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The impact of weather conditions and driver characteristics on road safety on rural roads

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Abstract

Weather consists a significant risk factor for safe driving behavior. The purpose of this study is to investigate the impact of weather conditions and time pressure on road safety on rural roads. To fulfill this objective, a driving simulator experiment was conducted and a questionnaire was filled in a sample of 42 young drivers. Statistical analyses were carried out using linear and binomial logistic regression models, which examined whether driving characteristics such as speed, distance from the right side of the road, reaction time or headway affect and can, therefore, predict road safety. The results demonstrated that snow and time pressure led to a significant increase in the probability of a crash. Real-time traffic and weather data could allow for identification of the impact of weather conditions and driver characteristics on road safety.

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Keywords: Driving performance; weather conditions; snow; time presure; aggressive driving; driving simulator.

1. Introduction

Weather is an environmental risk factor which partly determines the road conditions and the safe driving behavior. Adverse weather conditions encompass rain, fog, mist, snow, hail, sleet, strong wind or high temperatures which significantly affect collision, casualty rates, road safety and efficiency in the road transportation system (Wu et al., 2018). In Europe, 1% of total road crash fatalities are due to fog, mist or smoke, 11% by rain, 0.9% by snow and 0.4% by strong wind (European Commission, 2020). It should be noted that rain positively interacts with crash counts. In particular, extreme weather conditions and especially rainfall can lead to an increase in road crashes and serious injuries by 75% and 45%, respectively. Furthermore, dense fog and inclement weather can reduce visibility and, thus

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cause more or severe crashes (Abdel-Aty et al., 2011) while snow immediately after clear weather significantly increases certain types of crashes (El-Basyouny et al., 2014).

In addition, Zhang et al. (2005) indicated that crash risk was highest under snow conditions with an overall relative risk ratio 53.12%, which was higher compared to non-precipitation conditions. Another interesting study was conducted aiming to model the speed behavior in rural highways under adverse road-weather conditions (Yasanthi et al., 2021). The findings revealed that the simultaneous occurrence of pavement conditions and precipitation significantly affect driving speed and potentially expose drivers to increased safety risks. Similarly, as weather-related determinants, rainfall and wind speed had a remarkable effect on road safety and they were found to be statistically significant to crash frequency and severity estimations, respectively (Jung et al., 2011).

Gao et al. (2020) examined the impact of reduced visibility under hazy weather conditions on collision risk and car-following behavior in order to enhance the understanding of the relationship among driving performance, weather conditions and road safety. Results revealed that hazy weather conditions had a significant effect on traffic safety in terms of impaired car-following performance and increased collision risk. It was also demonstrated that the average reaction time as well as the variations in speeds under hazy weather conditions were higher, while time headway and distance under hazy weather conditions found to be lower compared to clear weather conditions. Zolali et al. (2021) investigated the effect of drivers' characteristics, time and weather conditions on driving speed in simulated conditions. The models applied showed that foggy weather strongly affects the speed selection behavior and drivers are able to reduce their speed approximately by 40%.

With regards to time pressure, findings from literature review showed that driving under time pressure is strongly associated with aggressive driving and consequently with an increased incidence of crashes (Beck et al., 2013). It was also observed that aggressive driving was positively related to both crashes and moving violations, while a positive relationship among driving anger, time pressure and aggressive driving was identified (Dahlen et al., 2012). A strong correlation between driver's mental state and road crashes was also highlighted (Hotta & Tanida, 2005).

It is worth mentioning that driving simulators allow for the examination of a range of driving performance measures in a controlled and relatively realistic driving environment (Pavlou et al., 2017). They also provide a safe environment for investigating various parameters (e.g. weather conditions, road type, lighting conditions), under different scenarios, in which drivers can negotiate very demanding situations on the road network (Papantoniou et al., 2015).

Based on the above, the aim of the current research is to quantify the impact of weather conditions (i.e. sun, rain, fog, snow) and time pressure on road safety in rural roads, through a driving simulator experiment. The most important key driving performance indicators, such as driving speed, headway distance, lateral position, steering angle variability, reaction time to the unexpected event and crash probability were examined order to identify whether adverse weather conditions and aggressive characteristics affect and can therefore predict road safety.

The paper is structured as follows. Initially, the effect of weather conditions and driver characteristics on road safety is discussed. In the next chapter, an overview of the data collected for the analysis is provided. Subsequently, the methodological approach as well as the theoretical background is presented. Then, the significant findings are drawn and the results of the statistical analysis performed are summarized. Lastly, conclusions are highlighted and the limitations along with some proposals for further research are clearly stated.

2. Data collection

2.1. Driving simulator experiment

For the purpose of this research, 42 young drivers (25 males and 17 females) aged 20-30 participated in a driving simulator experiment. The simulator experiment took place at the Laboratory of Traffic Engineering of the Department of Transportation Planning and Engineering of the School of Civil Engineering of the National Technical University of Athens (NTUA), where the driving simulator is located and certified by Foerst Driving Simulator FPF.

All participants went through the same experimental procedure. The driving simulator experiment started with a practice drive (15 minutes), until they fully familiarized with the simulation environment. Afterwards, the participants were invited to drive on a rural road under different weather conditions (i.e. sun, rain, fog and snow) and four driving scenarios were developed. The rural route was 1.5 km long, with a speed limit of 60 km/h, which contained a roundabout and three traffic controlled junctions. The traffic volume conditions in each session were low and the The sequence of routes (rain, fog, etc.) was random. Lastly, each scenario started without time pressure and, then, the route was carried out under time pressure (i.e. aggressive driving on command by the instructor).

The driving performance measures that were extracted by the driving simulator and were analyzed are shown in Table 1:

Table 1. Description of the driving performance measures used in the analysis

Independent Variables	Description
Mean speed	Mean speed of the driver's vehicle along the route, excluding the small sections in which incidents occurred, and excluding junction areas
Headway	Time distance between the front of the simulator vehicle and the front of the vehicle ahead
Reaction time at unexpected incidents	Time between the first appearance of the incident on the road and the moment the driver starts to brake in milliseconds
Lateral position	Vehicle's distance from the central road axis in metres
Lateral position variability	The standard deviation of lateral position
Wheel steering angle	The mean wheel steering angle in degrees
Steering angle variability	The standard deviation of steering angle

2.2. Questionnaire

Before the experimental processing, each participant was requested to fill in a questionnaire which was divided into four distinct sections: a) overall driving experience, b) event history, c) self–assessment, and d) attitude and behavior toward road safety. Participants have also provided valuable information with regards to demographic characteristics, such as age, gender, educational level, etc.

Figure 1 illustrates an overview of the impact of weather conditions (i.e. nice, fog, rain, snow) and time pressure (rush, not rush) on average speed per gender.

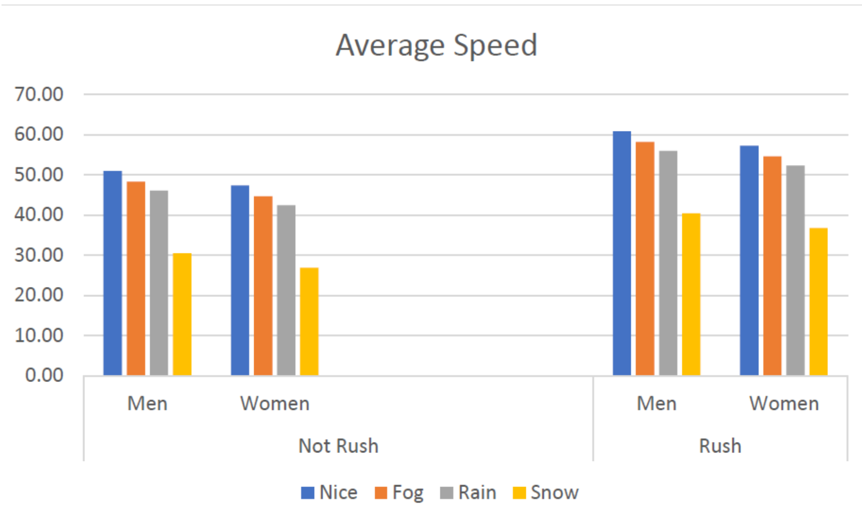

Fig. 1. Impact of weather conditions and time pressure on average speed per gender

3. Methodology

In the next step, the collected data (i.e. both from the simulator and the questionnaire) were analyzed and six regression models were implemented. In particular, statistical analyses were carried out using multiple linear and binomial logistic regression accounting models. This type of analysis was developed to examine whether driving characteristics such as the mean driving speed, the mean distance from the right side of the road, the variation of the mean steering angle, the mean reaction time to an unexpected event, the mean headway distance and the crash probability due to a dangerous event affect and can therefore predict road safety under adverse weather conditions.

3.1. Linear regression models

Linear regression is one of the most well-known statistical technique that uses several explanatory (independent) variables to predict the outcome of a response (dependent) variable. Linear regression can only be used when one has two continuous variables, i.e. an independent variable and a dependent variable. The basic equation of the multiple linear regression model is the following:

$$y_i = b_0 + b_1 * x_{1_i} + b_2 * x_{2_i} + \cdots + b_v * x_{v_i} + \varepsilon_i \qquad (1)$$

where: y_i is the dependent variable, b_0, b_1, b_2 is the slope coefficients for each explanatory variable, x_{i1}, x_{i2}, … , x_{iv} is the explanatory variables and ε_i is the the model's error term (also known as the residuals).

3.2. Binomial logistic regression models

Binomial logistic regression predicts the probability that an observation falls into one of two categories of a dichotomous dependent variable based on one or more independent variables that can be either continuous or discrete (i.e. the probability of a crash). The basic equation of the binomial logistic regression model is the following:

$$\frac{Pi}{1-Pi} = e^{a_0} * e^{a_1 x_1} * e^{a_2 x_2} * \ldots * e^{a_v x_v} \qquad (2)$$

where: P_i is the probability that Y occurs, x_1, x_2, … , x_n is the explanatory variables, α_1, α_2, ... , α_n is the slope coefficients for each explanatory variable and α_0 is the constant term that does not contain any variables in the model.

Within the current research, the aim of this analysis was to determine which observed independent variables were highly correlated with the dependent variable and which of them were inconsistent with each other. To that end, it was examined for all models separately whether the numerical results quantifying relationships among the examined variables, did satisfy the models' quality. It is worth noting that the values and signs of the multiple linear and binomial logistic regression coefficients bi must be reasonably explainable. Also, the constant coefficient of the equation, which considers all the parameters that have not been taken into consideration, should be the lowest possible. Lastly, the elasticity (ei) which shows how responsive one variable is to a change in another as well as the relevant influence elasticity (ei*) used for quantifying the influence of each individual variable are calculated, which allows for the comparison among the influence of different variables in a single model.

4. Results

The developing models along with their coefficients provided a clear understanding of the impact of weather conditions on driver behavior. To begin with, the linear regression model applied for average speed revealed that rain, fog and snow were negatively correlated to average speed. This means that in rainy, foggy and snowy conditions, drivers reduce their average driving speed in order to spot the potential hazards of the road. On the other hand, time pressure (rush) was positively correlated to average speed which implies that drivers increased their driving speed during the third part of their route. The negative value of the gender coefficient implies that as the value of the variable increases (males coded as 1, females as 2), the average speed gets lower. Regarding the parameter derived from the questionnaire: "whether participants have been involved in a crash with damages (CrashesWithDamage)", it was observed that the higher the average speed and the exceedance of speed limits was, the more likely was the chance to be involved in crash with damages. It should be noted that the snow and time pressure variables seemed to have 17.6 and 8.5 times, respectively, greater impact than the corresponding variable of DrivingRuralWeekly, which had the least significant influence.

With respect to the linear regression model applied for average headway, results indicated that time pressure was positively correlated to average headway. Moreover, snow was also positively correlated to average headway, as drivers managed to keep a safer distance between their own car and the vehicle in front, probably due to the wet or slippery road. Following the previous patterns with regards to the gender, it was observed that women drove more safely compared to men, as the former managed to keep a safer gap and a greater distance from the vehicle in front. At the same time, participants who answered that they were driving above the speed limit (DriveUpTheLimits), as well as those drivers who have been involved in other crashes (OtherCrashes), appeared to have a decreased average headway (i.e. distance from the vehicle in front). Similarly, users with more driving experience (DrivingExperience) were prone to keep a safer distance from the vehicle in front. It is worth mentioning that time pressure had the greatest impact (4.3 times) on average headway compared to the corresponding variable DrivingExperience, which appeared to have the least significant influence. The snow variable had the second greatest impact on average headway (3.1 times) than the DrivingExperience variable.

Moving on to the linear regression model applied for lateral position, it was revealed that snow and time pressure had the greatest impact on the lateral position model. The former causes more conservative driving near the right border of the road, while the latter causes driving closer to the opposite direction of vehicle's movement. Interestingly, rain and fog had a slight impact on lateral position, while in the self-declared variable (DriveDangerously) in which participants declared that they drive angrily, drivers tended to drive more in the center of the lane. It should be highlighted that the snow variable had the greatest impact on later position, with 2.6 times higher impact compared to the corresponding variable of fog, which had the least significant influence.

In terms of average reaction time at an unexpected event, results indicated that snow significantly increased the reaction time (by over 0.4 sec) due to the fact that in snowy conditions, participants tended to drive more carefully in order to avoid the crash probability. Equally important seems to be the answer to the questionnaire on how often someone drives under time pressure (DriveUnderPressure). It was demonstrated that the more frequently the user was driving under time pressure, the higher the average reaction time was, probably due to the increased attention. On the other hand, it was observed that female drivers had a higher average reaction time compared to males, while users involved in more crashes (TotalCrashes) also appeared to have increased reaction time, which is in line with the international literature. Participants who answered that they reduce their average speed when driving on snowy conditions (ReduceSpeedWithSnow), an increased reaction time was identified. Lastly, average speed did not seem to affect the average reaction time. Furthermore, the snow and DriveUnderPressure variables had the greatest impact (2.36 and 2.35 times, respectively) on reaction time compared to the corresponding variable of gender, which had the least significant influence. The multiple linear regression results are summarized in Table 2.

Table 2. Summary table of the five mathematical linear regression models developed

Independent Variables	**Average Speed**			**Average Headway**			**Average Reaction Time**			**Lateral Position**			**Std Average Wheel**		
	b_i	e	e*	b_i	e	e*	b_i	e	e*	b_i	e	e*	b_i	e	e*
TimePressure	9.902	0.19	8.5	384.245	0.63	6.9				-0.073	-0.13	-1.4	26.067	0.76	4.0
Fog	-2.703	-0.05	-2.3							0.051	0.09	1.0			
Rain	-4.901	-0.10	-4.2							0.071	0.13	1.4			
Snow	-20.463	-0.40	-17.6	277.559	0.46	5.0	-123.723	-0.07	-2.4	0.132	0.23	2.6	17.090	0.50	2.6
AgeGroup													-6.516	-0.19	-1.0
AverageSpeed							5.049	0.00	-	0.004	0.01	-			
Gender	-3.624	-0.07	-3.1	100.100	0.16	1.8	52.453	0.03	1.0						
DrivingExperience				-55.628	-0.09	-1.0									
DrivingRuralWeekly	-0.008	0.00	-												
CrashesWithDamage	1.162	0.02	1.0												
DriveUpTheLimits				-96.607	-0.16	-1.7									
OtherCrashes				-88.791	-0.15	-1.6									
TimesDrivingWithSnowYear				67.383	0.11	1.2									
DriveUnderPressure							-123.368	-0.07	-2.4						
TotalCrashes							68.615	0.04	1.3				8.693	0.25	1.3
ReduceSpeedWithSnow							55.767	0.03	1.1						
DriveDangerously										0.081	0.14	1.6			

Taking into account the findings delivered from the linear regression model applied for standard deviation average wheel, it was demonstrated that snow had the greatest influence in the model as it increases the steering angle variation significantly - it leads to nervous/unstable driving probably due to the slippery road surface. In addition, the higher the time pressure was, the greater the steering angle variation identified. This result seems reasonable, since the time pressure is strongly associated with aggressive driving, uncontrolled skidding off the road and less vehicle's motion stability. On the contrary, older drivers (AgeGroup) tended to have less variation of the steering wheel rotation, and this is probably due to the fact that they have more driving experience, so it is easier for them to operate the vehicle and perform a maneuver, when necessary. Finally, drivers who self-declared that they have been involved in a crash (TotalCrashes), tended to have an increased steering angle variation. In fact, these drivers may not have the ability to fully control their vehicle. It is important to mention that the time pressure variable had the greatest impact on standard deviation average wheel, with 4 times higher impact than the corresponding variable of age group, which had the least significant influence. This result confirms the difficulty of keeping the steering wheel steady under time pressure conditions, as drivers find it more difficult to control their vehicle. The snow variable had the second greatest impact on standard deviation average wheel (2.6 times) compared to the age group variable.

With regards to the binomial logistic regression model applied, it was revealed that time pressure significantly decreased the likelihood of a collision at an unexpected incident. The most likely explanation is that drivers have improved their concentration under time pressure, resulting in much more attention on the driving task. In addition, rain and snow increased the likelihood of a collision at an unexpected incident in a great extent. This was probably due to low visibility, slippery or wet road surface, braking difficulties etc. As far as gender is concerned, women seemed to be involved in fewer crashes compared to men, which is in line with the international literature and the fact that females are driving more carefully than males. Moreover, drivers who self-declared that they avoid driving in rainy conditions (AvoidDrivingWithRain) were more likely to cause a crash, while those who answered that they usually reduce their average driving speed during rain (ReduceSpeedWithRain) were involved in less crashes, probably due to their driving experience in adverse weather conditions. Finally, drivers who said that they often drive under time pressure (DriveUnderPressure) were less likely to be involved in a crash. It should be noted that the snow and rain variables had 11 and 4.3 times, respectively, greater impact than the corresponding variable of AvoidDrivingWithRain, which had the least significant influence. This finding can be explained by the danger of snow and rain due to low visibility and road slipperiness. Table 3 indicatively shows the binomial logistic regression model developed for the crash probability at a dangerous event.

Table 3. Summary table of the binomial logistic regression model developed

Independent Variables	**Crash probability at a dangerous event**			
	B	Wald	e	e*
TimePressure	-1.922	37.577	-0.42	-4.1
Rain	1.511	21.180	0.45	4.3
Snow	4.079	67.977	1.23	11.8
AvoidDrivingWithRain	0.334	3.429	0.10	1.0
ReduceSpeedWithRain	-0.223	4.219	-0.05	-0.5
DriveDangerously	-0.725	4.871	-0.16	-1.6
Gender	0.607	4.248	0.20	1.9

5. Discussion

The main findings revealed that rain led to a significant increase in the probability of a crash, while time pressure was a fact of concern for the drivers. In addition, snow had the greatest impact on the crash probability at a dangerous event, as well as fog had a considerable effect on mathematical models as well.

In the absence of an unexpected event, crash probability was increased by rush/time pressure due to loss of vehicle control. As it was clearly mentioned, snow led to a remarkable rise in the likelihood of a collision at an unexpected incident. This was probably due to the unfamiliarity of Greek drivers with snowy weather conditions and, therefore, slippery and wet road surface and low visibility (Kamga & Yazıcı, 2014). Similarly, rain had also a great impact on the crash probability. This conclusion is in line with international literature and it can be interpreted by the fact that due to the slippery road, drivers may lose the control of their vehicle in case of a dangerous event, resulting in a collision with the obstacle (Priyanka et al., 2021). Lastly, drivers who self-declared that they usually drive above the speed limit found to be less involved in crashes.

It was also found that snow resulted in a decreased reaction time, while participants who were driving under time pressure had an increased reaction time, probably due to the much more attention paid in the driving task. What's more, the average speed of the vehicle significantly decreased under snowy conditions (17km/h less) and considerably increased under time pressure conditions (average 8.5km/h more). This finding is consistent with what other studies have found (Weng et al., 2013). The same applied for rainy conditions, as it was identified that the average speed was significantly reduced (average 5 km/h) due to the slippery road surface and reduced adhesion.

As far as snow is concerned, a remarkable effect on the steering angle variability (i.e. very increased variability of steering) was observed. The aforementioned result is in agreement with literature findings which have proven that the wet road surface force drivers to perform harsh movements with the steering wheel, in an attempt to control their vehicle (Toffin et al., 2007). Snow had the greatest impact on the lateral position model as it caused more conservative driving near the right border of the road, while time pressure caused driving closer to the opposite direction of vehicle's movement.

Interestingly, it was indicated that male drivers exhibit more aggressive behavior, drive at higher speeds and maintain shorter headway distance from the vehicle in front than the more conservative female drivers in all weather conditions. This finding is in agreement with the international literature which have proven that the majority of women drive more carefully and ecologically than men (Braly et al., 2018).

6. Conclusions

The present research endeavored to identify the impact of weather conditions and time pressure on road safety on rural roads. To fulfill this goal, a driving simulator experiment was conducted and a questionnaire was filled in a sample of 42 young drivers. Statistical analyses were carried out using linear and binomial logistic regression models, which examined whether driving characteristics such as speed, distance from the right side of the road, reaction time or headway affect and can, therefore, predict road safety.

The results demonstrated that rain led to a significant increase in the probability of a road crash, while time pressure was a fact of concern for the drivers. In addition, snow had the greatest impact on the crash probability at a dangerous event, as well as fog had a considerable effect on mathematical models as well. In the absence of an unexpected event, crash probability was increased by rush/time pressure due to loss of vehicle control. Interestingly, it was revealed that male drivers exhibit more aggressive behavior, drive at higher speeds and maintain shorter headway distance from the vehicle in front than the more conservative female drivers in all weather conditions. Lastly, drivers who self-declared that they usually drive above the speed limit found to be less involved in crashes.

However, there are some limitations and restrictions that should be mentioned. More specifically, the influence of psychological status of participants, such as driver distraction, anger, sleepiness or fatigue were not examined in the present study, as only the driver data from the simulator experiment were used. Taking into consideration that drivers react differently under different circumstances with respect to weather and traffic conditions (i.e. high, medium or low traffic volumes), it would be of great interest to investigate driving performance using weather, traffic and driver data.

In general, it should be highlighted that naturalistic driving parameters are more significant in comparison with driver characteristics from the questionnaire, pinpointing the superiority of naturalistic driving data over self-declared data. In the future, real-time traffic data could allow for identification of the impact of weather conditions and driver characteristics on road safety. Future research efforts could consider additional drivers' age groups and extend the experiment to real driving conditions (at least regarding rain, which is relatively common weather phenomenon in Greece and Europe). The investigation of other significant factors could be also included in the future. For instance, the presence of a passenger, the drug abuse, the alcohol consumption or the seat belt use constitute some of the high risk factors that cause road crashes. As per future research directions, the examination of additional methods of analysis could be applied. In particular, factor analysis as well as microscopic data analysis of the database collected could be implemented through econometric techniques such as time-series analysis.

Finally, it is worth mentioning that the application of Intelligent Transportation Systems (ITS) in vehicles seems to be necessary, especially in difficult driving conditions (i.e. under heavy rain, fog or snow) in order to protect the driver from a very probable driving error. Findings of this study can contribute to a great extent to the effective traffic control and management to enhance road safety under hazy weather conditions. All in all, it is expected that this research can provide considerable gains to the society, since the stakeholders including policy makers and industry could rely on the results and recommendations regarding risk factors that appear to be critical for safe driving under adverse weather conditions and time pressure.

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