measure of the level of subjective sleepiness that an individual is experiencing. Individuals are required to indicate on a nine-point Likert scale how sleepy they are feeling (1 = extremely alert to 9 = very sleepy, great effort to keep awake, fighting sleep). KSS ratings were obtained every five minutes in the current study.

2.2.3 Driver Performance

Driver performance was assessed by the standard deviation of lateral position, the standard deviation of driving speed, and the number of rumble strip hits. Lateral position was calculated as the perpendicular distance (measured in meters) of the outer edge of the right front tyre to the inner edge of the right hand lane; Swedish vehicles drive on the right hand side of the road. The speed at which the vehicle was travelling was recorded in km/h. The sampling frequency of the driver performance data was 33.33 Hz.

2.3 Driving Simulator

The study utilised the Swedish National Road and Transport Research Institute (VTI) advanced moving base driving simulator (III) which is capable of simulating the forces associated with acceleration, deceleration, and centrifugal forces when driving a vehicle. The participant sat in the front half of a Volvo 850 passenger car that had a manual five-shift gearbox. The view the driver perceives consists of three channels of forward view of a total of 120º x 30º. Noise, infrasound and vibration levels inside the cabin corresponded to those of a modern vehicle. The simulated road had the dimensions and geometry of an existing rural road in Sweden; 9 meters wide in total, with each lane 3.75 meters wide. The entire roadway had a speed limit of 90 km/h and the road had a smooth curvature. The driving conditions were during the daytime with a clear line of sight. The driving scenario included oncoming traffic, but no vehicles were programed to appear in front of the participant's vehicle.

A key consideration for the current study was the stimuli the driver would receive upon hitting a rumble strip. Prior to the current study an instrumented vehicle drove on real milled rumble strips while recording the sound and vibration data. Measurement of the vibration data was recorded via accelerometers placed in the car cabin and on the steering wheel. The sound recordings from the instrumented vehicle were used in the simulator and the vibrations were recreated in the driving simulator via the hydraulic actuators for the cabin vibrations and the torque motor introduced vibrations in the simulator steering wheel. The time domain recordings and frequency domain data for the real and simulated milled rumble strip hits were compared and a no major difference was found (Anund et al., 2005) such that, the simulated milled rumble strips could be considered equivalent to the real road versions of milled rumble strips.

2.4 Procedure

The research protocol received ethical approval from VTI's research ethics committee and all participants signed a written consent form prior to taking part in the study. Participants were instructed not to drink any alcohol 72 hours before the study, not to eat food or drink any tea or coffee 3 hours before the study, and not to nap during the night shift prior to taking part in the study. Each participant took part in the study after working a night shift. Upon arrival at the driving simulator, each participant completed some demographic and traffic-related demographic questionnaires and then the electrodes were applied. Each participant then had a 10 minute practice drive in the driving simulator, including driving on the rumble strips, as well as practise with rating their subjective sleepiness with the KSS. After the practice drive the participants then completed a 90 minute simulated driving session, which started at approximately 08:00. At the end of the simulated driving session each participant was debriefed, the electrodes were removed, and they were sent home via a taxi.

2.5 Statistical Analyses

Examining the stability of effect from hitting the first five rumble strips utilised a series of 2 x 5 repeated measures ANOVAs with the first factor being pre-post hits and the second factor the hit number (1st to 5th rumble strip hit). The mean level of physiological and performance data for one minute immediately prior to the rumble strip hit to levels one minute after the rumble strip hit. The subjective data was sampled every five minutes and thus could not be used for this analysis. In total, 24 participants hit five rumble strips during their simulated drive, only their data is analysed for the first research question. The second research question, the overall trends of the physiological, subjective, and performance data during the simulated drive was examined with a series of repeated measures ANOVAs and a set of planned comparisons. The physiological, subjective (pre hit data only), and performance data were averaged into 15 minute time bins for this analysis. All planned comparisons (paired t-tests) applied the Bonferroni adjustment and the Greenhouse-Geisser correction was reported if the Sphericity assumption was breached. The third research question, the probability of hitting the first five rumble strips and the associated KSS level was performed by calculating the probability of hitting a rumble strip for each KSS levels by summing the number of times a hit occurred at each KSS and dividing that sum by the total rumble strip hits.

3. Results

3.1 Stability of the Alerting effect from hitting a rumble strip

Figure 1 displays the mean levels of physiological and performance data for pre and post rumble strip hit. As shown in Table 1, significant main effects for the pre-post factor were observed for blink duration and SDLP variables, with blink duration and SDLP decreasing after the rumble strip hit. Significant main effects for the hit number factor were also observed for blink duration, KSS, and SDLP variables; with blink duration, KSS, and SDLP increasing across the five rumble strip hits. Significant "pre-post x hit number" interactions were observed with the KDS mean and max variables. Planned comparisons revealed that after the first hit KDS mean levels significantly decreased ($t(23) = 3.81$, $p < .01$) as well as KDS max levels ($t(23) = 2.93$, $p < .01$). No significant changes in KDS mean or max levels were observed in subsequent rumble strip hits.

Table 1. 2 x 5 ANOVA statistics for the stability analysis ($N = 24$)

	ANOVA								
	Pre-post			Hit number			Pre-post x hit number		
Data source	*F*	*df*	η_p^2	*F*	*df*	η_p^2	*F*	*df*	η_p^2
Mean KDS (%)	3.74	1, 23	.14	1.69	4, 92	.16	**3.93****	4, 92	.15
Max KDS (%)	1.48	1, 23	.06	1.14	2.84, 65.36[b]	.05	**3.08***	4, 92	.12
Blink duration (ms)	**4.78***	1, 23	.17	**3.38***	2.19, 50.36[b]	.13	1.13	2.18, 50.08[b]	.05
KSS[a]	-	-	-	**13.31*****	4, 96	.38	-	-	-
SDLP (m)	**5.27***	1, 23	.19	**3.39***	4, 92	.13	1.81	4, 92	.07
SD speed (km/h)	1.46	1, 23	.06	0.26	4, 92	.01	1.41	4, 92	.06

* < .05, ** < .01, *** < .001. ANOVA, analysis of variance; df, degrees of freedom; KDS, Karolinska Drowsiness Scale; KSS, Karolinska Sleepiness Scale; SDLP, standard deviation of lateral position; SD, standard deviation. [a] Only the pre hit values are included as the KSS data was collected every five minutes and some hits occurred within this interval. [b] Greenhouse-Geisser correction applied.

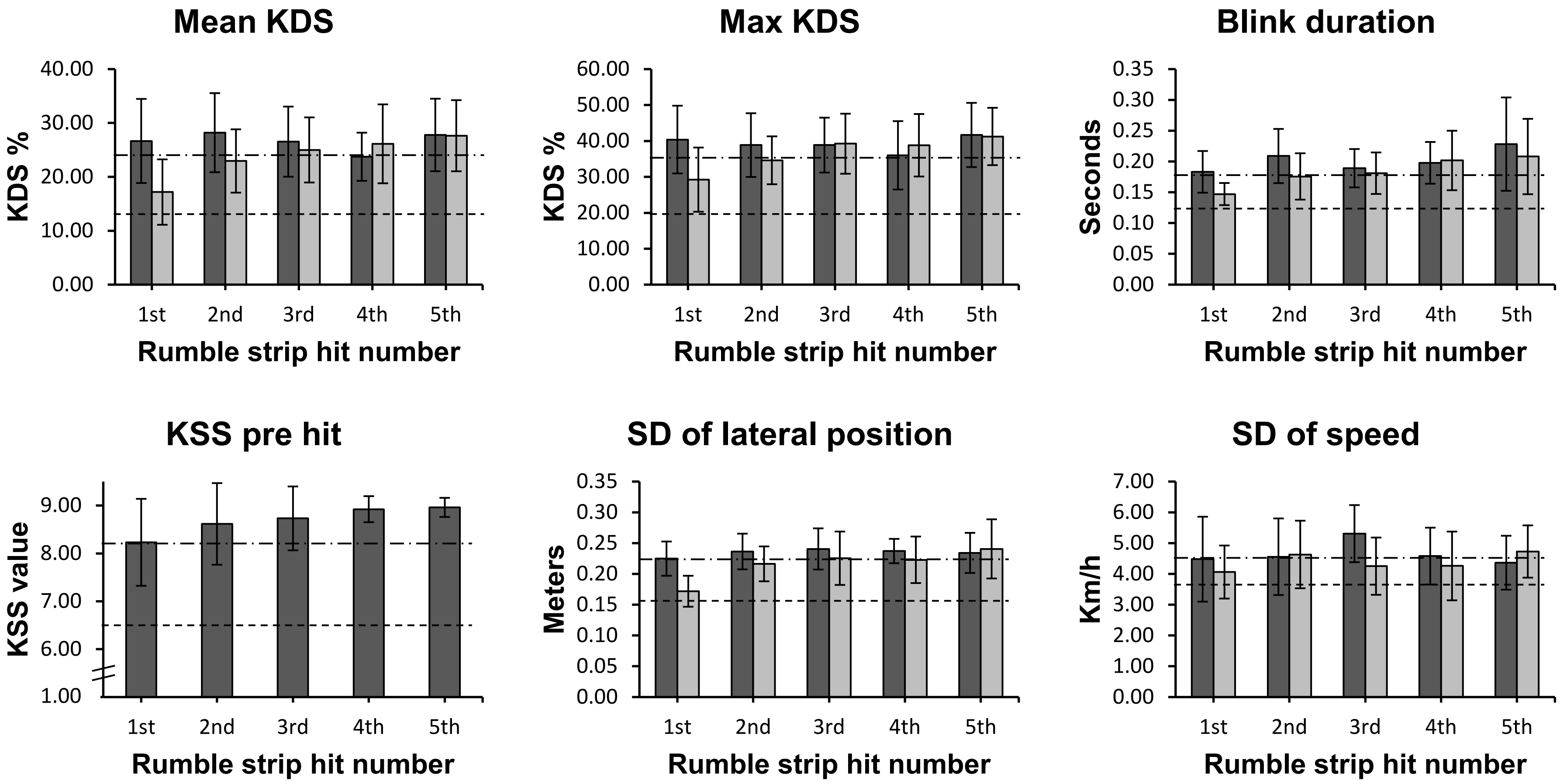

Figure 1. Mean levels of physiological and performance data for pre (dark grey) and post (light grey) rumble strip hit. Error bars represent one standard deviation. KDS, Karolinska Drowsiness Scale; The dashed lines represent the mean of the initial 3 mins of data, with the long dash-dot line representing the overall mean. KSS, Karolinska Sleepiness Scale - only the pre hit values are presented as the KSS data was sampled every five minutes and some hits occurred within this interval; SD, standard deviation.

3.2 Overall Trends

A repeated measures ANOVA was performed with the duration between rumble strip hits. As shown in Figure 2, the duration between rumble strip hits decreased significantly ($F(1.89, 43.46) = 26.87$, $p < .001$, $\eta_p^2 = .54$). Follow up analyses revealed that the durations between the first and second hits were significantly different ($t(30) = 4.78$, $p < .01$). No significant differences for the duration between successive hits were observed. Table 2 displays the results of the overall trends of the data. As seen in Table 2 all variables showed a significant increase over time. The planned comparisons confirmed increases of all variables from the first, to the second, and then the third 15 minute time bins, except for the SD of speed, which only increased between the second and third 15 minute time bins. The largest effect sizes were found for subjective sleepiness, number of rumble strip hits, and standard deviation of lateral position.

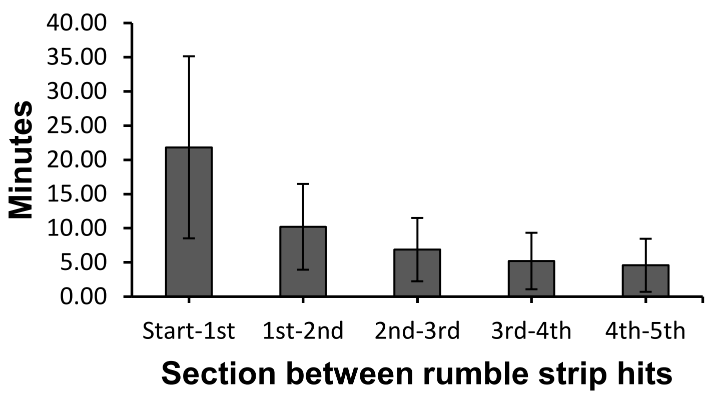

Figure 2. Duration between each of the five rumble strip hits

Table 2. Means, standard deviations (*SD*), and ANOVA statistics examining the overall trends of the simulated drive with rumble strip hits ($N = 36$)

	Mean (*SD*)			ANOVA			Planned comparisons	
Data source	1st 15 mins	2nd 15 mins	3rd 15 mins	F	df^{a}	η_p^2	1st – 2nd	2nd – 3rd
Mean KDS (%)	18.30 (9.90)	23.93 (11.05)	26.14 (11.78)	**15.72*****	1.44, 48.80	.32	**-4.72*****	**-2.05***
Max KDS (%)	28.04 (11.87)	34.83 (13.06)	37.48 (14.12)	**14.04*****	1.47, 50.11	.29	**-4.23*****	**-1.96**
Blink duration (ms)	0.14 (0.03)	0.16 (0.05)	0.19 (0.08)	**21.37*****	1.13, 38.50	.39	**-6.60*****	**-3.09****
KSS	7.17 (1.04)	8.00 (1.04)	8.44 (0.94)	**68.27*****	1.41, 47.88	.67	**-8.54*****	**-5.70*****
SDLP (m)	0.17 (0.04)	0.21 (0.05)	0.23 (0.07)	**39.70*****	1.43, 48.59	.54	**-6.58*****	**-3.14****
SD speed (km/h)	3.87 (1.03)	4.04 (1.10)	4.46 (1.36)	**9.92****	1.25, 42.63	.23	-1.45	**-4.69*****
Rumble strip hits	0.42 (0.94)	1.81 (2.81)	2.94 (4.04)	**49.25****	1.60, 54.24	.59	**-3.92*****	**-3.52****

* < .05, ** < .01, *** < .001. ANOVA, analysis of variance; Planned comparisons refer to Bonferroni corrected t-tests; KDS, Karolinska Drowsiness Scale; KSS, Karolinska Sleepiness Scale; SDLP, standard deviation of lateral position; SD, standard deviation. [a] Greenhouse-Geisser correction applied.

3.3 Subjective Sleepiness and Probability of hitting a Rumble Strip

The third research question was to examine the probability of hitting a rumble strips and the associated subjective sleepiness level on the KSS. Figure 3 shows the KSS values of when a hit occurred, plotted against the probability level. Levels 5 (neither alert nor sleepy Sleepy), 6 (some signs of sleepiness), and 7 (sleepy, no effort to stay awake) on the KSS were associated with a low probability levels for hitting a rumble strip. However, there was a rapid increase in probability of hitting the rumble strip at KSS level 8 (sleepy, some effort to stay awake) and an even steeper increase at KSS level 9 (very sleepy, great effort to keep awake, fighting sleep). A linear and exponential trend lines were fitted to the data. The exponential trend line provided the best fit to the actual data and accounted for 96% of the variance.

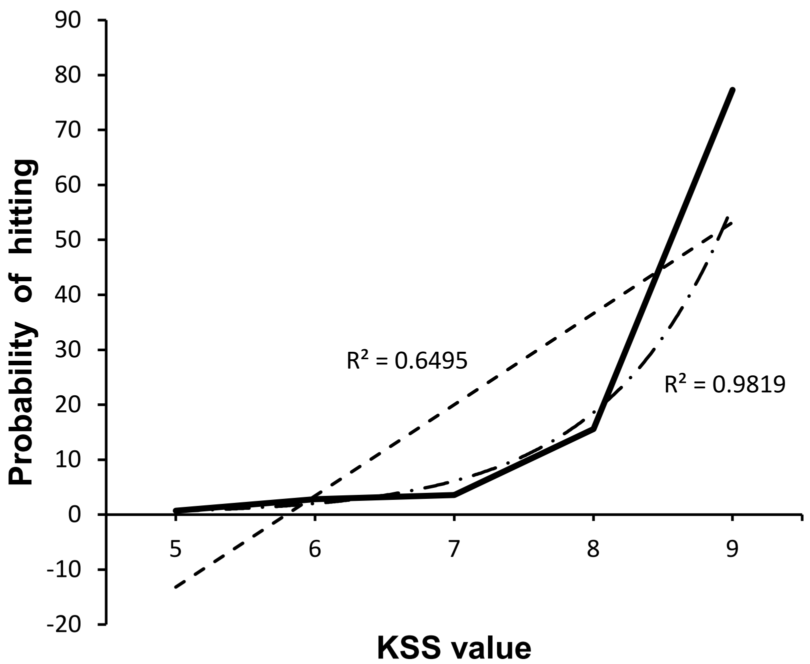

Figure 3. The relationship between level of Karolinska Sleepiness Scale (KSS) and probability of hitting the first five rumble strips. The solid line is the actual data, the dashed line is the liner trend line, and the long dash-dot line is the exponential trend line.

4. Discussion

The main finding from the current study when examining the specific effects of the rumble strip hits was an initial reduction of physiological sleepiness after the first rumble strip hit, which ceased to occur with subsequent rumble strip hits. The time between the duration between the first and second hits also reduced, while subjective sleepiness (KSS) increased. It was also found that the likelihood of hitting a rumble strip increased in an exponential manner with increases in KSS values.

The results of the current study extend the findings of Anund et al. (2008) of high levels of sleepiness indicators before a rumble strip hit, combined with a rapid reduction immediately after the hit, to the observation that the pre-post levels of sleepiness disappears over successive hits. The notion that successive jolts from the hits would reduce sleepiness was not confirmed in this study. Rather, the sleepiness indicators remained high and, if anything, the sharp reduction of inter-hit intervals indicates that the situation got worse with time. This is also evidenced in the increase of sleepiness as well the decrease of driving performance (SDLP) across hits. The observations suggest that sleepiness levels were too strong to permit any lasting alerting effect of a rumble strip hit. Considered together, the present results suggest that sleepiness is very resilient to even strongly arousing stimuli and increases across time, despite interference by rumble strips.

The potential reasons of a lack of a continued effect of the rumble strip hits deserve some discussion. First and foremost, the study participants took part in the study post-night shift. Previous research demonstrates the morning after continuous wakefulness is associated with an increase of sleep pressure (i.e., homeostatic pressure), even during the morning when the alertness promoting ascending phase of the circadian rhythm occurs (Åkerstedt and Gillberg, 1982). The magnitude of the effect from the rumble strip might not have been great enough to overcome the increased sleep pressure. An increase of arousal (e.g., movement/activity) while experiencing great sleep pressure, has a transient effect on reducing sleepiness (Bonnet and Arand, 1998). This was also demonstrated by Anund et al. (2008) where the arousing effects from the rumble strip hit lasted for 3-4 minutes.

It is also likely that time on task effects could have contributed to the obtained results. A gradual decrement of driving performance (i.e., increase of SDLP) was observed in the current study and previous research has shown that increases in SDLP is associated with increases of physiological indices of sleepiness owing to time on task effects (Campagne et al., 2004). It should be emphasized, however, that at least some increase in arousal must have occurred after later hits since the driver was able to get the car back into the right lane and remain on the road for some time before the next hit occurred. Possibly, that increase in arousal was too subtle or transient to be picked up by our measures and/or was hidden by an increase of effort that may have concealed any physiological changes.

Support for the current study's results can be found from a simulator study performed by Reyner and Horne (2000) that demonstrated during an early morning simulated drive after no sleep and with no caffeine, driving incidents (i.e., rumble strip hits) increased over the duration of drive but also increased in their frequency towards the later stages of the drive. The increases in rumble strip hits also coincided with increases in subjective sleepiness (KSS levels) and EEG defined signs of sleepiness (alpha and theta power) over the duration of the drive. The results of the current study could also be compared with a previous study of post-night shift simulator driving (Åkerstedt et al., 2005), even if no rumble strips were used. In that study all of the measures utilised, KSS, SDLP, and eye blink duration, increased across the duration of the drive. Similarly, when the overall trends in the current data were examined KSS, SDLP, and eye blink duration all increased. Additionally, the current study extends upon the Åkerstedt et al. (2005) results by showing that post-night shift driving results in increases in EEG defined physiological sleepiness (mean and max KDS) as well as the later increase in SD of speed maintenance. The current results suggest that extended periods of driving following a night shift are associated with significant increases in physiological and subjective sleepiness, as well as deterioration of driving performance indices and increases rumble strips hits.

To the best of our knowledge there is no data from similar research available specifically examining the immediate effects of hitting successive rumble strips on driver alertness and there is a need for more work in this area. In particular, it is necessary examine the current research questions to actual road environments as driving simulators are more soporific that driving on real roads (e.g., Hallvig et al., 2013). The use of a driving simulator coupled with the increased sleep pressure of having worked a nightshift, potentially could have limited the alerting effect of the rumble strip hit. It must be noted that fewer lane departures occur (i.e., two wheels outside the lane marking) and the time to the first lane departure increases when driving after a normal night of sleep compared to driving after working a nightshift (Åkerstedt et al., 2005). Considered together, there is a possibility that the real life driving situation when fully rested would provide a more long-lasting effect of the rumble strip hit.

Considering the obtained results in the current study, the action by the driver after hitting a rumble strip could have road safety implications. Clearly, rumble strips are effective at reducing the number of crashes as demonstrated by a decreases of 7-30% of the number of crashes on roads following the installation of shoulder and centre line rumble strips (Persaud et al., 2004, Wu et al., 2014, Vadeby et al., 2013). However, rumble strips are not a complete panacea for driver sleepiness. It might be possible for a driver to run off the road despite the presence of rumble strips if they ignore an early rumble strip hit and decide to continue driving when highly sleepy. Additionally, sleepiness affects a multitude of cognitive tasks, including decision making and risk acceptance (Killgore et al., 2006) and thus, if a sleepy driver ignores an earlier rumble strip hit, they could be prone to crashing in another manner other than running off the road. It is plausible to consider hitting a rumble strip as a proxy for a sleep-related close call or near-miss, and as such, the more close calls a driver experiences the greater the likelihood they will have a sleep-related crash (Powell et al., 2007). From a harm minimisation point of view, hitting a rumble strip should be regarded as a "take a break signal", where the driver can implementing the more effective sleepiness countermeasures such as napping or the consumption of caffeine (e.g., Horne and Reyner, 1996, Watling et al., 2014).

Ultimately, the decisions a driver makes regarding continuing to drive sleepy is paramount for road safety. This is highlighted with the probability of hitting a rumble strip and level of subjective sleepiness. The exponential relationship observed in the current study between subjective sleepiness and hits in the current study is similar to the relationship between subjective sleepiness and lane crossings during real driving (Hallvig et al., 2014) or the relationship between subjective sleepiness and lateral deviations in our previous study of post-night shift driving in a simulator (Ingre et al., 2006). Considered together, driving when KSS levels are around 8 or 9 is associated with serious performance impairment and drivers should consider recuperative actions before reaching these high levels of subjective sleepiness. These high levels of subjective sleepiness were quickly reached for many subjects in the current study and were associated with an increased probability of hitting a rumble strip.

The findings from the present study need to be considered in relation to the limitations of the study. As previously mention, the study paradigm utilised a driving simulator, which is associated with lower arousal levels (Hallvig et al., 2013). The lack of a non-sleep deprived driving condition for comparisons was a limitation. Reduced levels of sleep pressure might have permitted rumble strip hits to have a longer-lasting effect. This could be a pertinent issue that future on road driving studies could examine. Last, an experimental paradigm that examines drivers' tolerance to risk associated with an initial rumble strip hit and continuing to drive when sleepy could be explored with future work.

In summary, the current study has demonstrated an initial reduction of physiological sleepiness after the first rumble strip hit, which then ceased to occur with subsequent hits. Moreover, the results also demonstrate that driving a simulator post-night shift is associated with pronounced increases of sleepiness and decrements of driving performance. The results suggest that drivers who hit a rumble strip should perceive this as a queue to cease driving due to heightened levels of sleepiness and consider implementing an effective sleepiness countermeasure such as napping or caffeine ingestion.

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6. References

Åkerstedt, T., Anund, A., Axelsson, J. and Kecklund, G. Subjective sleepiness is a sensitive indicator of insufficient sleep and impaired waking function. *J Sleep Res*, 2014, 23: 240-52.

Åkerstedt, T. and Gillberg, M. Experimentally displaced sleep: Effects on sleepiness. *Electroencephalogr Clin Neurophysiol*, 1982, 54: 220-26.

Åkerstedt, T. and Gillberg, M. Subjective and objective sleepiness in the active individual. *Int J Neurosci*, 1990, 52: 29-37.

Åkerstedt, T., Peters, B., Anund, A. and Kecklund, G. Impaired alertness and performance driving home from the night shift: A driving simulator study. *J Sleep Res*, 2005, 14: 17-20.

Anund, A., Hjälmdahl, M., Sehammar, H., Palmqvist, G. and Thorslund, B. Placement and design of milled rumble strips on centre line and shoulder (No. VTI rapport 523A). 2005

Anund, A., Kecklund, G., Vadeby, A., Hjälmdahl, M. and Åkerstedt, T. The alerting effect of hitting a rumble strip--A simulator study with sleepy drivers. *Accid Anal Prev*, 2008, 40: 1970-76.

Bonnet, M. H. and Arand, D. L. Sleepiness as measured by modified multiple sleep latency testing varies as a function of preceding activity. *Sleep*, 1998, 21: 477-83.

Campagne, A., Pebayle, T. and Muzet, A. Correlation between driving errors and vigilance level: Influence of the driver's age. *Physiol Behav*, 2004, 80: 515-24.

Connor, J., Norton, R., Ameratunga, S. *et al.* Driver sleepiness and risk of serious injury to car occupants: population based case control study. *BMJ*, 2002, 324: 1125.

Gillberg, M., Kecklund, G. and Åkerstedt, T. Sleepiness and performance of professional drivers in a truck simulator--comparisons between day and night driving. *J Sleep Res*, 1996, 5: 12-15.

Hallvig, D., Anund, A., Fors, C., Kecklund, G. and Akerstedt, T. Real driving at night--predicting lane departures from physiological and subjective sleepiness. *Biol Psychol*, 2014, 101: 18-23.

Hallvig, D., Anund, A., Fors, C. *et al.* Sleepy driving on the real road and in the simulator--A comparison. *Accid Anal Prev*, 2013, 50: 44-50.

Hatfield, J., Murphy, S. and Job, R. F. S. Beliefs and behaviours relevant to the road safety effects of profile lane-marking. *Accid Anal Prev*, 2008, 40: 1872-79.

Hatfield, J., Murphy, S., Job, R. S. and Du, W. The effectiveness of audio-tactile lane-marking in reducing various types of crash: A review of evidence, template for evaluation, and preliminary findings from Australia. 2009, 41: 365-79.

Horne, J. A. and Reyner, L. A. Counteracting driver sleepiness: effects of napping, caffeine, and placebo. *Psychophysiology*, 1996, 33: 306-9.

Ingre, M., Åkerstedt, T., Peters, B., Anund, A. and Kecklund, G. Subjective sleepiness, simulated driving performance and blink duration: examining individual differences. *J Sleep Res*, 2006, 15: 47-53.

Kecklund, G. and Åkerstedt, T. Sleepiness in long distance truck driving: An ambulatory EEG study of night driving. *Ergonomics*, 1993, 36: 1007-17.

Killgore, W. D. S., Balkin, T. J. and Wesensten, N. J. Impaired decision making following 49 h of sleep deprivation. *J Sleep Res*, 2006, 15: 7-13.

Marvin, R. R. and Clark, D. An evaluation of shoulder rumble strips in Montana. In, 2003.

Merat, N. and Jamson, A. H. The effect of three low-cost engineering treatments on driver fatigue: A driving simulator study. *Accid Anal Prev*, 2013, 50: 8-15.

Persaud, B. N., Retting, R. A. and Lyon, C. A. Crash reduction following installation of centerline rumble strips on rural two-lane roads. *Accid Anal Prev*, 2004, 36: 1073-79.

Powell, N. B., Schechtman, K. B., Riley, R. W., Guilleminault, C., Chiang, R. P. and Weaver, E. M. Sleepy driver near-misses may predict accident risks. *Sleep*, 2007, 30: 331-42.

Radun, I. and Summala, H. Sleep-related fatal vehicle accidents: characteristics of decisions made by multidisciplinary investigation teams. *Sleep*, 2004, 27: 224-27.

Reyner, L. A. and Horne, J. A. Early morning driver sleepiness: effectiveness of 200 mg caffeine. 2000, 37: 251-56.

Vadeby, A., Anund, A., Björketun, U. and Carlsson, A. Safe Accessibility: Summarised Results. In. VTI, Sweden, 2013.

Watling, C. N., Smith, S. S. and Horswill, M. S. Stop and revive? The effectiveness of nap and active rest breaks for reducing driver sleepiness. *Psychophysiology*, 2014, 51: 1131-38.

Wu, K.-F., Donnell, E. T. and Aguero-Valverde, J. Relating crash frequency and severity: Evaluating the effectiveness of shoulder rumble strips on reducing fatal and major injury crashes. *Accid Anal Prev*, 2014, 67: 86-95.