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The Impact of Nighttime Driving on Young Drivers' Behavior and Safety in Cities Using a Driving Simulator

Armira Kontaxi[a]*, Dimosthenis Pavlou[b], Panagiotis Papantoniou[b], George Yannis[a]

[a]*National Technical University of Athens, 5 Heroon Polytechniou St., GR-15773, Athens, Greece*
[b]*University of West Attica, Agiou Spyridonos St., GR-12243, Egaleo, Athens, Greece*

Abstract

Nighttime driving is undoubtedly correlated with risky driving behaviors and is often considered as a risk exposure indicator that affects both accident probability and accident severity. The objective of the present study is to investigate the association between nighttime driving and young drivers' behavior and safety in an urban driving simulator environment. An experimental process on a driving simulator was carried out, in which 35 participants drove under different driving conditions (low/high traffic, daytime/nighttime conditions) in an urban environment. Then, linear regression statistical modelss were calibrated to investigate the impact of nighttime driving on the mean speed and on the mean reaction time. Moreover, in order to examine the influence of nighttime driving on accident probability, binary logistic method was used. Results indicate that, within the examined driving simulator environment, nighttime driving is associated with an increase in mean speed and mean reaction time, resulting in a statistically significant increase in the probability of being involved in a crash. These findings quantify the effects of nighttime driving on young drivers' behavior and safety under controlled urban simulation conditions and may provide preliminary evidence for future research and discussions on nighttime road safety interventions.

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Keywords: nighttime driving; driving simulator; road crashes; driving behavior; linear regression; binary logistic regression

1. Introduction

Road safety is a complicated scientific field of transport research due to the multidimensional nature of crash occurrence. Since road crashes impose serious problems in society in terms of human, economic, property damage and medical costs, they constitute major concern in the transportation industry. There are numerous causal factors

* Corresponding author. Tel.: +3077221575
E-mail address: akontaxi@mail.ntua.gr

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affecting crash occurrence and it is not surprising that so different factors appear important, since driving is such a complex task (Singh, 2015). The most crucial risk factors recognized in literature are human factors, unsafe road infrastructure, vehicle defects and inadequate enforcement of traffic laws (Peden & Sminkey, 2004; World Health Organization (WHO), 2020). In addition, environmental factors, like rain, snow or darkness influence as well the risk of road crashes as they change in a way the "normal" driving environment. Several studies have proved that drivers' ability to avoid collisions is impaired in darkness (Plainis et al., 2006; Åkerstedt et al., 2013; Sullivan & Flannagan, 2002).

Scientific research has shown that time of day influences both severity and rate of crashes (Behnood & Mannering, 2019;Clarke et al., 2006). The greater the severity of the crash, the more important is the effect of lighting conditions (Yannis et al., 2015). In the UK, crash severity was found to double during nighttime (Plainis & Murray, 2002). In the same context, according to the latest Hellenic Statistical Authority (Hellenic Statistical Authority, 2020) data for 2019 in Greece, crash severity is increased 3 to 5 times more at night in rural roads with no street lighting, but also in urban roads with good street lighting.

Based on the aforementioned, it is of high importance to assess the impact of nighttime driving on the driver's behavior and safety. Numerous studies have already tried to assess the contributions of this factor to crashes. However, the majority of the conducted studies seem to face some challenges; the identified risk factors that influence road crashes tend to be correlated to each other. In nighttime driving, for example, various factors affect driver's safety beyond the darkness itself; alcohol, drowsiness, circadian rhythm (Chipman & Jin, 2009), and sleepiness (e.g. (Lowden et al., 2009)) are important factors that may increase crash risk. Some authors identified voluntary risk-taking by drivers (Clarke et al., 2005), particularly young drivers, as a significant factor that increases the rate of road crashes at night and some others concluded that driving in the dark is also associated with a higher degree of perceptual errors such as distraction and lack of attention (Yan et al., 2022).

Furthermore, visual performance is impaired in low light conditions (lower luminance) and may thereby increase the reaction time to unexpected events on the road (Fors & Lundkvist, 2009). In this context, (Plainis & Murray, 2002) conducted a study where reaction times (RTs) to targets presented in the visual field of the driver, were measured for a range of stimulus variables, such as contrast, luminance and spatial frequency. Results showed that RTs are closely related to sensitivity and can therefore provide a method of measuring supra-threshold visual performance. The data were interpreted in terms of visual performance when driving, where a reduction in target visibility leads to increases in processing time when driving at nighttime. In other words, nighttime driving influences negatively visual search strategies, resulting in a high crash risk (Konstantopoulos et al., 2010).

Overall, driving simulators have often been employed to investigate driving performance measures during nighttime and daytime scenarios(Underwood et al., 2011; Bella et al., 2014; De Valck et al., 2006). More specifically, (Bella et al., 2014) used a driving simulator experiment to compare driver speed behavior under daytime and nighttime conditions. Results highlighted the significant role of segment length; drivers reduced their mean speed when they could not correctly perceive the length of the whole segment in the nighttime scenario, probably compensating for their driving impairment in the dark. On another note, aiming to investigate the hazard anticipation of novice and experienced drivers under daytime and nighttime conditions, (Garay-Vega et al., 2007) conducted a driving simulator study. Taking into account that experienced drivers are prone to observe potential hazards in specific areas of their visual display, the authors examined whether they would maintain their advantage in nighttime driving, as well. Results revealed that indeed the experienced drivers showed a better driving performance compared to the novice ones, even though the absolute level of their driving performance changed for both groups.

Based on the above, this research aims to investigate the impact of nighttime driving on different driving performance measures of young drivers on urban roads, through a driving simulator experiment. Particularly, mean speed, mean reaction time and the probability of getting involved in a crash are the dependent variables examined in order to render the impact of nighttime driving. Additionally, the effect of driving at night in combination with driving behavioral parameters and driver characteristics (gender, annual mileage, and driving habits) is investigated, as well.

2. Materials and Methods

Within the present research, a driving simulator experiment was conducted to examine the impact of nighttime driving on young drivers' behavior and safety in urban roads in combination with specific driver and road environment characteristics. The driving simulator experiment took place at the Department of Transportation Planning and Engineering of the National Technical University of Athens.

2.1. Experimental design

Taking into consideration that the scope of the research is to investigate the behavior of young drivers, the selection of participants was limited to drivers aged 18-30 years old. The experiment involved 35 volunteers, 23 men and 12 women with a valid driving license and an average driving experience of 5 years. Furthermore, participants completed a detailed questionnaire about their driving habits and their driving behavior with regard to nighttime driving, as well as demographic information. Additionally, it should be noted that the participants did not take any benefit regarding the participation in the experiment.

The driving simulator as described in other NTUA driving simulator studies (Yannis et al., 2014) consists of 3 LCD wide screens 40'' (full HD), total angle view 170 degrees, driving position and support base. The dimensions at a full development were 230x180 cm with a base width of 78 cm. The controls available to the driver are: 5 gears plus reverse gear, flash, wipers, lights, horn, brake and starter.

A familiarization session or 'practice drive' is typically the first step of all driving simulator experiments. During the familiarization with the simulator, the participants practiced in handling the simulator, keeping the lateral position of the vehicle, keeping stable speed, appropriate for the road environment and braking and immobilization of the vehicle.

After the practice drive, each participant was asked to drive the main part of the experiment; two sessions (~ 20min each) that correspond to lighting conditions:

- Daytime driving on an urban route that was 1.7 km long, with mixed traffic, separated by guardrails, and lane width 3.5 m. (Fig. 1)

Fig. 1. Frame from the simulation environment in daytime.

- Nighttime driving on an urban route that was 1.7 km long, with mixed traffic, separated by guardrails, and lane width 3.5 m (Fig. 2)

Fig. 2. Frame from the simulation environment in nighttime

To minimize learning effects, the order of daytime and nighttime scenarios was counterbalanced across participants. A short rest period was provided between sessions to avoid fatigue effects. No participant reported simulator sickness requiring termination of the experiment and no dropouts occurred during the data collection process.

More precisely, to meet the research objective i.e. the effect of nighttime driving on driving behavior and safety, some adjustments were made to the driving simulator setup. A thick dark curtain was placed around the driving simulator to block the light from the outside and therefore create a dark room, simulating the nighttime driving conditions, and providing the driver/participant with the feeling/sense of nighttime driving. In addition, it should be highlighted that the screens composing the driving simulator are very dark and only with the use of vehicle lights the driver can actually see the road. A screenshot of the nighttime driving scenario is presented on Fig. 2.

Within each session, two traffic scenarios were examined in a full factorial within-subject design. The traffic demand scenarios were (Papantoniou et al., 2017):

- QL: Low traffic conditions – with ambient vehicles' arrivals drawn from a Gamma distribution with a mean of 12 s, and variance of 6 σ2, corresponding to an average traffic volume of 300 vehicles/h.
- QH: High traffic conditions – with ambient vehicles' arrivals drawn from a Gamma distribution with a mean of 6 s, and variance σ2 = 3 s2, corresponding to an average traffic volume of 600 vehicles/h.

Furthermore, during each trial of the experiment, two unexpected events were scheduled to occur at fixed points along each drive (but not at the exact same point in all trials, so that the learning effects get minimized). More specifically, incidents concerned the sudden appearance of a pedestrian on the roadway as shown in figure 3.

2.2. Theoretical Background

Three models were developed to analyze the impact of nighttime driving on young drivers' behavior and safety in urban roads in terms of speed, reaction time and crash probability. Specifically, log-normal linear regression model was developed for mean speed, normal linear regression for reaction time and binary logistic regression model for crash probability. Crash probability was modeled as a binary variable, equal to one when a crash occurred during the simulated drive, otherwise, equal to zero. The analyses were conducted using SPSS Statistics (version 21).

Linear regression is a simple technique used to model a linear relationship between a continuous dependent variable and one or more independent variables. With respect to the mean speed model, the log-linear (log-normal) regression was applied as long as it described better the driver speed behavior in all driving scenarios. Both approaches were calibrated using the Ordinary Least Squares method. The basic equation of the multiple linear regression model is the Eq. (1) as presented below:

$$Y_i = \beta_O + \beta_1 * X_{1i} + \beta_2 * X_{2i} + \cdots . + \beta_v * X_{vi} + e_i \quad (1)$$

With respect to the crash probability model, since the dependent parameter consists of a binary variable, binary logistic regression is selected as the appropriate analysis method. A binary logistic regression estimates the probability that a characteristic is present (e.g. estimated probability of "success") given the values of explanatory variables. It leads to the development of a mathematical model that gives the odds of this event occurring, depending on factors that affect it. If the "utility function" is given by Eq. (2), then the probability P is given by Eq. (3):

$$U = \beta_0 + \beta_i * X_i \quad (2)$$

$$P = \frac{e^U}{e^U + 1} \quad (3)$$

For the categorical variables included in the models, nighttime driving was coded as 1 for nighttime and 0 for daytime conditions, traffic conditions were coded as 1 for high traffic and 0 for low traffic conditions, while gender was coded as 1 for female and 0 for male participants. Questionnaire-based variables were coded according to the participants' responses, with higher values corresponding to stronger agreement with the respective statement.

3. Results and Discussion

3.1. Modelling Mean Speed

The first model investigates the effect of several parameters, including nighttime driving, on the mean speed of the driver. Results are presented in Table 1.

Table 1. Model results for mean driving speed.

Independent variables	Mean driving speed				
	βi	*t*	*p value*	*Elasticity (ei)*	*Rel. elasticity (ei^*)*
Constant	1.682	39.849	0.000		
Nighttime driving	0.012	1.842	0.042	-0.004	1
Traffic conditions	-0.044	-4.030	0.000	-0.015	-3.752
Average of the distance from central axis	-0.019	-3.231	0.002	-0.038	-9.527
Age	-0.004	-2.764	0.007	-0.067	-16.753
Gender	-0.018	-2.127	0.035	-0.016	-4.000
Driver Avoids Driving At Night	-0.047	-4.299	0.000	-0.007	-1.753
Self-reported crash in daytime	0.023	2.855	0.005	0.007	-1.753
R^2	0.615				

Modelling results regarding driving speed reveal some interesting findings: Both driving simulator and questionnaire variables are found statistically significant and have an impact on driving speed. More precisely, driving in the examined nighttime urban simulator scenario was associated with slightly increased mean speeds compared to daytime driving. In addition, driving speed increases when the participant drives under low traffic conditions rather than high traffic conditions. Instead, mean speeds seem to be lower for increased mean distances from the central axis, probably implying that aggressive drivers maintain their vehicle close to the road axis and drive faster, while the more cautious ones drive at lower speeds closer to the right-hand line and move away from the road axis.

With respect to the independent variables obtained from the questionnaire, some noteworthy findings have occurred, as well. The variable "Age" has a negative relationship with the dependent variable, showing that as participant's age increases, their driving speed decreases. Regarding the gender of the participants, driving speed is found lower for female participants compared to male participants. Furthermore, drivers who avoid driving at night (statement via questionnaire), illustrate lower driving speeds, while drivers who have self-reported a crash during daytime show higher driving speeds.

For further investigation, relevant elasticities were calculated to shed light to the quantity of impact of independent variables on the dependent variable. Specifically, nighttime driving variable was not the one with the highest impact on mean speed (Table 1); this was the age of the participant. Its impact on mean speed is 16.75 times higher than that of nighttime driving. As far as the average distance from the central axis is concerned, its impact on mean speed is 9.53 higher than nighttime driving variable. Participant's gender and traffic conditions seem to have a similar effect on mean speed, 4.00 and 3.75 times higher than nighttime driving, respectively. Finally, "Driver Avoids Driving At Night" and "Self-reported crash during daytime" variables seem to have a similar impact on mean speed.

3.2. Modelling Reaction Time

As shown in Table 2, nighttime driving has an adverse impact on driver's reaction time at an unexpected event. Results indicate that participants show increased reaction times during nighttime compared to daytime driving, as the positive value of the coefficient β reveals. As for the other investigated variables, it is found that women are the ones that need more time to react at unexpected events compared to men, based on the positive sign of coefficient β. Moreover, the participants who illustrate a greater speed variation (Std of Driving Speed), show decreased reaction times which means that they correspond more quickly to unexpected events. Additionally, drivers who claim via the questionnaire to reduce their driving speed at nighttime show that the more they reduce their speed the shorter seem to be their reaction times at unexpected events, probably because of their alertness when driving.

Table 2. Model results for mean reaction time.

Independent variables	Mean reaction time				
	βi	*t*	*p value*	*Elasticity (ei)*	*Rel. elasticity (ei*)*
Constant	1526.670	5.969	0.000		
Nighttime driving	157.475	2.143	0.035	0.116	1
Gender	182.622	2.415	0.018	0.338	2.917
Std of Driving Speed	-55.343	-3.539	0.001	-1.030	-8.910
Speed reduction at nighttime	-192.357	-2.634	0.010	-0.428	-3.693
R^2	0.420				

Examining the elasticity of the independent variables, results indicate that nighttime driving variable was not the one with the highest impact on reaction time. Its impact is 2.91 times lower than participant's gender and 3.69 times lower than speed reduction at nighttime driving. Thus, the variable with the highest impact on reaction time is the standard deviation of mean speed, namely 8.91 times higher than nighttime driving, 3.06 and 2.41 times higher than participant's gender and speed reduction at nighttime driving respectively.

3.3. Modelling Crash Probability

Crash probability was modelled as a binary variable, equal to one when a crash occurred as a result of an unexpected incident during the simulated drive, and equal to zero otherwise. The respective model for crash probability is included in Table 3; in this case, goodness of fit results, Wald test and p values are reported for each variable. The elasticity and relevant elasticity values for each independent variable used in the model are also presented in the table

Table 3. Model results for crash probability.

Independent variables	Crash probability				
	βi	*Wald*	*p value*	*Elasticity (ei)*	*Rel. elasticity (ei*)*
Constant	-22.304	12.530	0.000		
Nighttime driving	1.531	4.567	0.035	1.860	2.623
Traffic conditions	2.897	5.726	0.017	8.254	11.626
Gender	2.853	7.075	0.008	1.363	1.925
Standard Deviation of Driving Speed	0.570	7.029	0.008	4.910	6.919
Average of the distance from central axis	1.297	4.172	0.040	2.447	2.570
Driver's reduced perception of real distances when driving at night	4.993	8.691	0.003	0.715	1
Hosmer & Lemeshow test	0.611				

Nighttime driving results in a statistically significant increase in crash probability compared to daytime driving. Moreover, modelling results show that crash probability increases with the increase of the traffic density; the denser the traffic load the higher the crash probability. Additionally, it is found that female participants show a higher probability of getting involved in a crash, compared to male participants. Two driving behavioral measures that have a positive effect on crash probability seem to be the standard deviation of mean speed and the average distance of the vehicle from central axis: the higher the values of these driving parameters, the greater the crash probability. Finally, results show that drivers who have admitted via the questionnaire their reduced perception of real distances when driving at night tend to have an increased crash probability, probably confirming their impairment in driving performance when driving at night.

Some interesting insights reveal when exploring the elasticities of the examined variables. The variable with the highest impact on crash probability is the variable of traffic conditions on the road; its impact is 11.62 times higher than driver's reduced perception of real distances when driving at night, which is the variable with the smallest impact on crash probability. Although nighttime driving is not the variable with the highest impact on crash probability, it has a statistically significant impact, namely 2.62 times higher than driver's reduced perception of real distances when driving at night and 1.36 times higher than the participant's gender. Regarding the quality of the model, the p-value of Hosmer & Lemeshow Test for goodness of fit is higher than 0.05, which suggests these models can be considered as acceptable.

4. Conclusions

The present paper aims to analyze the influence of nighttime driving on the behavior (driving speed and reaction time) and safety (crash probability) of 35 young drivers through a driving simulator experiment. The effects of nighttime driving were explored via three statistical models taking into consideration both driving behavioral indicators and driver characteristics.

Results indicate that nighttime driving leads to an increase of the mean speed, and the mean reaction time, as well as to a statistically significant increase of a crash probability. Although the differences between the performance measures are not so profound in terms of absolute value, they show a statistically significant degradation in drivers' behavior while driving at night, leading to an increase of the crash probability, as measured in a simulated environment.

Furthermore, drivers exhibited slightly higher mean speeds during the nighttime simulator scenarios. One possible explanation is that the urban environment examined in the simulator remained relatively well illuminated, which may have influenced speed choice. However, the present study did not directly investigate the mechanisms underlying this behavior and therefore no causal interpretation can be established. Future research should examine whether similar patterns are observed under different lighting conditions, rural environments, adverse weather, or real-world driving settings.

Within this environment, driving simulators have become a widely used tool for examining the impact of various risk factors to driver behavior and safety, with respect to individual driver differences and/or roadway design (Chaireti et al., 2020.; Zhao et al., 2019). They provide objective measurements of driving behavior in a safe environment and can evaluate performance under hazardous driving tasks that would be impossible in open-road experiments. Moreover, it should be highlighted that plenty confounding variables can be safely controlled in a virtual environment, rather than driving under naturalistic conditions. However, one of the concerning issues with respect to driving simulator studies, is the fact that drivers' behavior will be biased under simulated driving since there is not any risk involved. In fact, driving simulator validity constitutes a research limitation in the present study, as there is no way to confirm how accurate the results are in "real-world" driving. Nevertheless, considering that the relationship between fidelity and validity is not straightforward (Wynne et al., 2019), future research could further examine this issue.

The findings should be interpreted in light of several limitations. First, the sample consisted of only 35 young drivers and therefore does not represent the broader driving population. Second, the experiment was conducted in a controlled driving simulator and focused on a single urban route under specific lighting and traffic conditions. Consequently, the reported effects should be viewed as evidence from a controlled simulation environment rather than as directly generalizable estimates of real-world crash risk. Additional studies involving larger samples, different age groups, rural roads, adverse weather conditions, and naturalistic driving environments are required to confirm the observed relationships.

The results of this study may serve as a basis for further research using a similar experiment on a larger sample with participants of various age groups. Moreover, different driving environments and different traffic conditions should be further investigated, to explore the impairment caused by nighttime driving in different road environments (e.g., rural roads), adverse weather conditions, and so forth. Finally, for further statistical analysis and export of additional models, the implementation of other statistical methods would seem useful, such as Poisson and negative binomial regression, statistical models widely used for modeling road crashes (Sawalha & Sayed, 2011).

In summary, the identification of the parameters that have an impact on the behavior and safety of young drivers concerning nighttime driving and the consequent results may provide preliminary evidence that can support future research and inform discussions among policy makers, road authorities, and other stakeholders regarding nighttime driving safety.

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