Alcohol-Impaired Driving: Evaluating Its Impact on Urban Safety and Driver Behavior through Driving Simulator

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Abstract

Driving under the influence of alcohol is recognized as a significant hazard on road safety, significantly increasing crash risks and impairing driver responsiveness and judgment. Alcohol-related crashes account for a major portion of traffic-related fatalities and injuries, underscoring the urgent need for effective interventions and preventive measures. This study investigates the effects of alcohol-impaired driving in urban environments, employing a driving simulator to collect data from 35 participants. Each participant completed the same route four times, each under varying levels of Blood Alcohol Concentration (BAC): 0%, 0.03%, 0.06%, and 0.09%. Additional participant characteristics were gathered through a questionnaire. The analysis utilized linear and binary logistic regression models to assess variables such as average headway distance, response times to unexpected events, and the crash probability. The findings revealed that higher BAC levels correlate with an increased likelihood of crash occurrence and reduced headway distances. Furthermore, as BAC levels increased, drivers' reaction times to unexpected events extended.

Keywords: *alcohol consumption, drunk driving, road crashes, driver behavior, driving simulator, urban driving conditions*

1. Introduction

Road traffic crashes remain a major public health issue worldwide, causing approximately 1.19 million deaths each year, according to the latest Global Status Report on Road Safety by the World Health Organization (World Health Organization, 2023). These injuries represent the leading cause of death among children and young adults aged 5 to 29 years. In addition to fatalities, millions more suffer non-fatal injuries that frequently lead to long-term disabilities, psychological trauma, and significant economic costs. The global financial burden of road traffic crashes, including healthcare expenditures and productivity losses, is estimated to account for up to 3% of gross domestic product in many countries, with the greatest impact observed in low- and middle-income regions where the majority of these fatalities occur.

Although many factors contribute to the occurrence of road crashes, such as speeding, distracted driving, fatigue, and inadequate use of protective equipment, driving under the influence of alcohol continues to be one of the most preventable causes of traffic-related deaths and injuries. Alcohol-impaired driving remains a key challenge for road safety policy worldwide, despite ongoing enforcement efforts and public awareness campaigns. Recent global estimates indicate that approximately 6.6% of all road injuries are directly attributable to alcohol consumption, with higher burdens observed in

Europe, among men, young adults, and motorcyclists (Borges et al., 2021). These findings confirm the continuing significance of alcohol use as a major risk factor for traffic-related harm on a global scale.

The mechanisms by which alcohol increases the risk of road traffic crashes are well-documented. Alcohol consumption impairs a range of cognitive, perceptual, and motor functions critical for safe driving, including reaction time, visual attention, decision-making ability, and psychomotor coordination. Even at relatively low Blood Alcohol Concentration (BAC) levels, beginning at 0.03%, significant performance impairments have been observed, leading to slower responses to road hazards and an increased likelihood of errors. A systematic review by Dong et al. (2022) reported that alcohol intake reduces driver alertness and disrupts hazard perception, contributing directly to increased crash risk in both controlled and real-world driving scenarios (Dong et al., 2022).

The negative effects of alcohol on driving performance are well established, with alcohol impairing essential cognitive and motor functions such as reaction time, attention, decision-making, and coordination. Even at BAC levels below the legal limit in many regions, significant declines in driving ability have been observed. In a double-blind, placebo-controlled study, (Garrisson et al., 2022) demonstrated that BAC levels between 0.05% and 0.08% significantly impaired lane control and psychomotor performance, while drivers remained unaware of their diminished abilities, exposing a critical gap between perceived and actual competence (Garrisson et al., 2022). Supporting these findings, (Yadav & Velaga, 2019) reported substantial increases in reaction time up to 94% at a BAC of 0.08%, during pedestrian crossing events in a simulator study, confirming the dose-dependent relationship between alcohol levels and impaired driver responsiveness (Yadav & Velaga, 2019).

In addition to its physiological effects, alcohol consumption also impairs psychological judgment and decision-making, which play critical roles in risky driving behavior. Drivers under the influence often underestimate their impairment and overestimate their control behind the wheel. Behavioral theories such as the Theory of Planned Behavior suggest that attitudes, subjective norms, and perceived behavioral control shape the decision to drive after drinking. Consistent with this framework, Jie-Ling & Yuan-Chang (2021) demonstrated that behavioral intention and perceived control are the most significant predictors of drink-driving behavior, emphasizing the need to address these psychological factors in prevention strategies (Jie-Ling & Yuan-Chang, 2021). Similarly, qualitative findings from (Liu et al., 2021) revealed that many repeat offenders tend to adopt avoidance strategies to escape law enforcement, rather than refraining from impaired driving altogether, further highlighting the limitations of deterrence-based approaches alone (Liu et al., 2021).

While the relationship between alcohol consumption and impaired driving has been widely studied, most research has focused on rural or highway driving conditions. However, urban environments present additional challenges that may exacerbate the risks associated with alcohol impairment. High vehicle density, frequent intersections, pedestrian crossings, cyclists, and complex road layouts demand rapid responses, continuous attention, and precise vehicle control. These factors suggest that alcohol effects on driving behavior might be particularly pronounced in urban settings, where the margin for error is often smaller.

The present study aims to explore this issue by investigating how varying BAC levels influence key aspects of driving performance in an urban environment. Employing a controlled driving simulator, this research examines the effects of alcohol on headway distance, reaction time to unexpected events, and crash probability under realistic city traffic conditions. By providing quantitative evidence on the impact of alcohol consumption on urban driving behavior, the findings seek to inform public health strategies, support evidence-based policymaking, and contribute to the development of targeted educational interventions aimed at reducing alcohol-related traffic risks.

2. Materials and Methods

2.1 Driving Simulator

This study aimed to assess how varying BAC levels influence driver behavior in an urban environment, focusing on reaction time, headway distance, and crash probability. The experimental process was carried out using a high-fidelity FOERST FP driving simulator (**Figure 1**) located at the National Technical University of Athens (NTUA), Department of Transportation Planning and Engineering. The simulator features a motion-enabled seat, three full HD panoramic screens, and realistic vehicle controls, offering an immersive driving experience with a 170-degree field of view.

Figure 1: *Figure caption*

The simulated scenario replicated common urban driving conditions (**Figure 2**), including signalized intersections, pedestrian crossings, parked vehicles, and variable traffic flows. To assess hazard perception and responsiveness under alcohol influence, random unexpected events were introduced into the simulation, such as sudden pedestrian appearances and abrupt braking of lead vehicles.

Figure 2: *Urban Road Scenario - Low traffic flow*

A total of 35 volunteer drivers (21 male, 14 female), aged between 19 and 32 years, participated in the study. All participants held a valid driving license and were screened to exclude individuals with alcohol dependency, neurological conditions, or driving violations. Prior to the simulator sessions, each participant completed a structured questionnaire collecting demographic data, driving experience, alcohol consumption habits, and self-assessed behavior related to alcohol-impaired driving.

The experiment followed a within-subjects design where each participant completed four identical driving sessions under different BAC conditions: 0% (baseline), 0.03%, 0.06%, and 0.09%. BAC levels were verified before each run using a certified breathalyzer device. The sequence of BAC levels was randomized among participants to reduce order effects. Before data collection began, all participants completed a familiarization drive to minimize simulator adaptation bias.

During each driving session, the simulator continuously recorded key performance variables, including mean speed, headway distance, braking behavior, lane deviation, and reaction time to unexpected events. These metrics served as the primary indicators for evaluating the effects of alcohol consumption on driving performance. The main variables recorded and analyzed are summarized in **Table 1**.

Table 1: *Driving Simulator Variables*

Variable	Explanation
Time	Current real-time in milliseconds since start of the drive.
x-pos	x-position of vehicle in m.
y-pos	y-position of vehicle in m.
z-pos	z-position of vehicle in m
Road	Road number of the vehicle in [int].
Richt	Direction of the vehicle on the road in [BOOL] (0/1).
Rdist	Distance of the vehicle from the beginning of the drive-in m.
rspur	Track of the vehicle from the middle of the road in m.
ralpha	Direction of the vehicle compared to the road direction in degrees.
Dist	Driven course in meters since begin of the drive.
Speed	Actual speed in km/h.
Brk	Brake pedal position in percent.
Acc	Gas pedal position in percent.
Clutch	Clutch pedal position in percent.
Gear	Chosen gear (0 = idle, 6 = reverse).
RPM	Motor revolvation in 1/min.
HWay	Headway, distance to the ahead driving vehicle in m.
DLeft	Distance to the left road board in m.
DRicht	Distance to the right road board in m.
Wheel	Steering wheel position in degrees.
Thead	Time to headway, i.e., to collision with the ahead driving vehicle in ms.
TTL	Time to line crossing, time until the road border line is exceeded, in ms.
TTC	Time to collision (all obstacles), in ms.

To avoid learning effects, unexpected event placements were varied between sessions. Additionally, sufficient breaks were provided between runs to prevent simulator sickness and unrelated fatigue effects. All participants gave informed consent prior to their involvement, and the study adhered to ethical research standards.

2.2 Statistical Analysis

To investigate the effect of BAC on driver behavior, both linear and logistic regression models were applied depending on the nature of each dependent variable. Linear regression (**Eq. 1**) was used for continuous outcomes, while logistic regression was employed for modeling the binary outcome of crash involvement.

For continuous dependent variables such as reaction time, headway distance, and mean speed, the following general linear regression model was specified:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \dots + \beta_n X_{ni} + \varepsilon_i, \qquad \textbf{(1)}$$

Where:

- *Y_i represents the outcome variable for participant i*
- *$X_1, X_2, \ldots, X_n$ representing the independent variables.*
- *β_0 represents the intercept.*
- *ε_i is the residual error term.*

To examine the likelihood of crash involvement, the following logistic regression model (**Eq. 2**) was used:

$$Y_i = \ln\frac{P_i}{1-P_i} = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_n X_{ni}, \quad \textbf{(2)}$$

Where:

- *Y_i represents the dependent variable, which is assigned value 1 with probability of success P and value 0 with probability of failure 1-P.*
- *$X_1, X_2, \ldots, X_n$ representing the independent variables.*
- *β_0 represents the intercept.*

P_i denotes the probability that participant i was involved in a crash during the simulation session.

The threshold for statistical significance was set at $p < 0.05$. For linear regressions, model performance was evaluated using the coefficient of determination (R^2). For logistic regression models, robustness of fit was assessed via the prediction accuracy.

3. Results

The statistical analysis investigated the effects of alcohol consumption on key driving performance metrics, reaction time, headway distance, and crash probability, within an urban driving environment. The outcomes were modeled using linear and binomial logistic regression methods. Tables with regression coefficients, standard errors, t-values, p-values, and elasticity indices are provided to assess both the magnitude and statistical significance of each relationship. These models quantify the impact of BAC and other participant-specific behavioral and demographic variables on driving safety outcomes.

3.1 Headway Distance Model

The impact of alcohol consumption and selected driver characteristics on average headway distance was assessed using a linear regression model, as shown in **Equation 3**.

Avg_HWay = 109.201 - 7.102×(Scenario_No) + 10.115×(Gender) - 2.813×(Days_perweek_urban) - 5.951×(Beer_limit) , ***(3)***

Where:

- ***Avg_HWay****: Average distance to the lead vehicle (m).*
- ***Scenario_No****: Scenario representing BAC levels (e.g., 0: 0%, 1: 0.03%, 2: 0.06%, 3: 0.09%).*
- ***Gender****: Gender of the participant (e.g., 1 = male, 2 = female).*
- ***Days_perweek_urban****: Number of days per week the participant drives in urban settings.*
- ***Beer_limit****: Number of beers needed to reach legal alcohol limit (e.g., 1: 1 glass ... 4: 4 glasses).*

The linear regression model for average headway distance (**Table 2**) demonstrates that alcohol consumption significantly affects driver behavior. Specifically, the variable Scenario_No, which corresponds to increasing BAC levels, has a negative and statistically significant effect on the average distance to the preceding vehicle ($\beta = -7.102$, $p < 0.001$), indicating that higher alcohol levels are associated with reduced headway. The variable gender is positively associated with headway distance (β = 10.115, p = 0.005), with male drivers maintaining longer distances on average. The variable Days_perweek_urban also presents a negative effect (β = -2.813, p < 0.001), suggesting that drivers who use their vehicle more frequently in urban areas tend to maintain shorter distances. In addition, participants who reported higher values for Beer_limit, i.e., the perceived number of drinks required to reach the legal limit, also exhibited shorter headways (β = -5.951, p = 0.009), potentially due to underestimation of impairment. The model explains a moderate proportion of the variance in headway behavior (R^2 = 0.29; Adjusted R^2 = 0.26), indicating a moderate level of explanatory power. Also, relevat elasticity analysis highlights Gender as the most influential predictor (e* = -3.60) and then alcohol consumption (e* = 2.52).

Table 2: Model of Average Headway Distance Prediction

Independent Variables	βi	Std. Error	t Value	p-Value	e	e*
(Constant)	109.201	9.729	11.224	0.000 ***		
Discrete variables						
Scenario_No	-7.102	1.504	-4.722	0.000 ***	-0.07	2.52
Gender	10.115	3.540	2.857	0.005 ***	0.10	-3.60
Days_perweek_urban	-2.813	0.747	-3.763	0.000 ***	-0.03	1.00
Beer_limit	-5.951	2.256	2.683	0.009 **	-0.06	2.12
R^2 = 0.29						
Adjusted R^2 = 0.26						

** Significance at the 99% confidence level/*** 99.9%.

3.2 Reaction Time Model

To examine the impact of alcohol consumption and related behavioral factors on driver responsiveness, a linear regression model was developed using average reaction time as the dependent variable, as shown in **Equation 4**. The model includes as predictors the simulated alcohol scenario (Scenario_No), average alcohol consumption (Average_alcohol_quantity), estimated alcohol tolerance (Beer_limit), and typical return-home behavior after drinking (Returning_home_scenario).

Avg_ReactionTime = 1.021 + 0.108×(Scenario_No) + 0.204×(Average_alcohol_quantity) + 0.128×(Beer_limit) -0.14×(Returning_home_scenario), ***(4)***

Where:

- ***Avg_ReactionTime****: Average reaction time to sudden events during the simulation (s).*
- ***Scenario_No****: Scenario representing BAC levels (e.g., 0: 0%, 1: 0.03%, 2: 0.06%, 3: 0.09%).*
- ***Average_alcohol_quantity****: Self-reported average alcohol consumption per occasion (e.g., 1: 1 or fewer drinks, ..., 6: 6 or more).*
- ***Beer_limit****: Number of beers needed to reach legal alcohol limit (e.g., 1: 1 glass ... 4: 4 glasses).*
- ***Returning_home_scenario****: Typical behavior regarding return home after alcohol consumption (e.g., 1: would find another way, 2: would drive very carefully, 3: would drive normally).*

As presented in **Table 3**, the variable Scenario_No has a positive and statistically significant association with average reaction time (β = 0.108, p < 0.001), indicating that increased alcohol levels are associated with delayed responses to road events. Average_alcohol_quantity is also positively correlated (β = 0.204, p < 0.001), suggesting that individuals who typically consume more alcohol per occasion exhibit significantly slower reaction times. The variable Beer_limit is positively associated as well (β = 0.128, p =

0.006), implying that underestimation of impairment may be linked to reduced cognitive performance. In contrast, Returning_home_scenario has a negative coefficient (β = -0.140, p = 0.025), suggesting that individuals who tend to avoid driving after drinking may demonstrate relatively faster reactions under simulation conditions. The model captures a modest portion of the variance (20%) in reaction time (R^2 = 0.20; Adjusted R^2 = 0.17) reflecting the complex nature of cognitive performance under alcohol influence. Also, with elasticity values indicating that Average_alcohol_quantity exerts the strongest marginal influence (e* = 1.89).

Table 3: Model of Average Reaction Time Prediction

Independent Variables	βi	Std. Error	t Value	p-Value	e	e*
(Constant)	1.021	0.173	5.898	0.000 ***		
Discrete variables						
Scenario_No	0.108	0.031	3.429	0.000 ***	0.07	1.00
Average_alcohol_quantity	0.2041	0.053	3.883	0.000 ***	0.13	1.89
Beer_limit	0.1283	0.046	2.819	0.006 **	0.08	1.19
Returning_home_scenario	-0.14	0.062	-2.270	0.025 *	0.09	1.30
R^2 = 0.20						
Adjusted R^2 = 0.17						

* Significance at the 95% confidence level/**99%/*** 99.9%.

3.3 Crash Probability Model

To estimate the likelihood of crash involvement under the influence of alcohol, a binary logistic regression model was developed. The dependent variable is the occurrence of a crash, modeled as a function of alcohol level and prior driving behavior using a logit transformation, as shown in **Equations 5** and **6**:

$$\textit{Crash Probability} = \frac{e^{NumOfCrashesAverage}}{e^{NumOfCrashesAverage}+1}, \quad \textbf{(5)}$$

NumOfCrashesAverage = -2.4192 + 1.7238×(Scenario_No) - 0.0022×(Exceeded_breathalyzer_limit) - 0.1486×(Times_driven_intoxicated_last_year) - 0.5819×(Annual_family_income), ***(6)***

Where:

- ***NumOfCrashesAverage****: Occurrence of a crash (e.g., 0: no crash, 1: = crash).*
- ***Scenario_No****: Scenario representing BAC levels (e.g., 0: 0%, 1: 0.03%, 2: 0.06%, 3: 0.09%)*
- ***Exceeded_breathalyzer_limit****: Number of times the participant exceeded the legal breathalyzer limit in the past year.*
- ***Times_driven_intoxicated_last_year****: Number of times the participant drove after drinking alcohol in the past year.*
- ***Annual_family_income****: Annual household income (e.g., 1: < €10,000, 2: €10,000–25,000, 3: > €25,000).*

As shown in **Table 4**, Scenario_No is the most influential and statistically significant positive predictor of crash probability (β = 1.724, p < 0.001), confirming that higher BAC levels strongly increase the likelihood of simulated crash involvement. In contrast, previous experiences of exceeding the breathalyzer limit (Exceeded_breathalyzer_limit) and intoxicated driving incidents in the past year (Times_driven_intoxicated_last_year) are both negatively associated with crash risk, suggesting that drivers with such histories may adopt more cautious behaviors under observation ($\beta = -0.002$, $p < 0.001$; $\beta = -0.147$, $p = 0.015$, respectively). Additionally, Annual_family_income has a negative coefficient ($\beta = -0.582$, $p = 0.090$), indicating that higher income levels are marginally associated with reduced crash probability. The model achieves a correct classification rate of 78.57%, suggesting strong predictive accuracy in estimating crash likelihood, and elasticity values highlight Scenario_No as the most sensitive driver of crash risk (e = 0.972; e* = -5475.88).

Table 4: Model of Crash Probability Prediction

Independent Variables	βi	Std. Error	z Value	p-Value	e	e*
(Constant)	-2.419	0.789	-3.065	0.002 **		
Discrete variables						
Scenario_No	1.724	0.285	6.049	0.000 ***	0.972	-5475.88
Annual_family_income	-0.582	0.344	-1.694	0.090 ⁻	-0.002	1.00
Continuous variables						
Exceeded_breathalyzer_limit	-0.002	0.0006	-3.399	0.000 ***	-0.232	1304.3
Times_driven_intoxicated_last_year	-0.147	0.061	-2.424	0.015 *	-0.059	333.10
Accuracy = 78.57%						

* Significance at the 95% confidence level/**99%/*** 99.9%/⁻ 90%.

4. *Discussion*

This study explored the relationship between alcohol consumption and driving behavior through simulation-based analysis, using headway distance, reaction time, and crash probability as key outcome variables. The findings corroborate and expand upon existing literature by quantifying how BAC and related behavioral characteristics influence urban driving safety.

The regression model for headway distance confirmed that increasing BAC levels significantly reduce the distance maintained from a lead vehicle. This is consistent with previous work by Ahlström et al. (2023), who demonstrated that alcohol impairs attention and shortens time headways due to reduced cognitive control and risk assessment (Ahlström et al., 2023). Moreover, the present study adds to the understanding that self-reported tolerance levels (i.e., Beer_limit) also contribute to decreased headway, indicating a perceptual bias toward underestimating impairment. The reaction time model revealed a similar trend: higher BAC levels and greater alcohol consumption per occasion were associated with longer reaction times. This aligns with simulator-based evidence by Christoforou et al. (2013), who found that each 10% increase in BAC corresponded to a roughly 2% increase in reaction time, particularly among younger drivers (Christoforou et al., 2013). Interestingly, individuals who usually avoided driving after drinking (Returning_home_scenario) demonstrated relatively shorter reaction times in the simulation, possibly due to enhanced situational awareness or avoidance of high-risk behavior. This reinforces findings from Yadav & Velaga (2020), who noted that personal strategies to avoid intoxicated driving can mitigate acute performance deficits (Yadav & Velaga, 2020).

The crash probability model provided further evidence that alcohol levels directly increase crash risk, with Scenario_No as the most impactful predictor. This echoes the multivariate findings by Shyhalla (2014), who reported that alcohol-involved drivers are significantly more likely to initiate severe crashes, particularly when additional risky behaviors are present (Shyhalla, 2014). Interestingly, this study observed a negative association between past alcohol-related offenses and simulated crash risk, suggesting that prior exposure to negative outcomes may lead to behavioral adaptation or self-regulation during high-risk scenarios, a phenomenon consistent with findings by Yao et al. (2018), who reported that drivers with alcohol use disorder did not necessarily show higher crash rates when adjusted for BAC (Yao et al., 2018). Moreover, income level emerged as a marginally protective factor. This supports broader sociobehavioral studies indicating that higher socioeconomic status is associated with better vehicle safety, more cautious driving, and greater adherence to road safety norms (Stephens et al., 2017).

Collectively, these results suggest that alcohol-related impairment is not limited to physiological degradation, but is intertwined with self-perception, habitual behavior, and socioeconomic context. This complexity highlights the need for multifaceted interventions that combine enforcement with education tailored to behavioral risk profiles.

5. Conclusions

This study provides strong statistical evidence that alcohol consumption, even at low-to-moderate levels, significantly impairs critical aspects of driving behavior in urban conditions. Increased alcohol levels were consistently associated with shorter headway distances, longer reaction times, and higher crash probabilities. Behavioral traits such as self-estimated alcohol tolerance, past drinking and driving behaviors, and driving frequency also played a notable role in moderating or exacerbating these effects.

These findings highlight the importance of targeting both physiological impairment and cognitive biases in driver safety policies. Public awareness campaigns and enforcement efforts should emphasize not only the illegality of driving under the influence but also the subtle ways in which alcohol impairs risk perception and judgment, even in individuals who believe they can "handle" their consumption.

The models developed in this study demonstrated acceptable explanatory power and predictive accuracy, making them valuable tools for informing future simulation-based assessments and education programs. However, further research with larger and more diverse samples is recommended to validate and expand upon these conclusions.

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