Drivers' Behavior Analysis under Reduced Visibility Conditions Using a Driving Simulator

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***Abstract*—This study analyzes drivers' behavior under foggy conditions to determine the factors affecting speed reduction using a full-scale high-fidelity driving simulator. A 154-square-mile road network southwest of the Baltimore metro area is used for analysis with 102 participants. Off-peak traffic conditions were simulated to observe solely the effects of FOG on drivers' behavior. The participants' speeds before entering the fog area, in the fog area, and after the fog area are compared using a t-test, and the factors affecting speed variances are studied using a multinomial logistic model. The results illustrate that average speeds differ significantly before and after the onset of fog. However, when it comes to the comparison of average speeds during and after the fog area, the difference in average speed is trivial. Thus, the fog accounted for a reduction in speed before it was encountered, but in its aftermath the change in speeds were insignificant. A Chi-square correlation test shows that drivers' characteristics such as age, gender, household size, and work status turn out to be significantly associated with speed variations. The results from the multinomial logistic model indicate that, among all the variables, gender has a close relationship with speed variation. The analysis reveals that reduction in speed at the onset of fog is more prevalent among women than men.**

***Index Terms*—inclement weather; foggy conditions; visibility; driving simulator; choice model**

I. Introduction

The conditions and variations of weather significantly impact driving. This effect plays a major role in modern research concerning traffic operations. Fog/smoke or heavy rains are a main concern in traffic safety since they greatly reduce visibility for drivers, and fog is among the weather hazards that drivers are most concerned by [1]. Driving in foggy conditions poses multiple risks to automobile operators. Some findings have revealed that in cases of multiple car accidents especially those involving chain reactions, fog almost always plays a part in such incidents [2]. The Federal Highway Administration (FHWA) reported that around 600 fatalities and 16,300 injuries occur each year from fog-related crashes, and many of these injuries are severe. Low visibility by fog can also greatly reduce travel speeds and reduce roadway capacity by up to 12% [3].

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From a visual point of view, fog can be described and investigated as a reduction in contrast in the visual field. Usually one tends to have lower speeds when driving in foggy conditions. However slower speeds are not always accurate when describing driving behaviors in the fog. There are certain cases where there is an increase in speed in low visibility fog [3].

The characteristics and outcomes of crashes resulting from fog or smoke need to be understood in order to propose proper countermeasures. Florida is among the leading states that are taking such an initiative. The state of Florida has embarked on studies geared toward a conclusive evaluation of fog/smoke-related crashes in the state. Researchers have attempted to investigate crash injury severities using data modeling [2], [4]. A study by Abdel-Aty et al. used multinomial ordered logistic models to analyze crash severity and injury severity [2]. The study revealed that, with fog/smoke-related crashes, more vehicles are involved, and the severity of injuries is greater compared to clear-visibility crashes. The occurrence of such crashes is "more prevalent on high-speed roads, undivided roads, roads with no sidewalks, and two-lane rural roads". Based on the findings, the suggested measures to counteract crashes on such road types and locations are: reduced speed limits, introduction of road medians, and the improvement of road lighting to improve driver visibility in dark hours.

The effect of Variable Speed Limits (VSL) and Changeable Message Signs (CMS) on visibility-related crash reduction was studied by *Hassan and Abdel-Aty* [5] using survey questionnaires. Structural Equation Modeling (SEM) was used to analyze the data from 500 respondents. The findings of this study revealed that appropriately designed VSL and CMS can foster the achievement of uniform speeds. Therefore, in the event of sudden hazardous weather such as fog, the chances of accidents are significantly reduced. Such studies are, however, inconclusive given that they were based on surveys and not real-world situations [5].

Very few studies have used driving simulators for visibility reduction-related research. Driving simulators are being increasingly utilized for a variety of education and research purposes. They provide fairly realistic driving conditions by enabling users to drive in a virtual highway system. Driving simulators enable researchers to study driver behavior under conditions in which it would be illegal and/or unethical to place drivers. Yan *et al.* [3] utilized a driving simulator to study the effect of foggy

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conditions on drivers' speed control behavior in three different levels of risk. They found that drivers reduced their speed when visibility reduced; however, they could not respond in time to imminent changes in road geometries, emerging pre-crash events, and the change in speed of the leading vehicle. They also found that professional drivers drove more slowly and were more sensitive to potential risks.

Another study using a driving simulator suggested that inexperienced drivers do not manage driving responsibilities as appropriately as their experienced counterparts [6]. In conditions of clear visibility, experienced drivers drive faster, but in cases of reduced visibility, there is no significant difference between the speeds of the two groups. This study revealed that young drivers had a 25% greater probability of getting into a collision compared to experienced drivers.

Failure to maintain a safe distance behind lead vehicles is very likely the reason for the occurrence of rear-end collisions. *Kang et al.* [7] studied the effects of reduced visibility due to fog on car-following rendition using a driving simulator. The requirement was that drivers maintain a certain headway behind a lead vehicle. In the study, scenarios presented the likeness of five fog densities and three different speeds of lead vehicles. The performance of car-following was evaluated "using distance headway, variance of distance headway, root-mean-square (RMS) velocity error, control gain, phase angle, and squared coherence." Distance headway declined only at maximum fog density conditions studied, and an increase in fog density also resulted in greater RMS velocity error. The findings reveal that in response to speed variations in lead vehicles, drivers are faced with greater challenges than in response to variations in headway. Furthermore, the rate of speed change for lead vehicles is directly proportional to the effects of fog [7]. The objective of this study is to fill in the research gap concerning driver behavior under reduced visibility conditions using a driving simulator.

II. Methodology

Figure 1. Driving simulator at Morgan State University.

This study utilizes a high-fidelity driving simulator at the Safety and Behavioral Analysis (SABA) Center, Morgan State University. The simulator utilizes UC-win/Road by FORUM8 [8] to analyze drivers' behavior in the event of foggy conditions. Fig. 1 shows the driving simulator used for this study. The driving simulator allows for the creation of a driving environment with foggy conditions that resembles a real-life situation. Most simulation-based studies use a small sample, mostly students from their institution, which is a biased sample. The participants usually drive on a pre-defined road. However, this study recruited a large number of participants (102) from different socio-economic backgrounds and different familiarity levels with the study area to drive a fairly realistic and large road network, southwest of Baltimore, Maryland.

The speed analysis of the experiment is based on point speeds of 500 meters, 80 meters, and 20 meters, before the beginning of fog, after the beginning of fog, before the ending of fog, and after the ending of fog. Since comparing only one-point speed may not be a good indicator of speed change, the average speed of the aforementioned area was calculated and compared. T-tests were performed for the average speed of 500 meters before the beginning of fog area, the average speed of the entire fog area (2000 meters), and the average speeds of 500 meters after the fog ended to determine the speed changes due to fog. Fig. 2 presents a schematic view of the study area.

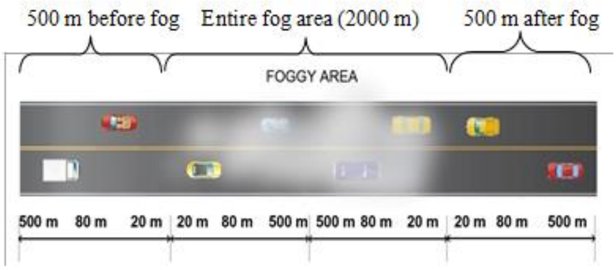

Figure 2. Illustration of roadway for vehicle speed analysis around fog area (not to scale).

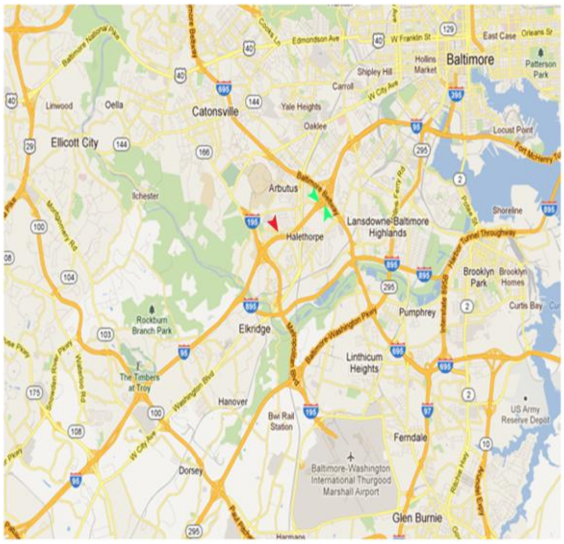

Figure 3. Study network

A bi-variate correlation analysis was performed among variables. Then a multinomial logistic regression model was applied to find the factors affecting speed reduction in the fog area.

The study network is 154 mi^2 from Route 100 in Ellicott City to downtown Baltimore as presented in Fig.

3. Two miles of a 13-mile stretch of I-95 with a posted speed limit of 55 mph are covered with fog.

Participants were solicited for the study through the distribution of fliers in the vicinity of Baltimore and Morgan State University (MSU) campus. The study was able to acquire 102 participants from different socioeconomic backgrounds. The number of males and females were 64% and 36% respectively. The subjects practiced with the simulator in order to get acquainted with its built network and features. Fig. 3 shows the study network, and the fog area is marked with arrows; Fig. 4 presents a schematic scene of the foggy area in the driving simulator environment.

Figure 4. Schematic scene of foggy area in the driving simulator environment

TABLE I. DESCRIPTIVE STATISTICS OF SUBJECTS' CHARACTERISTICS

Characteristics	Options	Percentages
Gender	Female	36%
	Male	64%
Age	<18	3%
	18-25	36%
	26-35	18%
	36-45	20%
	46-55	9%
	>55	14%
Education level	High school or less	31%
	College degree	32%
	Post graduate	37%
Job status (Work)	Unemployed	28%
	Work part-time	30%
	Work full-time	42%
Income level	< $20K	23%
	$20K- $30K	19%
	$30K- $50K	13%
	$50K- $75K	15%
	$75K- $100K	13%
	> $100K	17%
Household size (HHSize)	1	20%
	2	30%
	3	17%
	≥ 4	33%
Car ownership	0	9%
	1	38%
	2	30%
	≥ 3	23%
Annual mileage driven	≤ 8,000	29%
	8,001 - 15,000	35%
	15,001 - 30,000	25%
	≥ 30,000	11%

Table I summarizes participants' characteristics based on gender, age group, education level, job status, income stratum, household size, car ownership, and annual driving mileage.

III. ANALYSIS AND DISCUSSION

The point speed of participants at 500 meters, 80 meters, and 20 meters before the beginning of the fog area, after the beginning of the fog area, and after the end of the fog area was extracted from the simulator output. Fig. 5 presents the average speed of the participants at the aforementioned points. In the figure, 'b' and 'e' stand for the beginning and the end of the fog area. Negative numbers indicate before, and positive numbers show after. For example, -80b means 80 meters before the beginning of the fog area and 500e means 500 meters after the end the fog area. As presented in Fig. 5, the average speed drops when participants enter the fog area and it stays low after leaving the fog area.

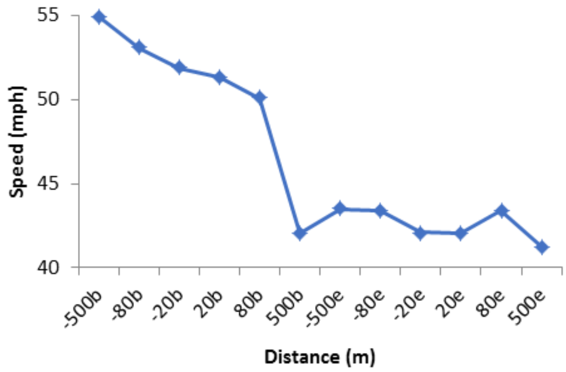

Figure 5. Illustration of speed variations at the different distances

The authors compared the average speeds of 500 meters before the fog starts with the average speeds of the entire 2000 meters of the fog area, and the average speeds of 500 meters after the fog ends with the entire fog area.

TABLE II. F-TEST RESULTS FOR AVERAGE SPEED COMPARISONS BETWEEN BEFORE FOG AND DURING THE FOG

	Average of 500 m before fog (I-95)	Average of entire fog period (I-95)
Mean	53.79 mph	42.11 mph
Variance	141.53 mph^2	70.28 mph^2
F	1.987	
P(F<=f) one-tail	0.002	
F Critical one-tail	1.462	

In the first comparison as shown in Table II, the F-test indicates that the variances are unequal. This necessitates the application of a T-test with unequal variances (Table III). The results of the t-test and F-test show that the average speed of vehicles significantly reduced from 53.79 mph to 42.11 mph due to foggy conditions.

For the second comparison as presented in Table V, a t-test with equal variances was performed since the F-test (Table IV) concludes that the variances are equal. The results show that there wasn't a significant increase in speeds after fog ended. Since 500 meters after the end of the fog might not be enough for the participants to increase their speeds back to what they were before the fog, the authors tested the average speeds of 1000 meters after the fog ended. However, the t-test yielded the same results.

The difference between the average speed of 500 meters before the fog and the entire fog area was calculated for each participant, categorized as shown in Table VI and used as the dependent variable.

TABLE III. T-TEST RESULTS FOR AVERAGE SPEED COMPARISONS BETWEEN BEFORE FOG AND DURING THE FOG

	Average of 500 m before fog (I-95)	Average of entire fog period (I-95)
Mean	53.79 mph	42.11 mph
Variance	141.53 mph^2	70.28 mph^2
t Stat	8.971	
P(T<=t) one-tail	9.86E-16	
t Critical one-tail	1.656	
P(T<=t) two-tail	1.97E-15	
t Critical two-tail	1.977	

TABLE IV. F-TEST RESULTS FOR AVERAGE SPEED COMPARISONS BETWEEN DURING THE FOG AND AFTER THE FOG

	Average of entire fog period (I-95)	Average of 1000 m after fog ended (I-95)
Mean	42.11 mph	43.64 mph
Variance	70.28 mph^2	51.90 mph^2
F	1.354	
P(F<=f) one-tail	0.109	
F Critical one-tail	1.500	

TABLE V. T-TEST RESULTS FOR AVERAGE SPEED COMPARISONS BETWEEN DURING THE FOG AND AFTER THE FOG

	Average of entire fog period (I-95)	Average of 1000 m after fog ended (I-95)
Mean	42.11 mph	43.64 mph
Variance	70.28 mph^2	51.90 mph^2
t Stat	-1.448	
P(T<=t) one-tail	0.075	
t Critical one-tail	1.656	
P(T<=t) two-tail	0.150	
t Critical two-tail	1.977	

TABLE VI. CORRELATION COEFFICIENT OF INDEPENDENT VARIABLES AND DEPENDENT VARIABLE

Average Speed of Fog Area – Average Speed of Before Fog (mph)	Dependent Variable (SpeedVar)
< 0	1
≥ 0 and < 10	2
≥ 10	3

Instead of a binary variable, reduce/not reduce the speed, the research team investigated the reduction/increase amount in 3 levels to investigate the factors affecting the amount of speed reduction as shown in Table VI.

A Chi-square test was conducted to measure the correlation of the categorical variables with the dependent variable. Among drivers' characteristics, age, gender, household size, and work status appeared to be significantly correlated with the speed variation as presented in Table VII.

TABLE VII. CORRELATION COEFFICIENT OF INDEPENDENT VARIABLES AND DEPENDENT VARIABLE

Variable	Value	Significance	Decision
Gender	11.603	0.009	
Age	12.043	0.007	
Household Size (HHSize)	12.892	0.005	
Cars	18.808	<0.0001	
Work	18.1	0.006	
Education	0.014	0.904	Reject
Mileage	0.154	0.192	Reject
Income	0.026	0.855	Reject

The logistic regression model results and goodness of fit are presented in Table VIII. Among all variables, only gender was found to have a close relationship with the speed variation of up to 10 mph due to fog.

TABLE VIII. LOGISTIC REGRESSION MODEL RESULTS

Speed Var	Variable	β	Standard error	Significance	Exp (β)
1	Gender	1.970	3.210	0.539	7.167
	Age	0.719	0.720	0.318	2.053
	Work	-1.248	1.706	0.464	0.287
	HHSize	2.410	1.809	0.183	11.130
	Car	-5.024	3.183	0.114	0.007
2	Gender	-1.135	0.590	0.054	0.322
	Age	0.154	0.199	0.438	1.167
	Work	-0.061	0.342	0.858	0.941
	HHSize	0.334	0.287	0.245	1.396
	Car	-0.194	0.360	0.590	0.007

There are fewer women in category 2 (speed reduction up to 10 mph) than men compared to category 3 (speed reduction more than 10 mph), indicating that women reduce their speed more than men do, with an odds ratio of 0.322.

IV. CONCLUSIONS

In an empirical study, the authors collected speed data in foggy conditions using a full-scale high-fidelity driving simulator to evaluate the factors affecting drivers' behavior in the case of reduced visibility conditions. The study, which involved subjects from various backgrounds and varying experiences with the study area, consisted of 577 experiments conducted by 102 participants. The findings reveal that there is significant reduction of speed due to the appearance of fog, but as far as the comparison of average speeds in fog and average speeds after fog is concerned, the difference in speed is not significant. This means that, at the onset of fog, participants slow down and this reduction in speed is maintained even after passing the foggy area, possibly as a precautionary measure.

The bi-variate correlation analysis shows that age, gender, household size, and work status have a significant correlation with speed variations. However, a multinomial logistic model indicates that gender is the only characteristic that has a close relationship with speed reduction due to foggy conditions. The revelations indicate that the average speeds of women are more affected by fog than those of men with speed reductions up to 10 mph. This implies that, women are possibly more cautious and have a responsible attitude than men while driving in foggy conditions. This observation in agreement with prior studies [9], [10]. As male participants are more inclined to take risks in terms of reduction in speed, in situations where the immediate dangers are not apparent, remedial measures should thus be targeted on influencing male driver behavior in such situations. Effective ways of doing this could be through educational campaigns and social media.

In localities where there are frequent incidences of sudden appearances of fog, VSL and dynamic message signs (DMS) should be employed to caution drivers about foggy conditions. The findings from this study with the additions of VSL and DMS could possibly lead to fewer crashes under reduced visibility conditions.

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