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The Effect of Mobile Phone Use, Traffic Environment, and the Interaction on Driving Performance of Adult Drivers: Empirical Findings from 2^2 Factorial Design Simulation

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ABSTRACT

The conventional belief that mobile phone usage adversely affects driving performance, particularly through driver distraction leading to accidents, underscores the importance of understanding its impact within the context of varying traffic environments. This study aims to investigate the individual and interactive effects of mobile phone use and traffic environment on driving performance. Two distinct experiments were conducted in a simulated driving environment, employing a 2^2 factorial design to examine these factors. Mobile phone use was assessed in both hands-free and hand-held modes, while traffic environments comprised rural and urban routes. Driving performance was evaluated using four measures: driver mental workload, error frequency, average speed, and lateral position changes. Our findings reveal that mobile phone use significantly affects all performance measures, while traffic environment predominantly influences average speed and lateral position changes. Specifically, both hands-free and hand-held modes are statistically significant in influencing mental workload. Additionally, the interaction between traffic environment and hand-held phone use notably affects error frequency. These results provide insights into the complex interplay between mobile phone use, traffic conditions, and driving performance.

1. INTRODUCTION

It is clear that using a mobile phone while driving is widely recognized as detrimental to road safety. The distraction it poses significantly increases the risk of accidents due to the cognitive demands of multitasking, regardless of the difficulty of the conversation [1]. Research consistently demonstrates a substantial rise in crash risk associated with mobile phone use while driving, reaching nearly three times the risk compared to non-use [2-5], and even up to 4.5 times higher [6]. Consequently, many countries have enacted laws to regulate mobile phone use while driving. For instance, Norway implemented a ban on handheld phone usage as early as 2000, while Indonesia's Law Number 22 of 2009 imposes fines or imprisonment for drivers caught using phones while driving.

There is no denying the significant rise in mobile phone usage over the past decade. An observational study by Huisingh and colleagues revealed that 31% of 3,265 drivers observed at intersections were engaged in phone conversations, while 16.6% were texting or dialing [7]. Another study found that 6% of 5,379 drivers observed in free-flowing traffic on a straight roadway were holding a mobile phone [8]. Similar behaviors were noted in studies conducted in Australia (5% of 5,813 drivers at intersections) [9], the United Kingdom (3% of 7,168 drivers in random locations) [10], Spain (14% of 6,578 drivers in random locations) [11], and Saudi Arabia (14% of 1,700 drivers at intersections and along highways) [12].

With the significant increase in mobile phone use, especially while driving, and the subsequent safety concerns, it is not surprising that researchers have devoted considerable attention to this issue. In the realm of traffic safety research, mobile phone use while driving has predominantly been studied in highly controlled experiments [13-17]. These experimental studies aim to explore the impact of mobile phone use on driving behavior, such as braking, driving speed, response to traffic signals, lateral position, as well as subjective workload indicators like mental demand, effort, and frustration [18]. Highly controlled experimental designs allow researchers to isolate specific effects of interest, such as the influence of mobile phone use on variations in driving speed and reactions to traffic signals. Given the exponential growth in mobile phone use and the associated safety concerns when used while driving, our study builds upon previous research to investigate the effects of mobile phone use (both hands-free and hand-held modes) on driving performance in an experimental setting.

In addition to examining the effects of mobile phone use on driving performance, we also consider the influence of traffic environment—specifically rural versus urban routes. Previous research [19] has explored mobile phone use across various driving environments, including quiet rural roads, busy ring roads, and urban settings. Matthews et al. [18] compared drivers' subjective workload when using hand-held versus hands-free phones on rural highways, while Brookhuis et al.

[19] investigated the effects of both hands-free and hand-held phones during dialing and conversation in different traffic conditions.

Unlike studies that rely on basic statistical comparisons (e.g., *t*-tests or one-way ANOVA), our research utilizes a 2^2 factorial design. This approach systematically examines all possible combinations of the two factors (traffic environment and mobile phone use) and their interactions. This factorial design allows for a more nuanced analysis of how these factors and their interactions affect driving performance, compared to simpler statistical methods. The interaction hypothesis could be informed by theories of cognitive load and task demand [20]. In complex urban environments, the mental workload imposed by driving might already be high. Adding the distraction of mobile phone use could disproportionately increase cognitive demands, especially if the phone use involves more complex tasks like texting. We assess driving performance using four key measures: subjective mental workload, error frequency, variations in driving speed, and lateral position changes. Additionally, we conduct rigorous statistical assumption checks to ensure the robustness and reliability of our findings.

The choice of factor levels in this study was influenced primarily by practical considerations and the desire to maintain manageable complexity in the experimental design. The decision to use a 2^2 factorial design, which involves two levels for each factor, was made to balance the depth of analysis with the feasibility of execution. By focusing on two levels for each factor, we can systematically explore their individual and interactive effects without overwhelming the model with excessive complexity.

(1) Urban and rural routes were selected as the traffic environment factors due to their representativeness of two distinct and commonly encountered driving conditions. Urban routes are characterized by higher traffic density and more frequent intersections, while rural routes generally offer less complex driving environments. This binary classification allows for a meaningful examination of how varying traffic conditions impact driving performance.

(2) Similarly, the choice of phone versus texting as modes of mobile phone distraction was driven by their prevalence and practical relevance. Phone conversations and texting represent two major forms of mobile phone use while driving, with distinct levels of cognitive and manual engagement. These modes are commonly encountered in real-world driving, making them appropriate for studying their differential effects on driving performance.

The remainder of the paper follows a structured outline. In the upcoming section, we introduce the research design, detailing the participants involved in the study, the setup of the two distinct experiments, the four specific measures employed, and a concise overview of the statistical analysis methods utilized. Moving forward to the third section, we present the results obtained from the study. Within this section, we not only display the findings but also explore correlations among the four measures and conduct thorough assumptions checking to ensure the validity of the statistical analysis. Finally, the last section of the paper is dedicated to discussing the implications of the study's findings. Here, we analyze and interpret the results in context, considering their broader significance and potential impact on understanding the effects of mobile phone use and traffic environment on driving performance.

2. RESEARCH DESIGN

2.1 Participants

Participation in this study was completely voluntary, with all participants provided clear information on the study's objectives, along with assurances of confidentiality and anonymity. Basic eligibility criteria for participation included possessing a valid driver's license and having at least one year of driving experience. A total of 20 participants, aged between 17 and 34 years, were recruited for this study. Roscoe [21] suggested that for simple experimental research with stringent controls (such as matched pairs), successful outcomes can be achieved with sample sizes as small as 10 to 20 individuals.

2.2 Experiments

Two distinct experiments were conducted. The first experiment aimed to evaluate the impact of the traffic environment and hands-free mode, while the second experiment examined the effect of the traffic environment and hand-held mode. Notably, the same group of individuals participated in both experiments.

The experiments were conducted using a Logitech G27 driving simulator, which includes a steering wheel, pedal set, transmission lever, driver's seat, CPU, sound system, and three LCD screens. To create realistic driving scenarios, we used the Euro Truck Simulator, chosen for its ability to closely mimic real-world driving conditions. A truck with a manual transmission was selected to enhance the realism of the driving experience.

Before starting the actual simulation, each participant underwent a "warm-up" period. This phase, lasting about ten minutes, allowed the simulator to run and gave participants time to adjust to the simulation environment and become familiar with the controls [22]. The warm-up aimed to reduce potential biases by minimizing initial performance variability and learning effects, ensuring that data collection began with participants well-acclimated to the simulation.

In each experiment, participants navigated through two distinct routes: (i) an urban road, representing congested urban areas characterized by numerous traffic signs and vehicles; (ii) a rural road, reflecting environments with frequent turns and fewer traffic signs. These contrasting traffic environments are hypothesized to impact driver performance, as suggested by previous studies [16, 23, 24]. Throughout their journeys along these routes, participants encountered distractions in two different mobile phone modes: (i) answering a phone call (referred to as "phone"); (ii) sending a text message (referred to as "texting"). The selection of mobile phone mode was based on the hypothesis that it would influence driver performance, as indicated in previous researches [25-27].

In Experiment 1, the mobile phone was mounted on the dashboard using a holder, thereby simulating a "hands-free" mode. In contrast, Experiment 2 involved holding the mobile phone in the participant's non-dominant hand—typically the less-preferred hand (e.g., the left hand for right-handed individuals). In this setup, participants handled phone calls or sent text messages with their non-dominant hand while maintaining control of the steering wheel with their dominant hand, thereby representing the "hand-held" mode. Each phone call lasted approximately one minute and was repeated three times during the experiments. This arrangement was designed to mirror common mobile phone usage scenarios while driving and evaluate their effects on driver performance under both hands-free and hand-held conditions.

2.3 Measurement

The driver's performance is evaluated using four measures:

(1) Rating Scale Mental Effort (RSME): This is a subjective measure of mental workload level. Participants rate their mental effort on a 150-point scale, represented by a 15-cm long vertical line with nine anchor points. Responses range from "absolutely no effort" to "extreme effort." The RSME can be completed in less than a minute [28, 29].

(2) Error frequency: This measure captures various driving errors, including collisions with objects or other vehicles, violations of traffic signs, and sudden braking incidents.

(3) Average speed: This measure calculates the average speed maintained by the driver during the simulation.

(4) Lateral position changes: This measure assesses the driver's deviation from the midline of the body, indicating their lateral movement within the driving lane. It is quantified by counting the number of times the driver changes their lateral position [30].

2.4 Statistical analysis

A 2^2 factorial design examines the effects of two independent factors, each with two levels, and their interactions on a response variable. In this study, the factors are: mobile phone use for hands-free (with two levels: "phone" and "texting"), mobile phone use for hand-held (with two levels: "phone" and "texting") and traffic environment (with also two levels: urban and rural). In this design, all possible combinations of the levels of the factors are investigated within each complete replicate of the experiment. This means that not only the main effects of the factors on the response are examined but also the interaction between the factors is explored. By using this design, the experiment is able to systematically assess both the main effects of each factor and their interaction on driving performance measures (e.g., mental workload, error frequency, speed, and lateral position).

We define the model as the following:

$$y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \varepsilon_{ijk} \quad (1)$$

where, y_{ijk} represents the response variable (in this study, it is the driver's performance), μ is the overall mean effect, τ_i is the effect of the ith level of the first factor, β_j is the effect of the ith level of the second factor, $(\tau\beta)_{ij}$ is the effect of the interaction between τ_i and β_j, ε_{ijk} is the statistical disturbance, subscript i (i = 1, 2), j (j = 1, 2), and k (k = 1, 2, …, 10) represents the level of the first factor, the level of the second factor, and the replication, respectively. Both factors are assumed to be fixed, and the factors are defined as deviations from the overall mean. Similarly, the interaction effects are fixed. In this study, we use ten replications; thus, there are 40 total observations (= 2×2×10).

The use of factorial design offers several advantages [31]:

(1) Efficiency: It is more efficient than conducting one-factor-at-a-time experiments, as it allows for the simultaneous examination of multiple factors within a single experiment.

(2) Interaction detection: Factorial design is useful when interactions between factors may be present. It helps to avoid drawing misleading conclusions by considering the combined effects of multiple factors.

(3) Estimation of factor effects: Factorial design enables the estimation of the effects of a factor at various levels of other factors. This yields conclusions that are valid across a range of experimental conditions, providing insights into how factors interact under different scenarios.

3. RESULTS

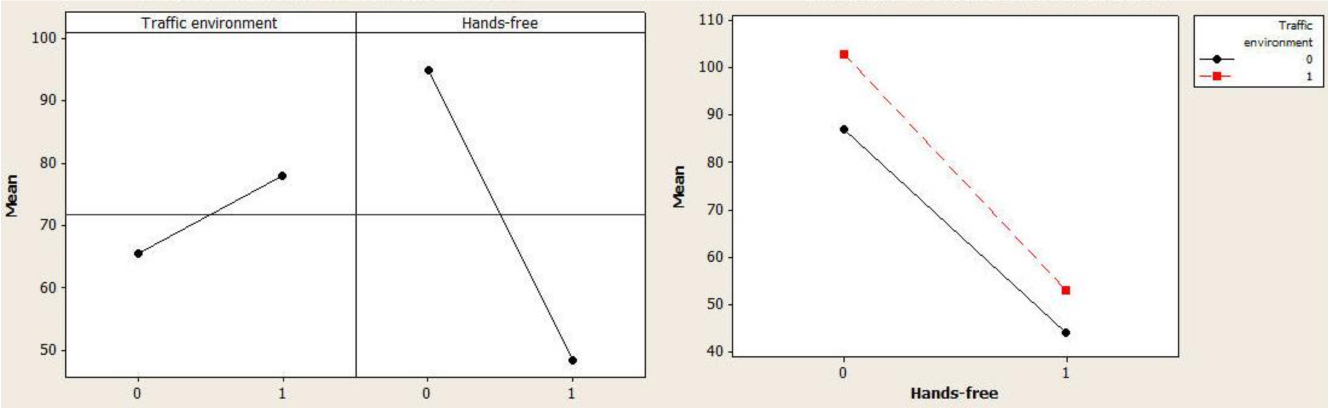
3.1 Experiment 1: Traffic environment vs. hands-free mode

In Experiment 1, we explore the impact of two factors: traffic environment (with two levels: urban and rural) and hands-free mode (also with two levels: "phone" and "texting"), on the driver's performance.

Table 1. ANOVA table of Experiment 1

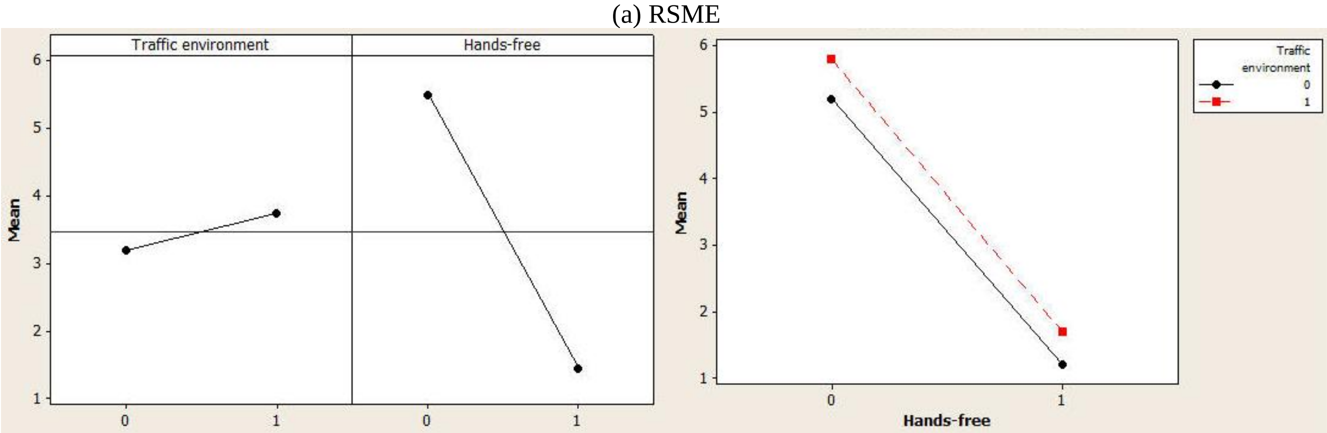
Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	p-Value
Panel A: RSME					
Traffic environment	1562.5	1	1562.5	2.24	0.143
Hands-free	21622.5	1	21622.5	31.05	0.000**
Interaction	122.5	1	122.5	0.18	0.677
Error	25070.0	36	696.4		
Total	48377.5	39			
Panel B: Error frequency					
Traffic environment	3.025	1	3.025	1.38	0.248
Hands-free	164.025	1	164.025	78.84	0.000**
Interaction	0.025	1	0.025	0.01	0.916
Error	78.9	36	2.192		
Total	245.975	39			
Panel C: Average speed					
Traffic environment	1518.8	1	1518.8	24.53	0.000**
Hands-free	2326.2	1	2326.2	37.58	0.000**
Interaction	6.1	1	6.1	0.10	0.756
Error	2228.6	36	61.9		
Total	6079.7	39			
Panel D: Lateral					
Traffic environment	11.025	1	11.025	3.30	0.078*
Hands-free	255.025	1	255.025	76.32	0.000**
Interaction	0.025	1	0.025	0.01	0.932
Error	120.3	36	3.342		
Total	386.375	39			

Note: *statistically significant at the level of 10%; **statistically significant at the level of 5%



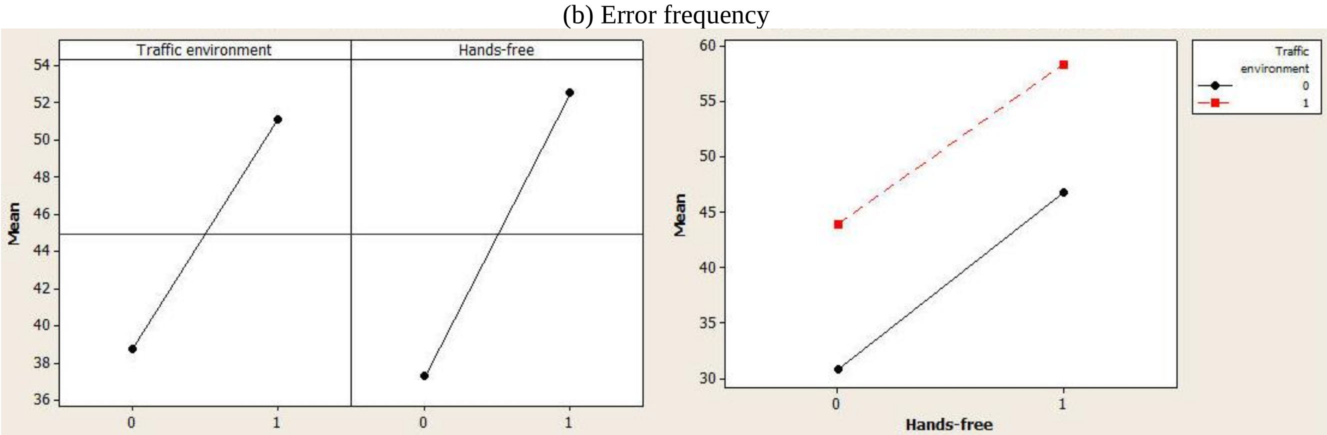
(i) Main effect (ii) Interaction

(a) RSME



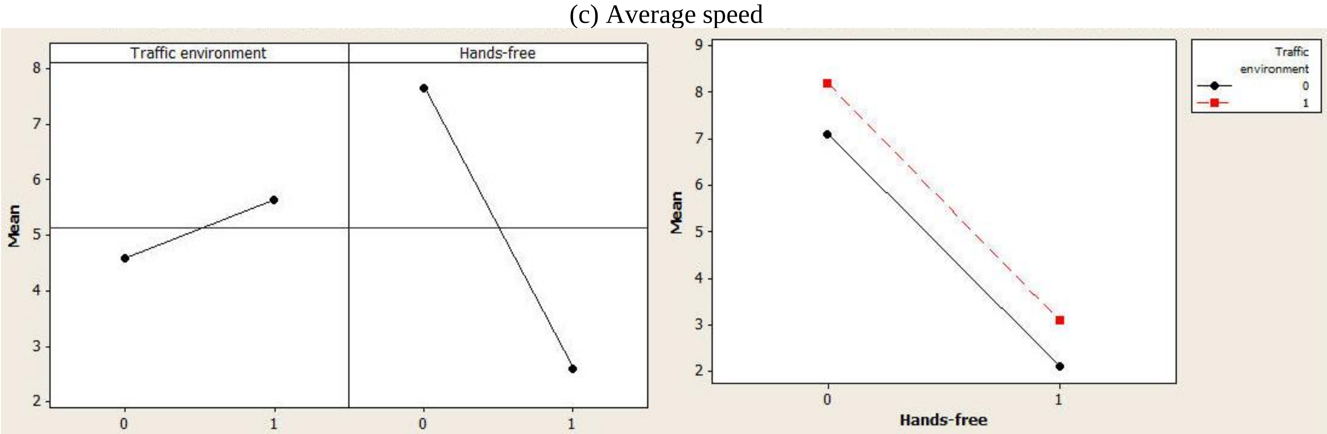
(i) Main effect (ii) Interaction

(b) Error frequency



(i) Main effect (ii) Interaction

(c) Average speed



(i) Main effect (ii) Interaction

(d) Lateral position

Note: Levels of traffic environment: 0 (rural), 1 (urban); Levels of hands-free mode: 0 (texting), 1 (phone)

Figure 1. Plots of Experiment 1

The primary measure of driver performance is the level of mental workload, assessed using the RSME. The analysis of variance (ANOVA) table is presented in Table 1 (Panel A). The results indicate that among the two factors, only the hands-free mode is statistically significant at the 5% level. The effect size is 48.5 for answering a phone call and 95 for sending a message (see Figure 1(a)). The other factor (i.e., traffic environment) and the interaction between these two factors are not statistically significant. From this, we can infer that the mental workload of a driver is higher when distracted by sending a message compared to answering a phone call. However, the type of route has no discernible effect on driver performance as measured by the RSME.

The second measure of the driver performance is the error frequency. The ANOVA table is presented in Panel B of Table 1. Similar to the previous result, only the hands-free mode is statistically significant at the 5% level. This finding indicates that the average number of errors for "texting" is higher than for "phone" (consistent with the previous result), with an effect of 5.5 for "texting" and 1.45 for "phone" (see Figure 1(b)). This finding suggests that when drivers are distracted by sending a text message, they tend to make more errors (such as hitting or bumping the truck into other objects and violating traffic signs) compared to when they are answering a phone call. The other factor, i.e., traffic environment, is not significant, implying that there is no discernible difference in driver performance when driving on urban roads versus rural roads.

Next, we analyze the impact of traffic environment and hands-free mode on the average speed. The results are presented in Panel C of Table 1. Unlike previous findings, these two factors are statistically significant in influencing average speed. However, the interaction between these factors is not significant. Figure 1(c) illustrates the average responses for each treatment combination. The effect sizes are 38.801 for the rural route and 51.125 for the urban route. It appears that drivers reduce their speed when navigating rural roads, which is reasonable considering the increased number of turns compared to urban roads. Additionally, the effect sizes are 52.589 for answering a phone call and 37.337 for sending a message.

The final measure is the lateral position. The results of Experiment 1 regarding lateral position are displayed in Panel D of Table 1. The effect of traffic environment on lateral position is statistically significant at the 10% level, while the effect of hands-free mode is significant at the 5% level. However, the interaction between these factors is not significant at any level (see Figure 1(d)). The effect sizes are 4.075 for the rural route and 4.875 for the urban route. Regarding the effect of hands-free mode, when drivers are distracted by sending a text message, they tend to change their lateral position more frequently than when answering a phone call (the effect sizes are 2.6 for "phone" and 7.65 for "texting".

3.2 Experiment 2: Traffic environment vs. hand-held mode

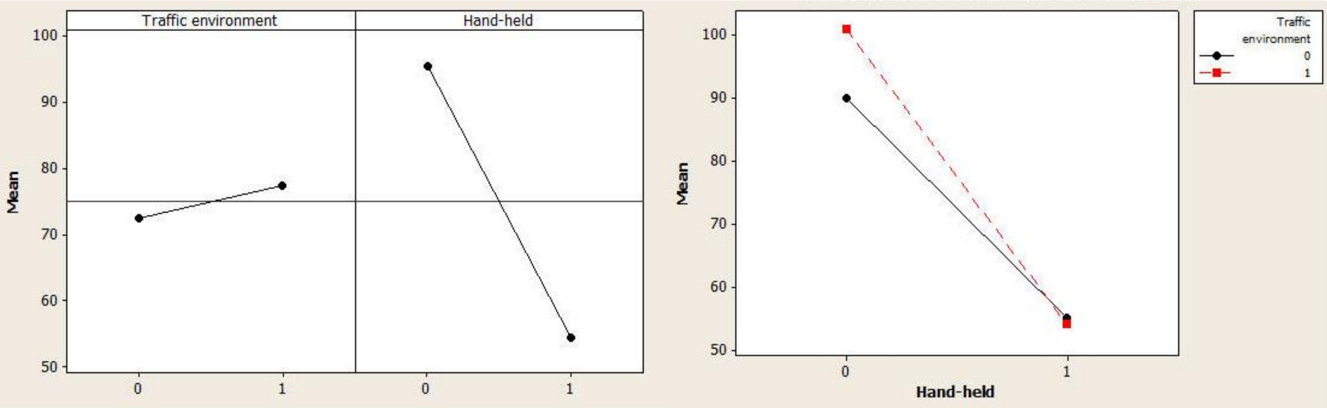
In Experiment 2, we examine the influence of traffic environment (urban and rural routes) and hand-held mode (answering a phone call or "phone" and sending a text message or "texting") on driver performance, measured by four metrics: subjective mental workload, number of errors while driving, average speed, and lateral position changes.

When the driver's mental workload is subjectively assessed using the RSME, it is affected solely by the mode of hand-held operation (with the traffic environment having no statistically significant effect), as shown in Panel A of Table 2. The effect sizes are 54.5 for "phone" and 95.5 for "texting" (refer to Figure 2(a)). Neither the traffic environment nor the interaction between this factor and hand-held mode are statistically significant. Similar to the findings of Experiment 1, we can conclude that the mental workload of a driver is higher when distracted by sending a text message compared to when answering a phone call, regardless of whether the operation is hand-held or hands-free.

Table 2. ANOVA table of Experiment 2

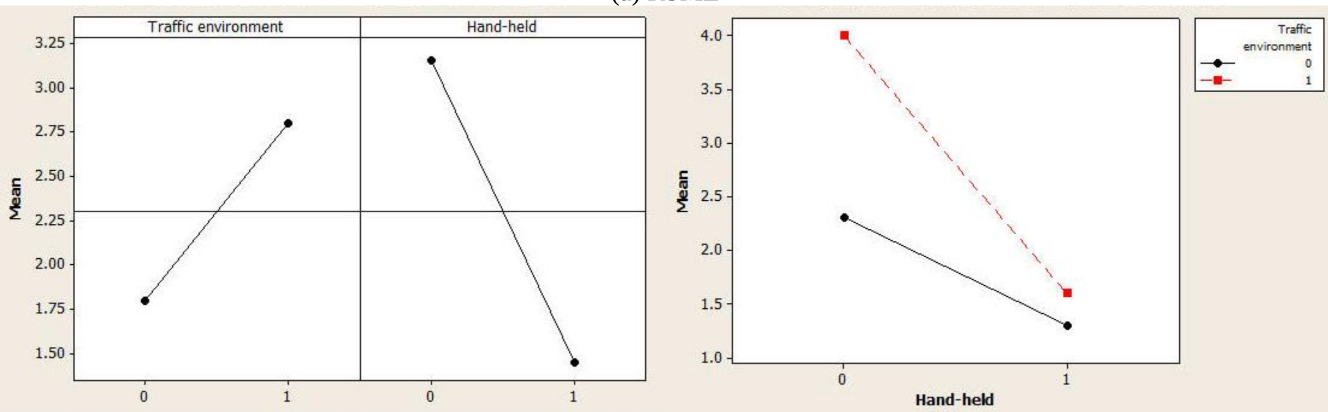
Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	*p-Value*
Panel A: RSME					
Traffic environment	250.0	1	250.0	0.33	0.567
Hand-held	16810.0	1	16810.0	22.43	0.000**
Interaction	360.0	1	360.0	0.48	0.493
Error	26980.0	36	749.4		
Total	44400.0	39			
Panel B: Number of errors					
Traffic environment	10.0	1	10.0	5.94	0.020**
Hand-held	28.9	1	28.9	17.17	0.000**
Interaction	4.9	1	4.9	2.91	0.097*
Error	60.6	36	1.683		
Total	104.4	39			
Panel C: Average speed					
Traffic environment	879.8	1	879.8	9.75	0.004**
Hand-held	3201.2	1	3201.2	35.48	0.000**
Interaction	81.9	1	81.9	0.94	0.347
Error	3247.7	36	90.2		
Total	7410.7	39			
Panel D: Lateral					
Traffic environment	14.4	1	14.4	4.82	0.035**
Hands-free	160.0	1	160.0	53.53	0.000**
Interaction	0.00	1	0.00	0.00	1.000
Error	107.6	36	2.989		
Total	282.0	39			

Note: *statistically significant at the level of 10%; **statistically significant at the level of 5%



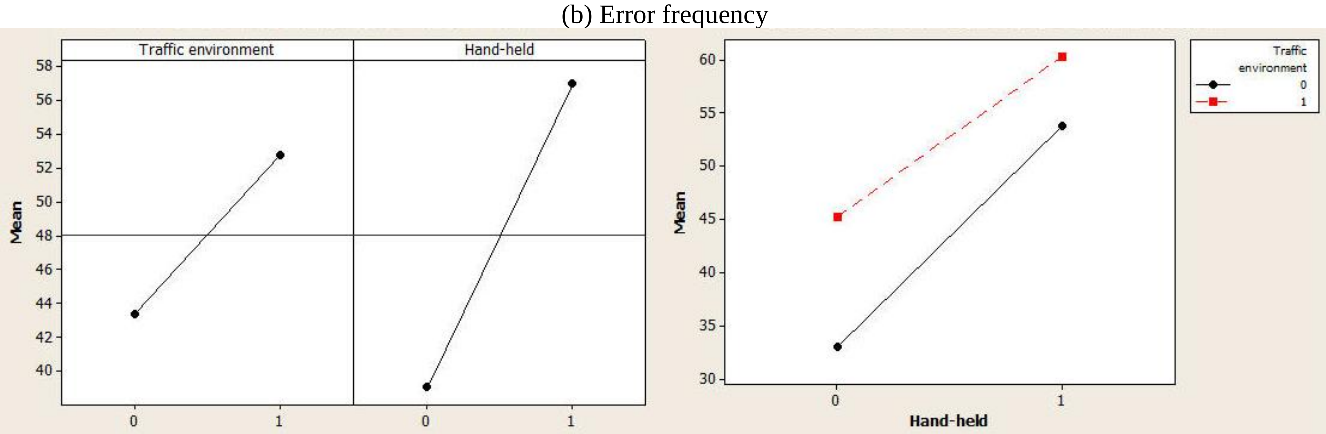
(i) Main effect (ii) Interaction

(a) RSME



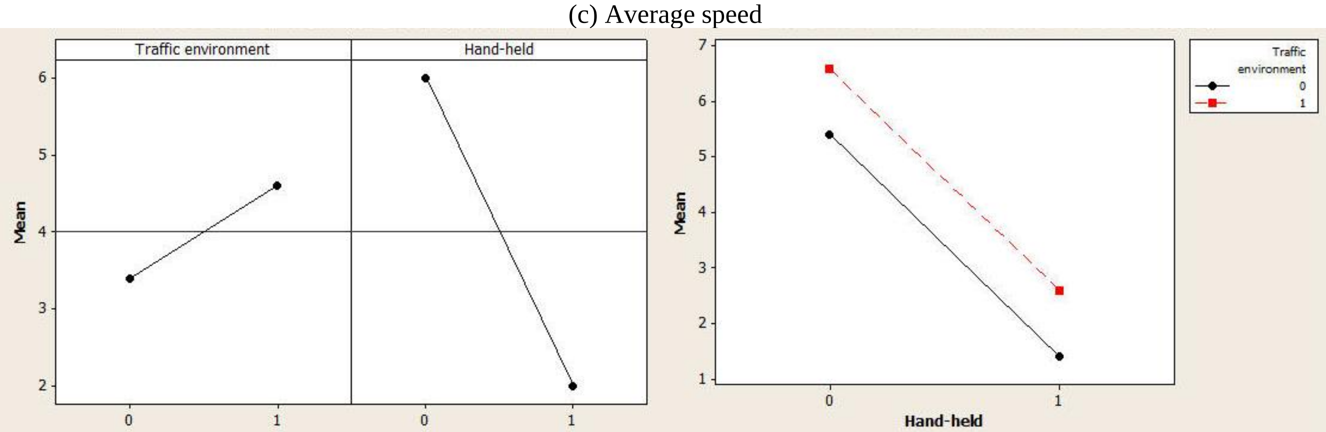
(i) Main effect (ii) Interaction

(b) Error frequency



(i) Main effect (ii) Interaction

(c) Average speed



(i) Main effect (ii) Interaction

(d) Lateral position

Note: Levels of traffic environment: 0 (rural), 1 (urban); Levels of hands-free mode: 0 (texting), 1 (phone)

Figure 2. Plots of Experiment 2

Table 3. Coefficients of correlation among the measures

		Measure	1	2	3	4	5	6	7	8
Experiment 1	1	RSME	1							
	2	Number of errors	0.573	1						
	3	Average speed	-0.453	-0.478	1					
	4	Lateral position	0.622	0.745	-0.552	1				
Experiment 2	5	RSME	0.782	0.428	-0.347	0.491	1			
	6	Number of errors	0.418	0.638	-0.004	0.451	0.437	1		
	7	Average speed	-0.415	-0.509	0.795	-0.584	-0.406	-0.037	1	
	8	Lateral position	0.579	0.638	-0.482	0.730	0.545	0.390	-0.509	1

Panel B of Table 2 indicates that the effects of traffic environment, hand-held mode, and the interaction between these two factors are statistically significant, at least at the 10% level, in influencing driver performance as measured by the number of errors. The effect sizes are 1.8 for the rural route, 2.8 for the urban route, 1.45 for "phone", and 3.15 for "texting" (refer to Figure 2(b)). This result differs significantly from the previous experiment, where only the hands-free mode was significant. Consequently, it can be inferred that when drivers are distracted by a phone call or a text message, whether on a rural or urban route, they are prone to making errors while driving.

In Experiment 2, the impact of traffic environment and hand-held mode on average speed (see Panel C of Table 2) mirrors that of Experiment 1. Both factors are statistically significant, but the interaction is not. The effect sizes are 43.357 for the rural route, 52.737 for the urban route, 56.993 for answering a phone call, and 39.101 for sending a text message (refer to Figure 2(b)). Compared to Experiment 1, the effect size of hand-held mode is higher than that of hands-free mode. This is not surprising, as when drivers hold the phone, they tend to reduce the vehicle's speed.

In terms of the effect of traffic environment, hand-held mode, and their interaction on lateral position (see Panel D of Table 2), the results are akin to those of Experiment 1: both factors have a statistically significant effect, but the interaction does not. The effect sizes are 3.5 for the rural route and 3.95 for the urban route. Regarding hand-held mode, when drivers are distracted by sending a text message, they are more likely to change their lateral position compared to when they answer a phone call (the effect sizes are 2 for "phone" and 6 for "texting", as shown in Figure 2(d)).

3.3 Correlations among the measures

In this section, we examine the correlation coefficients among the four measures (RSME, error frequency, average speed, and lateral position) in both experiments. The results are presented in Table 3. The sign—positive or negative—of the correlation coefficient indicates the direction of the relationship. A positive correlation suggests that the variables move in the same direction: as one variable increases, so does the other, and vice versa. Conversely, a negative correlation suggests that the variables move in opposite directions: an increase in one variable is associated with a decrease in the other, and vice versa.

A high positive correlation is evident between the same measures across different experiments, such as RSME in Experiment 1 and RSME in Experiment 2 (0.782). The number of errors is positively correlated with RSME, indicating that as drivers make more errors, their mental workload increases. Additionally, the number of errors is positively correlated with lateral position, suggesting that when drivers make more errors, they tend to change their lateral position frequently. Furthermore, lateral position shows a positive correlation with RSME, indicating that as drivers change their lateral position more frequently, their mental workload tends to increase. This finding is unsurprising given that lateral position exhibits a negative correlation with average speed: as drivers decrease their driving speed, they are more likely to change their lateral position frequently.

3.4 Assumptions checking

Assumptions in a common factorial design include the requirement for the dependent variable to be of metric measurement level (i.e., ratio or interval data), while the independent variables can be nominal or better. In this study, this assumption is met, as the dependent variables (RSME, number of errors, average speed, and lateral position) are interval (RSME) and ratio data (other measures).

The second assumption pertains to the residuals following a normal distribution. Specifically, none of the residuals are statistically significant at the 5% level, except for the lateral position residual in Experiment 2 (it is significant at the level of 1%). These results indicate that the normality assumption of the residuals holds.

The third assumption entails homoscedasticity of residual variances, meaning that the residual variances of all data points of the dependent variable are equal or consistent throughout the sample. Simply put, the variability in the measurement error should remain constant along the scale and not vary with larger values. To assess this assumption, Bartlett's test and Levene's test are employed. It is worth noting that none of the residuals are statistically significant at the 5% level, except for the number of errors residual in Experiment 1 (significant at the 1% level). This indicates that the assumption of homoscedasticity of residual variances generally holds.

4. DISCUSSION

The result of the study regarding the driving performance is summarized in Table 4.

Table 4. The effect of traffic environment and phone use on driving performance

Measures	Traffic Environment		Phone Use	
	Rural	Urban	Phone	Texting
RSME	0	0	-	+
Number of errors	-	+	-	+
Average speed	-	+	+	-
Lateral position	-	+	-	+

The RSME serves as a gauge of mental workload. An escalation in mental workload can impede driving tasks that rely on the driver's information processing abilities [32]. Interestingly, the traffic environment appears to have no bearing on the driver's mental workload: whether driving on a rural or urban route, the perceived effort remains consistent. Conversely, the mode of phone use significantly impacts driver performance (as evident in Panel A of Table 1 and Panel A of Table 2; both hands-free and hand-held modes are statistically significant in influencing mental workload). Hands-free mobile phone use is often considered more user-friendly because it does not require the driver to hold the phone. However, our experiments clearly show that both hands-free and hand-held modes result in a similar increase in mental workload. This finding corroborates the results reported by Törnros and Bolling [23]. Previous studies have shown mixed results regarding mental effort: some reported higher mental workload with hand-held phones compared to hands-free [25], while others found no significant difference between the two modes [18].

The traffic environment indeed plays a significant role in influencing the number of errors made by drivers. This measure, along with driving speed, is closely linked to crash risk and the severity of potential accidents. Drivers tend to make fewer errors when navigating rural routes compared to urban ones. This finding is logical, as urban areas typically present more crowded conditions with numerous traffic signs and vehicles. Regarding the impact of phone use mode on driver performance, the following observations are noted: when drivers are texting or sending text messages, they tend to commit more errors than when they are simply answering phone calls.

In terms of driving speed, drivers tend to reduce their speed when using a phone. However, the average speed reduction appears to be greater for the hands-free mode compared to the hand-held mode (56.993 for "phone" and 39.101 for "texting" in the hand-held mode, versus 52.589 for "phone" and 37.377 for "texting" in the hands-free mode). This disparity suggests varying degrees of compensation between the two modes.

One possible explanation for these results lies in the fact that when sending a message in the hands-free mode, drivers may need to divert their attention away from the road for a longer period compared to the hand-held mode. In the hand-held mode, when a driver needs to send a text message, they typically hold the phone closer to the upper part of the steering wheel. From this position, the mobile phone is much closer to the driver's frontal view than in the hands-free mode.

Engaging in a phone call affects driving speed, with hands-free mode appearing to induce a more pronounced compensatory effect compared to hand-held. This observation is consistent with other simulator studies, such as those reported in studies [23, 27], which also found that talking on the phone while driving led to a reduction in speed.

Lateral position deviation, a key measure of driving performance, is influenced by both the traffic environment and mobile phone use. On urban routes, drivers show greater deviation from the vehicle's midline, likely due to more frequent turns compared to rural routes. Additionally, texting while driving results in more pronounced lateral position deviations than making a phone call, indicating a potential reduction in safety.

Interestingly, the effect on lateral position deviation is more significant in both hands-free and hand-held modes of phone use. This contrasts with the study [25], which found greater deviation in hand-held mode. The discrepancy may be explained by the fact that in hand-held mode, the phone is closer to the driver's frontal view than in hands-free mode, leading to less distraction and increased driver alertness. This heightened awareness likely contributes to reduced lateral position deviation.

These findings challenge the common perception that hands-free mode is inherently safer than hand-held mode. While literature often suggests that hand-held mode is more hazardous due to its higher demand on the driver, scientific consensus remains elusive [23, 33, 34]. Redelmeier and Tibshirani [6] provide evidence that banning all cell phone use, regardless of mode, could significantly reduce accidents. For example, Redelmeier and Weinstein [35] estimated a 2% reduction in accidents from such a ban, while Cohen and Graham [36] projected a potential reduction of 2–21%, with a central estimate of 6%. These results underscore the complexity of distracted driving and highlight the need for further research and nuanced policy approaches.

5. CONCLUSION, IMPLICATIONS, AND LIMITATIONS

5.1 Conclusion

This study examines how mobile phone use and traffic environments (urban vs. rural) affect driving performance through two simulation experiments. In Expriment 1, we analyze the impact of traffic environments and hands-free mode (phone vs. texting). In Experiment 2, we analyze the impact of traffic environments and hand-held mode (phone vs, texting). It uses a 2^2 factorial design to study drivers' mental workload, errors, speed, and lateral position. The experiments were conducted on 20 participants using a driving simulator.

The results show that mobile phone use significantly affects driving performance, particularly increasing mental workload and error frequency. Texting is more detrimental than phone conversations. Hands-free and hand-held modes both raise mental workload, but texting increases it more than making phone calls. The traffic environment affects speed and lateral position changes, with drivers reducing speed on rural routes and showing greater lateral position deviation on urban roads. Texting contributes to more errors and lateral position changes. This study also highlights the complex interaction between mobile phone usage and traffic environments, showing that both affect driving behavior but in different ways.

5.2 Implications

Several policy implications regarding the findings of this research are given as follows. The enforcement of stricter regulations against texting while driving is a critical policy recommendation derived from this finding. The study demonstrates that texting while driving leads to a significant increase in mental workload, error frequency, and lateral position deviation when compared to answering a phone call. These results underscore the heightened risk associated with texting, as it exacerbates driver distraction more than other forms of mobile phone use. The observed increase in error rates and the tendency for drivers to deviate more from their lane when texting reflects a substantial impairment in driving performance, indicating a greater potential for accidents. Thus, implementing policies specifically targeting texting while driving could play a crucial role in mitigating these risks and enhancing overall road safety. By focusing regulatory efforts on the most distracting and hazardous phone-related activities, policymakers can more effectively address the significant safety concerns associated with texting while driving.

The research also suggests a nuanced approach to distracted driving legislation, recommending that laws should specifically address the type of phone use rather than broadly categorizing it as either hands-free or hand-held. Both modes of phone use—hands-free and hand-held—are shown to increase mental workload; however, texting significantly exacerbates this effect compared to answering phone calls. This distinction highlights the need for legislation to target the specific nature of the distraction. By focusing on the particular risks associated with texting, which have been demonstrated to result in higher mental workload and increased error rates, policies can be more precisely tailored to mitigate these specific hazards. Such an approach would ensure that regulations are not only comprehensive but also effectively address the varying degrees of distraction presented by different types of phone use, ultimately improving road safety.

Lastly, the findings indicate that while traffic environment—urban vs. rural—does not significantly impact mental workload or error frequency, it does affect driving speed. Therefore, a pertinent policy recommendation is to incorporate traffic environment factors into driver education campaigns. These campaigns should emphasize the importance of adjusting driving behavior based on road conditions, specifically highlighting the necessity of modulating speed according to the type of traffic environment. By acknowledging that speed adjustments are essential for safely navigating different environments, drivers can be better equipped to modify their driving practices and reduce the risk of accidents. Educating drivers about these environmental considerations can lead to improved road safety and more adaptive driving behavior in various traffic conditions.

5.3 Limitations

The findings of this research were obtained from experiments (or simulations). Driving simulations, while valuable for controlled experimentation, present several limitations in terms of ecological validity when compared to real-world driving scenarios. One primary limitation is the artificial environment in which simulations occur. These controlled settings may fail to capture the full complexity and unpredictability of actual driving conditions, such as the dynamic interactions with other drivers, varying road surfaces, and unexpected events. As a result, the findings from simulations may not fully generalize to real-world situations where drivers encounter a broader range of stimuli and challenges.

Another significant issue is simulator sickness, a phenomenon where participants experience symptoms like nausea, dizziness, and disorientation. This discomfort can impact driving performance and behavior, introducing variables that are absent in real-world driving. Such effects can skew results and reduce the ecological validity of the findings. Simulations also often lack the comprehensive sensory feedback that is present in actual driving, including the feel of the road surface, vehicle vibrations, and environmental auditory cues. The absence of these sensory inputs can affect the realism of the simulation, leading to potential discrepancies in driving behavior compared to real-world experiences.

Additionally, driving simulations may simplify traffic scenarios, failing to fully replicate the complexity of real-world traffic conditions. This includes variability in traffic density, diverse driver behaviors, and intricate road layouts. These simplifications can limit the extent to which simulated driving behaviors are representative of those in real-world scenarios.

Driver awareness of being observed in a simulation can also lead to adaptation in driving behavior. Participants might modify their driving style due to the knowledge that they are in a controlled environment, potentially resulting in more cautious or deliberate actions that do not accurately reflect typical real-world driving.

Equipment limitations further impact the ecological validity of simulations. Variations in the fidelity of visual and auditory systems, such as resolution, field of view, and response times, can affect the accuracy of the simulated environment, leading to differences between simulated and real-world driving experiences.

Finally, the short-term nature of most simulation studies does not account for the effects of long-term driving habits or the cumulative impact of distractions over extended periods. This limitation means that short-term simulations may not fully capture the long-term consequences of driving distractions or environmental factors, thereby constraining their relevance to real-world driving over time.

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