Accident Analysis and Prevention 50 (2013) 628–634

Contents lists available at SciVerse ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Driver's lane keeping ability with eyes off road: Insights from a naturalistic study

Yiyun Peng[a], Linda Ng Boyle[a,b,*], Shauna L. Hallmark[c]

[a] Department of Industrial & Systems Engineering, University of Washington, Seattle, WA 98195, USA
[b] Department of Civil & Environmental Engineering, University of Washington, Seattle, WA 98195, USA
[c] Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA 50010, USA

ARTICLE INFO

Article history:
Received 28 January 2011
Received in revised form 31 May 2012
Accepted 13 June 2012

Keywords:
Lane keeping ability
Driver inattention
Naturalistic study
Generalized estimating equations (GEE)

ABSTRACT

Many studies have shown that driver inattention can influence lane-keeping ability. The majority of studies on lane keeping have been conducted in controlled on-road networks or in simulated environments. However, few studies have examined lane-keeping ability in naturalistic settings for the same purpose. In this current study, the relationship between driver inattention and lane keeping ability was examined using naturalistic data for 24 drivers. Driver inattention was placed into two categories based on whether drivers were looking forward toward the roadway (inattention with eyes-on-road) or not looking forward (inattention with eyes-off-road) while engaged in a secondary task. Repeated measures regression models were used to account for within-subject correlations. The results showed that, after accounting for driving speed and lane width, the eyes-off-road significantly increased the standard deviation of lane position (SDLP). The findings from this study are consistent with other studies that show that the amount of time drivers spend looking away from the road can impact drivers' ability to maintain their lane position. Additionally, this paper demonstrates how driver inattention can be examined with real world data while accounting for the roadway, environment, and driver behavior.

1. Introduction

1.1. Background

Driver inattention has been a major focus of driver safety research (Klauer et al., 2006; Ranney et al., 2000; Wang et al., 1996). Early studies have shown that driver inattention can contribute up to 25% of vehicular crashes per year (Ranney et al., 2000; Wang et al., 1996). In recent years however, naturalistic studies have made it possible to gain additional insights on driver behavior and have actually demonstrated that 78% of crashes and 65% of near crashes (or evasive maneuvers to avoid a crash) are driver inattention related (Klauer et al., 2006). This higher contribution may relate to the historically underreported associations of driver inattention in police reported crashes (Neyens and Boyle, 2007). Thus, examining objective measures (i.e., driver performance) in addition to crash data may provide greater insights in driver inattention. For example, drivers' lane keeping performance (or lateral control ability), which is usually measured by lateral accelerations, standard deviation of lane positions (SDLP), and steering control performances, can be considered since degraded lane keeping performance may lead to run-off-road crashes or collisions with other vehicles (Allen et al., 1996). Specifically, the increase in SDLP can dramatically increase the probability of lane departures that lead to a crash (Allen et al., 1996).

Driver distraction, which is a subset of driver inattention (Lee et al., 2009; Pettitt et al., 2005), has been extensively studied and shown to significantly degrade drivers' lane keeping performance (Anttila and Luoma, 2005; Horrey et al., 2008, 2009; Reed-Jouns et al., 2008). Visual related distractions occur when drivers need to divert their eyes away from the roadway such as when texting, and non-visual related distractions occur when drivers do not divert their eyes but are still distracted in other ways, such as cognitively when talking on a cell phone. Both distractions have been examined with respect to drivers' lane keeping performance. For example, technology-based in-vehicle visual distractions, such as tuning the radio, using the CD player and iPod, and viewing a video on a DVD have been shown to increase the SDLP and lateral accelerations on curves (Chisholm et al., 2008; Funkhouser and Chrysler, 2007; Hatfield and Chamberlain, 2005; Salvucci et al., 2007; Wikman et al., 1998). Texting can also increase the number of lane departure events (Hosking et al., 2005), and dialing numbers on a cell phone can negatively impact driver's steering control (Brookhuis et al., 1991).

Non-technology based distractions, such as eating, have been shown to decrease drivers' lane keeping ability as well (Jenness et al., 2002). However, the effects of other activities on lane keeping, such as reaching for objects, grooming, reading, and writing

* Corresponding author at: Department of Industrial & Systems Engineering, University of Washington, Seattle, WA 98195, USA. Tel.: +1 2066160245; fax: +1 2066853072.
E-mail address: linda@uw.edu (L.N. Boyle).

0001-4575/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.aap.2012.06.013

have not been as fully explored. Bendak and Al-Saleh (2010) have suggested that distractions located outside the vehicle (e.g., billboards and other road furniture), can also decrease lane keeping ability.

The findings for non-visual related distractions are not as consistent in terms of lane keeping performance. Most studies have shown that merely listening to in-vehicle entertainment systems (i.e., iPod, DVD player, radio and CD player) has no effect on lane keeping ability (Hatfield and Chamberlain, 2005; Salvucci et al., 2007). Similarly, in the Liang and Lee (2010) study, cognitive and verbal secondary tasks were found to increase the steering error but have no negative effect on SDLP. However, there were test track studies that did reveal the negative impact of cognitive tasks on SDLP (Horrey et al., 2008, 2009).

Lane keeping performance can be used to assess the broader implications of driver inattention but has not been as thoroughly investigated. Naturalistic data provide a means for capturing the impact of inattention. In the 100-car naturalistic study by Klauer et al. (2006), driver inattention was observed to include a broader scope of driver behaviors that included distraction as well as non-specific eye glances (i.e., driver glances away from the roadway at no discernable object or person) and drowsiness. Using this definition of driver inattention, Klauer et al. (2006) found that regardless of glance location, eye glances that were more than 2 s away from the roadway due to inattention significantly increased the likelihood of having a crash or near crash by almost 2-fold. Specific to lane keeping, Liang and Lee (2010) have suggested that, regardless of the distraction type (i.e. visual or non-visual), longer eyes-off-road time is associated with larger SDLP. Additionally, Zwahlen et al. (1988) have suggested that unsafe SDLP values can be observed after 2–4 s of in-vehicle glances. These findings are consistent with Wickens (2002) multiple resource theory, which suggests that multiple tasks that compete for the same resources degrade the performance of one or more tasks. Since visual perception is the primary resource for maintaining lane position, driver inattention that also requires visual perception is expected to impact lane keeping performance (Liang and Lee, 2010). Therefore, understanding the influence of drivers' visual behavior on lane keeping performance is essential in studying driver inattention and improving driver safety.

1.2. Project objectives

This study used naturalistic driving data to examine the relationship between driver inattention (eyes-off-road and eyes-on-road) and lane keeping ability. Eyes-off-road was defined in this study as the moments when the driver glanced away from the forward roadway due to any non-driving related reasons. For example, eyes-off-road could include looking at a passenger, reaching for an object inside the vehicle, using an in-vehicle system, eating, texting, looking down in the vehicle toward an unknown distracter (i.e., the distracter cannot be identified by the researcher), or eyes closed due to sleepiness. Inattentive eyes-on-road was defined as the moments when the driver's attention was diverted from driving but the driver was still looking forward toward the roadway. This might include conversing with passengers, grooming, singing, smoking, or talking on cell phone. Additionally, attentive driving was defined as the moment when neither eyes-off-road nor eyes-on-road inattention was observed.

Compared to controlled studies, the value of naturalistic studies is the potential insights gained on driver initiated distractions in complex circumstances and the adaptive behaviors that can manifest while distracted (Dingus et al., 2006; Horrey and Lesch, 2009). Therefore, naturalistic data can be useful to identify a more accurate relationship between driver inattention and lane keeping ability. In this study, naturalistic data were used to examine the hypothesis that eyes-off-road can negatively impact driver's lane keeping ability when compared with inattention with eyes-on-road and attentive driving. A subsequent hypothesis relates to long glances off road and their relationship to larger SDLP when compared to short glances off road and attentive driving.

2. Method

2.1. Data source

The naturalistic driving data used in this study were a subset of data reduced from the University of Michigan Transportation Institute (UMTRI) Road Departure Crash Warning System (RDCW) Field Operational Test study. The RDCW system was designed to provide real time warnings to the driver when a drift to lane edge was detected. A curve-speed warning system was also incorporated to alert drivers when the speed while approaching or negotiating a curve was too high.

The original UMTRI study included 78 drivers from Michigan (39 males and 39 females, from 20 to 70 years old (mean = 45.0 years, sd = 16.6 years)). They were asked to drive as they normally would in an instrumented vehicle that was equipped with the RDCW system for four weeks (1 baseline week without feedback from the system and 3 feedback weeks). Driver activities were collected for both urban and rural areas in Michigan. The authors requested and received the first week of baseline data in the rural area to evaluate the relationship between inattention and lane keeping. Consequently, drivers did not receive the alerts triggered from the RDCW system and thus, their lane keeping performance as examined in this study was not influenced by the system. The dataset contained vehicle kinematic and roadway data, as well as driver face and forward view images for a total driving distance of approximately 4000 miles across the 78 drivers (LeBlanc et al., 2006).

The driver face images received from UMTRI were recorded at 10 Hz for two types of driving clips. One type was 5-s clips that were recorded every 5 min during the trip; these were collected for the original UMTRI protocol to study driver behaviors. The other type was 8-s clips that were recorded when a road departure or curve warning event was noted and alerts would have been triggered had the RDCW been active (4 s before and 4 s after the trigger). For the current analysis, only these two types of driving clips were used. Other clips in the original UMTRI study, recorded at 0.5 Hz, did not provide enough details to discern the driver's face. The 5- and 8-s clips were not distinguished from each other in the current study, since the RDCW system was not considered and thus did not impact the current study purpose.

2.2. Data reduction

Driver inattention with eyes-off-road and on-road were identified using the driver face images, and matched and merged into the vehicle kinematic data based on time stamps. Driving clips were removed from the data when drivers' eye locations were difficult to determine due to sunglasses or glare. Off-road glances that were considered driving-related (i.e., checking mirrors and instrument panels) were also excluded to avoid potential confounding.

Due to the variation in the roadway conditions in the naturalistic study, the entire 5- or 8-s driving clip was not always feasible for analysis. For example, the vehicle might start to enter a curve at the last 2 s during an 8-s clip. In order to keep a relative large sample size for analysis, a 3-s segment that met all data reduction criteria was extracted from each clip. The 3-s segments were first extracted based on driver inattention information. If any driver inattention was observed in a 5- or 8-s driving clip, the 3-s segment was extracted starting from the moment that the inattention was first observed. The extracted segment was then called inattentive

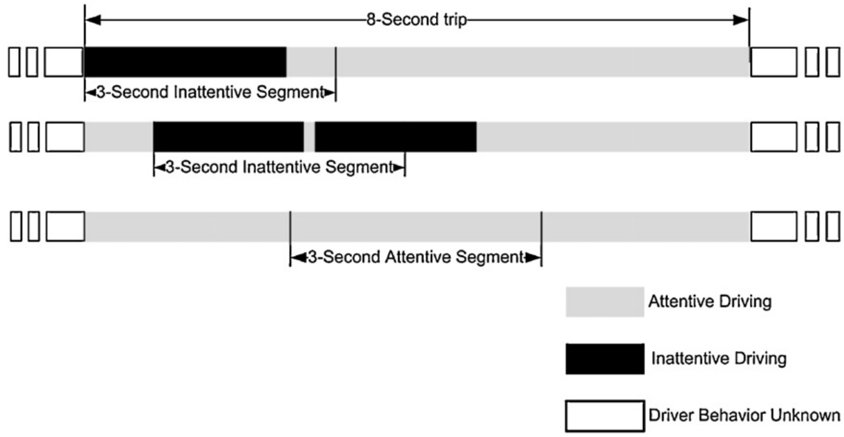

Fig. 1. Data extraction examples for inattentive and attentive driving clips.

driving. If there was no driver inattention observed in the driving clip, the 3 s were extracted from the middle of the entire clip and called attentive driving. It needs to be noted that the driver behavior information was not as accessible before and after the 5- or 8-s driving clip. Therefore, the attentive driving segment was purposely not extracted from the beginning of the entire clip in order to ensure that there was no inattention immediately prior. Fig. 1 shows some examples of how inattentive and attentive driving segments were extracted. After initially selecting the 3-s segments based on driver inattention, the segments were further reviewed and only those that involved driving on straight roadway sections (i.e., tangential without curves) on 2-lane rural (undivided, one lane/direction) and 4-lane divided (two-lane/direction) roads were retained. Further, a segment was excluded if the driving activity involved an intentional lane change or was at an intersection where the driver had to stop, yield, slow down, or scan for possible traffic. Weather and time of day were then identified and only daytime trips on dry roads were retained due to the limited number of data points available in other conditions. Consequently, the driving segments analyzed included only daytime driving on dry, rural 2-lane undivided and 4-lane divided straight sections.

In the reduced data set, each 3-s driving segment contained driver inattention information, vehicle forward speed, lane width and lane position (both from the lane tracking system), each recorded at 10 Hz. Lane position was defined as the distance between the vehicle longitudinal center to the lane center. For each segment, mean vehicle speed, mean lane width, and the standard deviation of the lane position (SDLP) values were calculated. Driver inattention type (eyes-off-road, eyes-on-road) and their durations (in s) were also recorded for each 3-s segment.

There were eight segments removed from the data analysis because of ambiguity in the specific inattention category. That is, even though the driver was engaged in one type of inattention at any given time (e.g., looked down, then looked back to the road, and then conversing with the passenger), these segments included driver inattention with both eyes-on-road and off-road. Therefore, it was difficult to determine which inattention type was associated with the performance decrement (if any). Based on this data reduction scheme, 71 driving segments from 24 drivers (16 male, 8 female) were retained. Driver age from this subpopulation ranged from 20 to 70 years, with a mean age of 41.2 years old (sd = 17.6 years). The number of driving segments for each driver varied from 1 to 9 (mean = 3, sd = 2).

2.3. Dependent and explanatory variables

Standard deviation of lane position (SDLP) is a widely used measure for examining lane keeping ability (Anttila and Luoma, 2005; Horrey et al., 2008, 2009; Reed-Jouns et al., 2008), and is used as the dependent variable in the current study. Allen et al. (1996) has suggested that SDLP can be used as a surrogate for overall driving safety, since an increase in SDLP is associated with an increase probability of lane departure (i.e., when the outside edge of the vehicle tires crosses the lane marking), a precursor of run-off-road crashes. It is noted that lane departure may actually be a more direct surrogate for driver safety (Blaschke et al., 2009; Hosking et al., 2005; Liang and Lee, 2010), but the number of lane departure events was limited in the current study.

Driver inattention type was used as an explanatory variable with three levels: inattention with eyes-off-road, inattention with eyes-on-road, and attentive driving. Since previous studies have suggested that long glances off road (i.e., a single off-road glance longer than 2 s) has a significant effect on lane keeping (Rockwell, 1988; Zwahlen et al., 1988), this effect was also examined in the current study. Eye glances were coded as a categorical variable with three levels: long, short, or no glances. Long glances were defined as the total proportion of eyes-off-road time (single or multiple glances) greater than or equal to 2 s (or ≥66.7%) during a 3-s driving segment. If the total proportion of time was less than 2 s (or <66.7%), then it was defined as a short glances. "No glances" were defined as those 3-s segments with no off-road glances.

The model also accounted for gender, age group, roadway type, mean speed, and mean lane width as these factors may have an influence on the outcome of SDLP. Age group was defined as a categorical variable with three levels: older driver (age ≥ 55 years), younger driver (age < 30 years) and middle-aged (≥30 and <55 years) drivers. The roadway type was coded as a two level dummy variable (2-lane rural or 4-lane divided). Lastly, mean speed and mean lane width were continuous variables.

2.4. Data analysis

Since a large number of drivers had multiple segments, repeated measures linear regressions were conducted in order to account for the within-subject correlations. The generalized estimating equations (GEE) method, which has been widely used for correlated data (Hanley et al., 2003) was used to estimate the parameter coefficients (using the GEE package in R statistics 2.12.1 version with the Driver ID being the repeated measure). An advantage of using the GEE method is that it produces reasonably accurate standard errors and confidence intervals, especially when there are many subjects that have small number of events (Hanley et al., 2003).

Since each driving segments were sampled at least 30 s apart, the correlation between any two segments for a driver was assumed to be related to the individual driving habits, and not on the

Table 1
Number of drivers and driving clips by age, gender and roadway type.

Variable	# of drivers	# of clips
Age		
Younger (<30 years)	10	24
Middle (≥30 and <55 years)	7	25
Older (≥55 years)	7	22
Gender		
Male	16	43
Female	8	28
Roadway		
2-Lane rural	20[a]	52
4-Lane divided	9[a]	19

[a] Drivers may have traversed over both the 2-lane rural and 4-lane divided.

performance observed in the previous segment. Therefore, an exchangeable correlation (i.e., the correlation between any two segments of a driver was the same) was used for the working correlation matrix in the GEE model. The dependent variable was appropriately transformed to meet the normality and homescedasticity requirements of linear regressions.

3. Results

3.1. Descriptive statistics

There were 71 driving segments (Table 1) and of these, 49 were inattentive driving (20 eyes-off-road, 29 eyes-on-road) and 22 were attentive driving. The most frequently observed driver inattention with eyes-on-road type was conversing with passengers ($n = 21$), which was consistent with the results from the complete dataset (UMTRI, 2006). The most frequently observed eyes-off-road type was in-vehicle glances ($n = 13$) which included looking at the center stack, looking down with unknown distracter (i.e., distracters could not be identified from the driver face images), reaching for objects, looking at passengers, or eating. Another type of eyes-off-road observed was looking outside of the windows ($n = 7$) at external distracters. Eye-closures due to drowsiness were not observed in the study. There appears to be a larger SDLP observed in the eyes-off-road inattentive segments than the eyes-on-road inattentive and attentive driving segments (Table 2). The accumulated time for off-road glances (single or multiple glances) in the 3-s segments ranged from 1 to 3 s (mean = 1.9 s, sd = 0.63 s). Boxplots of SDLP segmented for the eyes-off-road condition showed SDLP and its variation increased from 1 s to 3 s glance durations (Fig. 2).

3.2. Inferential statistics

Hypothesis 1. Inattentive driving with eyes-off-road will result in greater SDLP when compared to inattentive driving with eyes-on-road as well as attentive driving.

Table 2
Descriptive statistics by inattention types.

Response variable	Attentive driving	Eyes-on-road inattention	Eyes-off-road inattention
Mean driving speed (mph)			
Mean	54.28	54.08	60.46
sd	15.36	12.41	12.22
SDLP (feet)			
Mean	0.33	0.30	0.49
sd	0.23	0.16	0.33
Mean lane width (feet)			
Mean	12.4	11.8	11.7
sd	1.08	0.64	1.04

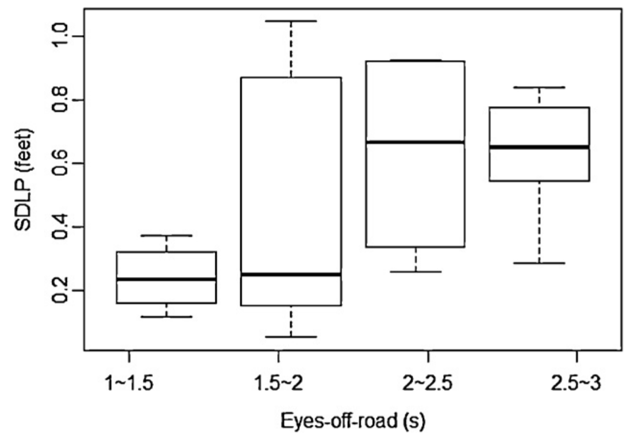

Fig. 2. Mean SDLP for off-road glance durations (from 1 to 3 s).

A linear GEE model that compared the three inattention types (inattentive eyes-off-road, inattentive eyes on-road, and attentive driving) was conducted on log-transformed SDLP to address this first hypothesis. Mean speed and mean lane width were included in the model as covariates since they may have an influence on SDLP. In addition, driver gender, age, and roadway types were included in the model. Pearson correlation tests were conducted on the explanatory variables and showed no apparent correlations between any pairs of the variables. The results (Table 3) showed that the SDLP was not significantly different between inattentive eyes-on-road and attentive driving, while there was a significant difference between inattentive eyes-off-road and attentive driving. In addition, increased mean lane width and mean driving speed were associated with larger SDLP. The model also revealed that both younger and older drivers tend to have larger SDLP compared to middle-aged drivers. There was only a marginal significant difference between eyes-off-road and on-road ($p = 0.07$). No significant differences were observed for roadway types or gender.

Hypothesis 2. Long glances off road (eyes-off-road ≥ 2 s) is associated with a larger SDLP when compared to short glances off-road (eyes-off road < 2 s) and attentive driving (no inattention observed).

Data that did not include driver inattention with eyes-on-road were used in this analysis (number of driving segments = 42, number of drivers = 18). Mean lane width and mean speed were included in the model as covariates. Pearson correlation tests were conducted and showed that there were no apparent correlations between any pair of explanatory variables. The results showed that long glances were associated with significantly larger SDLP when compared to attentive driving (Table 4). SDLP was also significantly larger for long glances when compared to the short ones ($p = 0.028$). However, there were no differences observed between short glances and attentive driving. Drivers appeared to have larger SDLP when driving on 2-lane rural roads than on 4-lane divided roads. Other variables such as gender and age did not have significant impacts on the outcome.

Based on the outcomes shown in Table 4, the SDLP can be computed for drivers who have long glances away from the road while traveling on a 2-lane rural road as:

$$\mathrm{SDLP}_{\text{long glances}} = \exp(-5.51 + 0.76 \times 1 + 0.24 \times 12 + 0.03 \times 55) = 0.803\,\mathrm{ft} \quad (1)$$

This estimate assumes that the lane width is 12 feet and the vehicle traveling speed is 55 mph. A similar estimate of SDLP can

Table 3
GEE model comparing SDLP (log transformed) of eyes-on-road and off-road inattention.[a]

Variable	Estimate	95%CI	se	z	Pr > |z|
Intercept	−4.84	(−6.92, −2.77)	1.06	−4.57	<0.0001
Driver inattention type					
Eyes-on-road (vs. attentive)	0.12	–	0.16	0.76	ns
Eyes-off-road (vs. attentive)	0.46	(0.00, 0.92)	0.23	1.96	0.050
Attentive (baseline)	–	–	–	–	–
Driver age					
Older (vs. middle)	0.33	(0.05, 0.61)	0.14	2.31	0.021
Younger (vs. middle)	0.46	(0.16, 0.76)	0.15	3.03	0.002
Middle (baseline)	–	–	–	–	–
Mean lane width (in feet)	0.22	(0.06, 0.38)	0.08	2.72	0.006
Mean speed (in mph)	0.01	(0.001, 0.02)	0.004	2.32	0.020

[a] Model equation: SDLP = exp($\beta_0 + \beta_1 \times$ Inattention type + $\beta_2 \times$ Age + $\beta_3 \times$ Mean lane width + $\beta_4 \times$ Mean speed + ε).

be obtained for an attentive driver as:

$$\mathrm{SDLP}_{\text{attentive driving}} = \exp(-5.51 + 0.24 \times 12 + 0.03 \times 55) = 0.375\,\text{ft} \qquad (2)$$

4. Discussion

The goal of this study was to examine the impact of driver inattention on drivers' lane keeping ability using naturalistic data. More specifically, two types of driver inattention, eyes-off-road and on-road, were compared with attentive driving. Previous controlled studies with simulators or closed test tracks showed that eyes-off-road and visual tasks that require in-vehicle glances (e.g., information system, CD and climate control) degraded drivers' lane-keeping abilities (Engström et al., 2005; Horberry et al., 2006; Liang and Lee, 2010). However, the results for auditory and cognitive tasks, which do not require in-vehicle glances (eyes-on-road inattention) were mixed (Bayly et al., 2009; Horrey et al., 2009).

In this study, we were able to account statistically for other factors from a natural setting (lane width, number of lanes, vehicle speed), which differs from previous studies. Driver inattention with eyes-on-road did not have a statistically negative effect on lane keeping ability and this is similar to other studies that examined auditory and cognitive distractions (Hatfield and Chamberlain, 2005; Salvucci et al., 2007). One possible explanation for this non-significant outcome provided by Liang and Lee (2010) is that drivers might actually recognize the potential risks of conversing (on phones or with passengers) and therefore adopt a more cautious strategy by maintaining a larger safety margin to the lane edge. It is also interesting to note that the findings from many studies on cognitive distractions are related more to response time and hazard detection (Anttila and Luoma, 2005; Horrey and Wickens, 2006), rather than lane variation.

As expected, eyes-off-road significantly decreased drivers' ability to maintain lane positions compared to attentive driving. The study results do confirm, to some degree, the conclusion of Klauer et al. (2006) that off-road glances longer than 2 s are related to more safety critical situations. However, there are differences in the definition of a long glance between this study and Klauer et al. (2006). In the current study, the long glances were defined based on the total proportion of time that a driver glanced away from the forward roadway within a 3-s driving segment. That is, the long glances can also encompass multiple off-road glances, while in Klauer et al. (2006), the long glance was based only on a single off-road glance. Our study showed that large portions of time spent looking away from the road decreased the ability that a driver could maintain the lateral vehicle position.

SDLP for eyes-off road was larger than for eyes-on road but the significance of this comparison was marginal ($p = 0.07$). The outcome is however, similar to what was observed in previous studies (Hurwitz and Wheatley, 2002; Serafin et al., 1993). One explanation for the marginal difference relates to the fact that long and short glances were both included in the analysis of eyes-off-road. The long glances (as noted earlier) had a strong effect on SDLP while the short glances had a minimal effect. The combination of the short and long glances lowered the mean and increased the variation of SDLP for the eyes-off-road segments. Therefore, when eyes-on-road and off-road were compared, the significant differences between the two were reduced due to this variation.

The roadway type, driver age, vehicle speed and lane width had significant effects on drivers' lane keeping ability. Specifically, drivers had a larger SDLP when driving on 2-lane rural roads than on 4-lane divided roads. As noted earlier, a larger SDLP is associated with a larger probability of lane departure, which has been described as a precursor to run-off-road crashes (Allen et al., 1996). Using US road configurations (of 12 feet lanes, 55 mph posted speed), the estimated SDLP for a 3-s driving segment was 0.8 feet for those drivers that had long glances off-road. Based on our data, the corresponding probability of lane departure at SDLP = 0.8 is 0.2% (based on a normal distribution, consistent with Zwahlen and

Table 4
GEE model comparing SDLP (log transformed) of longer and shorter duration eyes-off-road.[a]

Variable	Estimate	95%CI	se	z	Pr > |z|
Intercept	−5.51	(−7.80, −3.22)	1.17	−4.71	<0.0001
Eye glances					
Long glances (vs. attentive)	0.76	(0.31, 1.21)	0.23	3.29	0.0010
Short glances (vs. attentive)	−0.02	–	0.35	−0.05	ns
Attentive (baseline)	–	–	–	–	–
Roadway type					
4-Lane divided (vs. 2-lane rural)	−0.87	(−1.34, −0.40)	0.24	−3.61	0.0003
2-Lane rural (baseline)	–	–	–	–	–
Mean lane width (in feet)	0.24	(0.06, 0.41)	0.09	2.70	0.0069
Mean speed (in mph)	0.03	(0.01, 0.04)	0.01	3.16	0.0016

[a] Model equation: SDLP = exp($\beta_0 + \beta_1 \times$ Eye glances + $\beta_2 \times$ Roadway type + $\beta_3 \times$ Mean lane width + $\beta_4 \times$ Mean speed + ε).

Balasubramanian, 1974). Allen et al. (1996) have suggested that the probability of lane departure increases dramatically as the SDLP increases from 0.8 feet. For example, Zwahlen et al. (1988) observed a SDLP of 1.38 feet when drivers were operating a radio or the climate control, which resulted in a 3% chance of lane departure in a 12-foot lane and a 15% chance in a 10-foot lane. The calculated probability from our study is based on much shorter segments (only 3-s) due to real-world constraints in roadways (curvatures) and driver behavior (lane changing). Hence, the computed probabilities are much smaller than observed in controlled studies that encompass much longer driving segments with longer proportion of time driving distracted (e.g., 15-s driving segment in Zwahlen et al. (1988) study). It is possible that the SDLP continued to increase after the examined 3-s segments and the driver might have a higher probability of lane departure. It is also possible that the drivers continued to be distracted after the 3-s segments. Therefore, any larger effect of eyes-off-road on SDLP would not be included in the current analysis due to the 3-s cut-off time. It should be noted that this study differs from controlled studies in that drivers in real world situations may actually adjust their engagement levels during the distraction task, thereby reducing the impact on driving performance (Sayer et al., 2005). Thus, this adaptive behavior might explain the less substantial results from this study when compared to those observed in controlled studies. In controlled studies, drivers are actually encouraged to have continual engagement in the distracting task to quantify the maximum severity associated with these secondary tasks (Donmez et al., 2008; Salvucci et al., 2007; Strayer and Drew, 2004). It is always best to have longer segments of driving in a natural environment to better compare the distraction effects to those observed in controlled studies, and perhaps future naturalistic studies will provide that opportunity.

This study does provide insights on the implications of eyes off-road on lane keeping performance in real world driving environments. The results validated the hypothesis that when off-road glances from non-driving tasks occur, some degradation in lane keeping ability (i.e. SDLP) will happen, even when drivers do their best to adapt to real world driving conditions. This decrement was also associated with the proportion of time that driver's eye glances were directed away from the road during the examined time segments. Additional data is needed to consider the actual implications toward safety since there were limitations associated with this study.

A direct relationship between distracted driving and run-off-road crashes was not established in this study because no crashes were actually observed. It was also difficult to locate some specific sources of off-road glances and as such, it was not always possible to make comparisons among driver inattention types (e.g., text messaging, CD player, etc.). Cognitive distractions (e.g., lost in thoughts) could not be identified from the driver face images. Further, attentive driving segments extracted from 8-s clips may have more unsafe lane keeping than the inattentive segments. This potential sampling bias could reduce the significant differences between attentive and inattentive driving. The results of this study were also based on a limited sample size with unequal number of driving segments from each subject. Repeated measures were used to increase the statistical power of the analysis, but larger samples would have allowed the examination of interaction effects among driver inattention, traveling speed, lane width, and roadway types.

The use of naturalistic data has become more prevalent with advances in data collection methods. However, the occurrence of any crash type (e.g., run-off-road) for a specific situation (e.g., rural, straight road) using one study dataset is still quite rare. Both controlled and naturalistic studies provide insights for understanding driver safety (Boyle and Lee, 2010). Controlled studies have already shown that higher SDLP is related to unsafe driving performance and validating these findings in a naturalistic setting provides the ability to understand the context that unsafe driving occurs, and to examine the effectiveness of crash countermeasures in the real world.

Acknowledgments

The authors would like to thank the University of Michigan Transportation Research Institute (UMTRI) for providing the naturalistic driving study data, and for their assistance in working with the data. Any findings or conclusions are those of the authors and do not reflect the opinion or endorsement of UMTRI.

References

Allen, R.W., Parseghian, Z., Stein, A.C., 1996. A driving simulator study of the performance effects of low blood alcohol concentration. In: Proceedings of the Human Factors and Ergonomics Society, 40th Annual Meeting, Philadelphia, PA.

Anttila, V., Luoma, J., 2005. Surrogate in-vehicle information systems and driver behavior in an urban environment: a field study on the effects of visual and cognitive load. Transportation Research Part F 8, 121–133.

Bayly, M., Young, K.L., Regan, M.A., 2009. Sources of distraction inside the vehicle and their effects on driving performance. In: Regan, M.A., Lee, J.D., Young, K.L. (Eds.), Driver Distraction: Theory, Effects, and Mitigation. Taylor & Francis Group, Boca Raton, FL.

Bendak, S., Al-Saleh, K., 2010. The role of roadside advertising signs in distracting drivers. International Journal of Industrial Ergonomics 40, 233–236.

Blaschke, C., Breyer, F., Farber, B., Freyer, J., Limbacher, R., 2009. Driver distraction based lane-keeping assistance. Transportation Research Part F: Traffic Psychology and Behaviour 12 (4), 288–299.

Boyle, L.N., Lee, J.D., 2010. Using driving simulators to assess driving safety. Accident Analysis and Prevention 42, 785–787.

Brookhuis, K.A., De Vries, G., De Waard, D., 1991. The effects of mobile telephoning on driving performance. Accident Analysis & Prevention 23, 309.

Chisholm, S.L., Caird, J.K., Lockhart, J., 2008. The effects of practice with MP3 players on driving performance. Accident Analysis & Prevention 40, 704–713.

Dingus, T.A., Neale, V.L., Klauer, S.G., Petersen, A.D., Carroll, R.J., 2006. The development of a naturalistic data collection system to perform critical incident analysis: an investigation of safety and fatigue issues in long-haul trucking. Accident Analysis & Prevention 38, 1127–1136.

Donmez, B., Boyle, L.N., Lee, J.D., 2008. Mitigating driver distraction with retrospective and concurrent feedback. Accident Analysis & Prevention 40 (2), 776–786.

Engström, J., Johansson, E., Östlund, J., 2005. Effects of visual and cognitive load in real and simulated motorway driving. Transportation Research Part F: Traffic Psychology and Behaviour 8 (2), 97–120.

Funkhouser, D., Chrysler, S.T., 2007. Assessing Driver Distraction due to In-vehicle Video Systems Through Field Testing at the Pecos Research and Testing Center (No. SWUTC/07/473700-00082-1). Southwest Region University Transportation Center, College Station, TX.

Hanley, J.A., Negassa, A., Edwardes, M.D.d., Forrester, J.E., 2003. Statistical analysis of correlated data using generalized estimating equations: an orientation. American Journal of Epidemiology 157 (4), 364–375.

Hatfield, J., Chamberlain, T., 2005. The Effects of In-vehicle Audiovisual Display Units on Simulated Driving. NSW Injury Risk Management Research Centre, University of New South Wales, Sydney, Australia.

Horberry, T., Anderson, J., Regan, M.A., Triggs, T.J., Brownb, J., 2006. Driver distraction: the effects of concurrent in-vehicle tasks, road environment complexity and age on driving performance. Accident Analysis and Prevention 38 (1), 185–191.

Horrey, W.J., Lesch, M.F., 2009. Driver-initiated distractions: examining strategic adaptation for in-vehicle task initiation. Accident Analysis & Prevention 41, 115–122.

Horrey, W.J., Lesch, M.F., Garabet, A., 2008. Assessing the awareness of performance decrements in distracted drivers. Accident Analysis and Prevention 40, 675–682.

Horrey, W.J., Lesch, M.F., Garabet, A., 2009. Dissociation between driving performance and drivers' subjective estimates of performance and workload in dual-task conditions. Journal of Safety Research 40, 7–12.

Horrey, W.J., Wickens, C.D., 2006. Examining the impact of cell phone conversations on driving using meta-analytic techniques. Human Factors 48 (1), 196–205.

Hosking, S.G., Young, K.L., Regan, M.A., 2005. The Effects of Text Messaging on Young Novice Driver Performance. The National Roads and Motorists' Association Motoring Services, Melbourne, Australia.

Hurwitz, J.B., Wheatley, D.J., 2002. Using driver performance measures to estimate workload. In: Proceedings of the Human Factors and Ergonomics Society, 46th Annual Meeting, Pittsburgh, PA.

Jenness, J.W., Lattanzio, R.J., O'Toole, M., Taylor, N., 2002. Voice-activated dialing or eating a cheeseburger: which is more distracting during simulated driving? In: Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting, Pittsburgh, PA.

Klauer, S.G., Dingus, T.A., Neale, V.L., Sudweeks, J.D., Ramsey, D.J., 2006. The Impact of Driver Inattention on Near-crash/Crash Risk: An Analysis Using the 100-car Naturalistic Driving Study Data (No. DOT HS 810 594). Virginia Tech Transportation Institute.

LeBlanc, D., Sayer, J., Winkler, C., Ervin, R., Bogard, S., Devonshire, J., et al., 2006. Road Departure Crash Warning System Field Operational Test: Methodology and Results. The University of Michigan Transportation Research Institute (UMTRI), Ann Arbor.

Lee, J.D., Young, K.L., Regan, M.A., 2009. Defining driver distraction. In: Regan, M.A., Lee, J.D., Young, K.L. (Eds.), Driver Distraction: Theory, Effects, and Mitigation. CRC Press, Taylor & Francis Group, Boca Raton, FL, pp. 31–40.

Liang, Y., Lee, J.D., 2010. Combining cognitive and visual distraction: less than the sum of its parts. Accident Analysis & Prevention 42, 881–890.

Neyens, D.M., Boyle, L.N., 2007. The effect of distractions on the crash types of teenage drivers. Accident Analysis & Prevention 39 (1), 206–212.

Pettitt, M., Burnett, G., Stevens, A., 2005. Defining driver distraction. In: Proceedings of the World Congress on Intelligent Transport Systems, San Francisco, CA.

Ranney, T.A., Mazzae, E., Garrott, R., Goodman, M.J., 2000. NHTSA driver distraction research: past, present and future from <http://www-nrd.nhtsa.dot.gov/departments/Human%20Factors/driver-distraction/PDF/233.pdf>.

Reed-Jouns, J., Trick, L.M., Matthews, M., 2008. Testing assumptions implicit in the use of the 15-second rule as an early predictor of whether an in-vehicle device produces unacceptable levels of distraction. Accident Analysis and Prevention 40, 628–834.

Rockwell, T.H., 1988. Spare visual capacity in driving-revisited: New empirical results for an old idea. In: Gale, A.G., Freeman, M.H., Haslegrave, C.M., Smith, P., Taylor, S.P. (Eds.), Vision in Vehicles II. Elsevier Science Publishers B.V., Amsterdam, pp. 317–324.

Salvucci, D.D., Markley, D., Zuber, M., Brumby, D.P., 2007. iPod distraction: effects of portable music-player use on driver performance. In: Proceedings of the Human Factors in Computing System: CHI 2007 Conference, New York, NY.

Sayer, J.R., Devonshire, J.M., Flannagan, C.A., 2005. The Effects of Secondary Tasks on Naturalistic Driving Performance (No. UMTRI-2005-29). The University of Michigan, Industry Affiliation Program for Human Factors in Transportation Safety, Ann Arbor, MI.

Serafin, C., Wen, C., Paelke, G., Green, P., 1993. Car phone usability: a human factors laboratory test. In: Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting, Seattle, WA.

Strayer, D., Drew, F., 2004. Profiles in driver distraction: effects of cell phone conversations on younger and older drivers. Human Factors 46 (4), 640–649.

Wang, J., Knipling, R.R., Goodman, M.J., 1996. The role of driver inattention in crashes; new statistic from the 1995 crashworthiness data system (CDS). In: Proceedings of the 40th Annual Association for the Advancement of Automotive Medicine, Vancouver, BC.

Wickens, C.D., 2002. Multiple resources and performance prediction. Theoretical Issues in Ergonomics Science 3, 159–177.

Wikman, A.S., Nieminen, T., Summala, H., 1998. Driving experience and time sharing during in-car tasks on roads of different widths. Ergonomics 41 (3), 358–372.

Zwahlen, H.T., Adams, C.C.J., Debald, D.P., 1988. Safety aspects of CRT thouch panel controls in automobiles. In: Gale, A.G., Freeman, M.H., Haslegrave, C.M., Smith, P., Taylor, S.P. (Eds.), Vision in Vehicles II. Elsevier Science Publishers B.V., Amsterdam, pp. 335–344.

Zwahlen, H.T., Balasubramanian, K.N., 1974. A theoretical and experimental investigation of automobile path deviation when driver steers with no visual input. Transportation Research Record 520, 25–37.