Effect of lighting on frequency and severity of road accidents

George Yannis, PhD, Associate Professor - corresponding author
National Technical University of Athens, School of Civil Engineering,
Department of Transportation Planning and Engineering
5 Iroon Polytechniou str., GR-15773 Athens, Greece
Tel: +30 210 7721326
Fax: +30 210 7721454
E-mail: geyannis@central.ntua.gr

Alexandra Kondyli, PhD, Transportation Engineer
National Technical University of Athens, School of Civil Engineering,
Department of Transportation Planning and Engineering
5 Iroon Polytechniou str., GR-15773 Athens, Greece
Tel: +30 210 7721380
Fax: +30 210 7721454
E-mail: akondyli@gmail.com

Nikolaos Mitzalis, MSc, Civil Engineer
National Technical University of Athens, School of Civil Engineering,
Department of Transportation Planning and Engineering
5 Iroon Polytechniou str., GR-15773 Athens, Greece
Tel: +30 210 7721380
Fax: +30 210 7721454
E-mail: mitzalis@hotmail.com

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Abstract

The purpose of this study is to investigate the effect of lighting conditions on the frequency and severity of road accidents at both urban and rural roads in Greece. A total of 358,485 police recorded accidents were analyzed and the proposed models were developed with the use of log-normal regression. The application of these models led to the investigation of the influence of road lighting and other parameters such as weather conditions, accident type, vehicle type etc. on the number of casualties and injuries. It appears that road lighting contributes to the reduction of the number of accidents and their severity and that this influence increases with the increase of the severity of the accidents. The absence of street lighting during nighttime has the highest impact on the number of fatalities and serious injuries. The analysis results show that nighttime lighting has great potential in improving traffic safety and reducing the accident severity, especially for persons killed and seriously injured. The identification of the characteristics of lighting effect on road safety could be proved beneficial for road safety policy decision makers in order to design and implement the appropriate road safety measures (infrastructure improvement, safety campaigns, etc.).

Keywords: road accidents, lighting conditions, road safety, accident severity, log-normal regression.

1. Introduction

Driving is a complex task that involves the cognitive, psychomotor and visual-perceptual function of the driver in a continuously altering environment, which suggests that there are many factors that contribute to the occurrence of a road accident. A high percentage of road injuries is associated with human-related error (Hills, 1980). In addition, several researchers have provided evidence that drivers' ability to avoid collisions is impeded under dim lighting conditions (Owens and Sivak, 1993; Elvik, 1995; Sullivan and Flannagan, 2002). In the UK, accident severity (defined as the number of fatal collisions per 100 collisions) was found to double during nighttime (Plainis et al. 2006), whereas in the United States fatality rates (per vehicle miles) were found to be 3.5 times higher at night than during daytime (Owens and Sivak, 1993).

A comprehensive analysis of statistical data from 20 EU countries showed that the proportion of fatalities during darkness is 35.5% for outside built-up areas, 39.7% for built-up areas and 44.6% for motorways (ERSO, 2011). Irrespective of the area type, the majority of nighttime fatalities (58.5%) in the EU occur in complete darkness conditions (either the street lights are unlit or there are no street lights in place), whereas the remaining 41.5% corresponds to nighttime fatalities with the presence of lit street lights.

The impact of road lighting has been studied extensively in the literature. The International Commission on Illumination evaluated the effect of road lighting on accidents by analyzing 62 studies from 15 countries (CIE, 1992). Based on before-and-after studies it was concluded that the installation of road lighting reduces the number of nighttime accidents by 30%. In addition, the effect of lighting installation was greater for pedestrian-related accidents compared to all accidents.

Several researchers have studied the effect of road lighting conditions on traffic safety and driver behavior. Kulmala (1994) performed a before and after evaluation of implemented safety measures including road lighting at three-leg and four-leg intersections in Finland. After correcting for the regression-to-the-mean bias, Kulmala found that the number of accidents at three-leg intersections after the installation of road lighting was approximately 50% lower than the predicted number of accidents before the installation. The corresponding reduction of all injuries at four-leg intersections was approximately 11%.

Elvik (1995) evaluated the effect of road lighting by conducting a meta-analysis using the log-odds method of 37 studies during darkness hours in 11 countries. After controlling for regression-to-the-mean and secular accident trends, the author concluded that lighting conditions reduce by 65% nighttime fatal accidents, by 30% injury accidents and by 15% property-only-damage accidents.

Assum et al. (1999) studied drivers' risk-compensation and adaptation behavior when lighting conditions are present. The authors examined the hypothesis that drivers do not adjust their behavior, i.e., increase their speed, reduce their concentration or travel more, when road lighting is installed. To test this hypothesis, Assum et al. (1999) investigated driver behavior (e.g., speeds and concentration) during darkness hours before and after lighting was installed along a section in Norway. Driver behavior data during daylight and darkness hours for an adjacent roadway without lighting were used as controls. The analysis results revealed that drivers do compensate for road lighting by increasing their speeds and reducing their concentration; however, this compensation is not sufficient to make road lighting ineffective as an accident reduction measure, as it was found to increase safety significantly.

A rather comprehensive study by Bruneau et al (2001) on 770km of motorways in Quebec found that lighting reduces the nighttime accident rate by 33% compared to interchange lighting alone and by 49% compared to unlit motorways.

Elvik and Vaa (2004) summarized the results of 38 studies that evaluate the effect of road lighting along previously unlit roads on accidents. Based on a meta-analysis of these studies the effect of providing lighting was a 60% reduction of fatal accidents, and a 15% reduction of injury and property damage accidents, which indicates that the effect of road lighting is greater for more serious accidents. Elvik and Vaa (2004) also summarized the results of studies that investigated the effect of improving lighting conditions and of reducing lighting to save energy. It was concluded that upgrading existing lighting reduces the number of accidents during darkness, whereas reducing lighting was associated with an increase of the number of accidents.

Yannis et al. (2007) examined the relative accident risk of native Greek and foreign drivers as a function of the area type, the roadway segment (i.e., junction) and lighting conditions. The authors concluded that EU nationals have higher risk during nighttime compared to Greek nationals, which can be explained by the unfamiliarity of the former with the road infrastructure.

Recent work by Wanvik (2009a) analyzed the effect of road lighting on accidents in darkness using an interactive database of road accidents covering the period 1987 to 2006 on Dutch Roads. The accident database included 763,000 injury accidents and approximately 3.3 million damage accidents. Two estimators of the effect were used, namely, the odds ratio and the ratio of odds ratio. The odds ratio is based solely on the number of accidents, without considering an underlying distribution of traffic flow. The ratio of odds ratio estimator takes into account the distribution of accidents throughout the year. The results of the two methods were combined in meta-analysis techniques. The analysis revealed a slight increase of the effect of road lighting condition on accidents with fatalities (-49%) compared to injury accidents (-46%). It was also found that injuries are reduced by 50% during nighttime. When combining additional parameters such as weather conditions, type of accident, and driver-related characteristics it was found that the effect of road lighting is significantly smaller during adverse weather conditions than during fine conditions. In addition, the effect of road lighting on pedestrian and bicycle accidents are significantly larger than the effect on automobile and motorcycle accidents. Road lighting appeared to affect to the same extent all drivers, irrespective of their age.

Wanvik (2009b) also investigated the effect of road lighting on motorways considering different weather and road surface conditions. The author used a large database of accidents from 1987 to 2006 from the Netherlands, Britain and Sweden. Wanvik (2009b) found that road lighting reduces the number of injury accidents during darkness considerably (-49%) on Dutch motorways; however, this effect varies between countries. Road lighting also reduces collisions with lighting poles, while its effects are lesser during precipitation that during fine weather, and on wet road surfaces that on dry surfaces.

Johansson et al. (2009) examined the risk of accidents associated with darkness using three datasets of accident counts from Sweden, Norway and the Netherlands. The authors applied the odds ratio method by considering pairs of the same hours throughout the year, during which darkness or daylight conditions occur, depending on the part of the year. The authors also compared an hour with varying daylight to an hour that has daylight throughout the year to control for seasonal variations in the number of accidents. The results of this study suggest that the increase of accidents during darkness is fairly moderate. Pedestrians and cyclists were also found to be more affected compared to other road users' groups, whereas car occupants were not found to have increased risk.

Given the obvious impact of lighting conditions on road safety, several researchers have proposed lighting countermeasures for reducing the frequency and severity of accidents. Retting et al. (2003), Pegrum (1972), and Polus and Katz (1978) proposed improved lighting conditions such as increased intensity of road lighting, as a countermeasure for pedestrian-related accidents during nighttime. In addition, Coate and Markowitz (2004) suggested that daylight and daylight saving time could reduce pedestrian fatalities and motor vehicle fatalities by 13% and 3% respectively, of all corresponding fatalities in the 5:00 to 10:00 am and in the 4:00 to 9:00 pm periods. Recently, the Conference of European Directors of Roads (Yannis et al., 2008) investigated lighting as an effective investment for improving road safety, due to its high safety effects and low implementation costs. Nevertheless, the cost of electrical energy has lead some authorities to re-evaluate their policy on street lighting, and develop cost-benefit analyses that justify the installation or replacement of lighting schemes (Fox, 2009). Recent analysis of nighttime accidents on lit and unlit British roads showed that the accident saving benefits previously assumed have not been achieved in practice, leading to the publication of new lighting standards in 2007 (CEDR, 2009).

Researchers have also developed various models for predicting the severity of accidents as a function of several parameters including road lighting conditions. Several researchers (Lee and Abdel-Aty, 2005; Pai and Saleh, 2008; Chimba and Sando, 2009) developed an ordered probit model considering a broad range of independent variables, and they concluded that darkness increases the severity of injuries. Similarly, Savolainen and Mannering (2007) developed a nested logit model and a multinomial logit model, where they found that darkness increases the severity of single-vehicle crashes. Helai et al (2008) developed a hierarchical binomial logistic model and they concluded that, compared to daytime, nighttime increases the severity of accidents. Recent research by Christoforou et al. (2010) considered a random parameters ordered probit model, and it was found that daylight has a significant impact on the severity of accidents.

In conclusion, research has shown that road lighting may prevent traffic crashes, injuries and fatalities in several EU countries and in the United States; however, the effect of road lighting has not been studied for a country with poor road infrastructure network and high accident rates, like Greece. Therefore, the objective of this study is to evaluate the effect of lighting conditions on the severity and frequency of accidents for the first time in Greece, in conjunction with a variety of factors such as area type, weather conditions, road surface conditions, collision type, vehicle type, and passenger characteristics. In this way, it will be examined whether there is any particular effect of Greek lighting conditions (more sunny than several more Northern European countries) to the road accidents and their casualties.

2. Method

2.1. Dataset description

In Greece, accident reports are filled in by the Police for each accident with fatalities or injuries. The National Statistical Service of Greece (ELSTAT) is responsible for providing the police with a uniform accident reports' format, to ensure consistency and credibility of the accident-related information.

The data used in this research were obtained from the National Statistical Service of Greece (ELSTAT), which has as original source the police accident reports. The information documented into the police accident reports include the time of the accident (year, month, date, hour), the location characteristics (rural or urban area, roadway type), the type of the accident (head-on collision, rear-end collision, etc), the individuals involved in the accident, information on fatalities, serious injuries or light injuries, the type of maneuver causing the accident (overtaking maneuver, lane change, etc), weather conditions (rain, good weather, etc), and roadway surface conditions (icy roadway). Additional information related to the drivers' age and nationality, the age of the vehicles involved, the drivers' license category, as well as the safety equipment use (helmet, safety belt), are also provided. It should be noted that no important reported deficiencies are expected as far as the road infrastructure variables are concerned. It is further noted that traffic-related information is not available in the dataset; therefore this research focuses on casualty accidents' frequency and not to the respective risk rates (accidents per vehicle kilometers) in the Greek roadways.

This database covers the period from 1996 to 2008. A total of 358,485 accidents were analyzed as part of this research, together with the respective 23,866 (7%) fatalities, 39,666 (11%) serious injuries, and 294,953 (82%) light injuries. A summary of the data statistics used as part of this research is presented in Table 1.

Table 1 to be inserted here

The majority of all accidents reported both inside and outside built-up areas, occurred during daytime conditions. As shown in Table 1, fatalities, serious injuries and light injuries also occur very frequently during nighttime, inside and outside of built-up areas. With respect to the accident severity, fatalities occur more frequently outside build up areas, whereas serious injuries and light injuries are more common inside built-up areas.

Table 2 shows the percentages of fatalities, serious injuries, and light injuries by vehicle type as a function of nighttime lighting conditions and the area type.

Table 2 to be inserted here

From this table it is inferred that most of nighttime fatalities occurred on unlit roadways, and outside build-up areas. In addition, the most frequent vehicle types involved in fatal accidents during darkness are passenger cars and heavy vehicles. On the other hand, the majority of serious and light injuries occurred during sufficiently lit roadways and inside built-up areas. It is further noted that a high percentage of those accident occurred with the involvement of bicycles, motorcycles and buses, irrespective of the area type.

2.2. Methodological framework

This section presents the methodological framework undertaken in this research. The frequency and severity of road accidents were modeled through log-normal regression. Three separate models were developed that evaluate the effect of road lighting conditions and other variables on the number of fatalities, serious injuries and light injuries. The general formulation of the developed models is provided by the following equation:

$$\log(X_i) = Y_i * \beta_i \quad (1)$$
$$i \in \{\text{fatalities, serious injuries, light injuries}\}$$

Where X_i represents the vector of dependent variables (i.e., the number of fatalities, serious injuries and light injuries). Y_i is the vector of explanatory variables affecting the number of fatalities, serious injuries and light injuries. β_i is the corresponding vector of parameter values.

Most of the variables available in the dataset are discrete variables, except from the driver's age, which was treated as a continuous variable. As such, it was most appropriate for modeling purposes to represent those discrete variables as dummy variables. In addition, statistical tests were performed to identify potential bivariate correlations between the explanatory variables, and remove those from consideration. An absolute correlation value close to 1 denotes high correlation between the variables. A list of all non-correlated explanatory variables at a 1% significance level, which were eventually included in the model development, is presented in Table 3.

Table 3 to be inserted here

The developed log-normal models were further evaluated in terms of their elasticity. Although most of the variables presented in the models are discrete variables, an attempt was made to investigate the sensitivity of the three dependent variables (the number of fatalities, serious injuries and light injuries) to the marginal change of one or more of the independent variables.

The mathematical definition of the elasticity of *X* with respect to *Y* is provided by Equation 2:

$$e_{(X/Y)i} = \frac{\Delta Y_i}{\Delta X_i} * \frac{X_i}{Y_i} = \beta_i * \frac{X_i}{Y_i} \quad (2)$$

i ∈ *{fatalities, serious injuries, light injuries}*

Where β_i are the corresponding parameter values, X_i are the values of the dependent variable and Y_i are the values of the independent variables.

The evaluation of the relative influence of each independent variable on the dependent variables in terms of its elasticity is very useful for evaluating the effect of each variable separately, but also for comparing the effect of different variables of the same model. Although the measure of elasticity is often used for continuous rather than discrete variables, it was applied in this study as a proof of concept to demonstrate the influence of each independent variable on the number of fatalities, serious injuries and light injuries.

The following section presents the formulation of the developed models of fatalities, serious injuries and light injuries as well as the results of the elasticity analysis.

3. Results

3.1. Modeling the number of fatalities

The log-normal model specifications of the number of fatalities for the combined model are presented in Table 4. This table also shows the elasticities e_i for all discrete variables. All selected model variables are statistically significant at a 1% confidence level.

Table 4 to be inserted here

The developed model predicts that the number of fatalities depends on the area type, the lighting conditions, the collision type, the vehicle type, the driver characteristics, as well as weather-related conditions. With respect to lighting conditions, the model shows that during daytime the number of fatalities increases. This is most likely due to the increased traffic volumes that occur during daytime conditions. The model also shows that roadways with median configuration have increased number of fatalities, probably due to the increased severity and high probability of secondary accidents. As expected, rain was also found to increase the number of fatalities. In addition, the model suggests that runoff collisions and collisions with parked vehicles result in high number of fatalities, compared to the remaining collision types. Concerning the vehicle type, motorcycles over 50cc were found to be associated with high number of fatal accidents. Regarding gender, it was found that men are more frequently involved in fatal accidents than women, which is consistent with research findings from Greece (Yannis et al., 2007) and from the US (Beck et al., 2007). Lastly, although statistically significant, age was found to have a marginal effect on the number of fatalities, as the parameter value is very small.

The adjusted R-square value of the log-normal regression model is 0.437 which is considered to describe adequately the observed variability due to the large number of observations in the available dataset.

As it can be seen from Table 4, the analysis of elasticities revealed that from all variables related to lighting conditions, darkness is the most influential variable (elasticity value for no light is $e_i = 0.23$). It is also possible to compare the elasticity terms of lighting conditions, to provide a measure of the relative influence of the independent variables on the frequency of fatalities. In this case, a base elasticity value was considered, which corresponds to the variable with the smallest elasticity value (i.e, the day variable elasticity), and the remaining elasticities of lighting conditions variables were compared to that value. The results of this analysis are presented in Table 5.

Table 5 to be inserted here

As it is shown in Table 5, the relative elasticity of darkness versus the day (least influential variable) e_i* is 32.92. This suggests that the variable darkness is approximately 33 times more important than the daytime variable. Similarly, the dim lighting conditions and the sufficient lighting conditions are 1.57 and 1.10 times more important than the daytime variable.

3.2. Modeling the number of serious injuries

The second model developed as part of this research predicts the number of serious injuries as a function of road lighting conditions, pavement conditions, and vehicle-driver related attributes. This model does not differentiate between residential and non-residential area types as this variable was not found to be statistically significant. The log-normal model specifications for the number of serious injuries are presented in Table 6. All model variables are statistically significant at a 1% confidence level. This table also shows the elasticities e_i for all discrete variables.

Table 6 to be inserted here

The model suggests that most serious accidents occur during daytime conditions as well as during sufficient nighttime lighting conditions. In darkness, less serious accidents occur, possibly due to the decreased traffic volumes and therefore exposure of the vehicles. Raining conditions are also found to increase the number of serious injuries, compared to other weather conditions. Wet pavement conditions (e.g., icy road) were found to affect more the number of serious injuries compared to dry pavement conditions. The regression model also shows that runoff, head-on and rear-end collisions result in the highest number of serious injuries, whereas, collisions with parked vehicles/ objects have the least effect on this number. It is also found that heavy vehicles and bicycles yield increased number of serious injuries compared to the remaining vehicle types. This might be due to the increased severity of accidents that involve heavy vehicles, as well as the increased exposure of bicycle-related injuries. Lastly, the model shows that male drivers are more prone to serious injuries compared to female drivers, and that the number of accident increase with age, which is consistent with previous literature (Yannis et al., 2007; Beck et al., 2007).

The adjusted R-square value of the log-normal regression model is 0.430 which explains to a certain degree the observed variability due to the large number of observations in the dataset.

As it can be seen from Table 6, the analysis of elasticities revealed that, from all variables related to lighting conditions, darkness is the most influential variable (elasticity value for no light is e_i = 0.07). It is also possible to compare the elasticity terms of lighting conditions, to provide a measure of the relative influence of the independent variables on the frequency of fatalities. In this case, a base elasticity value was considered, which corresponds to the variable with the smallest elasticity value (i.e, the sufficient light variable elasticity), and the elasticities of the remaining lighting condition variables were compared to that value. The results of this analysis are presented in Table 7.

Table 7 to be inserted here

As it is shown in Table 7, the relative elasticity of darkness versus sufficient lighting (least influential variable) e_i* is 3.73. This suggests that the variable darkness is approximately 3.7 times more important than the sufficient lighting variable. Similarly, the dim lighting conditions and the daytime are 2.77 and 1.24 times more important than the sufficient light variable.

3.3. Modeling the number of light injuries

The final model developed predicts the number of light injuries as a function of road lighting conditions, area type, pavement conditions, and vehicle-driver related attributes. The log-normal model specifications for the number of serious injuries are presented in Table 8. All model variables are statistically significant at a 1% confidence level. This table also shows the elasticities e_i for all discrete variables.

Table 8 to be inserted here

This regression model shows that more light injuries occur inside built-up areas than outside built-up areas, which can be explained by the increased number of vehicles, bicycles and pedestrians in urban areas. In addition, the number of light injuries is increased during daytime conditions, whereas it is less in complete darkness, possibly due to the reduced traffic volumes during nighttime. With respect to weather, the model shows an increase in the number of light injuries during rain, compared to other weather conditions. In addition, most of light injuries are associated with pedestrian accidents and runoff collisions, whereas the side-impact collisions result in reduced number of light injuries. It is also found that commuter trips increase the occurrence of light injuries compared to other reasons for trips. This model suggests as well that male drivers have higher probability in being involved in light injuries than female drivers. Lastly, the number of light injuries decreases with increasing drivers' age.

The adjusted R-square value of the log-normal regression model is 0.324 which explains to a certain degree the observed variability due to the large number of observations in the dataset.

As it can be seen from Table 8, the analysis of elasticities revealed that, from all variables related to lighting conditions, daytime is the most influential variable (elasticity value for daytime is $e_i = 0.12$), whereas darkness is the least influential variable. It is also possible to compare the elasticity terms of lighting conditions, to provide a measure of the relative influence of the independent variables on the frequency of fatalities. In this case, a base elasticity value was considered, which corresponds to the variable with the smallest elasticity value (i.e, the no light variable elasticity), and the elasticities of the remaining lighting condition variables were compared to that value. The results of this analysis are presented in Table 9.

Table 9 to be inserted here

As it is shown in Table 9, the relative elasticity of daytime versus darkness (least influential variable) e_i* is 11.21. This suggests that the variable daytime is approximately 11.21 times more important than darkness. Similarly, the dim lighting conditions and the sufficient lighting conditions are 1.51 and 7.11 times more important than the no light variable.

4. Discussion

The objective of this study was to evaluate the effect of lighting conditions on the severity and frequency of accidents for the first time in Greece. The identification of the characteristics of lighting effect on road safety could be proved beneficial for road safety policy decision makers in order to design and implement the appropriate road safety measures (infrastructure improvement, safety campaigns, etc.). Three log-normal regression models were developed, that provide the number of fatalities, serious injuries and light injuries as a function of lighting conditions and additional parameters such as the area type, weather conditions, road surface conditions, type of collision and driver-specific characteristics. An elasticity analysis was also performed to evaluate the effect of each variable separately, but also for comparing the effect of different variables of the same model. A large dataset containing a total of 358,485 accidents in Greece from 1996 to 2008 were considered to develop the log-normal regression models.

The total number of fatalities on Greek roadways is affected by the area type, the lighting conditions, the weather conditions, the median configuration, the collision type, the vehicle type and the age and gender of the drivers. Serious injuries were found to be a function of the lighting conditions, raining and pavement conditions, collision type, vehicle type, as well as the age and gender of the drivers. The frequency of light injuries depends on the area type, the lighting conditions, the weather conditions, the collision type, the trip purpose, and the age and gender of the involved drivers. The models developed suggested that the higher the accident severity, the more important appeared to be the impact of lighting conditions.

The actual effect of road lighting conditions and accident frequency and severity was evaluated with the use of the parameter elasticities and relative elasticities. The elasticities analysis showed that the absence of street lighting during nighttime has the highest impact on the number of fatalities and serious injuries, compared to the remaining lighting variables. However, darkness was found to have the least effect on the number of light injuries, compared to other lighting conditions. This finding indicates that nighttime lighting has great potential in improving traffic safety and most importantly reducing the severity of roadway accidents.

For further research, it is suggested to explore the accident risk that is associated with lighting conditions on Greek roadways, considering additional variables related to vehicle exposure such as traffic volumes and vehicle-km driven, not available within this study. It is further suggested to conduct additional analysis on the available datasets and develop multilevel models that capture cross-level interactions that will improve the statistical fit of the current models. Additional data from other countries could be used to provide more generic models that describe the relationship between road lighting conditions and the severity and frequency of road accidents. The effect of lighting conditions can be further evaluated with the use of a driver simulator or within naturalistic driving experiments, to better understand driver behavior and vehicle interactions under varying lighting scenarios.

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