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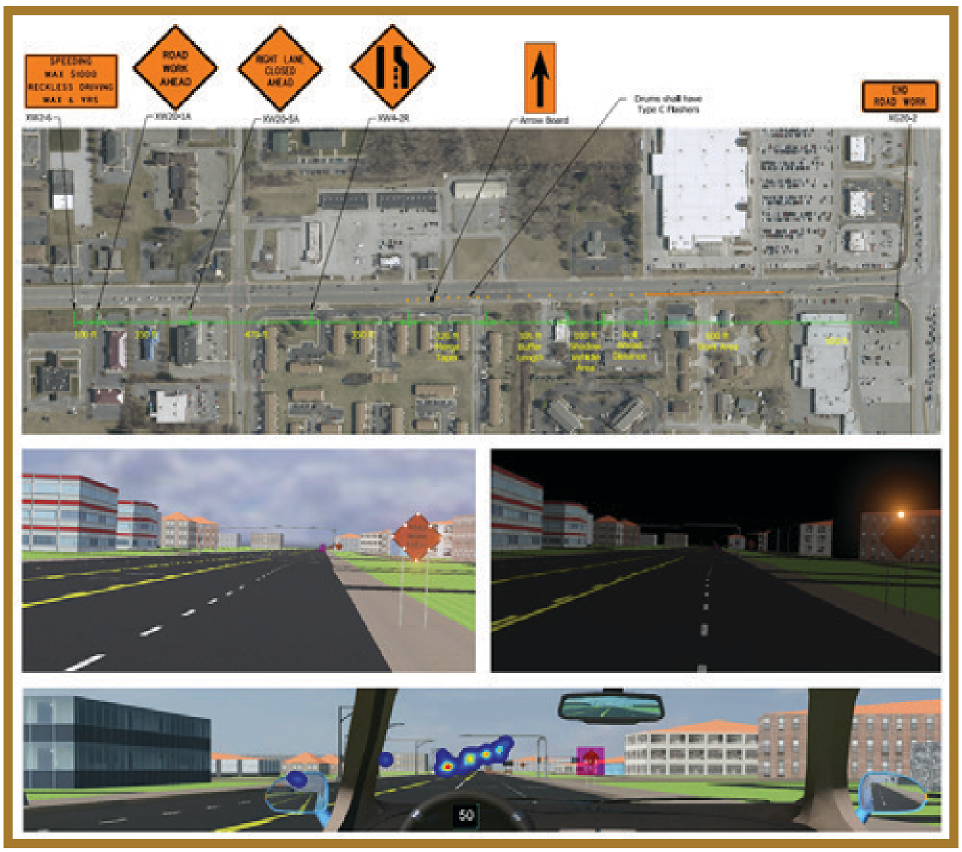
Exploration of Color Patterns for Improving Work Zone Safety and Perception



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16. Abstract

Work zone safety remains a persistent concern in the United States. Color patterns are an effective way to provide visual information for drivers. Existing studies explored the colors of work zone elements, while how the color patterns impact the drivers' perception, information processing, and overall safety in work zones is missing. Therefore, this study aims to systematically investigate color patterns based on human information processing theory to improve the overall safety and perception of Indiana work zones. Methodology of this study includes: (1) A literature review to summarize the current efforts; (2) Crash data analysis to identify the representative work zones; (3) Natural Language Processing (NLP) analysis to explore color-related root causes for work zone crashes based on Indiana crash data; (4) Interviews to propose the color-related countermeasures; and (5) Driving simulation experiment to evaluate the effectiveness of countermeasures. There are several key findings. First, the color-related root causes of work zone crashes in Indiana were proposed as follows: (1) poor visibility and brightness of color for work zone elements, (2) insufficient color contrast between work zone elements and the overall environment, especially in the areas of road geometry change and road surface conditions change, and (3) lack of changes in color for work zone elements in dangerous areas (e.g., entering the work zone, transition area, and road geometry and surface conditions change). Second, the effectiveness of proposed countermeasures was identified: (1) For lane closure scenario, fluorescent orange sign with orange LEDs was the most effective one in attracting attention (perception stage) and maintaining cognitive workload (cognition stage) during both daytime and nighttime as well as improving steering behaviors (action stage) during daytime. Fluorescent orange sign with orange beacon countermeasure was also effective in attracting attention during nighttime and maintaining cognitive workload during daytime. (2) For shoulder work scenario, fluorescent orange sign with orange LEDs was the most effective countermeasure in attracting attention and maintaining cognitive workload at night. Fluorescent orange sign with orange beacon countermeasure also helped attract attention during nighttime. Based on the findings, several recommendations were provided to improve work zone safety.

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EXECUTIVE SUMMARY

Introduction

Work zone safety remains a persistent concern in the United States, with 20%–30% more crashes occurring in work zones than on normal roads. Color patterns are an effective way to provide visual information for drivers, especially in work zones. Although existing studies have explored the root causes of work zone crashes, identified color-related factors, and proposed relevant countermeasures, they have not investigated how color patterns impact drivers' perceptions and overall safety in work zones. Therefore, this study aimed to fill this research gap by systematically investigating color patterns using human information processing theory to improve the overall safety and perception of Indiana Department of Transportation (INDOT) work zones. The methodology used in this study covered included the following: (1) a literature review to summarize current efforts related to work zone crashes as well as color-related factors; (2) a crash data analysis to identify representative work zones in Indiana; (3) a crash data analysis using the natural language processing (NLP) method to explore color-related root causes of Indiana work zone crashes; (4) interviews and a literature review to propose color-related countermeasures that reduce work zone crashes in Indiana; and (5) a driving simulation experiment to evaluate the effectiveness of proposed countermeasures in representative work zones.

Findings

According to crash data and literature, the color-related root causes of work zone crashes in Indiana are the following: (1) poor visibility and brightness of color for work zone elements (e.g., traffic signs, channelizing devices, pavement markings, etc.); (2) insufficient color contrast between work zone elements and the overall environment, especially in the areas of road geometry change (e.g., turn directions, intersections with traffic lights) and road surface conditions change (e.g., slippery roads); and (3) a lack of change in color for work zone elements in dangerous areas (e.g., entering the work zone, transition area, road geometry change, and road surface conditions change).

According to driving simulation experiment results, the effectiveness of the following proposed countermeasures was identified.

1. For the lane closure scenario, a fluorescent orange sign with orange LEDs was the most effective countermeasure. It attracted greater attention from drivers from longer distances (with mean differences of 164 feet and 153 feet more than the original design during daytime and nighttime, respectively). The sign also maintained drivers' cognitive workload during both the daytime and the nighttime, and it improved drivers' steering behaviors during the day by shifting vehicles to the left when there was a lane closure work zone in the right lane. A fluorescent orange sign with an orange beacon countermeasure was also effective in attracting greater attention from drivers and from longer distances at night (with a mean difference of 185 feet more than the original design). The sign also maintained drivers' cognitive workload and focus during the daytime. The two countermeasures were also more effective according to drivers.
2. For the shoulder work scenario, a fluorescent orange sign with orange LEDs was also the most effective countermeasure. It attracted greater attention from drivers and from longer distances (with a mean difference of 515 feet than the original design). The sign also maintained drivers' cognitive workload more at night. It was ranked as the most effective countermeasure based on drivers' self-evaluation. A fluorescent orange sign with an orange beacon countermeasure also helped attract drivers' attention from longer distances during the nighttime (with a mean difference of 431 feet more than the original design).
3. Time scenarios (with major differences in lighting conditions) had a significant impact on drivers' attention and cognitive workload under both lane closure and shoulder work scenarios, which emphasizes the importance of considering time scenarios when proposing and applying countermeasures to improve work zone safety.

Recommendations

Based on these findings, several recommendations are provided for lane closure and shoulder work scenarios.

- For the lane closure scenario, a fluorescent orange sign with orange LEDs countermeasure is recommended as the most effective solution to significantly impact drivers' perception and cognition stages during the daytime and the nighttime and to impact the action stage exclusively during the daytime. Moreover, a fluorescent orange sign with an orange beacon countermeasure is also recommended as an effective solution due to the significant impacts on the perception stage during the nighttime and the cognition stage during the daytime.
- For the shoulder work scenario, a fluorescent orange sign with orange LEDs countermeasure is also the most effective countermeasure because of its significant impact on drivers' perception and cognition stages at nighttime. A fluorescent orange sign with an orange beacon countermeasure also attracts drivers' attention from longer distances at nighttime.
- Since time scenarios (with major differences in lighting conditions) significantly influence drivers' attention and cognitive workload under both lane closure and shoulder work scenarios, when proposing and adopting the countermeasures, time scenarios should be considered to improve their effectiveness and reduce potential distractions.

This study proposed a comprehensive research method to evaluate new countermeasures in work zones within a virtual environment that considered drivers' perception, cognition, and action stages. It can be used to evaluate new countermeasures, especially the ones that are not included in standards. The results could provide preliminary evidence about the effectiveness of new countermeasures before potential field tests.

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1. INTRODUCTION

Work zone safety remains a persistent concern in the United States. Nationally, over 40,000 crashes happened in work zones each year (Indiana Department of Labor [IDOL], 2022). Between 1982 to 2019, around 28,636 individuals lost their lives in U.S. work zone crashes (Centers for Disease Control and Prevention [CDC], 2024). Specifically, in 2020, there were 857 fatalities in work zone crashes, which increased by 1.4% compared with 2019 numbers (Federal Highway Administration [FHWA], 2022). In Indiana work zones, 33 people were killed and more than 1,750 were injured in 2023, increased by 22.7% compared with 1,426 injuries in 2022 (Indiana Department of Transportation [INDOT], 2024). In particular, work zones have more hazardous elements due to the conflict between construction activities and traffic (Garber & Zhao, 2002; Zhang et al., 2018), which led to 20%–30% more crashes compared with normal roads, and the rate increased to 87% during night work activity (Ullman et al., 2008).

Color conveys information visually during driving (Lai, 2010). The *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) applied various sign colors, such as orange signs for temporary traffic control and fluorescent pink signs for incident management to improve safety (FHWA, 2023b). In particular, color patterns (i.e., the combination of colors, color schemes) is an effective way to provide visual information during driving (Lai, 2010; Proctor & Van Zandt, 2018; Yi et al., 2012). Appropriate color patterns could improve the efficiency of people's information perception and cognition and enable people to act quickly when minimizing visual fatigue (Yi et al., 2012). The color-coding theory from the psychology field also indicates that the unique color of targets could aid information identification and searching, which is unaffected by the number of items with other colors (Christ, 1975; Proctor & Van Zandt, 2018). As work zones have a high display density of elements from construction activity and traffic to be interpreted by drivers (Garber & Zhao, 2002; Zhang et al., 2018), applying the color patterns considering key work zone elements would be helpful. However, too many colors may cause confusion and distraction, resulting in increased response time (Lai, 2010). Therefore, it is necessary to understand work zone safety from the color-related perspective, especially considering different work zone elements.

The researchers reviewed literature about work zone safety, color patterns, and corresponding countermeasures. In particular, several reports from other state Departments of Transportation (DOTs) were reviewed, including Texas DOT (Schrock et al., 2004), WisDOT (DuPont & DeDene, 2017), Iowa DOT (Shaw et al., 2018), Michigan DOT (Zockaie et al., 2020), and Kentucky DOT (Lammers-Staats et al., 2021). In addition, FHWA's (2023b) *Manual on Uniform Traffic Control Devices* (MUTCD) and related guidelines and standards were reviewed to summarize the current design of signs and devices in the work zones. However, there is limited work considering the impact of color patterns on the overall perception and effectiveness of work zones, not to mention in INDOT work zones. Therefore, this study aims to fill the research gaps by systematically investigating color patterns considering human information processing theory for improving the overall safety and perception of the INDOT work zone.

2. PROBLEM STATEMENT

While existing studies have investigated the root causes of work zone crashes, color-related factors in work zone crashes, and different countermeasures to improve work zone safety, there is a lack of studies exploring the color-related root causes of work zone crashes and proposing the color-related countermeasures to improve work zone safety. Therefore, this study will address the gap by answering the following research questions.

1. What are the color-related root causes of Indiana work zone crashes?
2. What are current practices and efforts related to color patterns to prevent work zone crashes?
3. How to develop color-related countermeasures to improve the safety and perception of Indiana work zones?

INDOT has recognized the importance of color patterns and other potential factors (e.g., lighting elements, work zone layouts, locations of objects, etc.) in improving work zone safety. Specific objectives of this study include the following.

1. Summarize the current practices and efforts related to color patterns to prevent crashes in work zones.
2. Identify the representative work zones in Indiana.
3. Identify color-related root causes of Indiana work zone crashes.
4. Propose color-related countermeasures to improve the safety of Indiana work zones.
5. Evaluate the effectiveness of the proposed color-related countermeasures to improve work zone safety considering drivers' perception, cognition, and action.

3. LITERATURE REVIEW

Based on the literature review, general root causes of work zone crashes, color-related factors, and characteristics of Indiana work zones were identified, and the hypothesized color-related root causes for Indiana work zone crashes were proposed, as shown in Figure 3.1. In addition, color-related countermeasures were reviewed and summarized.

There are many studies discussing the causes of work zone crashes. Table 3.1 summarizes the general root causes of work zone crashes, including speeding, traffic controls, light conditions, roadway geometry, lane changes, work zone vehicles/workers/objects, weather and season, time of the day, traffic density, and sight distance. Although some causes are related to color, such as time of the day and poor light conditions, there is a lack of studies interpreting the causes from the color-related perspective.

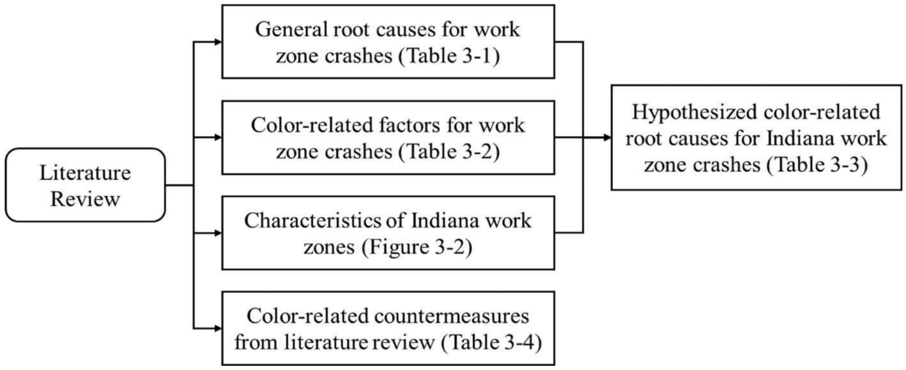


Figure 3.1 Process of literature review.

TABLE 3.1
General Root Causes of Work Zone Crashes from the Literature Review

	References						
General Root Causes	**Bai & Li, 2006; Li & Bai, 2009**	**Clark & Fontaine, 2015**	**Harb et al., 2008**	**Sze & Song, 2019**	**McAvoy et al., 2011**	**Schrock et al., 2004**	**Zhang et al., 2018**
Speeding	✓	✓	–	–	–	–	–
Inefficient/Inadequate Traffic Controls	✓	–	–	✓	–	✓	–
Confusion About/Failure to Notice Traffic Controls	✓	✓	–	✓	–	✓	–
Poor Light Conditions	✓	–	✓	–	–	✓	–
Roadway Geometry	✓	–	✓	–	✓	✓	✓
Lane Closure/ Changing/Narrowing	–	✓	✓	–	✓	✓	✓
Work Zone Vehicles/Workers/ Objects/etc.	–	✓	–	✓	✓	✓	–
Weather Condition/Season	✓	–	✓	–	–	✓	✓
Time of the Day	–	–	–	✓	–	–	✓
Traffic Density/Congestion	–	✓	–	–	✓	–	–
Limited Sight Distance	–	✓	–	–	–	–	–

TABLE 3.2
Color-Related Factors of Work Zone Crashes from the Literature Review

Color-Related Factors	**References**	**Explanations**
Color Contrast	Atchley & Dressel, 2006; Sheikholeslami et al., 2020	Color contrast of hazard properties and environment impact the visibility, which may interact with ambient light (day or night) and driving speed (Sheikholeslami et al., 2020). The insufficient color contrast between the warning signs and the vehicles on which they are mounted cannot attract the drivers' attention (Atchley & Dressel, 2006).
Brightness and Visibility of Color	Carlson & Chrysler, 2004; DuPont & DeDene, 2017; Hummer & Scheffler, 1999; Sayer & Mefford, 2004; Shaw et al., 2018	"Ghost marking" (visible remnants of old pavement marking) will impact driving safety (DuPont & DeDene, 2017; Shaw et al., 2018). The greater conspicuity of signs leads to operational changes or fewer crashes (Hummer & Scheffler, 1999). Retroreflective trim color of garments impacts the conspicuity and further influences drivers' attention (Sayer & Mefford, 2004). Colors of delineators may affect drivers' detection distances (Carlson & Chrysler, 2004).
Changes in Color	Lammers-Staats et al., 2021; Jenssen & Brekke, 1998; Meyer, 2002	Drivers cannot be aware that they are entering a work zone because they get used to the color of signs, traffic control devices, pavement markings, etc. (Lammers-Staats et al., 2021; Jenssen & Brekke, 1998). The exit ramp delineated by drums is difficult to identify for an interstate work zone because of the same colors (Meyer, 2002).

Moreover, existing studies explored some color-related factors in work zone crashes, as summarized in Table 3.2. The factors include color contrast, brightness and visibility of color, and changes in color. The combination of general root causes and color-related factors forms a basic understanding of work zone safety from the color-related perspective. However, existing studies only discussed one or two specific color-related factors. Also, existing studies mainly collect data through small-scale experiments in one specific work zone within a short period of time, which limits the application of results in different work zones at different times. A larger scale of crash data is needed to provide more widely applied color-related factors compared with the existing experiments of selected work zones during a short time period.

To better understand the characteristics of Indiana work zones, *Indiana Crash Facts 2019* (Thelin et al., 2020) was reviewed. Nine factors (as listed in the following bullet points) are identified to filter the most dangerous and representative work zones. For each factor, the value that caused the most accidents was selected. For example, the construction type that had the most accidents was lane closure. By considering all the nine factors, the dangerous and representative work zones can be selected as shown in Figure 3.2. Therefore, a work zone that has lane closure, in a suburban area, as an interstate road, during the day, with clear weather, with dry road surface condition, and with lane control between 3:00 pm to 5:59 pm during late fall or winter, can most easily cause collisions (fatal, non-fatal, and property damage) in Indiana.

- Construction type (the most): Lane closure
- Census locale (the most): Suburban
- Road class (the most): Interstate
- Light conditions (the most): Daylight
- Weather conditions (the most): Clear
- Surface conditions (the most): Dry
- Traffic control type (the most): Lane control
- Time of the year (the most): Late fall and winter (October, November, and January)
- Time of the day (the most): 3 pm to 5:59 pm

Integrating the general root causes and color-related factors from literature and characteristics of Indiana

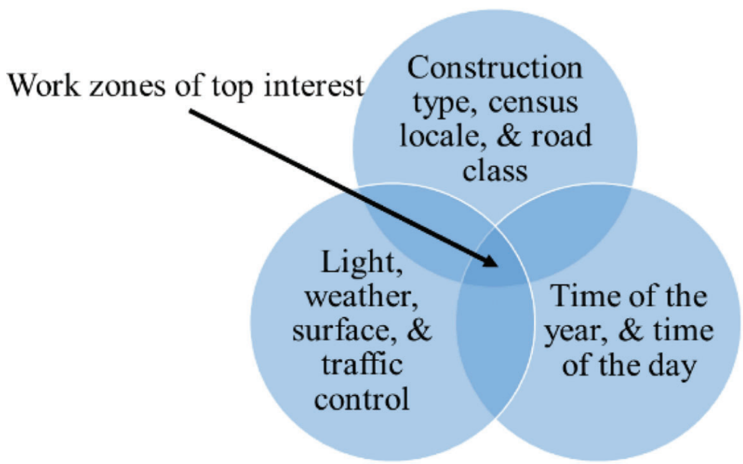


Figure 3.2 Identification of work zones of top interest based on Indiana crash statistics.

TABLE 3.3
Hypothesized Color-Related Root Causes for Indiana Work Zone Crashes

General Root Causes & Color-Related Factors from Literature	Hypothesized Color-Related Root Causes for Indiana Work Zones Crashes
Brightness and Visibility of Color	Poor brightness and visibility of color for work zone elements, such as the pavement markings, traffic signs, and channelizing devices related to lane closure and lane control
Color Contrast	Insufficient color contrast between work zone elements (e.g., pavement markings/signs/channelizing devices related to lane closure/control) and the overall environment
Changes in Color	Lack of changes in color for work zone elements (e.g., pavement markings/signs/channelizing devices) in dangerous areas, such as entry and exit of work zones and working area
Weather/Season Condition	Yellow color for the late fall season and snow weather (white color) for the winter season
Time of the Day	Sunset time (yellow/red color of the sunset) and night construction (black background)
Lighting	Flash pattern, glare level, and illumination level of daylight (e.g., sunset time) and artificial lights (e.g., at night)

TABLE 3.4
Color-Related Countermeasures from the Literature Review

Countermeasures	References
Orange pavement marking to delineate a work zone	Lammers-Staats et al., 2021; DuPont & DeDene, 2017; Shaw et al., 2018
Fluorescent signs: yellow and green	Jenssen & Brekke, 1998
Fluorescent orange sign	Hummer & Scheffler, 1999
Safety garments with retroreflective trim	Sayer & Mefford, 2004
Signs are surrounded by a fluorescent yellow-green border	Atchley & Dressel, 2006
Alternate color scheme (orange, white, and green stripes) for reflectorized drum	Meyer, 2002
Lighting plan	Anani, 2015
Green lights to the warning system of winter maintenance trucks	Zockaie et al., 2020

work zones from crash statistics, six hypothesized color-related root causes specifically for Indiana work zone crashes were identified and summarized in Table 3.3.

In addition, the researchers reviewed the literature to identify the existing color-related countermeasures, which are shown in Table 3.4, including the signs, channelizing devices, pavement markings, lights, etc.

4. METHODOLOGY

Figure 4.1 shows the overall research methodology of the study, including seven research tasks and three deliverables.

The first part includes Tasks 1–3. Task 1 is a literature review to summarize the current efforts related to work zone crashes as well as color-related causes and countermeasures, as shown in Session 3. Task 2 (Session 5) aims to identify the representative work zones in Indiana based on crash data, which could help promote the understanding of Indiana work zones and select the cases for driving simulation experiments in Task 6. Task 3 (Session 6) aims to identify the root causes of work zone crashes based on Indiana crash data. Natural language processing (NLP) method was applied to analyze the narratives in crash reports. Based on the three tasks, deliverable one is the identification of work zones of top interests and root causes of work zone crashes in Indiana.

The second part includes Task 4 (Session 7). This task aims to propose color-related countermeasures based on the identified color-related root causes of Indiana work zone crashes, literature review, and interviews with experts in Indiana. Based on this task, deliverable two is the development of countermeasures to reduce work zone crashes in Indiana.

The third part includes Tasks 5–7. Task 5 (Session 8) aims to simulate the selected work zones from Task 2 and countermeasures from Task 4 using Webots and

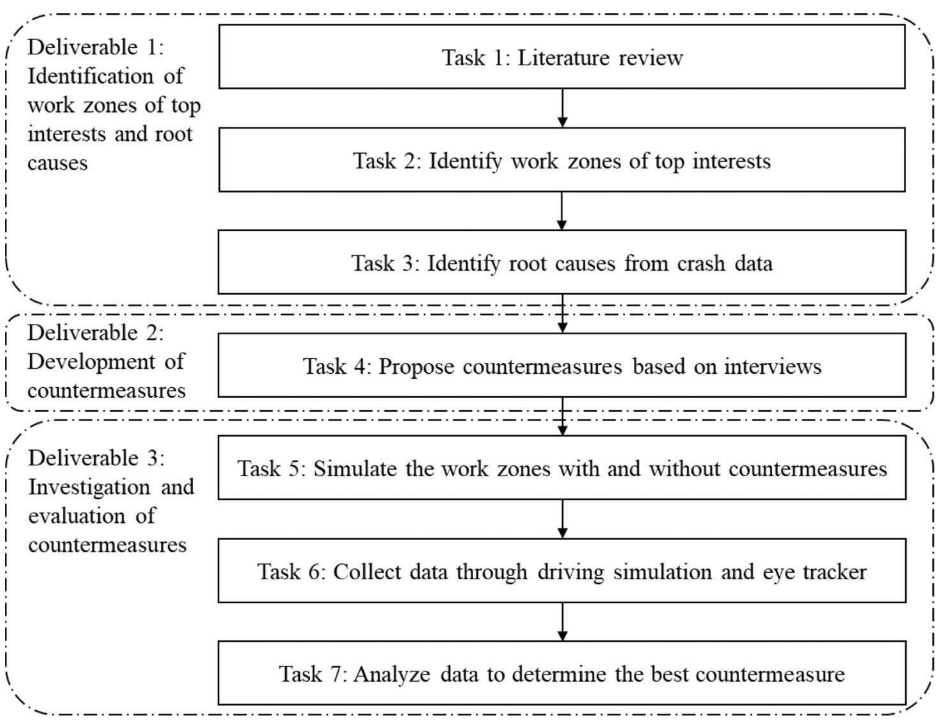


Figure 4.1 Research methodology.

Simulation of Urban Mobility (SUMO) software. The research team scenarios of the work zones with and without countermeasures in the experiment to evaluate the effectiveness of proposed countermeasures. Task 6 (Session 9) is about the process of data collection. A driving simulation experiment was designed to collect driving performance data using the simulator, eye movement data using an eye tracker, and demographic information and self-evaluation data using questionnaires. Based on the collected data, Task 7 (Session 9) aims to perform data analysis to evaluate drivers' perception, cognition, action, and self-evaluation of different countermeasures under different work zones to determine the best color-related countermeasure to reduce work zone crashes in Indiana. Deliverable 3 is the investigation and evaluation of countermeasures.

5. IDENTIFICATION OF WORK ZONES OF TOP INTEREST

To understand the work zones of top interest based on crash data, two main parts were included: (1) identify key parameters related to work zones of top interests from crash data, and (2) identify the most representative work zones from crash data, which were used in the driving simulation as explained in Session 8. The contents of this session were included in a conference paper (Wu, Chen, et al., 2024).

5.1 Key Parameters of Work Zones from Crash Data

To identify the key parameters related to Indiana work zone crashes, three data sources were used: (1) Safety Occurrence Reports (https://access.in.gov/client/signin/), (2) Automated Reporting Information Exchange System (ARIES) dataset (Indiana State Police, 2022), and (3) *Indiana Crash Facts 2019* (Thelin et al., 2020). Safety Occurrence Reports include crash/issue reports specifically in the Indiana Department of Transportation (INDOT) work zones, as recorded in the INDOT Safety Occurrence system. ARIES database covers all the crash records that happened in Indiana collected by the Indiana State Police. Crash data from the Safety Occurrence Reports were analyzed using natural language processing (NLP) to summarize the specific parameters, as explained in Session 6. *Indiana Crash Facts 2019* was reviewed as discussed in Session 3. Information from the three resources was combined to summarize the possible parameters of the work zones of top interests, as shown in Table 5.1. Overall, the key parameters include road condition (e.g., geometry), work zone elements (e.g., lane closure, traffic controls, workers, and vehicles), and environment (e.g., time, season, and weather). The key parameters provide a basic understanding of Indiana work zones of top interests.

5.2 Representative Work Zones from Crash Data

Then, to identify the most representative work zone for driving simulation, the researchers further analyzed the ARIES dataset specifically. The process of selecting the most representative work zone is shown in Figure 5.1.

At the beginning, 2,634 crash records in 2019–2022 from the ARIES dataset were extracted. The criteria for extracting crash data were: (1) primary factor: driver distracted, explain in narrative; other (driver), explain in narrative; other (vehicle), explain in narrative; other (environment), explain in narrative; speed too fast for weather conditions; road under construction; (2) construction type: intermittent or moving work, lane closure, work on shoulder, x-over/lane shift (all four choices); and (3) date of collision: 1/1/2019–12/31/2022.

TABLE 5.1
Possible Parameters for Work Zones of Top Interests

Category	Parameters	Indiana Crash Fact Book	Safety Occurrence Reports	ARIES Crash Reports
Road Condition	Road class (e.g., suburban area, interstate road)	✓	–	–
	Intersection with traffic lights	–	–	✓
	Turn directions	–	✓	
Work Zone	Lane closure/changing/narrowing	✓	✓	✓
	Traffic control/lane control	✓	✓	✓
	Work on shoulder	–	✓	–
	Employee/crew/workers	–	✓	–
	Truck and other INDOT vehicles	–	✓	✓
	Concrete barrier wall/concrete barricade	–	–	✓
	Signs for road closure	–	–	✓
	Ground guide	–	✓	–
Environment	Daylight	✓	–	–
	Clear weather	✓	–	✓
	Dry surface	✓	–	✓
	Late fall and winter (October, November, and January)	✓	–	–
	3:00 pm–5:59 pm	✓	–	–

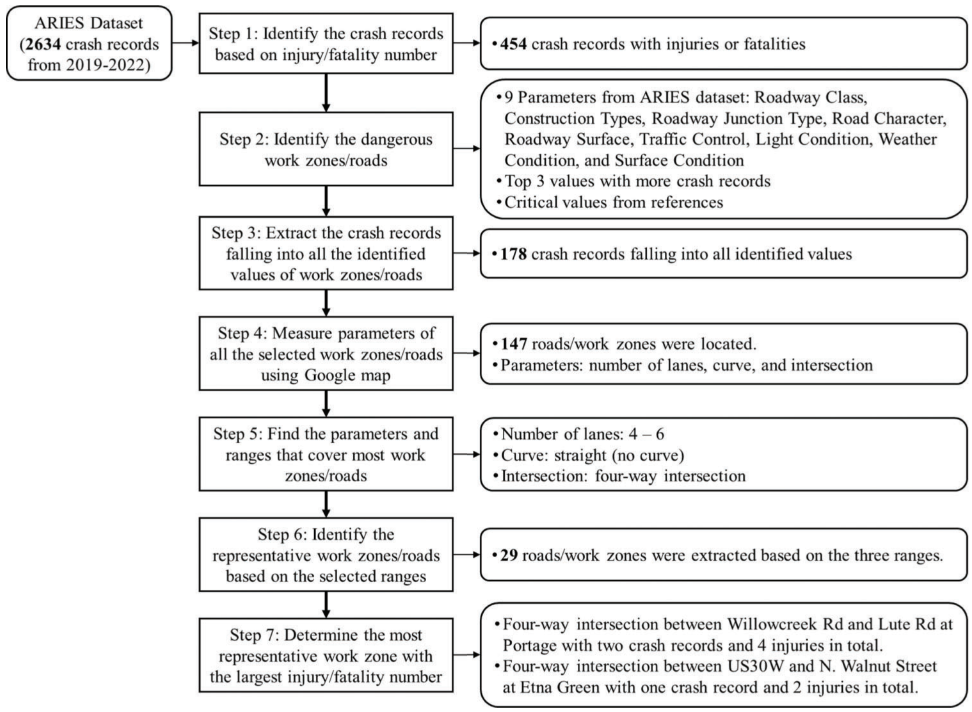


Figure 5.1 Process of selecting the work zone with top interests.

In step 1, the crash records having injuries or fatalities were identified as more dangerous cases. The "Number injured" and "Number dead" columns from the AREIS dataset were used. 454 out of 2,634 crash records (17.24%) that had people injured or dead were identified, in which 439 crash records only had injuries, 8 crash records only had fatalities, and 7 crash records had both injuries and fatalities. Then, in step 2, nine parameters from the ARIES dataset were used to identify the dangerous work zones, including roadway class, construction types, roadway junction type, road character, roadway surface, traffic control, light condition, weather condition, and surface condition. They are also the same nine parameters in the *Indiana Crash Fact 2019* book. The top 3 values with more crash records for each of those parameters as well as some other critical values from references were selected. The results are shown in Table 5.2, in which the selected values were *italicized.* For example, for light condition, daylight, dark (lighted), and dark (not lighted) were the top three values with a greater number of crash records. Dawn/dusk was also selected because *Indiana Crash Fact 2019* showed that late afternoon (3:00–5:59 pm) was a more dangerous time slot, which is related to dusk.

In step 3, the crash records falling into all identified values of nine parameters (*italic values* in Table 5.2) were extracted, resulting in 178 out of 454 crash records. Then, in step 4, the 178 crash records were located in Google Maps to measure the actual road sections. A total of 147 road sections were located, including 142 work zones that had one crash record per work zone, three work zones that had two crash records per work zone, and two work zones that had three crash records per work zone. Out of 147, 24 records containing missing/inaccurate location information were not located. For the 147 road sections, three road-related parameters were measured, including the number of lanes, road character (whether it is a curve or straight and which type of curve it is), and intersection (such as four-way intersection, T-intersection, ramp, etc.). One thing to note is that even though the AREIS dataset already covered the curve and intersection information, there were some inconsistencies between the real road situations and the information from the AIRES dataset, which has also been mentioned by an expert from the Indiana Department of Transportation work zone safety division. Also, it was found that there were some curves or intersections near the exact crash locations, which may be related to the crash but were not considered in the ARIES dataset. Therefore, manually checking the road character and intersection is necessary. In step 5, after collecting the values of road-related parameters, the range of each parameter that covers most work zones was identified to further narrow down work zones. Table 5.3 shows that 4 to 6 lanes (81 out of 147), straight roads without curves (101 out of 147), and four-way intersections (72 out of 147) were the most common values.

Moreover, in step 6, 29 representative work zones falling into the three ranges were extracted out of 147 work zones. Finally, in the last step, the most representative work zone with the largest number of injuries and fatalities from the 29 work zones was identified. Table 5.4 shows the number of injuries and fatalities in the 29 work zones. It was shown that 19 work zones only had one injury per work zone, five

TABLE 5.2
Summary of the Identified Values of Nine Parameters

Roadway Class	Number of Crashes	Construction Type	Number of Crashes	Roadway Surface	Number of Crashes
County Road	15	*Intermittent or moving work*	*73*	*Asphalt*	*378*
Interstate	*148*	*Lane closure*	*252*	*Concrete*	*73*
Local/City Road	*133*	*Work on shoulder*	*88*	Gravel	1
State Road or US Route	*148*	X-over/lane shift	41	Other	2
Other or Missing Value	10	–	–	–	–
Roadway Junction Type	**Number of Crashes**	**Weather Condition**	**Number of Crashes**	**Light Condition**	**Number of Crashes**
Four-way Intersection	*69*	Blowing sand/soil/snow	3	*Dark (lighted)*	*44*
Interchange	8	*Clear*	*315*	*Dark (not lighted)*	*62*
No Junction Involved	*353*	*Cloudy*	*65*	*Dawn/dusk*	*17* (Thelin et al., 2020)
Ramp	*8* (Sun et al., 2013)	Fog/smoke/smog	3	*Daylight*	*330*
T-intersection	*13*	*Rain*	*54*	Unknown	1
Y-intersection	3	Sleet/hail/freezing rain	1	–	–
	–	*Snow*	*13* (Thelin et al., 2020)	–	–
Road Character	**Number of Crashes**	**Traffic Control**	**Number of Crashes**	**Surface Condition**	**Number of Crashes**
Straight/Grade	*29*	*Lane control*	*81*	*Dry*	*357*
Straight/Hillcrest	*10*	No passing zone	2	*Ice*	*7*
Straight/Level	*186*	*None*	*82*	Loose material on road	6
Curve/Grade	*7* (Shen et al., 2021)	*Officer/crossing guard/ flagman*	*11* (El-Rayes et al., 2014)	Muddy	1
Curve/Level	*8* (Shen et al., 2021)	Other regulatory sign/ marking	11	*Snow/slush*	*5* (Thelin et al., 2020)
Curve/Hillcrest	1	Roundabout intersection	1	Water	6
Non-Roadway Crash	1	Stop sign and yield sign	7	*Wet*	*72*
Missing Value	212	*Traffic control signal*	*43*	–	–
	–	Other or missing value	216	–	–

Note: Selected values are italicized.

TABLE 5.3
Summary of the Values of Three Road-Related Parameters

Number of Lanes	< 4	4–6	> 6	–
Number of Work Zones	55	81	11	–
Curve Type	Simple curve	Reverse curve	Straight (no curve)	–
Number of Work Zones	26	20	101	–
Intersection Type	Four-way intersection	T-intersection	Ramp	No intersection
Number of Work Zones	72	41	19	15

Note: Some records have more than one type of intersection near the crash location. The nearest intersection type was selected. Within a four-way intersection, there are two roundabout records.

TABLE 5.4
Summary of 29 Work Zones

Number of Work Zones	1	1	3	5	19
Number of Fatalities Per Work Zone	2	0	0	0	0
Number of Injuries Per Work Zone	2	4	3	2	1

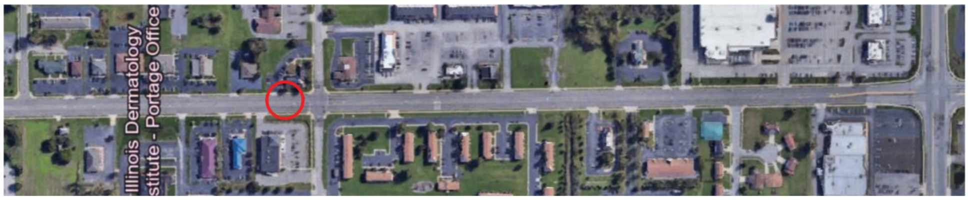


Figure 5.2 Road section of Willowcreek at portage.

Figure 5.3 Road section of US 30 W at Etna Green.

work zones had two injuries per work zone, three work zones had three injuries per work zone, one work zone had four injuries, and one work zone had two injuries and two fatalities.

According to Table 5.2, the top two work zone scenarios are lane closure and work on shoulder, which were selected as the two representative scenarios in this study. Even though the work zone near the four-way intersection between US 30 and N Oak Dr. at Plymouth had fatalities, it is a four-lane divided highway with railroad tracks near the intersection. The railroad tracks make the case too unique to be representative, which is supported by INDOT experts. Instead, the work zone near the four-way intersection between Willowcreek Rd and Lute Rd at Portage experienced two crashes and four injuries in total, covering both daytime and nighttime, making it more representative. Therefore, this work zone was selected as the lane closure case. The lane closure case is on an urban road without a shoulder lane; therefore, it cannot be used to simulate the shoulder work scenario. Then, the researchers reviewed the work zones in Table 5.4 to identify cases with shoulders and having higher number of fatalities and injuries. Finally, the work zone near the four-way intersection between US 30 W and N. Walnut Street at Etna Green with one crash record resulting in two injuries was selected as the shoulder work case.

Figure 5.2 shows the selected case for lane closure. It is a five-lane (with a dual left-turn lane in the center), two-way, local/city road in an urban area. The road surface is clear and dry, using asphalt. There is a traffic control signal in the intersection and the speed limit is 40 mph. According to the crash record, there were two crashes that happened in the same location: around 100 ft before the intersection between Willowcreek Rd and Lute Rd (red circle in Figure 5.2). The information on the two crash records is as follows.

- July 15, 2019, 2:29 pm, daylight, one injury, with lane control, rear-end crash. Narratives in crash record: *"Driver of vehicle #1 advised she was northbound on Willowcreek Rd in traffic approaching Lute Rd. She advised as she was slowing down her drink started to spill, and she went and grabbed for it and struck the rear of vehicle #2 that was stopped in traffic with her front end. Driver of vehicle #2 advised she was stopped in traffic on northbound Willowcreek Rd at Lute Rd when she was struck from behind in the rear bumper by the front end of vehicle #1."*
- August 31, 2019, 8:10 pm, dark (lighted), three injuries, with traffic control signal, rear-end crash. Narratives in crash record: *"Drivers 1 and 2 were southbound on Willowcreek at the intersection of Willowcreek and lute rd. Vehicle 1 crashed into the rear of vehicle 2. Driver 1 stated her child started crying and she looked back to check on him. When she turned her attention back toward the road, vehicle 2 was stopped in front of her and she struck the rear of the vehicle. Driver 2 stated he was stopped at the stop light and Willowcreek and lute when vehicle 1 struck his vehicle from behind."*

Figure 5.3 shows the selected case for shoulder work, which is a 4-lane, two-way, divided freeway in rural areas. The road surface is clear and dry, using asphalt. There is a traffic control signal in the intersection and the speed limit is 60 mph. According to the crash record, there was one crash that resulted in two injuries. The crash location was approximately 200 feet west of the intersection between US 30 W and N. Walnut Street (red circle in Figure 5.3). The information on this crash record is as follows.

- October 10, 2022, 6:23 pm, daylight, two injuries, with lane control, rear-end crash. Narratives in crash record: "*Driver of vehicle one (1) was traveling eastbound on W. US 30 in the area west of n. Walnut St. Driver of vehicle one (1) stated they momentarily looked down and noticed traffic was stopped when they looked back up. Driver of vehicle one (1) collided with the rear of vehicle two (2) who was stopped in traffic."*

6. IDENTIFICATION OF ROOT CAUSES BASED ON CRASH DATA

Crash data is one of the primary data sources for traffic safety studies (Imprialou & Quddus, 2019), including work zone safety (Ullman & Scriba, 2004; Yang et al., 2015), which records sufficient information on historical crashes, such as time, location, and crash-contributing factors (Imprialou & Quddus, 2019; Indiana State Police, 2022). More importantly, the crash data includes narratives, which describe more details about the crash scenarios and important insights into the crash causation (Das et al., 2021; Fitzpatrick et al., 2017; Kwayu et al., 2020). However, there are a large number of narratives with an unstructured form of information, which makes it hard to extract and interpret the information manually (Das et al., 2021; Kwayu et al., 2020). natural language processing (NLP) leverages artificial intelligence to process natural language text in a human-like manner, which can be used to extract information from text sources (Nadkarni et al., 2011; Xue & Zhang, 2021; Zhang & El-Gohary, 2016). NLP has been applied in traffic safety studies to analyze crash data. For example, Zhang et al. (2016) proposed a method based on NLP to extract features from crash narratives automatically. Kwayu et al. (2020) used NLP to extract information from Michigan's crash report narratives to understand the crash scenarios based on n-grams. Kwayu et al. (2021) further explored the key topics and their network topology from narratives for fatal crashes. In addition, Das et al. (2021) tested different NLP tools in analyzing crash narratives, such as text mining and topic modeling to understand the causes of motorcycle crashes. In this study, crash data in Indiana was analyzed using NLP to understand the root causes of work zone crashes. The contents of this session were included in a conference paper (Wu, Guo, et al., 2024).

6.1 Methodology of NLP Analysis

Figure 6.1 shows the flowchart of methodology used in this session, which includes three major steps: (1) narrative extraction and cleaning, (2) NLP analysis (n-grams and correlations), and (3) summary and interpretation of NLP results.

6.1.1 Narrative Extraction and Cleaning

This study utilized crash data from two resources to perform the NLP analysis: (1) Safety Occurrence Reports and (2) Automated Reporting Information Exchange System (ARIES) dataset (Indiana State Police, 2022). In total, 857 narratives from Safety Occurrence Reports and 1,835 narratives from the ARIES dataset were extracted.

For Safety Occurrence Reports, 999 reports between 2016–2021 were provided by INDOT. In the reports, there is a column "Why did this Occurrence happen?", which explains the causes of the work zone crashes. Thus, it was the target narrative. Finally, 857 narratives from 6 years were obtained for further analysis, as listed below.

- 2016: 132 records with 120 narratives
- 2017: 158 records with 133 narratives

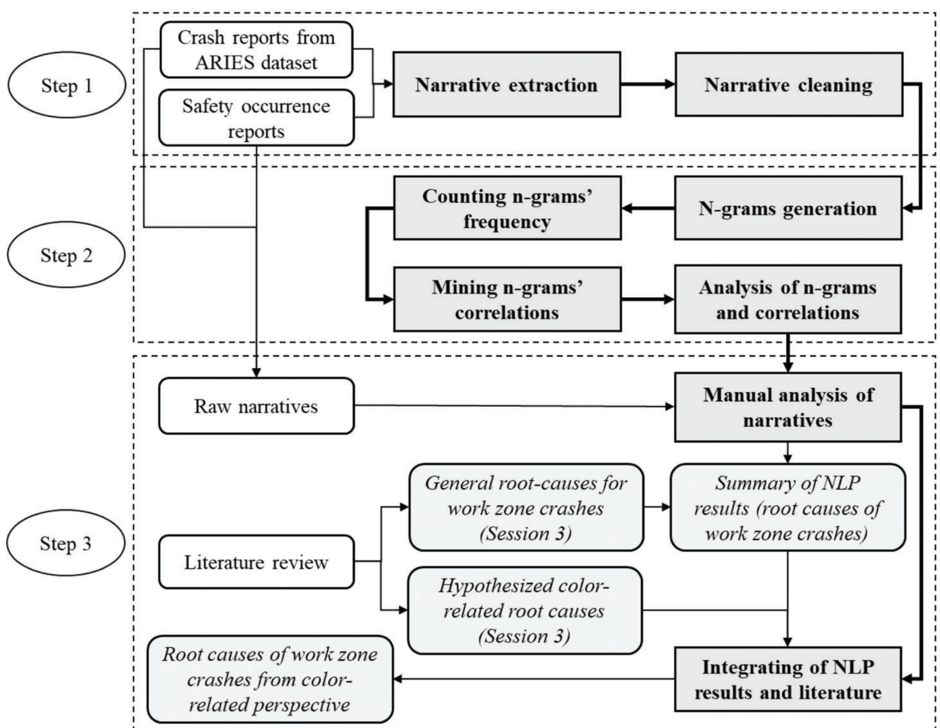


Figure 6.1 Process of identifying root causes for work zone crashes using NLP.

- 2018: 159 records with 131 narratives
- 2019: 161 records with 138 narratives
- 2020: 200 records with 176 narratives
- 2021: 189 records with 159 narratives

For the ARIES dataset, as the published ARIES crash data does not include narratives (Indiana State Police, 2022), the researchers contacted INDOT and Indiana State Police and got an account to the ARIES portal to get more information. In the portal, the authors extracted 1,835 crash reports using three criteria: (1) primary factor of crashes, which covered "road under construction," "drivers distracted," "speed too fast for weather conditions," "explain in narrative," "other (driver), explain in narrative," and "other (environment), explain in narrative." This criterion was used to obtain the crash reports related to road construction and human behaviors as well as reports having detailed explanations in narratives; (2) construction type, all four types were selected (i.e., "intermittent or moving work," "lane closure," "work on shoulder," and "x-over/lane shift"). It was used to further identify the crashes in work zones; and (3) date of collision, which covered 1/1/2019–12/31/2021 (2019: 644 crash reports; 2020: 509 crash reports; 2021: 682 crash reports). In the reports, there is a column "NARRATIVES," which is the target column of the NLP analysis. All the crash reports have corresponding narratives. Finally, 1,835 narratives from 3 years were used for further analysis.

Then, narrative cleaning was done before the formal analysis. Main tasks of narrative cleaning included: (1) converting texts to lowercase, (2) removing punctuations, numbers, special characters, and extra spaces, (3) tokenization, which means splitting the texts into tokens (e.g., words, phrases, and symbols), (4) removing stop words, such as "the," "a," "an," which add little value in providing information, and (5) stemming the tokens or reduce words to their root form (Kwayu et al., 2020; Zhang & El-Gohary, 2016). The tasks were performed leveraging the Python NLTK package (Kwayu et al., 2020; Zhang & El-Gohary, 2016). Specifically, stemming the tokens, Porter's Stemmer was applied to stemming the tokens.

6.1.2 NLP Analysis: n-grams and Correlations

After the data preparation, formal NLP analysis was performed, including generating the n-grams, counting the n-grams' frequency, and mining the correlations between top n-grams. Python NLTK package (Kwayu et al., 2020; Zhang & El-Gohary, 2016) was also applied to formal analysis. Unigrams (i.e., a single word), bigrams (i.e., a pair of two consecutive words, letters, or syllables), and trigrams (i.e., a sequence of three consecutive words, letters, or syllables) were generated. In this study, unigram to trigram is expected to be enough by balancing the information-extracting performance and data/resource requirements (Alonso et al., 2021). Only the n-grams that occurred in more than 5% of the total crash data were included to remove highly sparse n-grams (Kwayu et al., 2020). Then, frequencies of n-grams were counted. The higher frequencies indicate more appearances of the n-grams, which represent the more common and key information.

For the ARIES dataset, the n-grams whose frequency is larger than 91 (= 1,835 * 5%) were included. There were 276 unigrams and 126 bigrams. As for trigrams, because there were only 14 trigrams whose frequency was higher than 91, all the trigrams whose frequency ≥30 were further counted, which were 108 trigrams. For Safety Occurrence Reports, the n-grams whose frequency is larger than 42 (= 857 * 5%) were included. There were 42 unigrams. Because there were only 2 bigrams and 0 trigrams whose frequency was higher than 42, all the bigrams whose frequency ≥10 and trigrams whose frequency ≥4 were further counted, which were 40 bigrams and 23 trigrams. There were fewer n-grams from Safety Occurrence Reports than the ARIES crash reports because there were fewer narratives and fewer words and sentences in each narrative. Then, the top 50 unigrams, bigrams, and trigrams from the ARIES dataset and the top 30 n-grams from the Safety Occurrence Reports were generated.

Last, the frequency of each top unigram, bigram, and trigram in each narrative was calculated to get a matrix. Pearson correlation coefficients were calculated to identify the relations between these n-grams. Also, heat maps were generated to visualize these correlations. In addition, network graphs were drawn to further explore the relations between n-grams. The important cores in the network expressed the key information related to the crashes.

6.1.3 Summary and Interpretation of NLP Results

The third step was to interpret the NLP results. Raw narratives including the identified n-grams narratives from both datasets were checked manually to better understand the key n-grams and their correlations/networks. More importantly, for the ARIES dataset, although several criteria were applied to extract reports related to construction zones, after reviewing the narratives, the researchers noticed that there were still many narratives that did not mention work zone elements when explaining the crash scenarios. Thus, to better summarize the information related to work zone crashes, narratives were then selected randomly and read manually to further verify the results from NLP. One hundred narratives were reviewed manually, and 59% of them mentioned work zone related elements. Also, the general root causes for work zone crashes from the literature review identified in Session 3 were incorporated to further summarize and compare the NLP results. Lastly, the results from NLP and the hypothesized color-related root causes of Indiana work zone crashes from the literature review in Session 3 were combined to understand the root causes of work zone crashes from the color-related perspective.

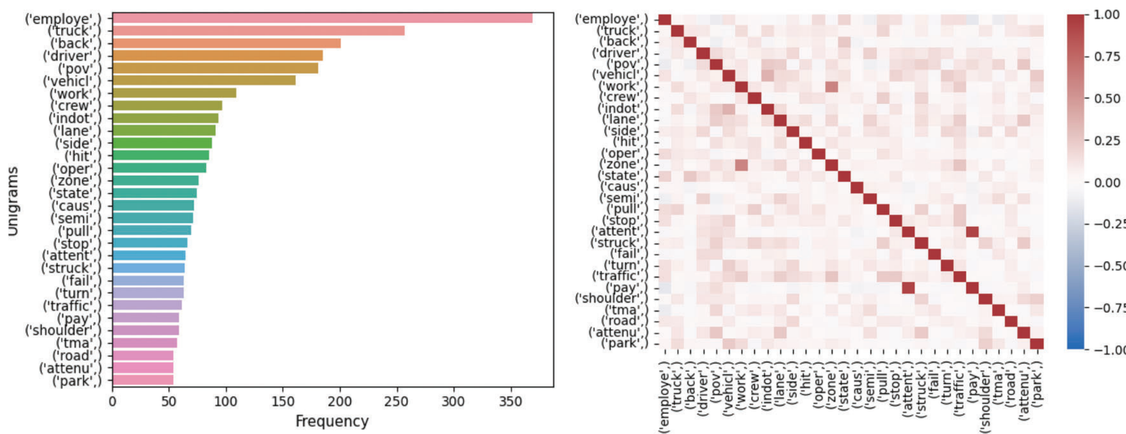
6.2 Results from Safety Occurrence Reports

Figures 6.2a and 6.2b show the frequency of the top 30 unigrams from Safety Occurrence Reports and their correlation coefficients. *employe*, *truck*, and *back* were the top three unigrams showing that work zone employees and trucks and the backing behaviors were key factors. Also, *crew, attent, turn, traffic,* and *shoulder* were key unigrams related to crews, attention, turn direction, traffic control, and work on shoulder. For heatmap, the deeper the red, the higher the correlations. *Attent* and *pay* showed the highest correlation. *Traffic* also had high correlations with many unigrams, such as *zone, stop, pull, lane*, and *work*.

Figures 6.3a and 6.3b show the top bigrams and their correlations. The bigram *(pay, attent)* was the top one emphasizing the importance of paying attention. The bigram *(rear, end)* showed that rear end was the major type of work zone crashes in Indiana. Also, several top bigrams mentioned *truck*, *crew*, or *driver*. For heatmap, *(rear, end)* and *(end, indot)*, *(crew, cab)* and *(back, crew)*, *(driver, side)* and *(side, mirror)* were the top three correlation pairs. Also, *(ground, guid)* had high correlations with *(side, mirror)* and *(driver, side)*, indicating that the ground guide was a key factor.

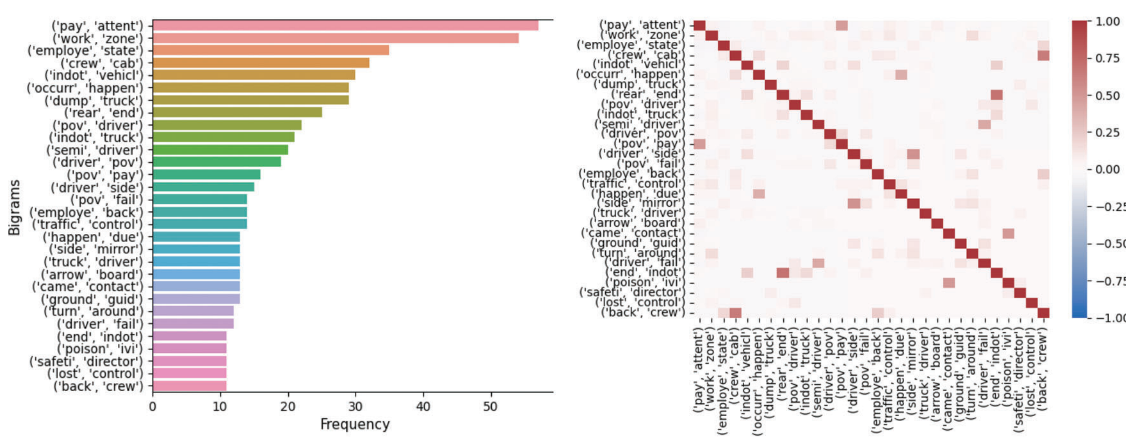
Figures 6.4a and 6.4b show the top trigrams and the correlation heatmap. The trigrams *(pov, pay, attent)*, *(driver, pay, attent)*, *(pay, attent, surround)*, *(truck, pay, attent)*, *(rear, end, indot)*, and *(pov, rear, end)* were the top ones emphasizing the importance of paying attention and the frequency of rear end crashes. The trigram *(enter, work, zone)* showed that many crashes happened when entering the work zone. Regarding the correlation, in addition to the information previously mentioned, the high correlation between *(chip, seal, oper)* and *(high, rate, speed)* indicated that high rate of speed was one cause.

In addition, Figure 6.5 shows the network graphs further illustrating the relationships between top n-grams. For network among unigrams (Figure 6.5a), *employe, pov* (personal owned vehicle), *lane, shoulder, traffic, crew*, *vehicl*, and *driver* were core unigrams. The network of bigrams (Figure 6.5b) showed that *(gound, guid)*, *(side, mirror)*, *(turn, around)*, *(rear, end)*, and *(lost, control)* were the core bigrams. Finally, network graph of trigrams (Figure 6.5c) indicated that the



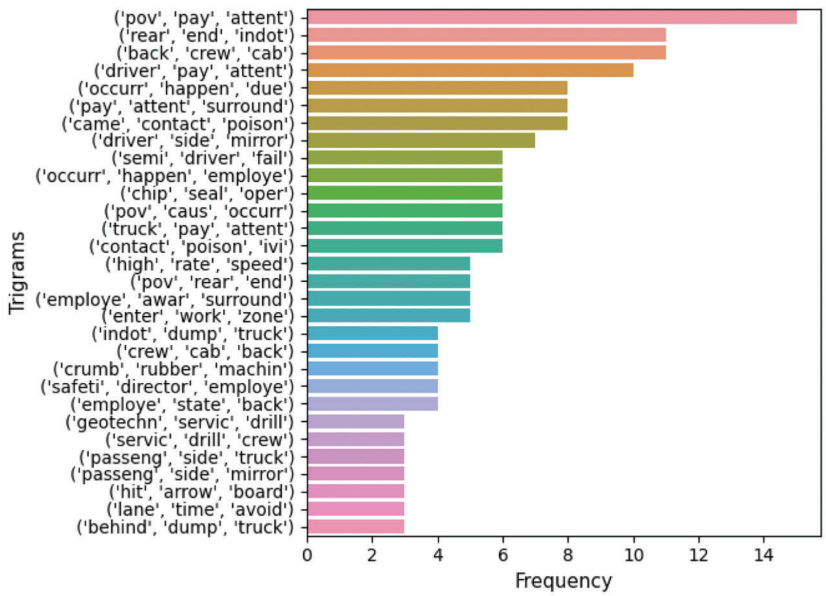
(a) (b)

Figure 6.2 Frequency and correlation heatmap of top 30 unigrams (Safety Occurrence Reports).

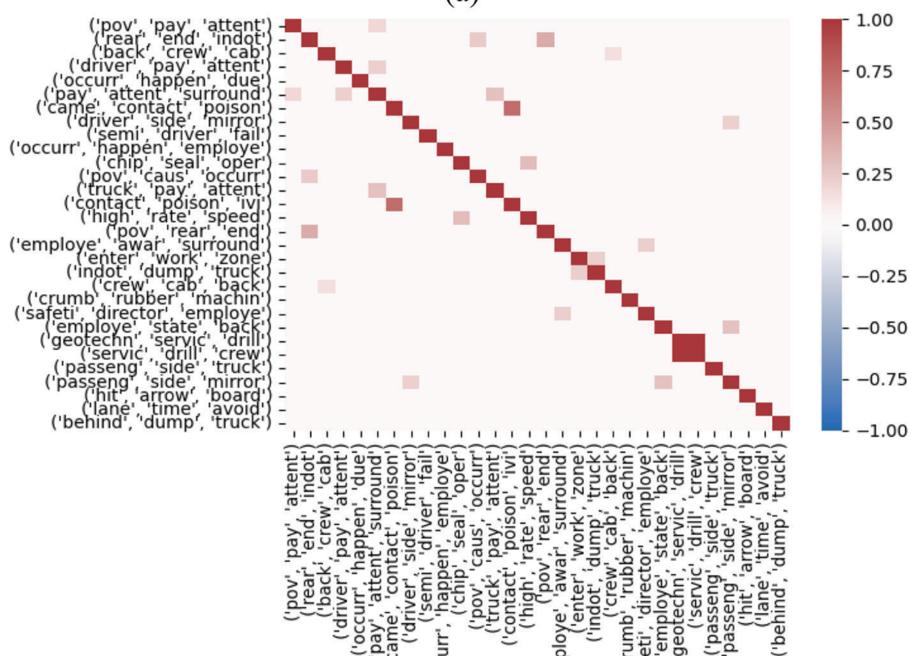


(a) (b)

Figure 6.3 Frequency and correlation heatmap of top 30 bigrams (Safety Occurrence Reports).



(a)



(b)

Figure 6.4 Frequency and correlation heatmap of top 30 trigrams (Safety Occurrence Reports).

trigrams were not related closely like unigrams and bigrams. The top core trigrams were *(pay, attent, surround)*, *(rear, end, indot)*, and *(passeng, side, mirror)*.

Finally, the key results from NLP analysis based on Safety Occurrence Reports were summarized in Table 6.1. There are 13 key points (i.e., key factors related to safety occurrences in INDOT work zones) falling into four categories: road and environment, work zone element, human, and others.

6.3 Results from ARIES Crash Reports

The top 50 unigrams from crash narratives in ARIES dataset include *lane, rear, traffic, construct, turn, light, intersect, truck,* and *trailer*, which were related to traffic lanes, traffic controls, rear end crashes, construction, turn directions, traffic lights, intersections, and truck and trailers. As for correlations, *rear* and *end*, *lane, right*, and *left*, *stop* and *traffic*, *light* and *intersect*, as well as *crash* and *time* were the top correlated unigram

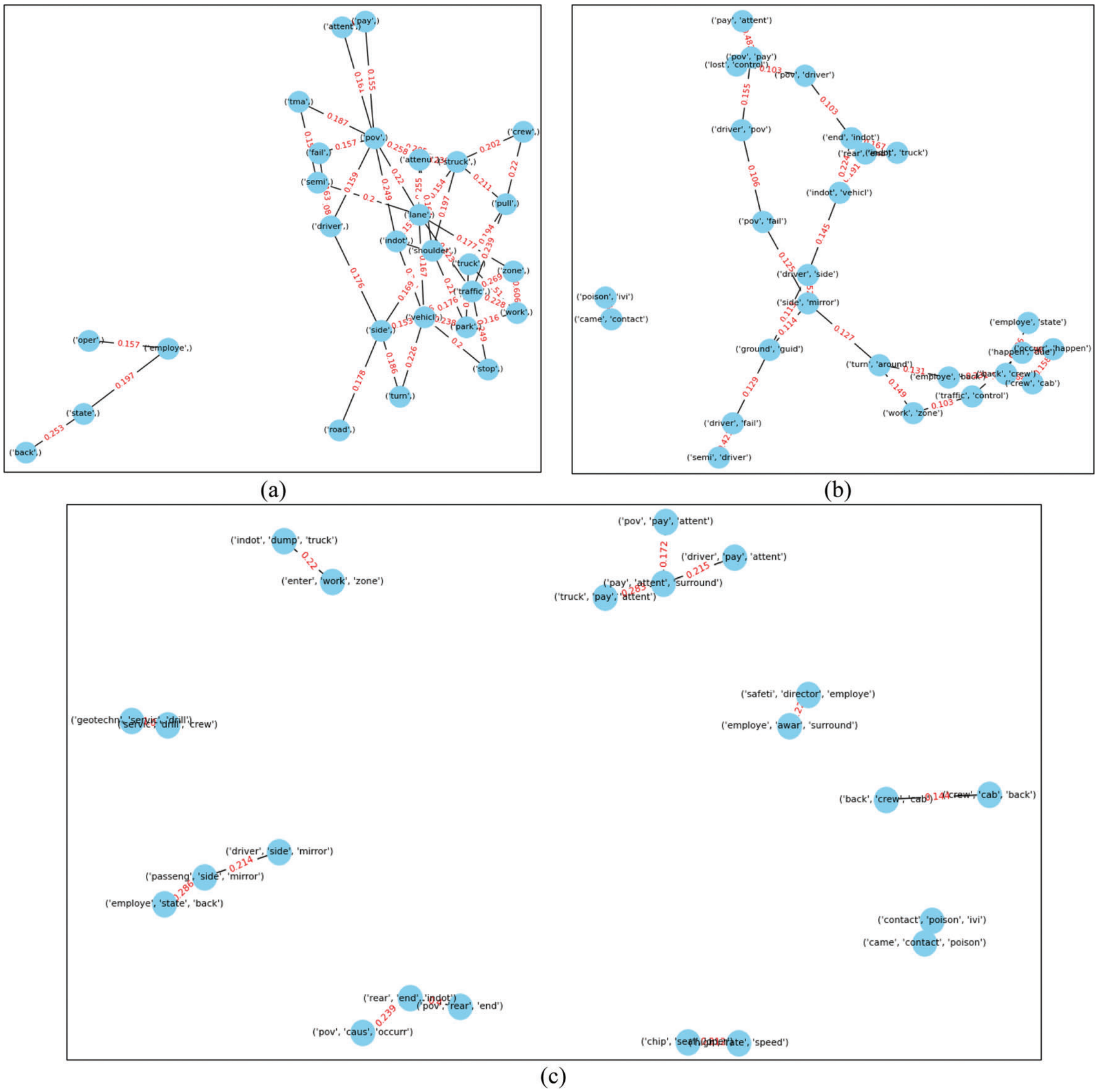


Figure 6.5 Network graph of top N-grams (Safety Occurrence Reports).

TABLE 6.1
Summary of the NLP Results from Safety Occurrence Reports

Category	No.	NLP Results from Safety Occurrence Reports
Road and Environment	1	Lane changing
	2	Traffic congestion or control due to construction
	3	Turn directions
Work Zone Element	4	Work on shoulder
	5	Truck and other INDOT work zone vehicles
	6	Entering the work zone
	7	The inappropriate use or missing of ground guide
	8	Work zone employee/crew/workers
Human	9	Drivers/workers did not pay attention.
	10	Backing behavior
	11	High rate of speed
Others	12	Side mirrors were damaged
	13	Rear end crashes

pairs. For more details, please see Figure D.1 in Appendix D.

The top 50 bigrams from crash narratives in ARIES dataset were *(rear, end)*, *(right, lane)*, *(left, lane)*, *(stop, traffic)*, *(construct, zone)*, *(road, surfac)*, *(concret, barrier)*, and *(crash, weather*), emphasizing the rear end crashes, lane changes and turn directions, traffic control, construction zone, road surface, concrete barriers, and weather condition. Then, *(road, surfac)* and *(crash, weather)*, *(crash, weather)*, *(surfac, dri)*, and *(road, surfac)*, *(rear, end)* and *(end, vehicl)*/*(end, v)* were highly related. For more details, please see Figure D.2 in Appendix D.

The top 50 trigrams from crash narratives in ARIES dataset included *(time, crash, weather)*, *(rear, end, vehicl)*, *(rear, end, v)*, *(road, surfac, dri)*, *(crash, weather, clear)*, *(clear, road, surfac)*, and *(weather, clear, road)*, which indicated the importance of weather condition, road surface, and common rear end crashes. The trigrams *(concret, barrier, wall)*, *(light, turn, green)*, *(stop, red, light)*, and *(road, close, sign)* further indicated the impacts of concrete barrier walls, traffic lights, and road closed sign on work zone safety. Also, there were high correlations among *(time, crash, weather)*, *(clear, road, surfac)*, *(weather, clear, road)*, *(road, surfac, dri)*, etc., showing the clear weather and dry road surface were common. For more details, please see Figure D.3 in Appendix D.

In addition, network graph of top unigrams showed that *turn, lane, rear, construct*, and *drivers* were the core keywords. For bigrams, *(lane, driver)*, *(rear, end)*, and *(stop, traffic)* were core n-grams in the network. As for trigrams, the network was more dispersed than unigrams and bigrams. For more details, please see Figure D.4 in Appendix D.

Finally, the key results from NLP analysis based on ARIES crash reports were summarized in Table 6.2. There are 12 key points (i.e., key factors related to Indiana work zone crashes) falling into four categories: road and environment, work zone element, human, and others.

6.4 Summary of NLP Results and Comparison with Literature

Table 6.3 summarizes the NLP results from Safety Occurrence Reports and the AREIS dataset as well as the causes of work zone crashes identified from the literature. 18 root causes were categorized into three groups (Others in Tables 6.1 and 6.2 were not included). Five root causes were supported by Safety Occurrence Reports, ARIES crash data, and literature review, including road geometry (e.g., turn directions, Intersections with traffic lights), lane closure, changing, or narrowing, traffic congestion due to construction, traffic control due to construction, and truck, trailer, and other work zone vehicles.

For road and environment, road geometry is a key cause. Narratives mentioned that *"Semi driver failed to turn around in the work zone, causing the semi-trailer to strike the boom inside of work zone."* Also, intersections with traffic lights are dangerous situations, especially when drivers want to turn directions. Narratives indicated *"Driver 1 was driving through the intersection with a yellow light when driver 2 pulled in front of her vehicle. Driver 2 was turning in the intersection when driver 1 struck her vehicle."* Then, road surface and weather conditions were emphasized, especially dry surface with clear or cloudy weather from crash data. Many narratives mentioned *"At the time of the crash, the weather was clear, and the road surface was dry."* For poor light conditions, time of the day, and limited sight distance, the Indiana crash data used in this study did not support those causes.

For work zone element, the first cause is lane closure/changing/narrowing/etc. Several narratives supported this finding, such as *"Semi crossing onto shoulder while merging from center lane to driving lane"* and *"Driver 1 did not observe the lane closure and the arrow board activated and flashing."* Then, crashes were related to traffic congestion or control due to construction. Some narratives were related to the causes, e.g., *"Vehicle 2 stopped in the travel portion of the roadway due to traffic congestion"* and *"Traffic on the turn lane is controlled by*

TABLE 6.2
Summary of the NLP Results from ARIES Crash Reports

Category	No.	NLP Results from ARIES Crash Reports
Road and Environment	1	Lane closure/changing/narrowing/etc.
	2	Traffic congestion or traffic control
	3	Intersections with traffic lights, especially when going through or turning directions
	4	Road surface and weather conditions
Work Zone Element	5	Construction
	6	Truck or trailer
	7	Concrete barrier wall/concrete barricade
	8	Road signs related to road closure
Human	9	Drivers' distraction
	10	Backing behavior
	11	Failed to stop/control the vehicle
Others	12	Rear end crashes

TABLE 6.3
Summary of the NLP Results and Comparison with Literature

Category	Root Causes of Work Zone Crashes	NLP Results from Safety Occurrence Reports	NLP Results from ARIES Crash Data	Literature Review (Session 3)
Road and Environment	Road geometry (e.g., turn directions, intersections with traffic lights)	✓	✓	✓
	Road surface and weather conditions	–	✓	✓
	Poor light conditions	–	–	✓
	Time of the day	–	–	✓
	Limited sight distance	–	–	✓
Work Zone Element	Lane closure/changing/narrowing/etc.	✓	✓	✓
	Traffic congestion due to construction	✓	✓	✓
	Traffic control due to construction	✓	✓	✓
	Truck, trailer, and other work zone vehicles	✓	✓	✓
	Work zone workers/crew/employee	✓	–	✓
	Work on shoulder	✓	–	–
	Entering the work zone	✓	–	–
	Road signs related to road closure	–	✓	–
	Concrete barrier wall/concrete barricade	–	✓	–
Human	High rate of speed	✓	–	✓
	Drivers/workers did not pay attention or distraction	✓	✓	–
	Backing behavior	✓	✓	–
	Failed to stop/control the vehicle	–	✓	–

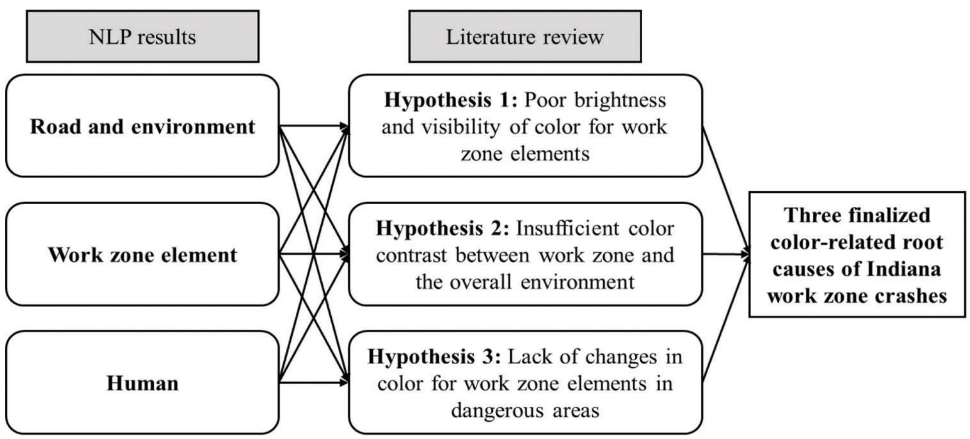


Figure 6.6 Finalized color-related root causes by integrating hypotheses and NLP results.

a yield sign." Next, trucks and other work zone vehicles were commonly included in crashes. Several narratives were related to this finding, such as *"Driver failed to yield when he was approaching salt truck."* and "*A truck was in the left lane and came over into the right lane causing him to swerve off of the road and hit the guardrail."* Work zone workers, crew, and employees were also a key factor. Narratives also supported this finding, such as *"Employee stepped back to avoid a car and was too close to skid steer."* Moreover, working on a shoulder is also a dangerous scenario. There were narratives related to it, such as *"the weak shoulder breaking off causing the machine to lean towards the ditch and turning over."* Then, the crash data indicates that crashes happened when entering the work zone. Narratives showed that *"Driver entered work zone striking INDOT dump truck."* In addition, the signs related to closed roads were important. Narratives supported this finding, such as *"Vehicle 1 attempted to go around closed road sign, left the roadway, and then got stuck in the ditch."* Finally, concrete barrier walls were included in many crashes. Narratives mentioned that *"Driver 1 lost control, went into a skid, and struck the concrete barrier wall in the restricted lane due to construction in the median area."*

For human-related factors, high rate of speed is a key cause of work zone crashes, such as the following.

- *"He was speeding and was cited for illegally passing in a no passing zone."*
- *"An upset Semi driver driving at high rate of speed cut over on INDOT truck patrolling on I-70 colliding with the front end of the truck causing damage to the hood and bumper."*

Then, narratives mentioned that crashes happened because drivers/workers did not pay attention or got distracted.

- *"This occurrence happened due to public's inattention in a work zone sign and spacing of signs were posted appropriately."*
- *"Public wasn't paying attention while driving through work zone."*
- *"Driver 1 was talking on her cell phone when she suddenly hit a concrete culvert."*

Also, backing was a common behavior related to crashes. Narratives supported this finding.

- *"Driver failed to use good judgment when backing a vehicle."*
- *"As Driver 1 was backing his pickup the left rear collided into the right rear of vehicle 2."*

In addition, many drivers mentioned that they failed to stop/control the vehicle.

- *"While waiting at the light, his foot slipped off of the brake pedal and his vehicle collided with V2."*
- *"When he applied his brake, he just slid."*

To further understand the root causes of work zone crashes from the color-related perspective, the summary of NLP results and the hypothesized color-related root causes (Session 3) identified based on the literature review were integrated, as shown in Figure 6.6. The hypothesized color-related root causes provide a deep understanding of Indiana work zone crashes considering color-related factors based on a literature review. The NLP results added more details to the hypotheses by revealing the root causes of Indiana work zone crashes based on crash data.

Finally, three hypothesized color-related root causes were verified and specified according to the crash data analysis.

1. Poor visibility and brightness of color for work zone elements: the work zone elements include traffic signs, channelizing devices, pavement markings, etc. related to the following situations.
    - Lane closure/changing/narrowing (e.g., Lane Closed Ahead sign and barricade)
    - Traffic congestion (e.g., Slow Traffic Ahead sign and Queue truck with a Be Prepared to Stop sign)
    - Traffic control (e.g., drums and barricades)
    - Truck, trailer, and other work zone vehicles (e.g., Truck sign)
    - Workers/crew/employee (e.g., Workers sign)
    - High rate of speed (e.g., Speed Limit sign and Speeding with Penalty sign)
    - Work on shoulder (e.g., Shoulder Work sign)
    - Entering the work zone (e.g., Road Work Ahead sign)
    - Road signs related to road closure (e.g., Road Closed Ahead sign and Detour Ahead sign)
    - Concrete barrier wall/concrete barricade for temporary traffic control
2. Insufficient color contrast between work zone elements and the overall environment: the work zone elements include similar items and situations mentioned in the first root-cause. In particular, the color contrast should be emphasized in the areas of road geometry change (e.g., turn directions, intersections with traffic lights) and road surface conditions change (e.g., slippery roads).
3. Lack of changes in color for work zone elements in dangerous areas: the work zone elements include similar items and situations mentioned in the first root-cause. The dangerous areas within work zones include the following.
    - Area when entering the work zone
    - Transition area where drivers are directed out of normal traffic due to lane closure, changing, narrowing, traffic control, shoulder work, and road closure
    - The areas of road geometry change, and road surface conditions change as discussed in the second root cause

The hypotheses about different seasons (i.e., yellow color for the late fall season and snow weather (white color) for the winter season), different time of the day (i.e., sunset time (yellow/red color of the sunset) and night construction (black background)), as well as different lighting conditions (i.e., flash pattern, glare level, and illumination level of daylights (e.g., sunset time) and artificial lights (e.g., at night)) were not verified by NLP results because the crash data did not reveal the key information related to season, time of the day, and lighting conditions.

7. COUNTERMEASURES

After determining the color-related root causes of work zone crashes in Indiana, this session aims to propose possible color-related countermeasures to increase the visibility and brightness of color, enhance the color contrast between work zone elements and the overall environment, and increase the changes in color for work zone elements in dangerous areas. Also, as there are hundreds of signs that could be used in the work zones, representative traffic signs were selected, which will be used in the driving simulation. Finally, an interview was conducted to collect experts' opinions regarding representative traffic signs and proposed countermeasures.

7.1 Representative Traffic Signs in Work Zones

When selecting representative traffic signs used in work zones, Federal MUTCD (FWHA, 2023b), Indiana MUTCD (INDOT, 2016), the Indiana *Work Zone Traffic Control Guidelines* (INDOT, 2023), and three representative INDOT Standard Drawings (including flagging, crossover, and lane closure) (INDOT, 2022) were explored. Figure 7.1 shows the relationship between those documents.

There are 173 signs in work zones from those documents in total (excluding regulatory signs in guideline and standard drawings), which can be divided into the following parts. (1) 147 signs from Part 6 of Federal and Indiana MUTCDs. (2) Area A in Figure 7.1: two signs (R2-12 and G20-5aP) in Federal MUTCD are not in Indiana MUTCD, which are

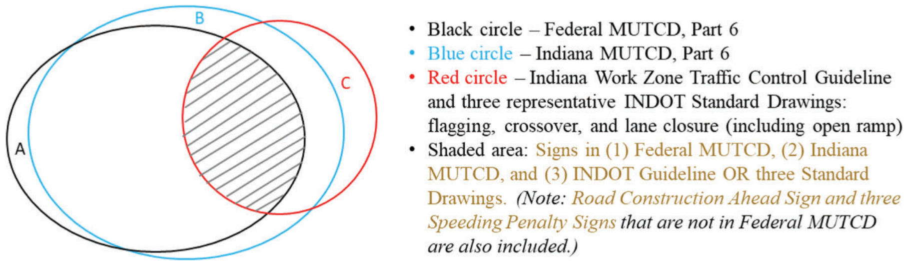


Figure 7.1 Relationships between documents.

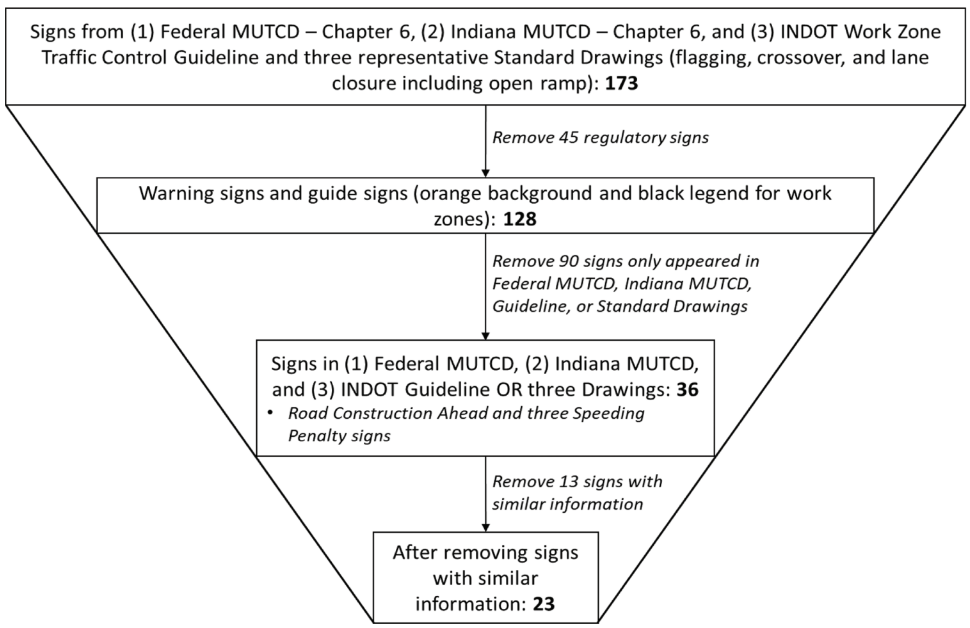


Figure 7.2 Process of sign selection.

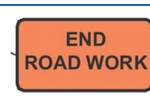
replaced by R2-Y12 and XG20-5P. (3) Area B in Figure 7.1: 13 new signs from Indiana MUTCD are not in the Federal MUTCD (e.g., Speeding Max $1,000 Reckless Driving Max 8 yrs (XW2-6), Road Construction Ahead (XW20-1)). (4) Area C in Figure 7.1: 2 signs (Exit (E5-1) and Ahead (W16-9P)) from the Indiana *Work Zone Traffic Control Guidelines* are not in Part 6 of both MUTCDs. Five signs without sign designations are different formats of existing signs (End Utility Work, Lane Narrows, Paint Crew Ahead, End Construction, and one large arrow, which means to keep right). Four signs from standard drawings are not in Part 6 of both MUTCDs (End Construction (XG20-2), Exit (XW109-1), Exit Open (XW106-2), Exit Closed (XW106-1)).

Starting from those 173 traffic signs, Figure 7.2 shows the process of sign selection. First, this study mainly focuses on the signs with unique colors when used in work zones (orange background with the black legend). Thus, 45 regulatory signs that have the same colors in work zones and general roads were removed, resulting in 128 warning and guide signs. Then, to extract the commonly used traffic signs, signs that appear in all three circles in Figure 7.1 were extracted, which is the shaded area, removing the other 90 signs that are only in one or two circles. One thing to note is that four signs that are not in Federal MUTCD were kept (i.e., the Road Construction Ahead sign and three versions of the penalty sign) because they are necessary signs in Indiana work zones, which are the key targets in this study. The 36 signs covered different shapes (diamond and rectangular), different types of information (words and symbols), and different locations (especially when entering the work zones). Last, to further narrow down the signs, 13 traffic signs with similar information were removed. For example, Road Work (with distance/ahead) (W20-1) and Road Construction Ahead (XW20-1) showed similar information. W20-1 was used in the Indiana *Work Zone Traffic Control Guidelines*, while XW20-1 was used in standard drawings. W20-1 was kept because it has a broader application to help generalize the results of this study to other States, while XW20-1 is the specific design for Indiana work zones. Finally, 23 traffic signs were kept, as shown in Table 7.1.

7.2 Color-Related Countermeasures

To propose color-related countermeasures, the existing color designs and possible alternatives of traffic

TABLE 7.1
Representative Traffic Signs

Sign	Figure	Sign	Figure	Sign	Figure
Speeding Max $1,000 Reckless Driving Max 8 yrs (XW2-6)		Workers (W21-1)		Lane Ends (W4-2)	
Lane(s) Closed (with distance) (W20-5)		Slow Traffic Ahead (W23-1)		Advisory Speed (W13-1P)	
One Lane Road (with distance) (W20-4)		Utility Work Ahead (W21-7)		Two-Way Traffic (XW6-3)	
Yield Ahead (W3-2)		Road Machinery Ahead (W21-3)		On Ramp (W13-4P)	
Road Work (with distance/ ahead) (W20-1)		Be Prepared to Stop (W3-4)		One-Direction Large Arrow (W1-6)	
Flagger (W20-7)		Road (Street) Closed (with distance) (W20-3)		Turn and Curve Sign (Reverse curve W1-4)	
Shoulder Work (W21-5)		End Road Work (G20-2)		Road Narrows (W5-1)	
Detour (with distance) (W20-2)		Exit Open (E5-2)			

signs, channelizing devices, pavement markings, and personal protective equipment (PPE) of workers from the Federal and Indiana MUTCDs were explored (INDOT, 2016; FHWA, 2023b). Also, some other potential new colors were identified from references as discussed in Session 3. Tables 7.2, 7.3, 7.4, and 7.5 show the possible color-related countermeasures with references. There were 11 designs for traffic signs, four designs for channelizing devices, two designs for pavement markings, as well as eight designs for PPE (including safety apparel and hard hats) for workers.

7.3 Interview Data Collection

7.3.1 Interview Questions

The interview contains four sections: (1) basic information, (2) representative traffic signs in work

TABLE 7.2
Possible Color-Related Countermeasures: Traffic Signs

No.	Countermeasure	Example	References: Sections from MUTCDs and Literature
1	Fluorescent orange sign with fluorescent yellow-green border		Atchley & Dressel, 2006
2	Doubling-up of fluorescent orange warning or guide sign		Section 2A.15 Enhanced Conspicuity for Standard Signs: B. Doubling-up of a standard regulatory, warning, or guide sign by adding a second identical sign on the left-hand side of the roadway (INDOT, 2016, p. 36).
3	Fluorescent orange warning sign with retroreflective orange flags		Section 2A.15: E. Adding one or more red or orange flags (cloth or retroreflective sheeting) above a standard regulatory or warning sign, with the flags oriented so as to be at 45 degrees to the vertical. (INDOT, 2016, p. 36) Section 6F.02: Standard orange flags or flashing warning lights may be used in conjunction with signs (INDOT, 2016, p. 586).
4	Fluorescent orange warning or guide sign with a yellow warning beacon		Section 2A.15: G. Adding a warning beacon (see Section 4L.03) to a standard regulatory (other than a STOP or a Speed Limit sign), warning, or guide sign (INDOT, 2016, p. 36). Section 4L.03 Warning Beacon: A Warning Beacon shall consist of one or more signal sections of a standard traffic signal face with a flashing CIRCULAR YELLOW signal indication in each signal section. A Warning Beacon shall be used only to supplement an appropriate warning or regulatory sign or marker (INDOT, 2016, p. 534). Section 6F.02: Standard orange flags or flashing warning lights may be used in conjunction with signs (INDOT, 2016, p. 586).
5	Fluorescent orange warning or guide sign with an orange warning beacon		
6	Fluorescent orange warning or guide sign with white LED units on the border		Section 2A.15: J. Adding light emitting diode (LED) units within the symbol or legend of a sign or border of a standard regulatory, warning, or guide sign, as provided in Section 2A.07 (INDOT, 2016, p. 36). Section 2A.07 Retroreflectivity and Illumination: Light emitting diode (LED) units may be used individually within the legend or symbol of a sign and at the border of a sign, except for changeable message signs, to improve the conspicuity, increase the legibility of sign legends and borders, or provide a changeable message. If used, the LEDs shall have a maximum diameter of 1/4 inch and shall be the following colors based on the type of sign: White, yellow, or orange, if used with temporary traffic control signs (INDOT, 2016, pp. 29–30). Zockaie et al., 2020
7	Fluorescent orange warning or guide sign with yellow LED units on the border		
8	Fluorescent orange warning or guide sign with orange LED units on the border		
9	Fluorescent orange warning sign with an orange retroreflective strip on the sign support		Section 2A.15: K. Adding *a strip of retroreflective material to the sign support* in compliance with the provisions of Section 2A.21 (INDOT, 2016, p. 36). Section 2A.21 Posts and Mountings: Where engineering judgment indicates a need to draw attention to the sign during nighttime conditions, a strip of retroreflective material may be used on *regulatory and warning sign supports*. If a strip of retroreflective material is used on the sign support, it shall be at least 2 inches in width, it shall be placed for the full length of the support from the sign to within 2 feet above the edge of the roadway, and *its color shall match the background color of the sign*, except that the color of the strip for the YIELD and DO NOT ENTER signs shall be red (INDOT, 2016, p. 44).

(Continued)

TABLE 7.2
(Continued)

No.	Countermeasure	Example	References: Sections from MUTCDs and Literature
10	Fluorescent orange warning or guide sign with a yellow flash warning light		Section 6F.02 General Characteristics of Signs: Standard orange flags or *flashing warning lights* may be used in conjunction with signs (INDOT, 2016, p. 586). Section 6F.83 Warning Lights: Warning lights are *portable, powered, yellow, lens-directed, enclosed lights*. When warning lights are used, they shall be *mounted on signs* or channelizing devices (INDOT, 2016, p. 624).
11	Fluorescent orange warning or guide sign with an orange flash warning light		

zones, (3) color-related countermeasures, and (4) comments. The interview questions are listed in Appendix A.

First, the basic information section collected participants' working positions, working experiences related to work zones and Indiana work zones, and self-evaluation of the level of expertise in key topics related to the interview using a 5-point scale. Second, the 23 traffic signs with designations and figures were listed in three subsections based on the locations of the signs. First, eight traffic signs that are usually used when entering the work zones were listed for participants to rank. Following this question, some signs that could be used instead of the eight signs were listed for participants to select the top one. For example, participants should select the top one from Road Work (with distance/ahead) (W20-1), Workers (W21-1), Slow Traffic Ahead (W23-1), Utility Work Ahead (W21-7), and Road Machinery Ahead (W21-3) signs. Second, two traffic signs that are usually used at the end of the work zone or when the drivers leave the work zone were listed for participants to rank. Third, seven traffic signs that are used both in general road and work zones (changed to orange) were listed. When ranking or selecting signs, participants were required to provide answers for each of the five criteria: commonly used, effectiveness to reduce crashes, drivers' attention, reducing speed, and overall importance. In addition, participants were asked to provide any other important work zone signs. Third, color-related countermeasures with example figures for signs, channelizing devices, pavement markings, and PPEs were listed. Participants were required to (1) select the countermeasures that could be used in work zones based on their experiences evaluating the feasibility of the countermeasures, and (2) select the countermeasures that could be effective in reducing work zone crashes based on their experiences evaluating the effectiveness of the countermeasures. Participants were also encouraged to provide any other feasible/effective countermeasures during this section. Finally, any other comments and suggestions from the participants were asked at the end of the interview.

7.3.2 Process and Participants

Regarding the process of conducting interviews, Purdue IRB approval was obtained before collecting data (#IRB-2022-1609). Then, invitation emails were sent out to potential participants, who are experts in work zones or color-related issues. After getting their responses, individual virtual meetings were scheduled to perform the interview by Teams, which lasted for 30–120 minutes per interview. The transcriptions of interviews were compiled based on the recordings. Finally, answers to interview questions and comments from participants were summarized.

The interview had 11 participants from various perspectives—including INDOT, Federal highway, manufactory, contractor, and university representatives—to get comprehensive opinions. Figure 7.3 summarizes the results of participants' work positions and experiences. Figures 7.3a and 7.3b indicate that the participants covered various working positions from different organizations, supporting the ideas from different roles in work zone safety. Figure 7.3c shows that the participants had an average of 12.41 years of working experience related to work zones, with 9.86 years specifically in Indiana. Participants also explained their main tasks related to work zones, including updating relevant standards, specifications, and drawings, reviewing work zone plans (including planning, safety, etc.), setting up work zones, performing construction work, and doing field reviews of work zones. Moreover, Table 7.6 shows the number of participants for each level of expertise of six items. Overall, most participants evaluated themselves as advanced or expert for those items, indicating that they were able to provide professional and informative responses.

7.4 Interview Results

7.4.1 Representative Traffic Signs

For the eight signs that are usually used when entering work zones, Road Work (with distance/ahead) (W20-1) was the most representative one that was

TABLE 7.3
Possible Color-Related Countermeasures: Channelizing Devices

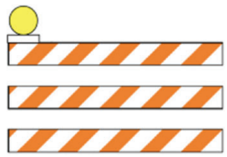
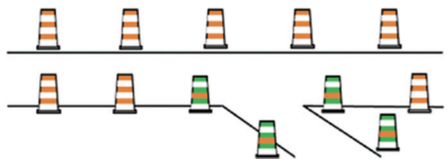
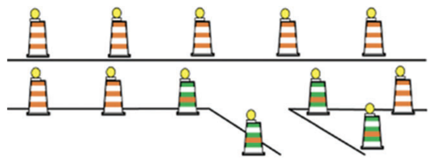
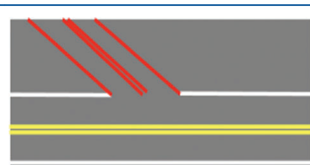
No.	Countermeasure	Example	References: Sections from MUTCDs and Literature
1	Fluorescent orange and white drum with yellow warning light		Section 6F.63 Channelizing Devices: Warning lights may be added to channelizing devices in areas with frequent fog, snow, or severe roadway curvature, or where visual distractions are present (INDOT, 2016, p. 614). Section 6F.83 Warning Lights: Warning lights are portable, powered, yellow, lens-directed, enclosed lights. When warning lights are used, they should be mounted on signs or channelizing devices (INDOT, 2016, p. 624).
2	Fluorescent orange and white barricade with yellow warning light		
3	Fluorescent orange, white, and green drum for exit ramp		Meyer, 2002 Sections related to warning lights in channelizing devices, which are the same as No. 1 and 2.
4	Fluorescent orange, white, and green drum for exit ramp with warning lights		

TABLE 7.4
Possible Color-Related Countermeasures: Pavement Markings

No.	Countermeasure	Example	References: Sections from MUTCDs and Literature
1	Orange pavement markings		Lammers-Staats et al., 2021; DuPont & DeDene, 2017; Shaw et al., 2018
2	Red pavement markings for one-way roadways, ramps, or travel lanes that shall not be entered		Section 3A.05 Colors: Markings shall be yellow, white, red, blue, or purple. When used, red raised pavement markers or delineators shall delineate: A. Truck escape ramps, or B. One-way roadways, ramps, or travel lanes that shall not be entered or used in the direction from which the markers are visible (INDOT, 2016, p. 352). Wu et al., 2020

ranked in the top three in all five criteria, which is also a required sign in Indiana work zones. Then, Flagger (W20-7), and Lane(s) Closed (with distance) (W20-5) were also representative as they were ranked in the top three in four criteria. In addition, Speeding Max $1,000 Reckless Driving Max 6 yrs (XW2-6) was ranked in the top three in two criteria and is also a required sign. Second, for the two signs at the end of the work zones or leaving the work zones, End Road Work (G20-2) was the most commonly used one because it is the only sign that can be used at the end of work zones (another version is End Construction specifically for Indiana), while Exit Open (E5-2) was ranked better for the remaining four criteria. Participants mentioned that Exit Open is important in specific situations because it provides information that drivers are looking for. Third, for the remaining seven signs, Lane Ends (W4-2) was the most representative sign, which was the top one in all five criteria, followed by Turn and Curve Sign (Reverse curve W1-4), which was ranked in the top three in all criteria. One-Direction Large Arrow (W1-6) was also evaluated as a representative one that ranked in the top three in four criteria.

TABLE 7.5
Possible Color-Related Countermeasures: PPE for Workers

No.	Countermeasure	Example	References: Sections from MUTCDs and Literature
1	Fluorescent yellow-green with yellow and silver stripes		Section 6D.03 Worker Safety Considerations: All workers, including emergency responders, within the right-of-way who are exposed either to traffic or to work vehicles and construction equipment within the TTC zone shall wear high-visibility safety apparel that meets the Performance Class 2 or 3 requirements of the ANSI/ISEA 107–2004 publication entitled *American National Standard for High-Visibility Safety Apparel and Headwear*, or equivalent revisions, and labeled as meeting the ANSI 107-2004 standard performance for Class 2 or 3 risk exposure, except as provided in Paragraph 5 (INDOT, 2016, p. 574). Section 6E.02 High-Visibility Safety Apparel: For daytime and nighttime activity, flaggers shall wear high-visibility safety apparel that meets the Performance Class 2 or 3 requirements of the ANSI/ISEA 107–2004 publication and labeled as meeting the ANSI 107-2004 standard performance for Class 2 or 3 risk exposure. The apparel background (outer) material color shall be fluorescent orange-red, fluorescent yellow-green, or a combination of the two as defined in the ANSI standard. The retroreflective material shall be orange, yellow, white, silver, yellow-green, or a fluorescent version of these colors, and shall be visible at a minimum distance of 1,000 feet. The retroreflective safety apparel should be designed to clearly identify the wearer as a person (INDOT, 2016, p. 576).
2	Fluorescent yellow-green with white and silver stripes		
3	Fluorescent orange-red with yellow-green and silver stripes		
4	Fluorescent orange-red with yellow and silver stripes		
5	Fluorescent orange-red with white and silver stripes		
6	Red hard hat		Turner et al., 1997
7	Yellow hard hat		
8	Blue hard hat		Color circle supports the color contrast between blue and orange.

Participants also provided comments regarding those traffic signs. Some participants mentioned that the more commonly used signs would be less effective because people may be too familiar with them and then stop reading those signs. Thus, new color designs could be applied to those signs to enhance their effectiveness. Also, participants indicated that every sign is important, and they are just used in different scenarios. Therefore, the specific representative traffic signs that will be used in the simulation experiment should also be based on the selected case.

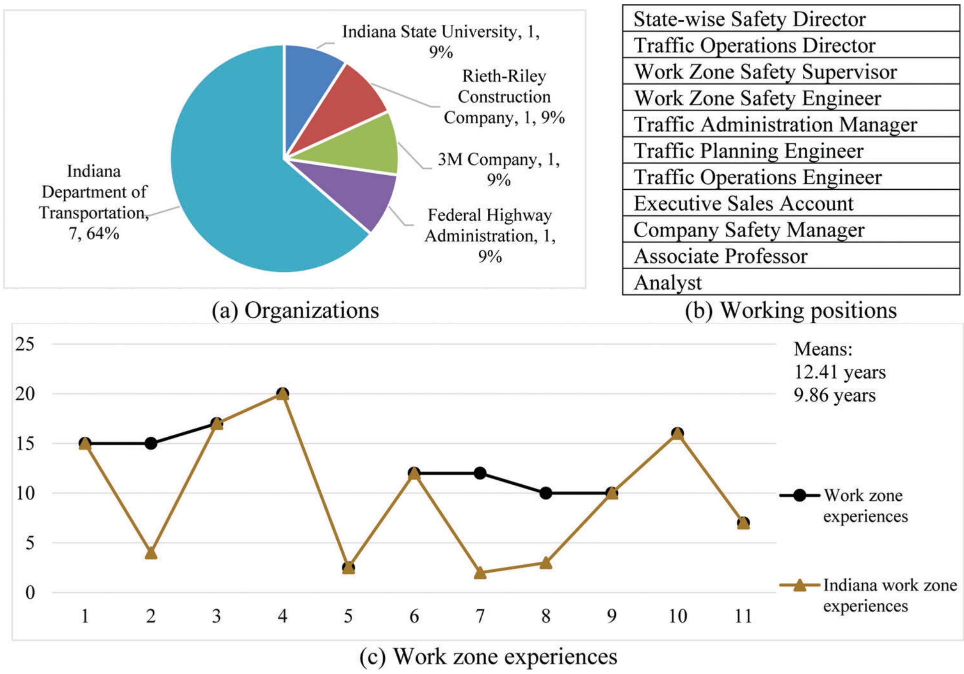


Figure 7.3 Basic information of participants.

TABLE 7.6
Expertise Level of Participants

	Items					
Levels	**Application of Traffic Signs in Work Zones**	**Color Code of Traffic Control Devices**	**Design of Traffic Signs in Work Zones**	**Design of Channelizing Devices in Work Zones**	**Design of Pavement Markings in Work Zones**	**Design of PPE for Workers**
Beginner	1	1	1	1	1	2
Novice	0	0	2	0	0	1
Intermediate	1	3	1	2	3	3
Advanced	7	4	5	6	5	5
Expert	2	3	2	2	2	0
Total	*11*	*11*	*11*	*11*	*11*	*11*

Finally, nine representative signs were selected from the 23 signs. When entering work zones, Road Work (with distance/ahead) (W20-1) and Speeding Max $1,000 Reckless Driving Max 6 yrs (XW2-6) are two representative and required signs. At the end of work zones, End Road Work (G20-2) is the representative one. For some specific scenarios, the following six signs are representative ones: Lane(s) Closed (with distance) (W20-5) for lane closure, Flagger (W20-7) for flagging scenario, Exit Open (E5-2) for open ramp, Lane Ends (W4-2) for lane ends scenario, Turn and Curve Sign (Reverse curve W1-4) for work zones with curves, and One-Direction Large Arrow (W1-6) for scenarios requiring specific directional guidance. The exact signs and formats used in the driving simulation experiment should be adjusted based on the selected case and scenarios. More details of the ranks of traffic signs are listed in Table D.1 in Appendix D.

7.4.2 Color-Related Countermeasures

For traffic signs, doubling-up of fluorescent orange sign, fluorescent orange sign with an orange warning beacon, and fluorescent orange sign with orange LED units are the top three countermeasures that most participants (at least 8 out of 11) agreed with their feasibility and effectiveness. The color (i.e., orange) that was supported by most participants was selected in one type of design. Then, for channelizing devices, even though fluorescent orange and white drum with yellow warning light and fluorescent orange and white barricade with yellow warning light were identified as feasible and effective countermeasures by 9 out of 11 participants, they are already standard requirements in Indiana work zones, which do not need to be investigated further. Also, fluorescent orange, white, and green drums for the exit ramp would be the feasible and effective countermeasure supported by 9 out of

11 participants. Moreover, for pavement markings, orange pavement marking is a more effective countermeasure, while both countermeasures are feasible according to the interview results. However, the orange pavement marking is currently being evaluated in Indiana work zones in ongoing research (SPR-4935), which indicates that it is not necessary to be tested in the driving simulation. Finally, for PPE for workers, many participants indicated that the current design of safety apparel in INDOT would be more effective and safer than the proposed designs. And the new designs of hard hats were not supported by many participants.

Participants also provided comments and suggestions regarding color-related countermeasures. First, participants emphasized the importance of only applying the new designs for some important signs that we really want people to read and keep orange to let people know they are in work zones. Thus, the selected countermeasures will only be applied to a limited number of signs to avoid overwhelming information. Second, even though this study aims to provide new color-related designs, some participants indicated that too many colors in the work zones would lead to distractions, which should be considered when proposing countermeasures. Third, when proposing the countermeasures, the consistency of standards across different states should be considered to reduce the learning/education needs of drivers. Last, some participants mentioned not over-using lighting in work zones, which may also distract drivers.

Based on the results, three sign countermeasures (doubling-up of fluorescent orange sign, fluorescent orange sign with orange warning beacon, and fluorescent orange sign with orange LED units) and one drum countermeasure (fluorescent green, orange, and white drum for exit ramp) are possible countermeasures that can be further tested. Table D.2 in Appendix D shows the details of results and summary of comments from participants regarding the feasibility and effectiveness of color-related countermeasures.

Then, literature related to those countermeasures was explored to help determine the final countermeasures that will be tested in the driving simulation. Exiting studies explored doubling-up of speed limit signs under truck platooning situation (Alsghan, 2018), rectangular rapid flashing beacon (RRFB) (i.e., a rectangular-shaped LED mounted adjacent to standard pedestrian and School Crossing warning signs) (Fitzpatrick & Park, 2021; Rista & Fitzpatrick, 2020); Pedestrian- or School-Crossing warning signs with light-emitting diodes (LEDs) embedded in the borders (Fitzpatrick et al., 2022; Fitzpatrick & Park, 2021; Fitzpatrick et al., 2023; Rista & Fitzpatrick, 2020); and LED-enhanced Do Not Stop on Tracks sign (Baron & daSilva, 2019; Hellman, 2021). However, there is a lack of studies investigating the three countermeasures proposed in this study for work zone signs. Therefore, three sign countermeasures should be further investigated in the experiment.

For drum countermeasure, an existing study already investigated two layouts of the same countermeasure on an exit within an interstate work zone (green drums on one side of the ramp or both sides of the ramp) by on-site recording data (Meyer, 2002). Also, the sign countermeasures and the drum countermeasures are not comparable because they have different functions, locations, numbers, etc., which will impact drivers' eye movement and driving performance. Moreover, sign countermeasures have a larger application than drum countermeasures. Sign countermeasures can be applied to all work zone signs, especially in dangerous areas (e.g., entering the work zone and transition area), while the drum countermeasure can only be used when there is an open ramp. In addition, including drum countermeasure in the experiment requires participants to exit through the ramp each time, which means they will leave the work zone early without passing the *End Road Work* sign. The data collection at the end of the work zone will be impacted for all countermeasures. Therefore, to achieve an exact comparison between countermeasures and reduce any potential risks and issues that will impact data collection, this experiment will only include three sign countermeasures. After testing the three sign countermeasures and finding the most effective one, a follow-up experiment may be conducted to test the most effective sign countermeasure and the drum countermeasure later.

8. DRIVING SIMULATION

After determining the representative work zones (Session 5), traffic signs (Session 7), and color-related countermeasures based on root causes (Session 7), this session aims to simulate the selected work zones with and without selected countermeasures in a driving simulation for the experiment. The initial driving simulation platform was developed using Webots and SUMO software in another study by the research team (Zhang et al., 2024; 2025). Based on the representative work zones as well as unique elements and countermeasures, the initial platform was modified to simulate different components, such as the road environment, work zone elements, streetlights, etc.

8.1 Key Elements of the Driving Simulation

The key elements in the driving simulation are as follows.

- *Two work zone scenarios:* Work zone scenario is a key factor impacting the work zone safety and performance of countermeasures based on the comments from interviewees. Thus, the top two construction types from the ARIES dataset (Table 5.2) were selected to be simulated in the driving simulation, which are lane closure scenario and shoulder work scenario. As listed above, two separate work zones were selected for the two work zone scenarios, with different layouts and traffic signs/devices.

- *Three countermeasures:* Three sign countermeasures proposed in Session 7 were simulated in the driving simulation, including (1) doubling-up of fluorescent orange sign, (2) fluorescent orange sign with orange warning beacon, and (3) fluorescent orange sign with orange LEDs. For beacons and LEDs, they were set up as constantly on (no flashing) both day and night.
- *One sign will be changed:* In this study, the countermeasures were only applied to one sign in each work zone scenario, which is the sign before the transition area (Right Lane Closed Ahead sign for lane closure scenario as shown in Figure 8.1 and Right Shoulder Closed Ahead sign for shoulder work scenario as shown in Figure 8.2). Other traffic signs and traffic control devices remained the same throughout the driving simulation.
- *Two-time scenarios:* As the comparison between daytime and nighttime would be important for beacon- and LED-enhanced signs, and both daytime and nighttime were examined when testing the sign with beacons or LEDs in one existing study (Fitzpatrick & Park, 2021), this experiment will include both daytime and nighttime. According to the ARIES dataset (Table 5.2), the top two light conditions are also daylight and dark (with/without lights). Therefore, daytime and nighttime are two-time scenarios included in the driving simulation. The major differences between them are lighting conditions. For the daytime scenario, all lighting conditions were set up following daylight conditions—daylights with other lighting devices are off in the environment (e.g., no streetlights, no flashing lights for drums, etc.). For the nighttime scenario, all lighting conditions were set up following the nighttime lighting conditions: do not have daylights with other lighting devices in the environment are on (e.g., having streetlights when there are streetlights for the selected road, having flashing lights for the drums if required, etc.). The countermeasures with beacon and LEDs and other traffic control devices that are required to be on both day and night (e.g., arrow board in the lane closure scenario) were kept on in two-time scenarios.
- *Traffic flow:* No traffic flow in the same direction as the participants was provided, to avoid any interferences in their driving behaviors. The traffic flow was set up in the opposite lanes without interacting with drivers. The traffic volume was determined using the Annual Average Daily Traffic (AADT) data from the Traffic Count Database System (https://indot.public.ms2soft.com/tcds/tsearch.asp?loc=Indot&mod) to help provide a realistic traffic scenario. Specifically, the traffic lights in the four-way intersections were controlled to make sure that when the drivers approach the intersection, the lights will be green in their driving direction and red in the intersected direction. In this way, no turning traffic was included in the intersection and the traffic will not influence the drivers in the experiment.

8.2 Layouts of the Selected Work Zones

As discussed in Session 5, two work zones were selected based on a seven-step process and crash data for the two work zone scenarios. The drawings of the work zone layouts with corresponding traffic signs and controls identified in Session 7 are listed in Figures 8.1 and 8.2. The work zone layouts were determined following the Indiana *Work Zone Traffic Control Guideline* (INDOT, 2023), INDOT Standard Drawings of lane closures and shoulder work (INDOT, 2022), as well as Indiana MUTCD (INDOT, 2016), which were created with the help of INDOT experts.

Figure 8.1 shows the lane closure work zone near the four-way intersection between Willowcreek Rd and Lute Rd at Portage, Indiana. The total length of the road section is 3,860 ft. The road geometry was retrieved from Google Maps. In this layout, the following traffic signs and traffic control devices are included: Speeding with penalty sign, Road Work Ahead sign, Right Lane Closed Ahead sign, Lane Ends sign, arrow boards (big arrow in the figure, which is on both day and night), merge taper with drums having Type C flashers (which is only on at night), buffer length having drums without flashers, shadow vehicle area with roll ahead distance, work area, and End Road Work sign. All the distances in the figure were calculated based on Indiana MUTCD, the *Indiana Work Zone Traffic Control Guideline*, and standard drawings. Before the Speeding penalty sign, in the driving simulation, a speed limit sign (40 mph) was added at the beginning to remind the drivers of the speed limit of the road section. The target traffic sign where the countermeasures were applied is the Right Lane Closed Ahead sign, which was put at the location

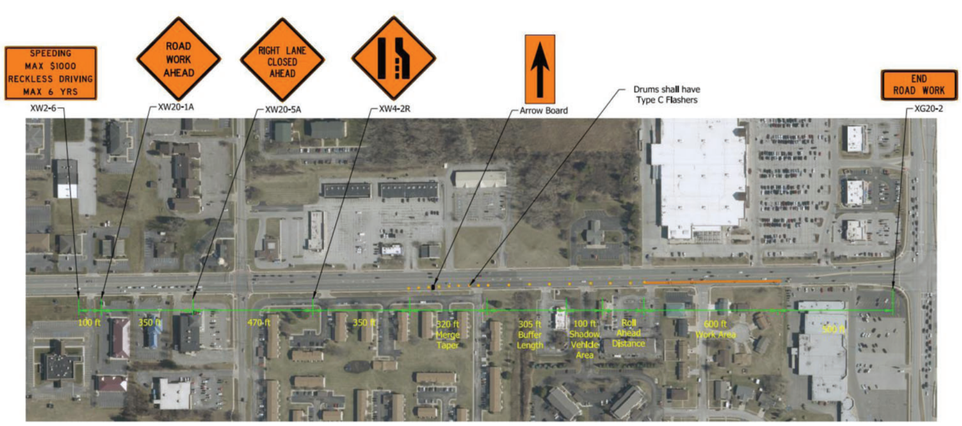


Figure 8.1 Drawing of the selected work zone with lane closure scenario.

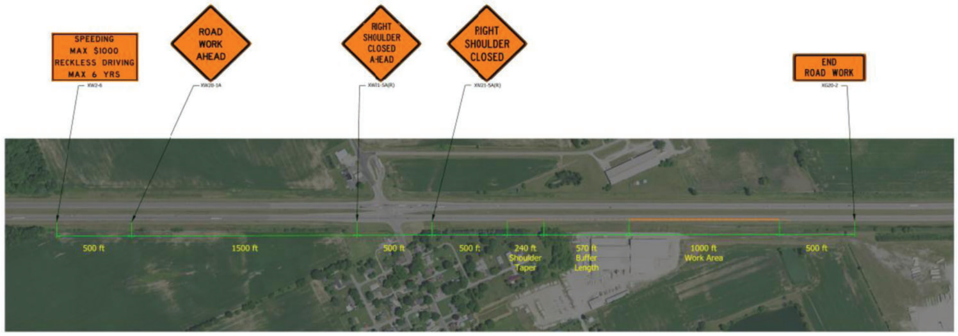


Figure 8.2 Drawing of the selected work zone with shoulder work scenario.

Figure 8.3 Experiment set up in lab.

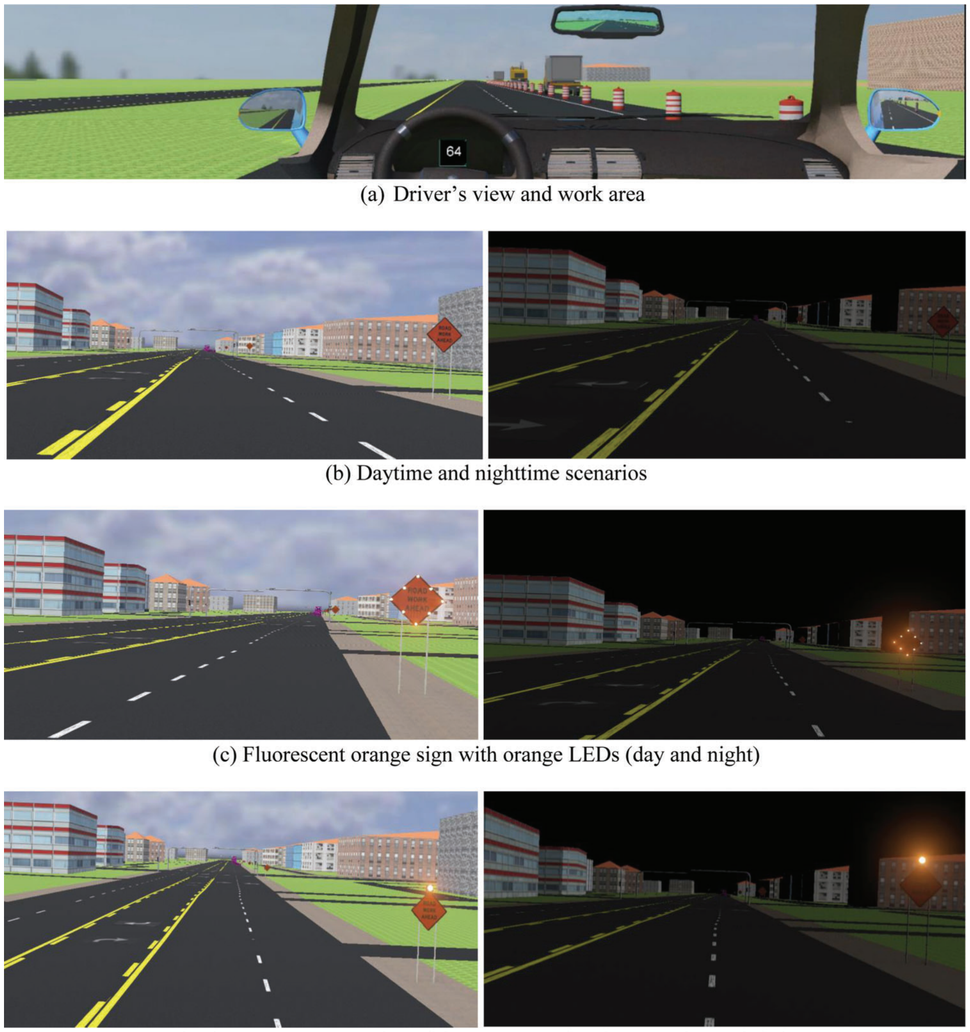
of the two crashes identified from the crash records (around 100 ft before the intersection between Willowcreek Rd and Lute Rd, as shown in Figure 5.2).

Figure 8.2 shows the work zone with shoulder work scenario near the four-way intersection between US 30 W and N. Walnut Street at Etna Green, Indiana. The total length of the road section is 5,310 ft. The road geometry was retrieved from Google Maps. In this layout, the following traffic signs and traffic control devices are included: Speeding with penalty sign, Road Work Ahead sign, Right Shoulder Closed Ahead sign, Right Shoulder Closed sign, shoulder taper with drums, buffer length with drums, work area, and End Road Work sign. Similarly, before the Speeding with penalty sign, a speed limit sign (60 mph) was added at the beginning of the road section. All distances in the drawing were determined based on the documents listed above. The target traffic sign where the countermeasures were applied is the Right Shoulder Closed Ahead sign, which was put at the location of the crash identified from the crash record (around 200 feet west of the intersection between US 30 W and N. Walnut Street, as shown in Figure 5.3).

8.3 Scenario Simulation

Webots is an open-source tool that is used to simulate robots. It can model, program, and simulate robots and the related environment (https://cyberbotics.com/). In this study, Webots was used to create a virtual road environment (e.g., road geometry, trees and buildings, sky, etc.) and traffic scenario (e.g., the driver's view, vehicles, etc.). SUMO is also an open-source tool to achieve traffic simulation (SUMO, 2025). It was used to create the road point file based on the OpenMapStreet data (https://www.openstreetmap.org/). The Logitech G29 racing wheel (including the steering wheel, brake, and gas pedal) was used in the experiment set up for the drivers to interact with the driving simulation. Figure 8.3 shows the experiment set up in the lab, covering three monitors, a mounted eye tracker (Gaze Point 3), and the Logitech racing wheel and pedals.

Figure 8.4 shows the example screenshots of the driving simulation scenarios and different countermeasures. Figure 8.4a is the driver's view of the simulation, including rear mirrors, speed panel (the number is the speed of the vehicle (mph)), road, and the overall environment. Figure 8.4b shows examples of two-time scenarios in the driving simulation. Left side is the daytime scenario with a clear day, and the right side is the nighttime scenario without daylight. Figure 8.4c shows the example work area setting in the driving simulation from the driver's view. In the work area, working vehicles and equipment (e.g., truck, backhoe, etc.) and traffic control devices (e.g., drums) were included, but it is assumed that no active workers are in the work area for both work zones. Figure 8.4d



(a) Driver's view and work area

(b) Daytime and nighttime scenarios

(c) Fluorescent orange sign with orange LEDs (day and night)

(d) Fluorescent orange sign with orange warning beacon (day and night)

Figure 8.4 Example screenshots in driving simulation.

shows examples of the countermeasure of fluorescent orange sign with orange LEDs both during daytime and nighttime. The LEDs were set up as constantly on in all scenarios. Figure 8.4(e) shows the examples of the countermeasure of fluorescent orange sign with orange warning beacon both at daytime and nighttime. The beacon was also set up as constantly on in all scenarios.

9. DRIVING SIMULATION EXPERIMENT: DATA COLLECTION AND ANALYSIS

After finishing the driving simulation, this session aims to discuss data collection through a driving simulation experiment, including demographic information, driving performance, eye movements, and self-evaluation, and the data analysis to evaluate the proposed color-related countermeasures in two selected work zones. As the two selected work zones have different work zone scenarios (lane closure and shoulder work), different signs applied the countermeasures (Right Lane Closed Ahead sign and Right Shoulder Closed Ahead sign), and different work zone layouts (as shown in Figures 8.1 and 8.2), separate experiments were conducted for lane closure case and shoulder work case, respectively.

9.1 Experiment Design

To conduct the driving simulation experiments, Purdue IRB approval was obtained before collecting data (#IRB-2023-1668). A 2*4 within-subject experiment design was applied in each work zone scenario (each experiment). According to the power analysis of the Analysis of Variance (ANOVA) test (power = 0.95), the minimum sample size for each work zone scenario is 24, as shown in Figure D.5 in Appendix D. Considering the potential comparison between two work zone scenarios, in which the minimum sample size is 64 based on power analysis (power = 0.90), the sample size was determined to be 64. The target participant numbers are 32 for the lane closure experiment and 32 for the shoulder work experiment. The experiment design for all participants in two experiments is listed in Table D.2 in Appendix D.

For the lane closure experiment, the 2*4 design includes the two-time scenarios and 4 countermeasures (3 countermeasures and one original design). The parameters are explained as follows.

- Number of work zone scenarios = 1 (lane closure).
- Number of time scenarios = 2 (daytime and nighttime).
- Number of countermeasure conditions in each scenario = (Number of sign countermeasures + 1)$^{(\text{Number of signs that will be changed})}$ = 4.
- Number of total trials = Number of countermeasure conditions in each scenario × Number of total scenarios = 4 × 2 = 8.

The length of the formal road section in each trial is around 3,860 feet, and the speed limit is 40 mph. In addition, there is a transition section before the formal road section, which is about 1,758 feet long and will take approximately 30 seconds to drive through. Thus, the estimated total time per trial is around 2 min. Latin square design was applied to balance the order effect of two-time scenarios. For example, the first participant did the daytime scenario first, followed by the nighttime scenario. Then, the second participant did the nighttime scenario first, followed by the nighttime scenario. It can achieve that we have the same number of participants who started with daytime and nighttime. In addition, four countermeasures (three countermeasures and one original design as the control group) were set up as random sequences to balance the order effect.

For the shoulder work experiment, the 2*4 design parameters are explained as follows.

- Number of work zone scenarios = 1 (shoulder work).
- Number of time scenarios = 2 (daytime and nighttime).
- Number of countermeasure conditions in each scenario = (Number of sign countermeasures + 1)$^{(\text{Number of signs that will be changed})}$ = 4.
- Number of total trials = Number of countermeasure conditions in each scenario × Number of total scenarios = 4 × 2 = 8.

The length of the formal road section in each trial is around 5,310 feet, and the speed limit is 60 mph. A transition section before the formal road section was also added, which is about 2,640 feet and typically takes approximately 30 seconds to drive through. Thus, the estimated total time per trial is also around 2 min. Latin square design was applied to balance the order effect of two-time scenarios. Four countermeasures were set up as random sequences to balance the order effect.

9.2 Data Collection

9.2.1 Experiment Procedure

The experiment procedure for both the lane closure experiment and the shoulder work experiment covers the following four steps.

- Step 1: The research team recruited participants using flyers and emails. The target participants should have a valid Indiana driver's license. Both on-campus and off-campus resources have been explored to recruit diverse participants.
- Step 2: Participants who are interested in the experiment should complete a pre-survey (as listed in Appendix B). The pre-survey covers demographic information (including gender (Babić et al., 2020; Sagaspe et al., 2010; Yan et al., 2009), age (Andrews & Westerman, 2012; Lee et al., 2003; McGwin & Brown, 1999), education level, occupation, industry, ethnicity, marital status, household income, and visual ability (Ackerman et al., 2008) and driving experience (Babić et al., 2020; Lehtonen et al., 2014) (covering general driving experience and work zone experience). Participants also need to provide available time slots for the experiment at the end of the survey. Each participant can only participate in one experiment, which makes the two experiments (lane closure and shoulder work) independent.
- Step 3: After receiving the information, researchers selected the participants considering demographic information to achieve a representative sample in Indiana. From FHWA highway statistics (FHWA, 2023a), the drivers in Indiana cover 49.04% males and 50.96 females, and the age distribution is: 18–29 years old: 20.57%, 30–39 years old: 16.77%, 40–49 years old: 15.83%, 50–59 years old: 16.80%, 60–69 years old: 16.14%, ≥70 years old: 13.89%. Thus, the target participants would be: 16 females and 16 males, with the age distribution as: 18–29 years old: 7, 30–39 years old: 5, 40–49 years old: 5, 50–59 years old: 5, 60–69 years old: 5, ≥70 years old: 5. Also, participants with different education levels, ethnicities, and occupations were included. Email and calendar invitations were sent to the selected participants to clarify the scheduled time slots for the experiment.
- Step 4: Participants should come to the lab at Purdue University to finish the driving simulation experiment. Each experiment takes around 45 minutes. The detailed procedure is as follows.

1. Researchers introduce the experiment background and steps to the participants. Participants need to read and sign the consent form. Researchers should also sign the form and provide a copy to participants.
2. Researchers guide the participants to calibrate the eye tracker and driving seat.
3. Participants finish a 5-minute training session, which includes driving during both daytime and nighttime. The training sessions were simulated using the same road section as the formal experiment, without all the work zone elements (traffic signs, drums, trucks, etc.) but having the speed limit sign. It aims to make the participants familiar with the operation of the driving simulator. Researchers communicate with

the participants to ensure they understand all operations and do not have any discomfort or issues.

4. Participants finish all formal experiment sections (8 trials), with a 1-minute break between trials. The total formal driving part takes around 25 minutes. Researchers monitor the progress and participants' performance during the experiment. But there is no communication with the participants so as not to interfere with them.
5. Participants complete a post-survey (as listed in Appendix C). The post-survey aims to collect participants' subjective evaluations of the proposed countermeasures regarding perception, cognition, and action during driving, as well as the level of fatigue and level of motion sickness after the driving simulation experiment. Perception, cognition, and action are the three stages of human information processing (Proctor & Van Zandt, 2018), which explains how people get, analyze, and respond to the information (e.g., information from the traffic sign with/without countermeasures).
6. Researchers provide an Amazon Gift Card ($90) as compensation to each participant, let participants sign the log, and make sure participants do not have any discomforts or symptoms before they leave.

9.2.2 Indicators for Eye Movement, Driving Performance, Synchronized Data and Self-Evaluation

This section will introduce the key indicators collected during the driving simulation experiment and their meanings, which cover the eye movement data, driving performance data, and self-evaluation of drivers about the countermeasures. According to human information processing theory (Proctor & Van Zandt, 2018), perception, cognition, and action are the three major stages in which people receive information from the environment (e.g., visual information and audio information), analyze information and make decisions based on attention resources (e.g., short-term memory, long-term memory, logistic analysis, etc.), and respond to the environment by taking actions. In the driving simulation experiment, the perception stage mainly refers to obtaining the information visually, which is measured by eye movement data. The cognition stage focuses on how drivers analyze the perceived information and make decisions regarding driving, which is also measured by eye movement data. The action stage indicates the driving behaviors, which is measured by the driving performance data. Also, to better understand the impacts of countermeasures, we synchronized eye movement and driving performance data using python to further explore how the countermeasures influence the perception and action stages. In addition, in the self-evaluation survey, the three stages were also referred to by designing questions covering different stages.

9.2.2.1 Indicators of Eye Movement Data. Table 9.1 outlines the key indicators of eye movement data, which were collected by the eye tracker. The eye movement indicators cover two categories: fixation and pupillometry.

Fixation indicates the gaze samples that locate within a spatially limited region (about 0.5°) for a minimum period of time (e.g., the minimum allowed fixation duration is usually in the range of 80–150 msec) (Nyström & Holmqvist, 2010). Fixation indicators include fixation number and fixation duration. Fixation number is also called the fixation counts/frequency, which is the number of times (counts) the participant fixates on area of interests (AOIs) from the moment they were visible to the participant (Najar & Sanjram, 2018). AOI in the eye movement analysis is a segment of a stimulus space that identifies a portion of the stimulus that is meaningful in the experimental design of a study (Holmqvist et al., 2022). In this experiment, as our research goal is to evaluate the effectiveness of countermeasures, the AOI was defined as the area of traffic signs that the countermeasures were applied (i.e., Right Lane Closed Ahead sign and Right Shoulder Closed Ahead sign). A higher fixation number suggests more active visual scanning of the element (Babić et al., 2020), indicating a higher level of attention to the AOI (i.e., the traffic sign in this experiment) (Babić et al., 2020; Vignali et al., 2019). It implies that the countermeasure is more effective in capturing the drivers' active attention (Babić et al., 2020; Qin et al., 2018), which is related to the perception stage of human information processing. Fixation duration indicates the period of time when the eye is relatively still and fixating on the AOIs and it was calculated by computing total fixation durations in seconds within AOI from the moment it was visible to the participant (Najar & Sanjram, 2018). Longer fixation durations indicate higher cognitive/mental workload (de Greef et al., 2009; Holmqvist et al., 2022), which suggests that drivers focus more on the AOIs to analyze information (Babić et al., 2020), related to the cognition stage. It shows that the countermeasure can hold greater concern and focus of drivers, which may imply better engagement with the work zone (Ahlström et al., 2021; de Greef et al., 2009; Jimenéz et al., 2012).

Pupillometry indicates the pupil diameters of drivers (de Greef et al., 2009), which is measured by both Left Pupil Mean Diameter (LPMD) and Right Pupil Mean Diameter (RPMD). A larger pupil diameter is typically linked to a higher level of attention and mental workload (de Greef et al., 2009; Holmqvist et al., 2022), indicating that drivers pay more attention, concern, and focus on the countermeasure (de Greef et al., 2009; Liang & Lee, 2008; Radhakrishnan et al., 2023). The indicators are related to both perception and cognition stages.

In a word, these eye movement indicators provide a comprehensive measurement of drivers' perception and cognition regarding the countermeasures. Higher values related to the indicators suggest that the countermeasure is more effective in capturing drivers' attention and sustaining information understanding and

TABLE 9.1
Indicators for Eye Movement Data Analysis

Category	Definitions	Indicators	Meanings	Stages	Units
Fixation	Eye movements located within a spatially limited region	Fixation number (FN)	More fixations → higher level of attention → better countermeasure (Babić et al., 2020; Qin et al., 2018; Vignali et al., 2019)	Perception	Number
		Fixation duration (FD)	Longer duration → higher mental/ cognitive workload → greater concern and focus → better countermeasure (Ahlström et al., 2021; Babić et al., 2020; de Greef et al., 2009; Holmqvist et al., 2022; Jimenéz et al., 2012)	Cognition	Second
Pupillometry	Diameter of pupil	Left pupil mean diameter (LPMD) Right pupil mean diameter (RPMD)	Larger → higher level of attention and mental workload → more attention, concern, and focus → better countermeasure (de Greef et al., 2009; Holmqvist et al., 2022; Liang & Lee, 2008; Radhakrishnan et al., 2023)	Perception and cognition	mm

decision-making, which may support safer driving behaviors in the work zones.

9.2.2.2 Indicators of driving performance data. Table 9.2 shows the indicators used to measure driving performance in the experiment, including speed, acceleration/deceleration, and lateral position, which are the most commonly used indicators in the driving simulation study (Awan et al., 2019; Babić et al., 2020).

Driving speed indicates the change in the position of the vehicle in a unit of time (Babić et al., 2020). Mean speed is the most commonly used driving performance indicator (Alhomaidat et al., 2023; Almallah et al., 2021; Awan et al., 2019; Domenichini et al., 2017; Huang & Bai, 2019; Hussain et al., 2020; Vignali et al., 2019). In this study, the mean speed measures the average driving speed across the entire road section, starting from the speeding penalty sign and ending at the End Road Work sign. Lower mean speed is associated with better and safety driving performance as it reflects better speed control and more cautious driving behaviors (Almallah et al., 2021; Domenichini et al., 2017; Huang & Bai, 2019; Vignali et al., 2019). Speed reduction/difference is also a common indicator of driving performance (Alhomaidat et al., 2023; Hussain et al., 2020; Vignali et al., 2019). In this study, speed reduction refers to the speed differences at the initial position of the road (the speeding penalty sign) and the location of the countermeasure. Negative difference (end speed – initial speed) shows the reduction of speed. A lower value indicates more effective speed control, suggesting that drivers reduce speed in response to the countermeasure, which means the countermeasure is effective.

Acceleration indicates the change in speed in a unit of time (Babić et al., 2020). Mean acceleration in this study refers to the average acceleration across the entire road section, starting from the speeding penalty sign and ending at the End Road Work sign. Lower mean acceleration values indicate smoother and safer driving, as drivers exhibit better control over their speed changes, reducing the risk of sudden stops or jerky movements (Almallah et al., 2021; Awan et al., 2019; Eboli et al., 2016; Vignali et al., 2019).

In addition, lateral position measures the distance from the center of the vehicle to the right lane edge line (Babić et al., 2020). It indicates the distance of the vehicle position to the lane boundaries. A higher lateral position reflects earlier lane-changing behavior, which is often seen as a proactive and safer response in work zones (Almallah et al., 2021; Eboli et al., 2016; Wynne et al., 2019).

To sum up, these driving performance indicators provide a comprehensive measurement of drivers' behaviors. Lower mean speed and acceleration, higher speed reduction at the countermeasure location, and earlier lane changing and control behaviors indicate better driving performance and improved work zone safety relating to the countermeasure.

9.2.2.3 Indicators of synchronized data. Through matching the timeframes of eye movement data and driving performance data, which were collected from different platforms, the two types of data were synchronized to further explore the effectiveness of countermeasures. In the synchronization process, the locations where the drivers first fixated on the countermeasure were identified based on the eye movement videos. The synchronization data analysis focuses on the road section during the two seconds before and after the drivers' first fixation locations

TABLE 9.2
Indicators for Driving Performance Data Analysis

Indicators	Explanations	Meanings	Stages	References
Mean Speed (mph)	The average driving speed was measured across the entire road section (starting from the speeding penalty sign and ending at the end road work sign).	A lower mean speed indicates better driving performance, as it reflects a controlled and cautious driving behavior.	Action	Alhomaidat et al., 2023; Almallah et al., 2021; Awan et al., 2019; Domenichini et al., 2017; Huang & Bai, 2019; Hussain et al., 2020; Vignali et al., 2019
Speed Reduction (mph)	Initial speed: driving speed at the speeding penalty traffic sign. End speed: driving speed at the countermeasure location. Speed reduction = End speed - Initial speed.	A negative value indicates the reduction of speed. A lower value suggests better driving performance, as it indicates better speed control.	Action	Alhomaidat et al., 2023; Rahman et al., 2017; Vignali et al., 2019
Mean Acceleration (m/s^2)	Driving acceleration during the entire road section (starting from the speeding penalty sign and ending at the end road work sign).	A lower mean acceleration reflects better speed control and better driving performance.	Action	Almallah et al., 2021; Awan et al., 2019; Eboli et al., 2016; Vignali et al., 2019
Lateral Position (feet)	It indicates the distance from the center of the vehicle to the right lane edge line.	A higher lateral position suggests the drivers change lanes earlier, indicating better driving performance.	Action	Almallah et al., 2021; Awan et al., 2019; Babić et al., 2020; Wynne et al., 2019

(four seconds in total). Table 9.3 shows the indicators used to measure the synchronized data, including first-fixation distance to countermeasure, gas pedal variation, steering variation, speed variation and lateral position variation.

First-fixation distance to countermeasure is a critical indicator representing the distance between the vehicle and the countermeasure when the driver first fixated on the countermeasure (Costa et al., 2018; Vignali et al., 2019). A higher value of this indicator shows that the countermeasure could effectively capture the drivers' attention at longer distances, highlighting its visibility and potential to provide early warnings. It is particularly important in work zones where early detection of countermeasures can significantly improve safety by allowing more time for reaction. This indicator is related to the perception stage of human information processing regarding how drivers receive visual information.

Then, there are four indicators related to the action stage about driving performance variations between 2 seconds before and after the location where drivers first fixated on the countermeasure, including gas pedal variation, steering variation, speed variation, and lateral position variation. In particular, the variation was calculated as the difference between the mean value during the two seconds before the location where drivers first fixated on the countermeasure and the mean value during the two seconds after the location. Gas pedal variation indicator focuses on the changes in gas pedal positions. A negative value indicates that the driver is releasing the gas pedal, signaling deceleration, while a positive value shows that the driver is accelerating. A higher absolute value of the indicator reflects greater variation in gas pedal use behaviors before and after drivers first fixated on the countermeasure. Steering variation captures the changes in steering angle, where a negative value suggests the vehicle is turning toward the right and a positive value indicates the vehicle is turning to the left. A higher absolute value indicates greater steering activity, signifying a higher level of reaction to the countermeasure. Speed variation, calculated as the difference between speeds before and after, identifies deceleration with negative values and acceleration with positive values. A higher absolute value indicates more speed changes due to the countermeasure. Lateral position variation assesses the vehicle's positional changes relative to the road. Positive values suggest a shift toward the left lane, while negative values indicate changing to the right lane. Higher absolute values indicate more changes in lateral positions before and after the first fixation on the countermeasure.

To sum up, these indicators for synchronized data analysis provide a comprehensive measurement to understand how drivers respond to countermeasures in the perception and action stages of human information processing.

9.2.2.4 Post-survey about self-evaluation of countermeasures. Post-test questionnaire is a commonly used method to collect feedback/thoughts on the driving experience and on the driving simulator itself (Hussain et al., 2020). Also, subjective measures of countermeasures are an effective method to evaluate drivers' feedback (Calvi et al., 2019). In this study, after the driving part, a survey was used to evaluate the effectiveness of the countermeasures based on participants' subjective evaluation.

TABLE 9.3
Indicators for Synchronized Data Analysis

Indicators	Explanations	Meanings	Stages	References
First-fixation distance to countermeasure (feet)	Distance between the vehicle and the countermeasure at the moment when the driver first fixates on the countermeasure	A higher value → the driver could see the countermeasure at a longer distance (the countermeasure is more effective in attracting the driver's attention)	Perception	Costa et al., 2018; Vignali et al., 2019
Gas pedal variation (%)	Gas Pedal Variation = After Gas Pedal - Before Gas Pedal	A negative value → the driver is releasing the gas pedal (decelerating); A positive value → the driver is accelerating; A higher absolute value → greater variation in gas pedal behavior	Action	Deng et al., 2020; Ding et al., 2016; Fugiglando et al., 2019
Steering variation (°)	Steering Variation = After Steering - Before Steering	A negative value → the driver is turning the steering wheel to the right (moving closer to the right lane); A positive value → the driver is turning the steering wheel to the left; A higher absolute value → greater variation in steering behavior	Action	
Speed variation (mph)	Speed Variation = After Speed - Before Speed	A negative value → the driver is decelerating; A positive value → the driver is accelerating; A higher absolute value → greater speed variation	Action	Brewer et al., 2006; Li et al., 2013
Lateral position variation (feet)	Lateral Position Variation = After Lateral Position - Before Lateral Position	A negative value → the vehicle is moving closer to the right lane; A positive value → the vehicle is moving closer to the left lane; A higher absolute value → greater variation in lateral position	Action	Almallah et al., 2021; Kang et al., 2023

Note: After value: the mean value during the 2 seconds after the driver's first fixation on the countermeasure; Before value: the mean value during the 2 seconds before the driver's first fixation on the countermeasure; Variation: the variation before and after the driver's first fixation on the

To achieve comprehensive analysis of countermeasures, all three stages of human information processing were covered by the following questions (see details of the survey in Appendix C).

- Q1: Which countermeasure(s) did you notice during the driving?
- Q2: Which countermeasure(s) attracts your attention?
- Q3: Which countermeasure(s) helps you understand the sign more quickly?
- Q4: Which countermeasure(s) makes you more aware of the work zone?
- Q5: Which countermeasure(s) better helps you make decisions about driving behaviors?
- Q6: Which countermeasure(s) helps you improve your driving behavior?

Questions 1 and 2 are about the perception stage and whether the drivers notice the countermeasure and whether it attracts their attention. Questions 3, 4, and 5 are about the cognition stage, covering whether the countermeasure could help convey information more quickly, make the drivers more aware of the work zone, and help them make decisions regarding driving behaviors. Question 6 is about the action stage, indicating the exact driving performance/behavior improvement. For all questions, three countermeasures (doubling-up of fluorescent orange sign, fluorescent orange sign with orange beacon, and fluorescent orange sign with orange LEDs) and "None of them" options were provided. Participants can select all answers that apply.

For each question, the selection percentage for each countermeasure of the total 32 participants for each experiment was calculated as the indicator, using the following equation.

$$\textit{Selection percentage of each countermeasure } (\%) = \frac{\textit{Number of participants selecting the countermeasure}}{\textit{Total number of participants}} * 100\%$$

The selection percentage reflects the proportion of participants who consider the countermeasure to be effective. A higher selection percentage indicates that a greater number of participants agreed the countermeasure is beneficial for their driving task. For example, if a countermeasure has a selection percentage of 75% for Q6, it means that 75% of the total 32 participants believe the countermeasure is effective in improving their driving behaviors.

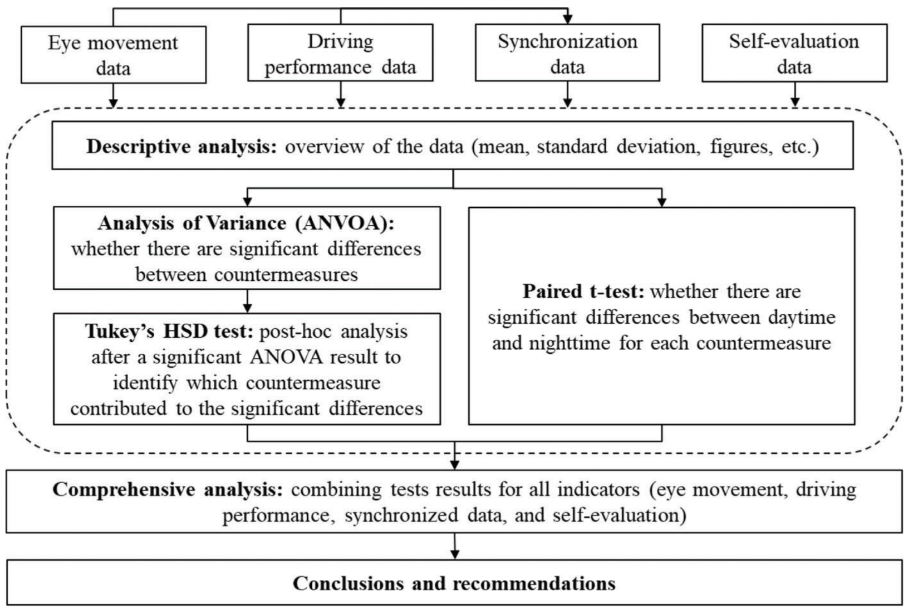


Figure 9.1 Data analysis methods.

9.3 Data Analysis Methods

Figure 9.1 shows the relationship between different data analysis methods used in this study and the results. For all indicators of eye movement data, driving performance data, synchronized data, and self-evaluation data, three types of data analysis methods—descriptive statistics, statistical hypothesis tests, and comprehensive analysis—were sequentially applied if applicable.

First, descriptive statistics were applied to show the trend of the data and basic relationships between variables. Boxplots were generated to visualize the collected data. Then, statistical hypothesis tests were applied to analyze the statistical relationships between variables, which could indicate whether there were significant differences between countermeasures and which countermeasure(s) contributed to the significant difference. Finally, a comprehensive analysis was employed to identify the effective countermeasures for each experiment (each work zone scenario) combining all data and results.

9.3.1 Descriptive Statistics

Descriptive statistics were used to summarize and provide an overview of the data collected. Key measures such as mean, standard deviation, minimum, and maximum were calculated for each variable (eye movement indicators, driving performance indicators, and self-evaluation results) to describe the central tendency and variability within the dataset. These statistics could provide an initial understanding of the patterns and distributions across different countermeasures. Specifically, for eye movement data, heatmaps of representative participants were generated to show examples of participants' visual attention and fixation (Najar & Sanjram, 2018).

9.3.2 Statistical Hypothesis Tests

Statistical hypothesis tests were employed to determine whether there were statistically significant differences between countermeasures regarding eye movement, driving performance, and self-evaluation, considering daytime and nighttime scenarios, and which countermeasure(s) contributed to the significant difference. Several statistical tests were used based on research questions and data structure.

9.3.2.1 One-way ANOVA test. To determine whether there are significant differences in drivers' eye movements, driving performance, and self-evaluation, considering both daytime and nighttime, between the original design and three different countermeasures, the one-way Analysis of Variance (ANOVA) analysis was performed. Python software was applied to conduct the analysis.

1. Hypothesis of ANOVA test
   - *Null Hypothesis (H_0):* There is no significant difference in the metric across all groups (three countermeasures and one original design); the mean values for all groups are equal: $\mu_1 = \mu_2 = \mu_3 = \mu_4 = c$.
   - *Alternative Hypothesis (H_a):* At least one group's mean value for the metric is significantly different from the others: $\mu_i \neq c$
2. Results interpretation
   - In the results, when P-value > 0.05, H_0 is not rejected, indicating that there is no significant difference between the groups.
   - On the contrary, if P-value < 0.05, H_a is accepted, which means at least one group is significantly different from the others.

Where, μ_i is the mean value for group *i*; *c* is a constant value; P-value is the result of ANOVA test.

9.3.2.2 Tukey's HSD Test. Tukey's Honestly Significant Difference (HSD) test is a post-hoc analysis conducted after a significant ANOVA result to identify which specific groups are significantly different from one another. While the ANOVA test determines whether at least one group differs from others, Tukey's HSD test provides pairwise comparisons of all group means. It ensures that the family-wise error rate is controlled, minimizing the risk of false positives when performing multiple comparisons. In this study, Tukey's HSD test was applied to compare the effectiveness of all pairs of countermeasures. This test helps identify which countermeasures had a significant impact on eye movements, driving performance, and self-evaluation of countermeasures.

1. Hypothesis of Tukey's HSD test
   - *Null Hypothesis (H_0):* The means of the two groups being compared are equal (e.g., $\mu_1 = \mu_2$).
   - *Alternative Hypothesis (H_a):* The means of the two groups being compared are not equal (e.g., $\mu_1 \neq \mu_2$).
2. Results interpretation
   - If the P-value for a pairwise comparison is less than 0.05, the null hypothesis is rejected, indicating a statistically significant difference between the two groups.
   - The test also provides confidence intervals for the mean difference, which further aids in understanding the magnitude and direction of differences between groups.

9.3.2.3 Paired T-test. The Paired t-test is a statistical method used to compare the means of two related groups or conditions. Unlike the Tukey's HSD test, which evaluates differences across all pairs of groups independently, the Paired t-test is designed to analyze data where measurements are taken from the same participants or subjects under two different conditions. In this study, Paired t-tests were used to compare countermeasures under different experimental conditions (i.e., daytime and nighttime scenarios). The results further provide insight into the impacts of countermeasures on drivers' eye movement and driving performance under different time conditions.

1. Hypothesis of Paired t-test
   - *Null Hypothesis (H_0):* There is no difference between the paired conditions (e.g., $\mu_1 = \mu_2$).
   - *Alternative Hypothesis (H_a):* There is a significant difference between the paired conditions (e.g., $\mu_1 \neq \mu_2$).
2. Results interpretation
   - If the P-value is less than 0.05, the null hypothesis is rejected, indicating that the two conditions are significantly different.
   - The test also provides the mean difference, confidence intervals, and the direction of the effect.

9.3.3 Comprehensive Analysis

The statistical hypothesis tests discussed above focused on each indicator separately. After the tests, a comprehensive analysis combining results from eye movement data, driving performance data, and self-evaluation data was performed to provide a robust, multidimensional understanding of the effectiveness of countermeasures. Eye movement indicators, such as fixation number, fixation duration, and pupillometry, evaluate drivers' attention and cognitive workload related to the perception and cognition stages, while driving performance indicators, like speed, acceleration, and lane position, evaluate objective driving behaviors related to the action stage. Self-evaluation data captures subjective perceptions of the effectiveness of countermeasures. Statistical methods, including ANOVA, Tukey's HSD, and Paired t-tests, identify significant differences and pairwise comparisons across countermeasures. By integrating these data sources, the comprehensive analysis highlighted the countermeasure that balances attention capture, better driving behavior, and drivers' satisfaction, to provide recommendations to improve work zone safety.

10. EVALUATION OF EFFECTIVENESS OF COUNTERMEASURES: RESULTS AND DISCUSSIONS

Based on the driving simulation experiment data collection and analysis discussed in Session 9, this session introduces the results of data analysis and relevant discussions. The results are from two separate experiments: lane closure experiment and shoulder work experiment as discussed before. Data collection and analysis processes are the same for both experiments.

10.1 Lane Closure Experiment

10.1.1 Participants

A total of thirty-four participants were recruited for the lane closure scenario driving simulation experiment. One participant (female, 40 years old) did not complete the entire experiment due to motion sickness; the data from another participant (male, 30 years old) was excluded as an outlier because he exceeded the speed limit by 300% and had multiple crashes during the driving experiment, which is totally different from other participants and is unlikely to happen in the general population. Finally, the experimental data of thirty-two participants were included in the data analysis, following the list shown in Table 9.1. All participants (16 males and 16 females) had valid Indiana drivers licenses. Figure 10.1 provides a comprehensive breakdown of the demographic information of thirty-two participants in the lane closure experiment, covering age, gender, ethnicity, education, and occupation.

Figure 10.1a shows the age and gender distribution. The ages of the participants ranged from 19 to 76 years old, with a mean age of 46.75 and a standard deviation of 18.18. The gender distribution is balanced between males and females. The age and gender distribution of the participants is consistent with the distribution of age and gender in Indiana drivers (FHWA, 2023a), supporting that the participants could represent Indiana drivers. Then, Figure 10.1b shows the ethnicity distribution, with White as the majority, followed by Asian, Hispanic or Latino, Native American, or American Indian and mixed ethnicities. It reflects the diversity of ethnicity in the sample. Figure 10.1c shows the education background, with bachelor's degree, master's degree, associate degree, and some college education as the major parts. It indicates that the sample also has diversity in education levels. Regarding occupations (Figure 10.1d), the participants covered a wide range of occupations based on occupational categories (U.S. Bureau of Labor Statistics, 2023), including educational instruction and library, life, physical, and social science, management and arts, design, entertainment, and sports, etc. Overall, the participants' demographic information demonstrates a diverse demographic range, supporting the representativeness of the selected sample.

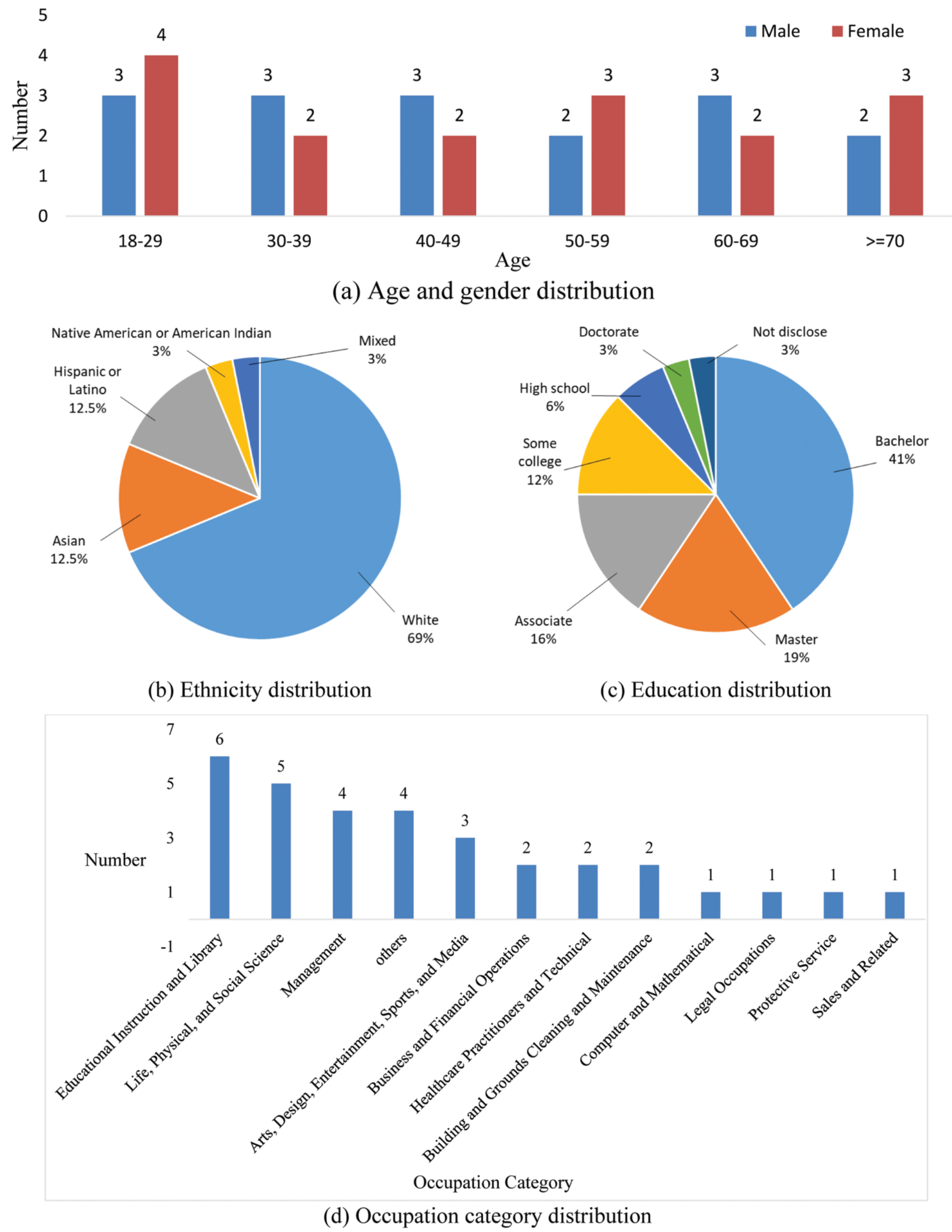


Figure 10.1 Demographic information of participants for lane closure experiment.

10.1.2 Eye Movement

Regarding the results of eye movement data, four indicators introduced in Table 9.2 were discussed: fixation duration, fixation number, the left pupil diameter, and the right pupil diameter. Before explaining each eye movement indicator, the example heatmaps of representative participants were generated to visualize the eye movement distribution of participants. Figure 10.2 shows the heatmaps of one representative participant's eye movement patterns during the lane closure experiment under daytime and nighttime conditions, respectively.

The red-highlighted regions represent areas with longer fixation durations, suggesting that the driver focused more intensely on these areas. During daytime scenario (Figure 10.2a), the heatmap indicates that the participants gaze was primarily concentrated on the roadway. distributed across various areas, including the rearview mirror, the roadway ahead, and the dashboard. The countermeasure was labeled with a green rectangle as the area of interest (AOI). During the nighttime scenario (Figure 10.2b), the heatmap shows that the same participants gaze was distributed across various areas, including the rearview mirror, the roadway ahead, and traffic light.

10.1.2.1 Fixation number. The results of the fixation number indicator cover four parts: descriptive statistics, ANOVA test, Tukey's HSD test, and Paired T-test.

10.1.2.1.1 Descriptive statistics. Figure 10.3 shows the boxplot of fixation number for the original design of traffic signs in work zones (fluorescent orange sign (C1)) and three countermeasures (doubling-up of fluorescent orange sign (C2), fluorescent orange sign with orange LEDs (C3), and fluorescent orange sign with orange beacon (C4)) under daytime and nighttime conditions. Table 10.1 summarizes the mean and standard deviation (SD) of fixation number under daytime and nighttime conditions.

It shows that LEDs (C3) had the highest average fixation numbers and the greatest variability under both daytime and nighttime scenarios, suggesting it is more effective in attracting drivers' attention. The original design (C1) and doubling-up (C2) show lower average fixation numbers, indicating they attracted less attention from drivers. Beacon (C4) demonstrated a moderate level of fixation numbers across countermeasures, with nighttime fixation numbers (mean = 3.0312) slightly exceeding daytime (mean = 2.4688).

10.1.2.1.2 Results of ANOVA test. Table 10.2 presents the ANOVA test results for fixation number across different countermeasures during both daytime and nighttime. The P-values (P-value = 0.0318 and <0.01, respectively) show that there were statistically significant differences in fixation number across countermeasures and the original design during both daytime and nighttime scenarios. It indicates that some countermeasures show significantly more effectiveness in attracting drivers' attention.

10.1.2.1.3 Results of Tukey's HSD test. As the ANOVA results show that there were significant differences, Tukey's HSD test was further performed to identify the differences through pairwise comparison among C1–C4. Table 10.3 shows the results of Tukey's HSD test for fixation number during daytime and nighttime. During daytime, there were statistically significant differences only between doubling-up (C2) and LEDs (C3), with a mean difference of 2.375 and a P-value of 0.0306. This result suggests that LEDs (C3) attracted drivers' attention better compared to doubling-up (C2) during daytime. All other pairwise comparisons are not statistically significant (P-values exceed 0.05). During the nighttime, significant differences were observed between LEDs (C3) and both the original design (C1) and doubling-up (C2). Specifically, LEDs (C3) had a significantly higher fixation number than the original design, with a mean difference of 3.0938 and a P-value less than 0.01, and a higher fixation number than doubling-up, with a mean difference of 3.1562 and a P-value less than 0.01. Other comparisons also showed no statistically significant differences. These

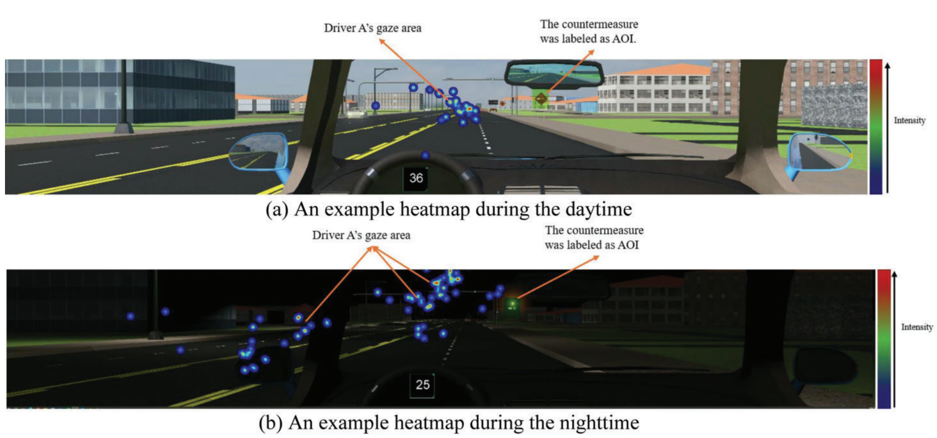


Figure 10.2 Example heatmaps of a representative participant in a lane closure experiment.

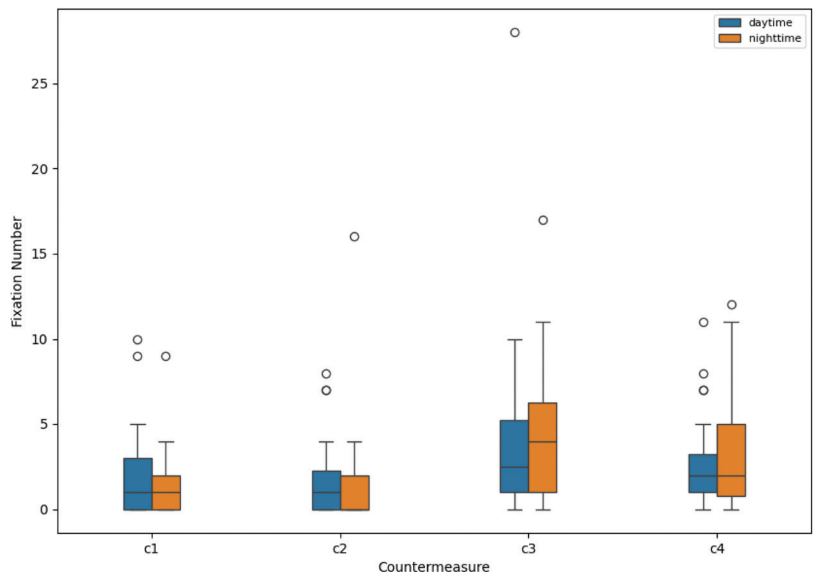


Figure 10.3 Boxplot of fixation number (lane closure).

TABLE 10.1
Mean and Standard Deviation (SD) of Fixation Number (Lane Closure)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	1.9375	2.5519	1.5938	2.2268	3.9688	5.2578	2.4688	2.6879
Nighttime	1.2500	1.8316	1.1875	2.8898	4.3438	3.7897	3.0312	3.4964

TABLE 10.2
ANOVA Test Results for Fixation Number (Lane Closure)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	105.4609	35.1536	3.0344	0.0318
	Error	124	1,436.5312	11.5849	–	–
	Corrected Total	127	1,541.9921	–	–	–
Nighttime	Model	3	222.6563	74.2188	7.7529	<0.01
	Error	124	1,187.0625	9.5731	–	–
	Corrected Total	127	1,409.7188	–	–	–

results suggest that during nighttime, the LEDs (C3) countermeasure was particularly effective in attracting drivers' visual attention compared to the original design (C1) and doubling-up (C2), while beacon (C4) did not differ significantly in fixation number from the other countermeasures.

10.1.2.1.4 Results of Paired t-test. The Paired t-test compared the differences in fixation number between daytime and nighttime for each countermeasure, as shown in Table 10.4. All P-values were larger than 0.05, showing that there are no statistically significant differences between daytime and nighttime in fixation number for all three countermeasures and the original design. It shows that between daytime and nighttime, all four groups showed similar effectiveness in attracting drivers' attention.

10.1.2.2 Fixation duration. The results of the fixation duration indicator also cover four parts: descriptive statistics, ANOVA test, Tukey's HSD test, and Paired T-test. The main results are summarized as follows. Detailed tables and figures are listed in Appendix E.1.1.1.

10.1.2.2.1 Descriptive statistics. Table 10.5 summarizes the mean and standard deviation (SD) of fixation durations for C1–C4 under daytime and nighttime conditions. During daytime, beacon (C4) showed the highest mean fixation duration (mean = 0.2551

TABLE 10.3
Tukey's HSD Test Results for Fixation Number (Lane Closure)

Time Scenarios	Group 1	Group 2	Mean Difference	P-value	Lower	Upper	Reject
Daytime	Original design (C1)	Doubling-up (C2)	-0.3438	0.9776	-2.5597	1.8722	FALSE
	Original design (C1)	LEDs (C3)	2.0312	0.0849	-0.1847	4.2472	FALSE
	Original design (C1)	Beacon (C4)	0.5312	0.9241	-1.6847	2.7472	FALSE
	Doubling-up (C2)	LEDs (C3)	2.3750	0.0306	0.1590	4.5910	TRUE
	Doubling-up (C2)	Beacon (C4)	0.8750	0.7332	-1.341	3.0910	FALSE
	LEDs (C3)	Beacon (C4)	-1.500	0.2962	-3.7160	0.7160	FALSE
Nighttime	Original design (C1)	Doubling-up (C2)	-0.0625	0.9998	-2.0769	1.9519	FALSE
	Original design (C1)	LEDs (C3)	3.0938	0.0006	1.0794	5.1081	TRUE
	Original design (C1)	Beacon (C4)	1.7812	0.1029	-0.2331	3.7956	FALSE
	Doubling-up (C2)	LEDs (C3)	3.1562	0.0005	1.1419	5.1706	TRUE
	Doubling-up (C2)	Beacon (C4)	1.8438	0.0856	-0.1706	3.8581	FALSE
	LEDs (C3)	Beacon (C4)	-1.3125	0.3297	-3.3269	0.7019	FALSE

TABLE 10.4
Paired T-test Results for Fixation Number (Lane Closure)

Countermeasures	T-Statistic	P-value
Original design (C1)	1.3617	0.1831
Doubling-up (C2)	0.6842	0.4989
LEDs (C3)	-0.3762	0.7093
Beacon (C4)	-0.9163	0.3666

seconds, SD = 0.3018), followed by LEDs (C3) (mean = 0.2166 seconds, SD = 0.2278), while doubling-up (C2) exhibited the lowest mean fixation duration (mean = 0.0966 seconds, SD = 0.1592). Compared to the original design (C1), LEDs (C3) and beacon (C4) had higher average fixation duration, while doubling-up (C2) showed lower fixation durations with a narrow range of distribution. At nighttime, LEDs (C3) achieved the highest mean fixation duration (mean = 0.2497 seconds, SD = 0.1674), while the original design (C1) had the lowest fixation duration (mean = 0.064 seconds, SD = 0.107). These results highlight the better performance of LEDs during nighttime regarding cognition. Doubling-up (C2) was less effective than the original design (C1) in maintaining drivers' focus and workload under both time scenarios. The presence of outliers, particularly for LEDs (C3) and doubling-up (C2) under the nighttime scenario, indicates some variability in participants' responses. Figure E.1 in Appendix E shows the boxplot of fixation duration.

10.1.2.2.2 Results of ANOVA test. The results of the ANOVA test show that there were statistically significant differences between C1–C4 regarding fixation durations during both daytime and nighttime, with the P-values smaller than 0.05 (P-value = 0.0312 during daytime and <0.01 during nighttime). It suggests that some countermeasures are more effective in maintaining drivers' cognitive workload and focus. A post-hoc test (Tukey's HSD test) was performed to further identify which specific countermeasures differ significantly. More details of ANOVA test results are listed in Table E.1 in Appendix E.

10.1.2.2.3 Results of Tukey's HSD test. The Tukey's HSD test results indicate that there were significant differences between doubling-up (C2) and LEDs (C3), as well as doubling-up (C2) and beacon (C4), during daytime (P-value = 0.0439 and 0.0413, respectively). Doubling-up (C2) showed significantly lower level of effectiveness in maintaining drivers' workload and focus during daytime. LEDs (C3) and beacon (C4) were more effective during daytime. Regarding nighttime scenario, LEDs (C3) showed significant differences in fixation duration compared to the original design (C1) (mean difference = 0.1857, P-value < 0.001) and doubling-up (C2) (mean difference = 0.1382, P-value < 0.01). Thus, LEDs (C3) were more effective at maintaining drivers' workload and focus than the original design (C1) and doubling-up (C2) at night. Other countermeasures did not show significant differences. More details of Tukey's HSD test results are listed in Table E.2 in Appendix E.

10.1.2.2.4 Results of Paired t-test. The analysis shows no statistically significant differences for any of the countermeasures regarding fixation duration between daytime and nighttime, with all P-values larger than 0.05. It indicates that all four countermeasures (including the original design) showed similar effectiveness in maintaining drivers' cognitive workload and focus across different time scenarios. More details of Paired t-test results are listed in Table E.3 in Appendix E.

TABLE 10.5
Mean and Standard Deviation (SD) of Fixation Duration (Lane Closure)

Time Scenarios	Original Design (C1)		Doubling-Up (C2)		LEDs (C3)		Beacon (C4)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Daytime	0.1898	0.2734	0.0966	0.1592	0.2166	0.2278	0.2551	0.3018
Nighttime	0.0640	0.1070	0.1115	0.2358	0.2497	0.1674	0.1690	0.1433

TABLE 10.6
Mean and Standard Deviation (SD) of the Left Pupil Diameter (Lane Closure)

Time Scenarios	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Daytime	3.7336	0.9078	3.6008	0.7204	3.7072	0.8084	3.6031	0.6632
Nighttime	4.5220	0.9392	4.6579	1.0022	4.5809	1.0178	4.5234	0.9077

10.1.2.3 Left pupil diameter. The results of the left pupil diameter indicator cover three parts: descriptive statistics, ANOVA test, and Paired T-test. The main results are summarized as follows. Detailed tables and figures are listed in Appendix E.1.1.2.

10.1.2.3.1 Descriptive statistics. Table 10.6 summarizes the mean and standard deviation (SD) of left pupil mean diameter for C1–C4 under daytime and nighttime conditions. During daytime, the original design (C1) had a mean pupil diameter of 3.7336 mm (SD = 0.9078), while doubling-up (C2), LEDs (C3), and beacon (C4) showed similar mean values around 3.6–3.7 mm with slightly lower variability. This consistency in the left pupil diameter suggested a similar level of attention and cognitive load across countermeasures in daylight conditions. During nighttime, the mean left pupil diameter increased compared to daytime, with C2 (doubling-up) showing the highest mean of 4.6579 mm (SD = 1.0022). Also, the relatively higher standard deviations at nighttime suggested that individual responses varied more under low-lighting conditions, potentially due to differing levels of adjustment to nighttime conditions among participants. The boxplot of left pupil mean diameter (Figure E.2) and relevant explanations are in Appendix E.

10.1.2.3.2 Results of ANOVA test. According to ANOVA test results, both P-values are larger than 0.05 (P-value = 0.8599 and 0.9357, respectively). No statistically significant differences were identified between countermeasures and original design regarding the left pupil mean diameters. Details of ANOVA test results are listed in Table E.4 in Appendix E.

10.1.2.3.3 Results of Paired t-test. The Paired t-test results show that there were significant differences in left pupil mean diameters between daytime and nighttime for all countermeasures (including the original design), with all P-values less than 0.01. The negative T-statistics (i.e., -4.9087 for the original design, -7.8887 for doubling-up, -9.267 for LEDs, and -7.1153 for beacon) indicate that left pupil mean diameters were consistently larger at nighttime than daytime. The results highlight a significant effect of time scenarios on pupil diameters, regardless of the countermeasure. It indicates that drivers may have different levels of attention and cognitive workload between different time scenarios. More details of Paired t-test results are listed in Table E.5 in Appendix E.

10.1.2.4 Right pupil diameter. Similarly, the results of the right pupil diameter indicator cover three parts: descriptive statistics, ANOVA test, and Paired T-test. The main results are summarized as follows. Detailed tables and figures are listed in Appendix E.1.1.3.

10.1.2.4.1 Descriptive statistics. Table 10.7 summarizes the mean and standard deviation (SD) of right pupil mean diameter for C1–C4 under daytime and nighttime conditions. During the daytime, the original design (C1) had a mean pupil diameter of 3.6730 mm (SD = 1.0934), with similar values for doubling-up, LEDs, and beacon, ranging from 3.5075 to 3.5805 mm, indicating the consistency of right pupil mean diameters across countermeasures under daylight scenario. At nighttime, the right pupil mean diameter increased for all countermeasures, with LEDs (C3) having the highest mean of 4.5391 mm (SD = 1.1371), followed closely by doubling-up and beacon. This increase reflected the expected physiological response of the pupils dilating in darkness. Additionally, the higher standard deviations at nighttime, particularly for LEDs, suggested that individual variations in pupil response were greater in low-lighting conditions. Overall, the data indicates that nighttime conditions led to larger pupil diameters, while variations across countermeasures were less obvious. The boxplot of right pupil mean diameter (Figure E.3) and relevant explanations are in Appendix E.

TABLE 10.7
Mean and Standard Deviation (SD) of Right Pupil Mean Diameter (Lane Closure)

	Original Design (C1)		Doubling-Up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	3.6730	1.0934	3.5075	0.7278	3.5805	0.7745	3.5106	0.6790
Nighttime	4.2649	0.7867	4.4439	0.8920	4.5391	1.1371	4.4201	0.8777

10.1.2.4.2 Results of ANOVA test. According to ANOVA test results, both P-values were larger than 0.05 (P-value = 0.2777 and 0.4756, respectively). No statistically significant differences were identified between countermeasures and the original design regarding the left pupil mean diameters. The results are consistent with the results of the left pupil mean diameter indicator. Tukey's HSD test is not needed for this indicator. Details of ANOVA test results are listed in Table E.5 in Appendix E.

10.1.2.4.3 Results of Paired t-test. The results show that there were significant differences in the right pupil mean diameters between daytime and nighttime for all countermeasures (including the original design), with all P-values less than 0.01. The negative T-statistics indicated that the right pupil mean diameters were consistently larger at nighttime than at daytime. The results highlight a significant effect of time scenarios on pupil diameters, regardless of the countermeasure, which is consistent with the results of left pupil mean diameter. Drivers have different levels of attention and cognitive workload between different time scenarios. Details of Paired t-test results are listed in Table E.7 in Appendix E.

10.1.3 Driving Performance

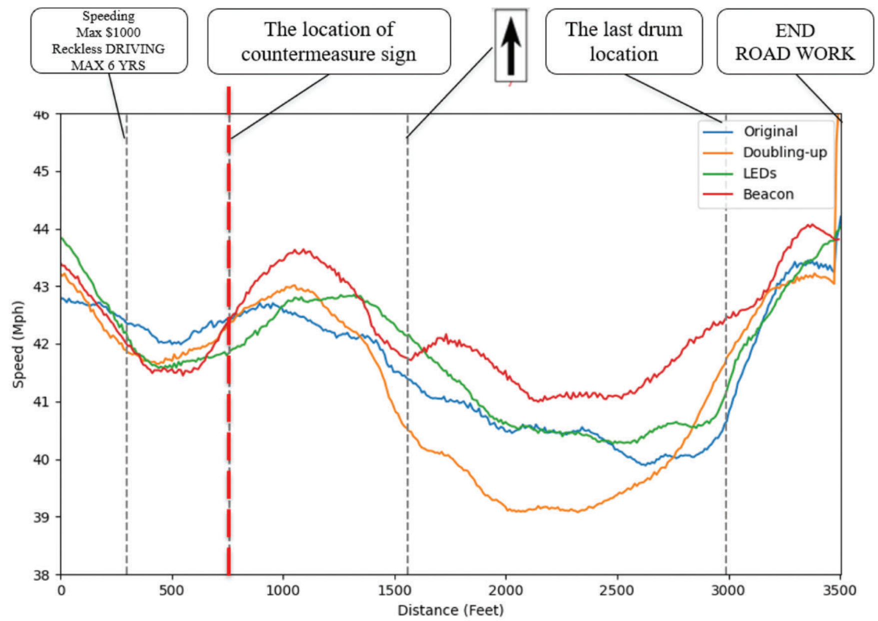
Regarding the results of driving performance data, four indicators introduced in Table 9.3 were discussed: mean speed, speed reduction, acceleration, and lateral position.

10.1.3.1 Mean speed. Figure 10.4 shows the relationship between vehicle speed and distance during daytime and nighttime. In the figure, vehicle speed data was plotted across distance (in feet) for the original design and three countermeasures (doubling-up, LEDs, and beacon). Key reference points along the route, such as the location of the traffic sign applying different countermeasures and the last drum location, were marked by dashed lines. The figure provides insight into the variations in vehicle speed in response to each countermeasure under the lane closure experiment.

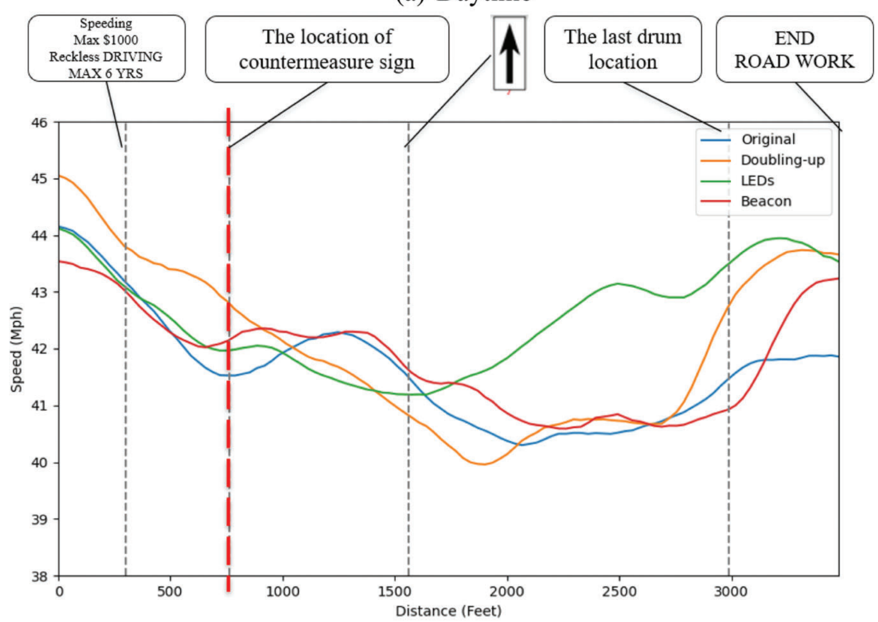
During the daytime (Figure 10.4a), vehicle speed gradually decreased as vehicles approached the traffic sign location, marked by the first dashed line. A slight speed increase was observed as vehicles approached the countermeasure sign location, marked by the red dashed line. The vehicle speed exhibited a similar trend for all countermeasures. In the approach zone (between the first dashed line and the red dashed line), beacon (C4) resulted in the lowest speed, followed by LEDs, doubling-up, and the original condition. In the work zone area (between the third and fourth dashed lines), all speed lines initially showed a decrease, followed by an increase. Specifically, doubling-up (C2) demonstrated obvious speed variation. LEDs (C3) and the original design (C1) exhibited similar and moderate speed variations, while beacon (C4) showed higher vehicle speeds with lower speed variation compared to the others. During the nighttime (Figure 10.4b), in the approach zone (between the first dashed line and the red dashed line), all countermeasures resulted in a similar speed decrease with a consistent reduction ratio, suggesting that all countermeasures influenced driver performance. In the work zone area (between the third and fourth dashed lines), most lines showed a trend of initial speed decrease followed by an increase, except for LEDs, which displayed a continuous speed increase.

Then, the main results of descriptive analysis, ANOVA test, and Paired t-test related to the mean speed were introduced in the following subsections. Detailed tables and figures are listed in Appendix E.1.2.1.

10.1.3.1.1 Descriptive statistics. Table 10.8 shows the vehicle speed data for the original design (C1) and three countermeasures (doubling-up (C2), LEDs (C3), and beacon (C4)) under daytime and nighttime conditions. It shows that mean speeds were fairly consistent across all countermeasures, with small differences between daytime and nighttime conditions, suggesting that drivers generally maintained similar speeds regardless of time scenarios. However, beacon (C4) showed slightly higher variability, particularly during daytime, as indicated by a wider spread in vehicle speed and a higher standard deviation (SD = 10.5104). The table also reveals that beacon (C4) has the highest mean speed during daytime (44.0581 mph) compared to the other countermeasures, suggesting a possible influence of this countermeasure on speed variability. Overall, these results indicate that while time scenarios had a limited impact on vehicle speed, beacon (C4) may contribute to greater variability in speed, particularly during daytime. The boxplot of mean speed (Figure E.4) and relevant explanations are in Appendix E.



(a) Daytime



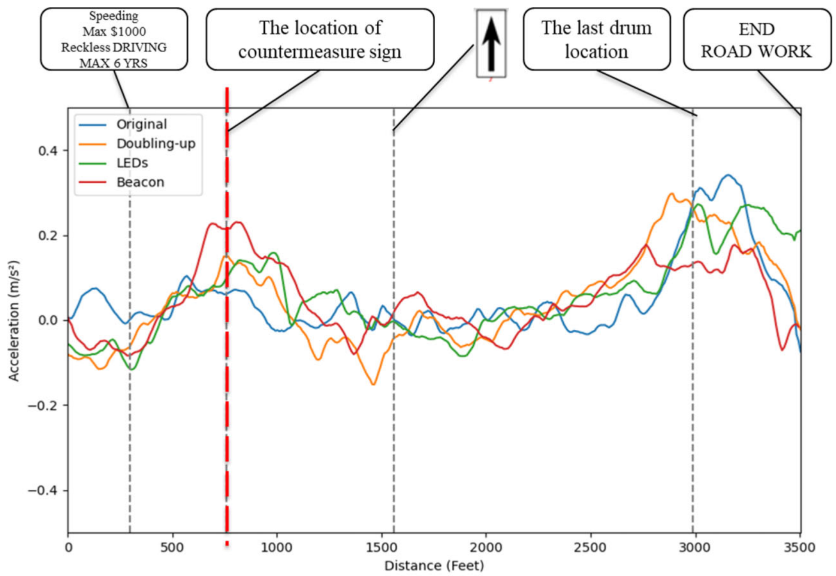
(b) Nighttime

Figure 10.4 Relationship between vehicle speed and distance (lane closure) during the daytime and nighttime.

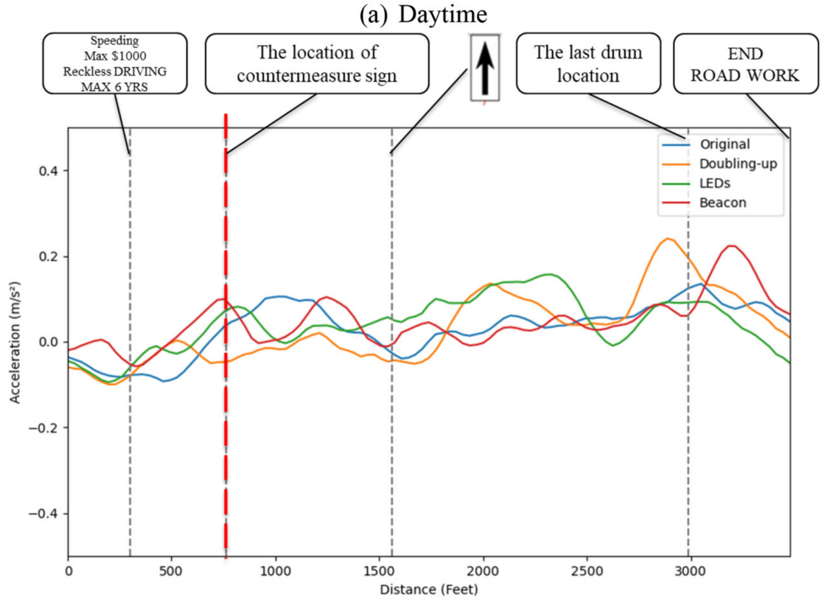
TABLE 10.8
Mean and Standard Deviation (SD) of Vehicle Speed (Lane Closure)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	42.8471	8.1264	42.0617	6.3294	42.9939	7.5791	44.0581	10.5104
Nighttime	42.7492	7.8144	43.4328	8.9015	43.6024	7.4397	43.0593	8.0535

10.1.3.1.2 Results of ANOVA test. As both P-values were larger than 0.05 (P-value = 0.8145 and 0.9749, respectively), no statistically significant differences were identified between countermeasures (including the original design) regarding the mean speed. Thus, there was no evidence to support that any countermeasures contributed to better driving performance measured by mean speed. Details of



(a) Daytime



(b) Nighttime

Figure 10.5 Relationship between vehicle acceleration and distance (lane closure) during daytime and nighttime.

ANOVA test results are listed in Table E.8 in Appendix E.

10.1.3.1.3 Results of Paired t-test. There were no significant differences in mean speed between daytime and nighttime for all countermeasures (including the original design), with all P-values larger than 0.05. The result suggested that drivers maintained a consistent speed regardless of the time scenarios for these countermeasures. Details of Paired t-test results are listed in Table E.9 in Appendix E.

10.1.3.2 Speed reduction. For speed reduction, the results cover three parts: descriptive statistics, ANOVA test, and Paired T-test. Main results are summarized as follows. Detailed tables and figures are listed in Appendix E.1.2.2.

10.1.3.2.1 Descriptive statistics. Table 10.9 shows the speed reduction data for the original design (C1) and three countermeasures (doubling-up (C2), LEDs (C3), and beacon (C4)) under both daytime and nighttime conditions. It indicates that the mean speed reductions for nighttime were consistently lower across the countermeasures, such as -2.7993 mph for the original design (C1) and -2.5385 mph for doubling-up (C2). Among the countermeasures, doubling-up (C2) and LEDs (C3) showed the largest reductions

TABLE 10.9
Mean and Standard Deviation (SD) of Speed Reduction (Lane Closure)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	-0.1378	5.0789	-1.4956	5.3071	-1.7215	4.9261	-0.7861	5.2411
Nighttime	-2.7993	6.3060	-2.5385	4.6684	-2.1312	4.9954	-1.1777	3.9971

TABLE 10.10
Mean and Standard Deviation (SD) of Vehicle Acceleration (Lane Closure)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	0.0504	0.0580	0.0429	0.0663	0.0519	0.0463	0.0538	0.0643
Nighttime	0.0314	0.0507	0.026	0.0598	0.0464	0.0442	0.0453	0.0440

in both conditions, especially at night, while beacon (C4) exhibited the least reduction overall. These results indicate that drivers tended to reduce their speed more at night, with doubling-up (C2) and LEDs (C3) being more effective compared to the original design (C1) and beacon (C4). The boxplot of speed reduction (Figure E.5) and relevant explanations are in Appendix E.

10.1.3.2.2 Results of ANOVA test. As both P-values were larger than 0.05 (P-value = 0.5996 and 0.5959, respectively), no statistically significant differences were observed between countermeasures considering the speed reduction during both daytime and nighttime. It indicates that even though the descriptive statistics show that there were differences in speed reduction performances among countermeasures, no statistical evidence supports that any countermeasure was more effective in speed reduction. Details of ANOVA test results are listed in Table E.10 in Appendix E.

10.1.3.2.3 Results of Paired T-test. As all P-values were above 0.05, no significant differences in speed reduction between the two-time scenarios were identified for these countermeasures. Overall, the results suggest that the time scenarios do not significantly impact speed reduction. Details of Paired t-test results are listed in Table E.11 in Appendix E.

10.1.3.3 Mean acceleration. Figure 10.5 illustrates the relationship between vehicle acceleration and distance for lane closure experiments. The acceleration data is plotted across distance (in feet) for the original design and three countermeasures, similar to Figure 10.4 for the vehicle speed. Key reference points along the route, such as the location of the countermeasure sign and the last drum location, were marked by dashed lines.

During daytime, vehicle acceleration trends show that beacon (C4) resulted in the highest increase acceleration in the approach zone (between the first and red dashed lines), followed by LEDs (C3), doubling-up (C2), and the original design (C1), indicating more cautious when driving with beacon. Beacon (C4) produced a noticeable peak in acceleration shortly after the countermeasure sign location, suggesting a sudden adjustment in speed possibly due to increased drivers' attention. In the work zone (between the third and fourth dashed lines), all countermeasures exhibited an initial deceleration followed by acceleration, with doubling-up (C2) showing the most variation, while LEDs (C3) and the original design (C1) maintained moderate and consistent patterns. At nighttime, acceleration trends were similar, with all countermeasures showing consistent acceleration in the approach zone. In the work zone area, most countermeasures showed a deceleration-acceleration trend. All countermeasures showed some convergences in acceleration levels, while LEDs (C3) and beacon (C4) continued to exhibit slightly higher variability.

Then, the main results of descriptive analysis, ANOVA test, and Paired t-test related to the mean acceleration were introduced in the following subsections. Detailed tables and figures are listed in Appendix E.1.2.3.

10.1.3.3.1 Descriptive statistics. Table 10.10 provides the mean and standard deviation (SD) for each condition, showing slightly higher mean accelerations during daytime for most countermeasures. The accelerations between countermeasures were small (i.e., all mean values were between 0.04–0.07). The boxplot of mean acceleration (Figure E.6) and relevant explanations are in Appendix E.

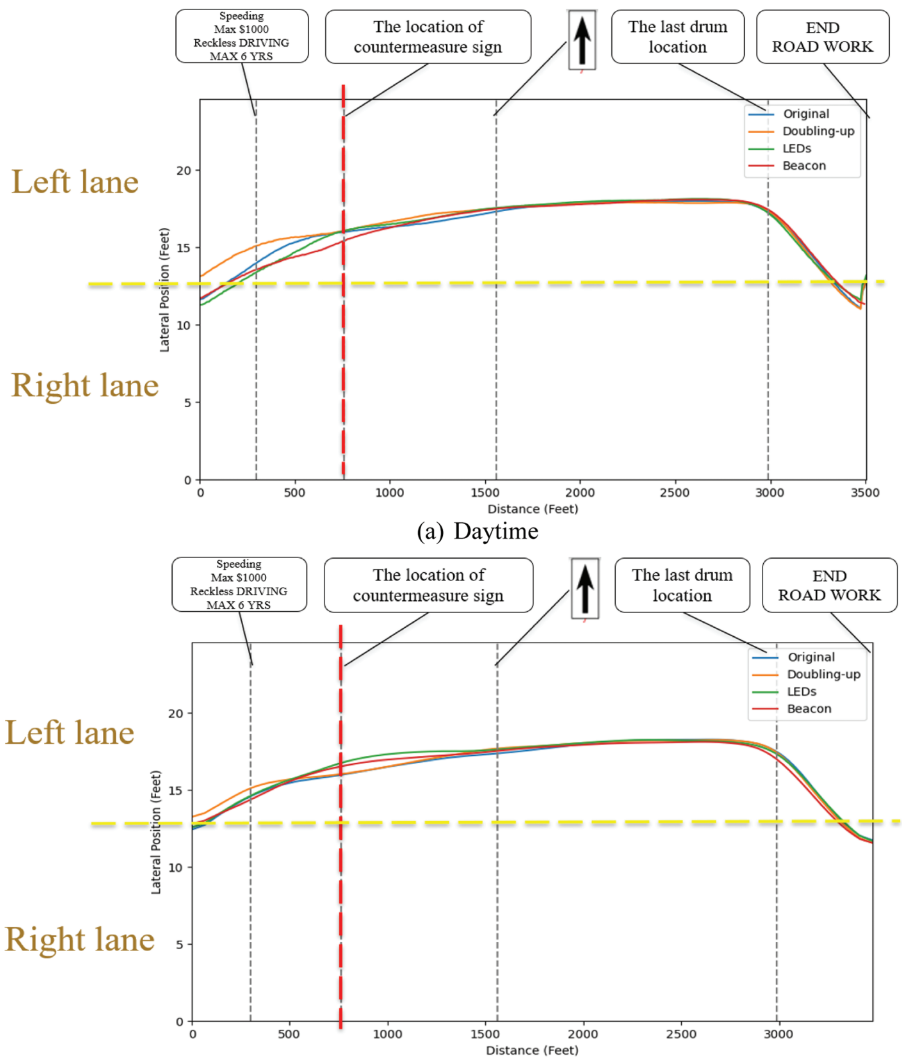
10.1.3.3.2 Results of ANOVA test. According to ANOVA test results, no statistically significant differences were identified between countermeasures considering the mean acceleration during both daytime and nighttime, with both P-values larger than 0.05

(P-value = 0.8961 and 0.2725, respectively). It indicates that even though the descriptive statistics show that there were differences in acceleration performances among countermeasures, no statistical evidence supports that any countermeasure was more effective in influencing mean acceleration. Details of ANOVA test results are listed in Table E.12 in Appendix E.

10.1.3.3.3 Results of Paired T-test. The Paired t-test results indicate that no significant differences in mean acceleration between the two-time scenarios were identified for these countermeasures, as all P-values were above 0.05. Overall, the results suggest that the time scenarios do not significantly impact drivers' mean acceleration performance. Details of Paired t-test results are listed in Table E.13 in Appendix E.

10.1.3.4 Lateral position. Figure 10.6 illustrates the relationship between vehicle lateral position and distance under the lane closure experiment. Lateral position data was plotted across distance (in feet) for the original design and three countermeasures: doubling-up, LEDs, and beacon. The left and right lanes were indicated, with a yellow dashed line marking the boundary between them. Key reference points, including the location of the countermeasure sign and the last drum location, were marked by dashed lines.

During the daytime, all lines demonstrated a gradual shift toward the left lane before reaching the countermeasure sign location. Notably, doubling-up (C2) showed a slightly earlier lateral shift compared to the other countermeasures. In the work zone area, all lines followed a similar pattern, suggesting that the countermeasures did not affect drivers' lateral positioning performance. At nighttime, a similar trend was observed, with all countermeasures leading to a gradual shift toward the left lane. However, the differences between countermeasures were less pronounced compared to the daytime. Doubling-up (C2) and LEDs (C3)



(a) Daytime

(b) Nighttime

Figure 10.6 The relationship between lateral position and distance (lane closure) during daytime and nighttime.

TABLE 10.11
Mean and Standard Deviation (SD) of Vehicle Lateral Position (Lane Closure)

Time Scenarios	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Daytime	17.8646	1.5853	18.1398	1.6275	17.9334	1.4548	17.8579	1.8105
Nighttime	18.1549	1.5821	18.2360	1.5412	18.3050	1.4520	18.1672	1.6125

exhibited nearly identical patterns, indicating a comparable influence on lane positioning at night. By the last drum location, all conditions converged to a similar lateral position, reflecting a consistent driver response across all countermeasures.

Then, the main results of descriptive analysis, ANOVA test, and Paired t-test related to the lateral position were introduced in the following subsections. Detailed tables and figures are listed in Appendix E.1.2.4.

10.1.3.4.1 Descriptive statistics. Table 10.11 shows that the mean lateral position values were slightly higher at nighttime across the original design and three countermeasures, indicating that vehicles tended to be positioned slightly farther from the right lane edge at night. Standard deviations were relatively consistent between day and night, suggesting similar variability in vehicle positioning. The boxplot of lateral position (Figure E.7) and relevant explanations are in Appendix E.

10.1.3.4.2 Results of ANOVA test. According to ANOVA test results, no statistically significant differences were identified between countermeasures considering the lateral position during both daytime and nighttime, with both P-values larger than 0.05. It indicates that even though the descriptive statistics show some potential differences in lateral position performances among countermeasures, no statistical evidence supports that any countermeasure was more effective in influencing the lateral position indicator. Details of ANOVA test results are listed in Table E.14 in Appendix E.

10.1.3.4.3 Results of Paired T-test. The Paired t-test results shown in Table 10.26 indicate that no significant differences in lateral position between the two-time scenarios were identified for these countermeasures, as all P-values were above 0.05. Overall, the results suggest that the time scenarios do not significantly impact drivers' lateral position performance. Details of Paired t-test results are listed in Table E.15 in Appendix E.

10.1.4 Synchronized Data

Regarding the results of synchronized data, five indicators introduced in Table 9.4 were discussed: first-fixation distance to countermeasure, gas pedal variation, steering variation, speed variation, and lateral position variation.

10.1.4.1 First-fixation distance to countermeasure. The results of the first-fixation distance to countermeasure indicator cover four parts: descriptive statistics, ANOVA test, Tukey's HSD test, and Paired t-test. Main results are summarized as follows. Detailed tables and figures are listed in Appendix E.1.3.1.

10.1.4.1.1 Description statistics. Table 10.12 summarizes the mean and standard deviation (SD) of the first-fixation distance to countermeasure under daytime and nighttime scenarios. During daytime, LEDs (C3) had the highest mean first-fixation distance at 626.673 feet (SD = 174.572), followed by beacon (C4) at 576.77 feet (SD = 191.908). Doubling-up (C2) achieved a mean distance of 531.836 feet (SD = 215.292), while the original design (C1) showed the lowest mean distance of 463.135 feet (SD = 184.284). At nighttime, beacon (C4) demonstrated the highest mean first-fixation distance at 649.244 feet (SD = 211.481), indicating its effectiveness under low-light conditions. LEDs (C3) followed closely with a mean of 616.967 feet (SD = 187.455), while doubling-up (C2) achieved a mean of 537.314 feet (SD = 205.226). The original design (C1) still exhibited the least visibility, with a mean distance of 464.414 feet (SD = 150.493). The boxplot of the first-fixation distance to countermeasure (Figure E.8) and relevant explanations are in Appendix E.

10.1.4.1.2 Results of ANOVA test. According to ANOVA test, during both daytime and nighttime, statistically significant differences were identified between the countermeasures (P-value = 0.03 and 0.013, respectively). The result shows that some countermeasures were more effective than others in attracting drivers' attention at longer distances. Details of ANOVA test results are listed in Table E.16 in Appendix E.

10.1.4.1.3 Results of Tukey's HSD test. According to the Tukey's HSD test, during the daytime, a statistically significant difference was observed between the original design (C1) and LEDs (C3), with a P-value of 0.021. The mean difference was 163.538 feet, indicating that LEDs (C3) attracted drivers' attention more effectively than the original design (C1) under daytime conditions. No other significant differences were identified between the countermeasures during the daytime. During the nighttime, there were significant differences between LEDs (C3) and the original design (C1) as well as between beacon (C4) and the original

TABLE 10.12
Mean and Standard Deviation (SD) of First-Fixation Distance to Countermeasure (Lane Closure)

Time Scenarios	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Daytime	463.135	184.284	531.836	215.292	626.673	174.572	576.77	191.908
Nighttime	464.414	150.493	537.314	205.226	616.967	187.455	649.244	211.481

TABLE 10.13
Mean and Standard Deviation (SD) of Gas Pedal Variation (Lane Closure)

Time Scenarios	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Daytime	-0.029	0.122	0.006	0.052	0.018	0.056	-0.017	0.085
Nighttime	-0.003	0.045	-0.023	0.036	0.018	0.056	-0.011	0.106

design (C1). The P-values were 0.044 and 0.015, respectively, with mean differences of 152.553 feet for LEDs (C3) and 184.830 feet for Beacon (C4) compared with the original design (C1). The results indicate that both LEDs (C3) and beacon (C4) could attract drivers' attention better at night than the original design (C1). Overall, the findings highlight the better performance of LEDs (C3) in attracting drivers' attention during both daytime and nighttime. Beacon (C4) is also more effective in the perception stage than the original design (C1) at nighttime. More details of Tukey's HSD test results are listed in Table E.17 in Appendix E.

10.1.4.1.4 Results of Paired T-test. According to the Paired t-test results, with all P-values larger than 0.05, no statistically significant differences were identified between daytime and nighttime for each countermeasure. The countermeasures could attract drivers' attention at similar distances between daytime and nighttime. Details of Paired t-test results are listed in Table E.18 in Appendix E.

10.1.4.2 Gas pedal variation. For gas pedal variation, the results cover three parts: descriptive statistics, ANOVA test, and Paired T-test. Main results are summarized as follows. Detailed tables and figures are listed in Appendix E.1.3.2.

10.1.4.2.1 Description statistics. Table 10.13 summarizes the mean and standard deviation (SD) of gas pedal variation under daytime and nighttime scenarios. During daytime, doubling-up (C2) and LEDs (C3) exhibited positive mean values (0.006 and 0.018, respectively), suggesting slight acceleration after seeing the countermeasures. The original design (C1) and beacon (C4) showed negative mean values (-0.029 and -0.017, respectively), indicating drivers were releasing the gas pedal (deceleration) after seeing the countermeasures. The original design (C1) demonstrated the highest variability (SD = 0.122), while doubling-up (C2) had the lowest variability (SD = 0.052). At nighttime, LEDs (C3) maintained a positive mean value (0.018, SD = 0.056), reflecting consistent slight acceleration. In contrast, the original design (C1) exhibited near-neutral behavior (-0.003, SD = 0.045), while doubling-up (C2) and beacon (C4) showed negative mean values (-0.023, SD = 0.036; -0.011, SD = 0.106, respectively), indicating deceleration. Figure E.9 in Appendix E shows the boxplot of gas pedal variation.

10.1.4.2.2 Results of ANOVA test. According to the results of ANOVA test, during both daytime and nighttime, no statistically significant differences in gas pedal variation were observed between the countermeasures (P-value = 0.208 and 0.286). It indicates that the first fixation of countermeasures did not significantly influence drivers' gas pedal behaviors. Details of ANOVA test results are listed in Table E.19 in Appendix E.

10.1.4.2.3 Results of Paired T-test. According to the Paired t-test results, with all P-values larger than 0.05, no statistically significant differences were identified between daytime and nighttime for each countermeasure. Gas pedal variation remains consistent across different time scenarios. Details of Paired t-test results are listed in Table E.20 in Appendix E.

10.1.4.3 Steering variation. For steering variation, the results cover four parts: descriptive statistics, ANOVA test, Tukey's HSD test, and Paired T-test. Main results are summarized as follows. Detailed tables and figures are listed in Appendix E.1.3.3.

10.1.4.3.1 Description statistics. Table 10.14 summarizes the mean and standard deviation (SD) of steering variation under daytime and nighttime scenarios. During daytime, the mean steering variation was negative for the original design (C1) and doubling-up (C2) at -0.401° (SD = 0.791) and -0.094° (SD = 0.393), respectively, suggesting slight rightward steering adjustments after the first fixation on the countermeasures.

TABLE 10.14
Mean and Standard Deviation (SD) of Steering Variation (Lane Closure)

Time Scenarios	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Daytime	-0.401	0.791	-0.094	0.393	0.062	0.463	0.004	0.454
Nighttime	-0.035	0.278	0.113	0.641	-0.239	0.785	0.038	0.399

LEDs (C3) and beacon (C4) showed positive mean values of 0.062° (SD = 0.463) and 0.004° (SD = 0.454), reflecting minimal leftward adjustments. The original design (C1) exhibited the highest variability (SD = 0.791), while beacon (C4) had the lowest variability (SD = 0.454). At nighttime, doubling-up (C2) had a positive mean of 0.113° (SD = 0.641), indicating the leftward adjustment, while LEDs (C3) showed a negative mean of -0.239° (SD = 0.785), indicating the rightward adjustment. LEDs (C3) exhibited the highest variability at nighttime (SD = 0.785), while the original design (C1) demonstrated the lowest (SD = 0.278). Figure E.10 in Appendix E shows the boxplot of steering variation.

10.1.4.3.2 Results of ANOVA test. The results of the ANOVA test for steering variation show that, during daytime, a statistically significant difference was observed between the countermeasures (P-value = 0.026), indicating that some countermeasures influenced steering behavior more than others. However, during nighttime, no significant differences were identified (P-value = 0.218), suggesting consistent steering behavior variation across countermeasures. Details of ANOVA test results are listed in Table E.21 in Appendix E.

10.1.4.3.3 Results of Tukey's HSD test. According to the results of Tukey's HSD test, during the daytime, a statistically significant difference was observed between the original design (C1) and LEDs (C3), with a P-value of 0.022 and a mean difference of 0.463. It indicates that LEDs (C3) had a greater impact on steering variation compared to the original design (C1). No other significant differences were identified during the daytime scenario. The findings suggest that LEDs (C3) were more effective in influencing drivers' steering behaviors (more leftward steering adjustments) after they first fixated on it during daytime. For nighttime scenario, no significant differences were identified, which is consistent with the ANVOA results. More details of Tukey's HSD test results are listed in Table E.22 in Appendix E.

10.1.4.3.4 Results of Paired T-test. According to the Paired t-test results, all P-values were larger than 0.05. Thus, no statistically significant differences were identified. The results suggest that steering variation remains consistent across different time scenarios for all countermeasures. Details of Paired t-test results are listed in Table E.23 in Appendix E.

10.1.4.4 Speed variation. For speed variation, the results cover three parts: descriptive statistics, ANOVA test, and Paired T-test. Main results are summarized as follows. Detailed tables and figures are listed in Appendix E.1.3.4.

10.1.4.4.1 Description statistics. Table 10.15 summarizes the mean and standard deviation (SD) of speed variation under daytime and nighttime scenarios. During daytime, all countermeasures exhibited negative mean speed variations, indicating deceleration after the first fixation location of countermeasures. LEDs (C3) showed the most deceleration with a mean speed variation of -0.519 mph (SD = 1.140), followed by beacon (C4) of -0.327 mph (SD = 1.381). The original design (C1) and doubling-up (C2) showed less deceleration with mean variations of -0.201 mph (SD = 1.009) and -0.204 mph (SD = 1.094), respectively. At night, doubling-up (C2) showed the lowest negative variation of -0.026 mph (SD = 1.900). LEDs (C3) showed a moderate negative variation of -0.162 mph (SD = 1.509), while beacon (C4) and the original design (C1) had greater deceleration with mean variations of -0.427 mph (SD = 1.174) and -0.482 mph (SD = 1.359), respectively. Figure E.11 in Appendix E shows the boxplot of speed variation.

10.1.4.4.2 Results of ANOVA test. The results of the ANOVA test show that, during both daytime and nighttime scenarios, no statistically significant differences in speed variation were observed between the countermeasures (P-value = 0.763 and 0.764, respectively). The results indicate that countermeasures did not significantly influence drivers speed variations before and after the first fixation location. Details of ANOVA test results are listed in Table E.24 in Appendix E.

10.1.4.4.3 Results of Paired T-test. The Paired t-test results for speed variation across countermeasures between daytime and nighttime scenarios show that all P-values were larger than 0.05. Thus, no statistically significant differences were identified. The results suggest that speed variation remains consistent across different time scenarios for all countermeasures. Details of Paired t-test results are listed in Table E.25 in Appendix E.

10.1.4.5 Lateral position variation. For lateral position variation, the results cover three parts: descriptive statistics, ANOVA test, and Paired T-test.

TABLE 10.15
Mean and Standard Deviation (SD) of Speed Variation (Lane Closure)

Time Scenarios	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	-0.201	1.009	-0.204	1.094	-0.519	1.14	-0.327	1.381
Nighttime	-0.482	1.359	-0.026	1.9	-0.162	1.509	-0.427	1.174

Main results are summarized as follows. Detailed tables and figures are listed in Appendix E.1.3.5.

10.1.4.5.1 Description statistics. Table 10.16 summarizes the mean and standard deviation (SD) of lateral position variation under daytime and nighttime scenarios. During daytime, the original design (C1) demonstrated the highest mean lateral position variation of 0.947 feet (SD = 1.356), followed by LEDs (C3) with a mean variation of 0.718 feet (SD = 1.367). Beacon (C4) and doubling-up (C2) exhibited smaller mean lateral position variations of 0.647 feet (SD = 0.962) and 0.422 feet (SD = 0.759), reflecting more stable lane-keeping behavior and a tendency to move closer to the left lane. At night, LEDs (C3) exhibited the highest mean lateral position variation of 1.03 feet (SD = 1.487), followed by beacon (C4) and the original design (C1) (0.906 feet (SD = 1.076) and 0.837 feet (SD = 1.011), respectively). Doubling-up (C2) demonstrated the smallest mean variation of 0.389 feet (SD = 0.984). Figure E.12 in Appendix E shows the boxplot of lateral position variation.

10.1.4.5.2 Results of ANOVA test. The results of the ANOVA test for lateral position variation in the lane closure experiment show that, during both daytime and nighttime, no statistically significant differences in lateral position variation were observed between the countermeasures (P-value = 0.567 and 0.468), indicating similar lateral positioning behavior across all countermeasures. The results indicate that countermeasures did not significantly influence drivers' lateral position variations before and after the first fixation location. Details of ANOVA test results are listed in Table E.26 in Appendix E.

10.1.4.5.3 Results of Paired T-test. With all P-values larger than 0.05, no statistically significant differences were identified through the Paired t-test results for lateral position variation across countermeasures between daytime and nighttime scenarios. The results suggest that lateral position variation remains consistent across different time scenarios for all countermeasures. Details of Paired t-test results are listed in Table E.27 in Appendix E.

10.1.5 Self-Evaluation

Regarding the results of self-evaluation data from post-survey, the main results of descriptive analysis, ANOVA test, and Tukey's HSD test are discussed as follows. Detailed tables and figures are listed in Appendix E.1.4.

10.1.5.1 Descriptive statistics. Table 10.17 summarizes the participants' subjective evaluations of three countermeasures—doubling-up (C2), LEDs (C3), and beacons (C4)—based on a post-survey conducted after the driving simulation experiment.

The results indicate that beacons consistently achieved the highest average selection percentage (79.69%), followed by LEDs (71.88%) and doubling-up (30.73%). Specifically, beacons showed obvious better results in questions related to attention (Q2), awareness of the work zone (Q4), and improving driving behavior (Q6). LEDs showed better performance in questions about attracting attention (Q2) and awareness (Q4), while doubling-up received lower selection percentages across all questions. All results are based on participants' self-evaluation and perceived effectiveness instead of their real performance. More details are summarized as follows.

- Q1: Beacons had the highest percentage (84.38%) for being noticed, with LEDs also performing well (75.00%).
- Q2: Beacons and LEDs equally attracted participants' attention (81.25% each), which was better than doubling-up (15.63%).
- Q3: LEDs (59.38%) and beacons (71.88%) helped participants understand the sign more quickly, while doubling-up (12.50%) showed limited effectiveness in this regard.
- Q4: Beacons and LEDs were rated as more effective (81.25%) in making participants more aware of the work zone.
- Q5 and Q6: Beacons consistently received high evaluation scores, indicating its effectiveness in helping participants make better decisions and improve driving behavior.

10.1.5.2 Results of ANOVA test. The results of ANOVA test show that there was a statistically significant difference between the three countermeasures regarding the self-evaluation selection percentage, with P-value smaller than 0.01. Further analysis could identify which specific countermeasure differs in perceived effectiveness. Details of ANOVA test results are listed in Table E.28 in Appendix E.

10.1.5.3 Results of Tukey's HSD test. Tukey's HSD post-hoc test was performed to compare the participants' self-evaluation between each pair of countermeasures. The results show that there was a significant

TABLE 10.16
Mean and Standard Deviation (SD) of Lateral Position Variation (Lane Closure)

Time Scenarios	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Daytime	0.947	1.356	0.422	0.759	0.718	1.367	0.647	0.962
Nighttime	0.837	1.011	0.389	0.984	1.03	1.487	0.906	1.076

TABLE 10.17
Results of Selection Percentages Based on the Post-Survey (Lane Closure)

Questions	Countermeasures		
	Doubling-up (%)	LEDs (%)	Beacon (%)
Q1	40.63	75.00	84.38
Q2	15.63	75.00	81.25
Q3	12.50	59.38	71.88
Q4	40.63	81.25	81.25
Q5	40.63	71.88	78.13
Q6	34.38	68.75	81.25
Average value	30.73	71.88	79.69

difference between beacon and doubling-up (P-value $<$ 0.01), with the negative mean difference value showing that beacon was rated as more effective than doubling-up by the participants. Also, a significant difference between LEDs and doubling-up was identified (P-value $<$ 0.01). The positive mean difference supports that LEDs was more effective than doubling-up according to self-evaluation of drivers. In contrast, beacon and LEDs did not show significant differences. More details of Tukey's HSD test results are listed in Table E.29 in Appendix E.

10.1.6 Comprehensive Analysis Results and Discussions

The comprehensive analysis of the lane closure experiment reveals insights into the effectiveness of three countermeasures (doubling-up, LEDs, and beacon) and the original design considering various aspects and indicators, including eye movement, driving performance, synchronized data, and subjective evaluations. Table 10.18 summarizes the results of statistical hypothesis tests covering all indicators. Figure 10.7 shows the findings across three stages of human information processing and considering self-evaluation.

According to the ANOVA tests, three countermeasures and one original design showed significant differences in fixation number, first-fixation distance to countermeasure, fixation duration, steering variation, and self-evaluation, covering all three stages of human information processing and combining objective and subjective data.

- For fixation number, LEDs (C3) countermeasure was more effective in attracting drivers' attention than doubling-up (C2) countermeasure during daytime and nighttime as well as the original design (C1) during nighttime. Therefore, LEDs countermeasure is more effective in attracting attention in the perception stage.
- Regarding first-fixation distance to countermeasure, LEDs (C3) can be seen at a significantly longer distance than the original design during daytime with a mean difference of 164 feet. During nighttime, both LEDs (C3) and beacon (C4) had significantly longer first-fixation distance to countermeasure than the original design, with mean differences of 153 feet for LEDs (C3) and 185 feet for Beacon (C4). Therefore, the LEDs (C3) countermeasure can attract drivers' attention early during both daytime and nighttime, and beacon (C4) countermeasure can also attract drivers' attention early at night.
- As for fixation duration, LEDs (C3) countermeasure was also the more effective one in maintaining drivers' cognitive workload and focus during daytime than doubling-up (C2) countermeasure and during nighttime than both doubling-up (C2) and the original design (C1). Beacon (C4) countermeasure could also be considered during daytime, which has significantly larger fixation duration than doubling-up (C2) countermeasure.
- Steering variation is the only indicator related to drivers' action stage that shows significant results. LEDs (C3) countermeasure was more effective in influencing drivers' steering behaviors than the original design (C1). After the first fixation on LEDs (C3) countermeasure, drivers used the steering to move vehicles more to the left as there was a lane closure work zone on the right lane.
- Based on drivers' self-evaluation using subjective data, LEDs (C3) countermeasure and beacon (C4) countermeasure showed significantly better average performance than doubling-up (C2) countermeasure.

Therefore, the results show that LEDs countermeasure is the most effective one in attracting drivers'

TABLE 10.18
Summary of Statistical Hypothesis Tests Results (Lane Closure)

Category	Indicators	Meanings	ANOVA Test on Countermeasures	Paired T-Test on Time Scenarios
Drivers' perception	Fixation Number	More fixations → higher level of attention → better countermeasure	√ (both daytime and nighttime)	×
	First-fixation Distance to Countermeasure	Higher value → the driver could see the countermeasure at a longer distance (more effective in attracting the driver's attention)	√ (both daytime and nighttime)	×
Drivers' cognition	Fixation Duration	Longer duration → higher mental/cognitive workload → greater concern and focus → better countermeasure	√ (both daytime and nighttime)	×
	Left Pupil Diameter[1]	Larger → higher level of attention and mental workload → more attention, concern, and focus → better countermeasure	×	√
	Right Pupil Diameter[1]		×	√
Driving performance (Drivers' action)	Mean Speed	Lower mean speed (average driving speed across the entire road section) → better driving performance	×	×
	Speed Reduction	Higher value of speed reduction (speed of sign with countermeasures minus speed of the speeding penalty sign) → better driving performance	×	×
	Mean Acceleration	Lower mean acceleration (average acceleration during the entire road section) → better speed control and better driving performance	×	×
	Lateral Position	Higher lateral position (distance from the center of the vehicle to the right lane edge line) → the driver changes lanes earlier and has better driving performance	×	×
	Gas Pedal Variation	Negative value → the driver is releasing the gas pedal (deceleration); Higher absolute value → greater gas pedal behavior variation before and after the driver's first fixation on the countermeasure	×	×
	Steering Variation	Negative value → the driver is turning the steering wheel to the right (moving closer to the right lane); Higher absolute value → greater variation in steering behavior	√ (daytime only)	×
	Speed Variation	Negative value → the driver is decelerating; A higher absolute value → greater speed variation	×	×
	Lateral Position Variation	Negative value → the vehicle is moving closer to the right lane; Higher absolute value → greater variation in the lateral position	×	×
Self-evaluation	Average Selection Percentage	Higher average percentage → better countermeasure	√	–

Note: √ = significant difference; × = non-significant difference; – = did not examine the impacts.
[1]The indicator covers both perception and cognition stages.

attention (perception stage), maintaining drivers' cognitive workload and focus (cognition stage), as well as improving drivers' steering behaviors (action stage). The significant impacts of LEDs countermeasure in the perception and cognition stage cover both daytime and nighttime, while it has significant influences in the action stage during daytime only. Then, beacon countermeasure is also an effective choice that can attract drivers' attention early at night and maintain drivers' cognitive workload and focus during daytime. The results based on objective data are also consistent with drivers' self-evaluation results using subjective data.

In addition, the Paired t-test results showed that time scenarios had significant impacts on pupil diameters (both left and right mean values). The left and right pupil diameters were significantly larger during nighttime than daytime, mainly indicating drivers' different responses to time scenarios (with major differences in lighting conditions) and potentially more cautious and focused driving during nighttime (low-lighting conditions).

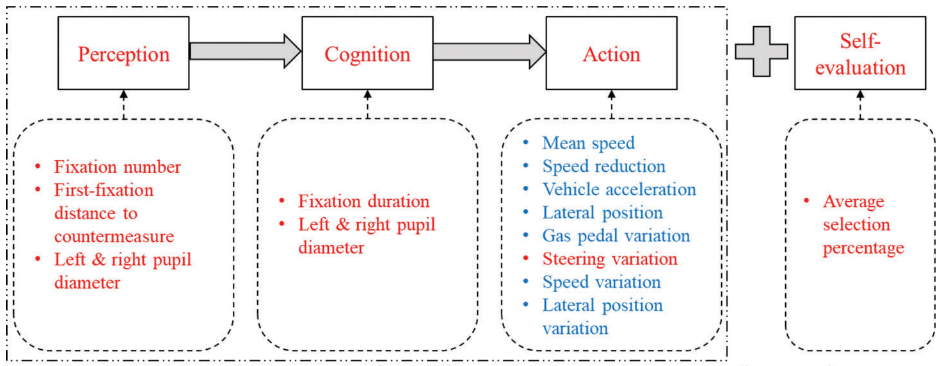


Figure 10.7 Summary of findings in lane closure experiment.

10.2 Shoulder Work Experiment

10.2.1 Participants

A total of thirty-two participants were recruited for the shoulder work experiment. The demographic information is summarized in Figure 10.8.

For gender distribution (Figure 10.8a), the sample had an equal number of males and females (16 each). All participants held valid Indiana driver's licenses. Their ages (Figure 10.8a) ranged from 18 to 83 years, with a mean age of 47.25 years and a standard deviation of 18.36 years. The age and gender distribution of participants also follow the Indiana driver's statistics (FHWA, 2023a). For ethnicity distribution (Figure 10.8b), 69% of participants identified as White, 13% as Black or African American, and 9% each as Hispanic or Latino and Asian, ensuring the diversity of participants. For educational distribution (Figure 10.8c), 31% of participants held a master's degree, 25% had some college education, and 19% completed high school, indicating a broad range of educational backgrounds. Finally, the occupation category distribution (Figure 10.8d) was also diverse in the sample based on the occupational category (U.S. Bureau of Labor Statistics, 2023), with the largest group (7 participants) being in educational instruction and library roles, followed by life, physical, and social sciences (6 participants), and other categories. The diversity of demographic information of participants supports that the sample could help represent Indiana drivers, supporting the reliability and validity of the results.

10.2.2 Eye Movement

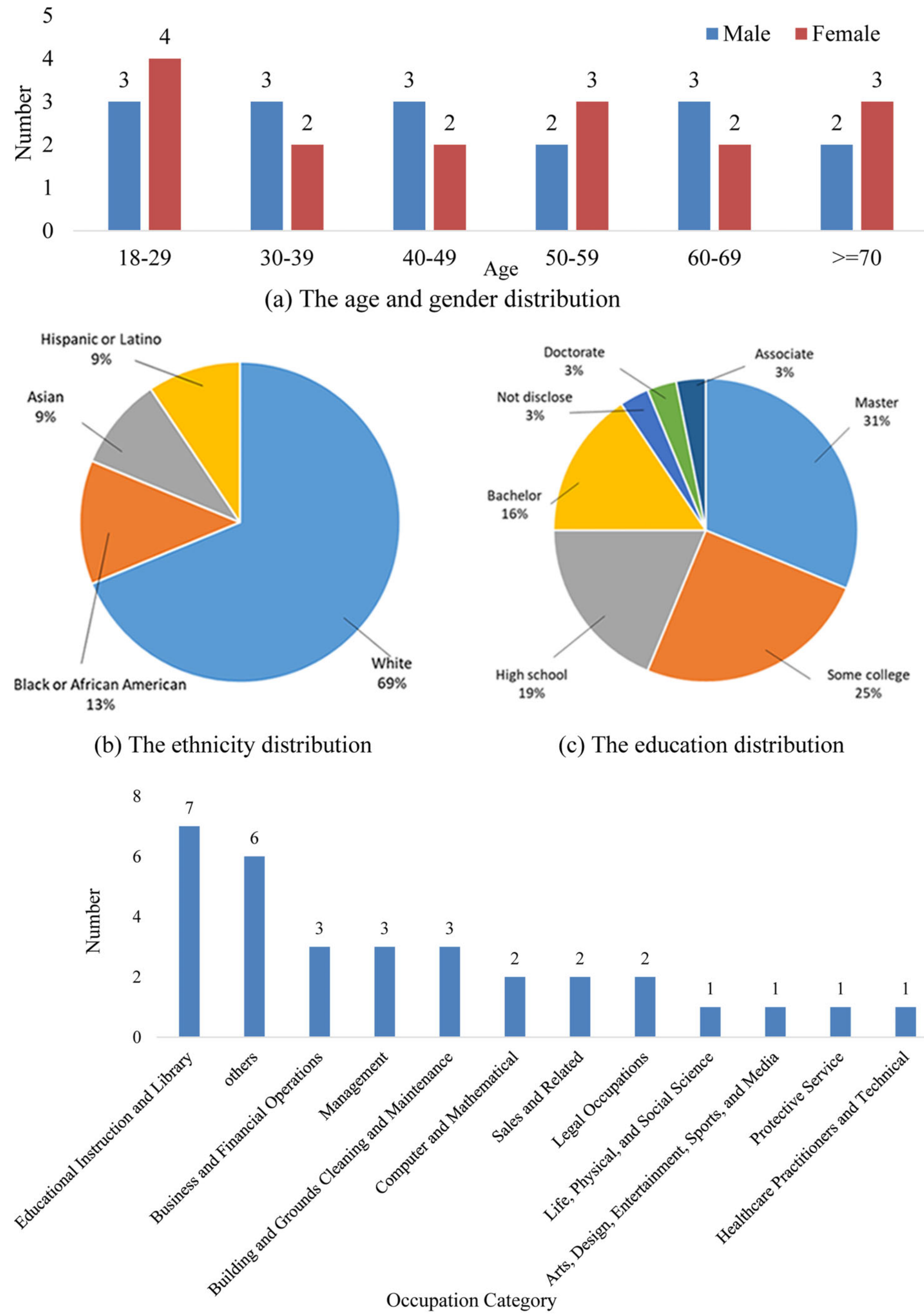
Similar to the lane closure experiment, four eye movement indicators (fixation duration, fixation number, the left pupil diameter, and the right pupil diameter) and example heatmaps based on eye movement data were discussed. Figure 10.9 presents heatmaps of one representative participant's eye movement patterns during the shoulder work experiment under daytime and nighttime conditions.

In the daytime scenario (Figure 10.21a), the heatmap reveals that the driver's gaze is primarily focused on the traffic light area. The regions highlighted in red indicate longer fixation durations, suggesting that these areas attract more attention from the driver. This pattern reflects active visual scanning across key locations in the driving environment. In the nighttime scenario (Figure 10.21b), the heatmap shows that the same driver's gaze is distributed across multiple areas, including the roadway ahead, and the countermeasure. The countermeasure, labeled as an Area of Interest (AOI) with a green rectangle, is also identified as a focal point of attention. These patterns highlight how changes in time scenarios (with major differences in lighting conditions) influence drivers' attention and interaction with countermeasures.

10.2.2.1 Fixation number. The results of the fixation number indicator cover four parts: descriptive statistics, ANOVA test, Tukey's HSD test, and Paired t-test. The main results are summarized as follows. Detailed tables and figures are listed in Appendix E.2.1.1.

10.2.2.1.1 Descriptive statistics. Table 10.19 summarizes the mean and standard deviation (SD) of fixation number for C1–C4. During daytime, doubling-up (C2) had the highest mean fixation number (4.2188) with the greatest variability (SD = 4.0698), while the original design (C1) had the lowest mean (2.5312, SD = 3.2027). At nighttime, LEDs (C3) exhibited the highest mean fixation number (5.7188, SD = 5.1758), demonstrating their strong effectiveness in attracting drivers' attention under low-light conditions, while doubling-up (C2) had the lowest number (2.5625, SD = 2.4222). The original design consistently showed low fixation numbers across both time scenarios, indicating limited attention-capturing ability. The boxplot of fixation number (Figure E.13) and relevant explanations are listed in Appendix E.

10.2.2.1.2 Results of ANOVA test. The results of ANOVA test for the fixation number indicator show that there were no statistically significant differences in fixation numbers between countermeasures during



(a) The age and gender distribution

(b) The ethnicity distribution

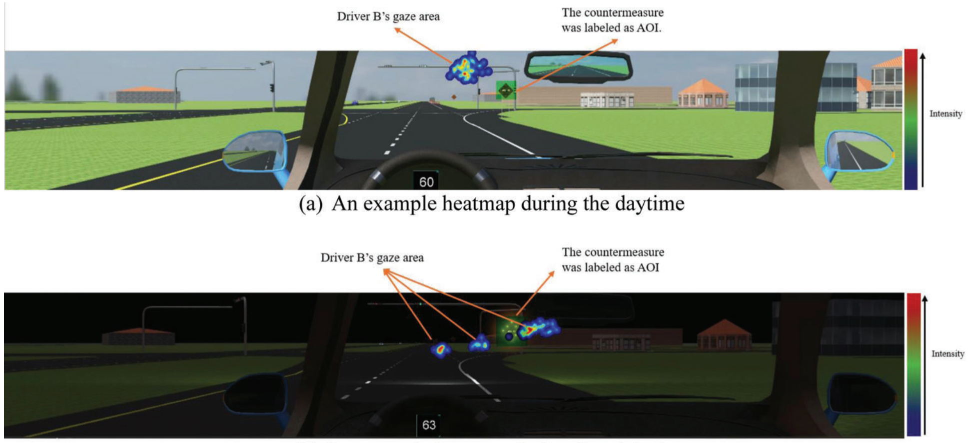
(c) The education distribution

(d) The occupation category distribution

Figure 10.8 Demographic information for shoulder work experiment.

daytime (P-value = 0.1925). However, during nighttime, significant differences were identified in fixation numbers for C1–C4 (P-value = 0.0022). It suggests that some countermeasures are more effective at capturing drivers' attention at night. Details of ANOVA test results are listed in Table E.30 in Appendix E.

10.2.2.1.3 Results of Tukey's HSD test. According to the results of Tukey's HSD test, for daytime scenario, no statistically significant differences were identified, which is consistent with the ANOVA results. During nighttime, LEDs (C3) showed significantly more fixations than the original design (C1) and doubling-up (C2) (with P-values < 0.05 and mean differences of 3.3125 and 3.1562), indicating that LEDs could attract drivers' attention better. More details of Tukey's HSD test results are listed in Table E.31 in Appendix E.



(a) An example heatmap during the daytime

(b) An example heatmap during the nighttime

Figure 10.9 Example heatmaps of a representative participant in shoulder work experiment.

TABLE 10.19
Mean and Standard Deviation (SD) of Fixation Number (Shoulder Work)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	2.5312	3.2027	4.2188	4.0698	3.0312	3.1875	2.7500	2.8737
Nighttime	2.4062	2.9715	2.5625	2.4222	5.7188	5.1758	3.9375	4.1732

10.2.2.1.4 Results of Paired T-test. The Paired t-test results indicate that only LEDs (C3) showed a statistically significant difference (P-value = 0.0025), with higher fixation numbers during nighttime, highlighting its enhanced effectiveness in capturing drivers' attention during a nighttime scenario. For other countermeasures, no significant differences in fixation numbers were identified between daytime and nighttime (P-value > 0.05). Details of Paired t-test results are listed in Table E.32 in Appendix E.

10.2.2.2 Fixation duration. The results of the fixation duration indicator also cover four parts: descriptive statistics, ANOVA test, Tukey's HSD test, and Paired T-test. The main results are summarized as follows. Detailed tables and figures are listed in Appendix E.2.1.2.

10.2.2.2.1 Descriptive statistics. Table 10.20 summarizes the mean and standard deviation (SD) of fixation durations for C1–C4 under daytime and nighttime scenarios. During daytime, beacon (C4) had the highest mean fixation duration (0.2346 seconds) with the largest variability (SD = 0.3326), while the original design (C1) had the shortest mean fixation duration (0.1152 seconds). At nighttime, the LEDs (C3) recorded the highest mean fixation duration (0.2331 seconds), with moderate variability (SD = 0.1747), while doubling-up (C2) had the shortest mean duration (0.1308 seconds). Across both time scenarios, the fixation duration for the original design (C1) remained consistently low, suggesting the limited effectiveness of the original design in capturing driver attention. The boxplot of fixation number (Figure E.14) and relevant explanations are listed in Appendix E.

10.2.2.2.2 Results of ANOVA test. The ANOVA test results for fixation duration show that, during daytime, no statistically significant differences were identified among the four countermeasures (P-value was larger than 0.05). During nighttime, there were statistically significant differences (P-value = 0.0359), indicating that at least one countermeasure exhibited a significantly different mean fixation duration compared to the others. This suggests that the effectiveness of the countermeasures in capturing drivers' attention varies under a nighttime scenario. Details of ANOVA test results are listed in Table E.33 in Appendix E.

10.2.2.2.3 Results of Tukey's HSD test. Tukey's HSD test results further identify which countermeasure contributed to the significant differences. It shows that during daytime, no significant differences were observed between all pairs, similar to the results of the ANOVA test. During nighttime, a statistically significant difference between doubling-up (C2) and LEDs (C3) was identified, with a mean difference of 0.1023 (P-value = 0.0459). It indicates that LEDs (C3) were more effective in maintaining drivers' workload and focus during nighttime time compared to doubling-up (C2). No other pairwise comparisons showed significant differences. More details of Tukey's HSD test results are listed in Table E.34 in Appendix E.

TABLE 10.20
Mean and Standard Deviation (SD) of Fixation Duration (Shoulder Work)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	0.1152	0.1524	0.1768	0.1734	0.1766	0.1866	0.2346	0.3326
Nighttime	0.1382	0.1531	0.1308	0.1249	0.2331	0.1747	0.1802	0.1636

TABLE 10.21
Mean and Standard Deviation (SD) of the Left Pupil Diameter (Shoulder Work)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	3.7459	1.1248	3.6490	0.8625	3.6901	0.9092	3.6814	0.9007
Nighttime	4.6147	1.4663	4.4973	1.3030	4.5378	1.3539	4.5294	1.1907

10.2.2.2.4 Results of Paired T-test. The Paired t-test results indicate that no significant differences in fixation duration were identified between daytime and nighttime for all countermeasures, with all P-values larger than 0.05. It shows the consistent cognitive performances of countermeasures across daytime and nighttime scenarios. Details of Paired t-test results are listed in Table E.35 in Appendix E.

10.2.2.3 Left pupil diameter. The results of the left pupil diameter indicator cover three parts: descriptive statistics, ANOVA test, and Paired T-test. The main results are summarized as follows. Detailed tables and figures are listed in Appendix E.2.1.3.

10.2.2.3.1 Descriptive statistics. Table 10.21 summarizes the mean and standard deviation (SD) of left pupil mean diameter for C1–C4. Across all conditions, nighttime pupil diameters were consistently higher than daytime, indicating increased pupil dilation under low-lighting conditions. Also, the variability was greater at nighttime, as shown by wider interquartile ranges and more outliers. Among all countermeasures, the nighttime condition for the original design (C1) exhibited the largest range, suggesting diverse pupil dilation responses. Then, the table shows that during daytime, the mean pupil diameter was relatively consistent across all countermeasures, ranging from 3.649 mm (C2) to 3.7459 mm (C1), with low variability (SD $<$ 1.2). At nighttime, the mean the left pupil diameter increased substantially compared to daytime, with values ranging from 4.4973 mm (C2) to 4.6147 mm (C1). The standard deviations were also higher at nighttime, reflecting greater inter-individual variability in pupil dilation. These results underscore the impact of lighting conditions on pupil diameter across different countermeasures. The boxplot (Figure E.15) and relevant explanations are listed in Appendix E.

10.2.2.3.2 Results of ANOVA test. According to the ANOVA test results, no statistically significant differences in left pupil mean diameter among the countermeasures were identified (P-values were larger than 0.05). This result suggests that the countermeasures had a similar effect on drivers' left pupil diameters under both daytime and nighttime scenarios. Details of ANOVA test results are listed in Table E.36 in Appendix E.

10.2.2.3.3 Results of Paired T-test. The Paired t-test compared left pupil mean diameter between daytime and nighttime conditions for C1–C4. The t-statistics for all comparisons were strongly negative, ranging from -7.2776 to -8.6476, with all P-values $<$ 0.01, indicating the statistically significant differences in left pupil mean diameter between daytime and nighttime scenarios for all countermeasures. These results confirmed that pupil dilation was significantly larger at nighttime compared to daytime, likely due to the low-lighting conditions at night. The consistency across all countermeasures suggests that this effect was not dependent on specific countermeasure design, instead, it was mainly due to drivers' physiological responses to changes in lighting conditions. Details of Paired t-test results are listed in Table E.37 in Appendix E.

10.2.2.4 Right pupil diameter. Similarly, the results of the right pupil diameter indicator cover three parts: descriptive statistics, ANOVA test, and Paired T-test. The main results are summarized as follows. Detailed tables and figures are listed in Appendix E.2.1.4.

10.2.2.4.1 Descriptive statistics. Table 10.22 summarizes the mean and standard deviation (SD) of the right pupil mean diameter. During daytime, the mean pupil diameters were relatively uniform, ranging from 3.5656 mm (C2) to 3.6934 mm (C1), with low standard deviations (SD $<$ 1.2). At nighttime, the mean pupil diameters increased. The original design (C1) had the largest increase of right pupil mean diameter from daytime to nighttime (daytime: 3.6934 mm,

TABLE 10.22
Mean and Standard Deviation (SD) of Right Pupil Mean Diameter (Shoulder Work)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	3.6934	1.1265	3.5656	0.8567	3.6666	0.977	3.6189	0.9548
Nighttime	4.61	1.3519	4.4054	1.1209	4.5235	1.3867	4.5641	1.4201

nighttime: 4.61 mm). Standard deviations were also higher during nighttime, reflecting increased variability in attention and cognitive load levels. The boxplot (Figure E.16) and explanations are listed in Appendix E.

10.2.2.4.2 Results of ANOVA test. The ANOVA test results for the right pupil mean diameter indicate that no statistically significant differences in right pupil mean diameters among four countermeasures were identified (both P-values were larger than 0.05). All countermeasures had a similar effect on the right pupil mean diameter during both daytime and nighttime, reflecting similar levels of attention and cognitive load. Details of ANOVA test results are listed in Table E.38 in Appendix E.

10.2.2.4.3 Results of Paired T-test. The Paired t-test results compared to the right pupil mean diameter between daytime and nighttime conditions for all countermeasures. The t-statistics for all countermeasures are strongly negative, ranging from -7.7875 to -9.3333, with P-values < 0.01. These results indicate statistically significant increases in right pupil mean diameter during nighttime compared to daytime across all countermeasures, which are consistent with the results of left pupil mean diameters. This consistent trend highlighted the substantial effect of reduced lighting comparing nighttime with daytime on pupil dilation, regardless of the countermeasure. Details of Paired t-test results are listed in Table E.39 in Appendix E.

10.2.3 Driving Performance

Regarding the results of driving performance data, four indicators introduced in Table 9.3 were discussed: mean speed, speed reduction, acceleration, and lateral position.

10.2.3.1 Mean speed. Figure 10.10 shows the relationship between vehicle speed and distance for shoulder work under different countermeasures.

During daytime, doubling-up (C2) resulted in the greatest reduction in vehicle speed, demonstrating its effectiveness at encouraging drivers to slow down through the work zone. In contrast, the original design (C1) consistently maintained higher vehicle speed, indicating its limited influence on driving speed. LEDs (C3) and beacon (C4) showed moderate speed reductions but were less effective compared to doubling-up. Across all countermeasures, vehicle speed decreased steadily after encountering the sign with countermeasures, reached its lowest point near the middle of the work zone (between the first and last drum locations), and began to recover near the "End Road Work sign. At nighttime, speed reductions were more obvious, reflecting a higher level of driver responsiveness to countermeasures probably due to the reduced visibility during nighttime. LEDs (C3) and beacon (C4) were particularly effective at night, with speed reductions observed throughout the work zone. Beacon (C4) achieved the most substantial reduction in nighttime speeds, followed closely by LEDs (C3), whereas the original design (C1) resulted in the least speed reduction.

Then, the main results of descriptive analysis, ANOVA test, and Paired t-test related to the mean speed were introduced in the following subsections. Detailed tables and figures are listed in Appendix E.2.2.1.

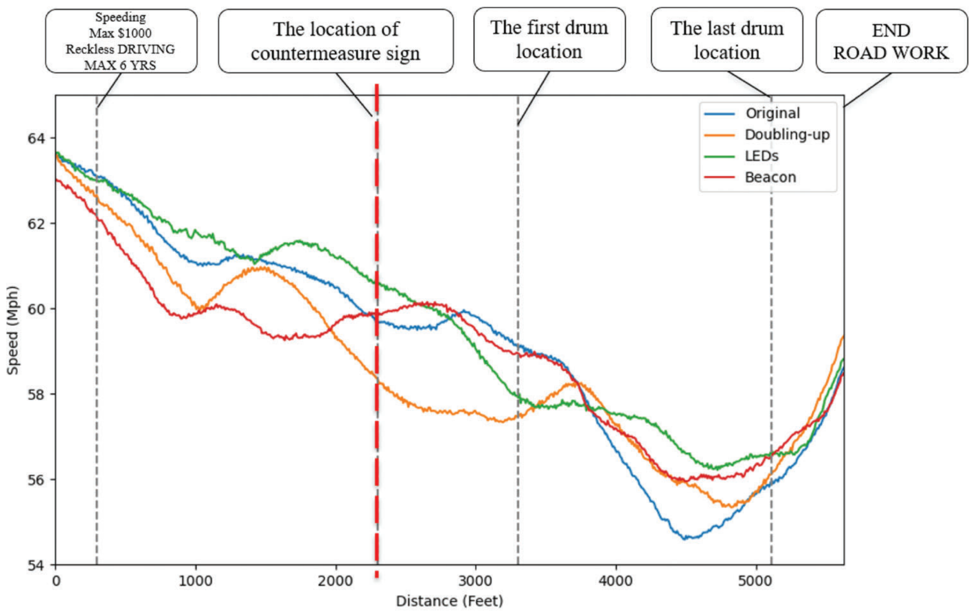
10.2.3.1.1 Descriptive statistics. Table 10.23 provides the mean and standard deviation (SD) of vehicle speed. The mean speed during daytime ranged from 59.2486 mph (C2) to 59.9073 mph (C3), with standard deviations between 4.9922 and 5.9280. At nighttime, mean speeds slightly increased for most countermeasures, ranging from 59.8019 mph (C4) to 60.2319 mph (C1). Also, there was a higher variability in vehicle speed during nighttime according to standard deviations, particularly for LEDs (C3) (SD = 7.3369) and beacon (C4) (SD = 6.7074). The boxplot (Figure E.17) and explanations are listed in Appendix E.

10.2.3.1.2 Results of ANOVA test. According to the ANOVA results for mean speed, both P-values were larger than 0.05, indicating no statistically significant differences in mean speed between countermeasures during both daytime and nighttime scenarios. It suggests that the countermeasures did not have significant impacts on driving speed under the shoulder work scenario. Details of ANOVA test results are listed in Table E.40 in Appendix E.

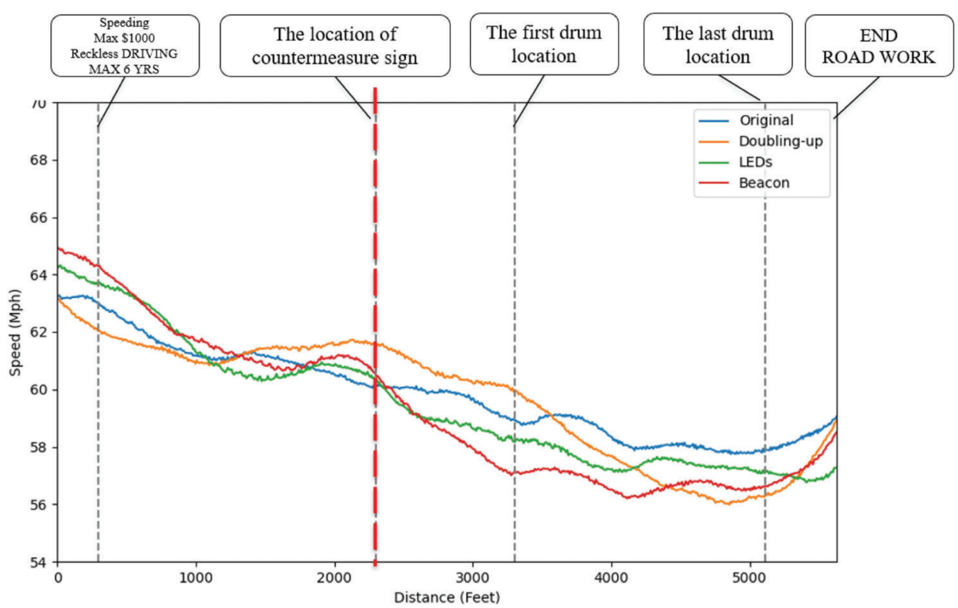
10.2.3.1.3 Results of Paired T-test. The Paired t-test compared mean speed between daytime and nighttime for countermeasures. None of the comparisons showed statistically significant differences, with all P-values exceeding 0.05. Therefore, mean speed

TABLE 10.23
Mean and Standard Deviation (SD) of Vehicle Speed (Shoulder Work)

Time Scenarios	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Daytime	59.4517	5.1585	59.2486	5.9280	59.9073	5.9199	59.2649	4.9922
Nighttime	60.2319	5.5282	60.0762	5.6134	59.8939	7.3369	59.8019	6.7074



(a) Daytime



(b) Nighttime

Figure 10.10 Relationship between vehicle speed and distance (shoulder work) during daytime and nighttime.

remained consistent between daytime and nighttime scenarios, regardless of the countermeasures. Details of Paired t-test results are listed in Table E.41 in Appendix E.

10.2.3.2 Speed reduction. For speed reduction, the results cover three parts: descriptive statistics, ANOVA test, and Paired T-test. Main results are summarized as follows. Detailed tables and figures are listed in Appendix E.2.2.2.

10.2.3.2.1 Descriptive statistics. Table 10.24 summarizes the means and standard deviations (SD) of vehicle speed reductions. Doubling-up (C2) showed the largest mean speed reduction during the daytime (-4.24 mph, SD = 7.92), while Beacons (C4) were most effective at nighttime (-3.37 mph, SD = 5.53). LEDs (C3) consistently demonstrated smaller reductions (-2.43 mph daytime, -2.83 mph nighttime) with moderate variability, and the original design (C1) exhibited moderate effectiveness (-3.21 mph daytime, -2.85 mph nighttime) with high variability. These results indicate that countermeasure performance varies by time of day, with doubling-up (C2) being most effective in the daytime and Beacon (C4) performing better at night, while LEDs (C3) offer limited effectiveness in both scenarios. The boxplot (Figure E.18) and explanations are listed in Appendix E.

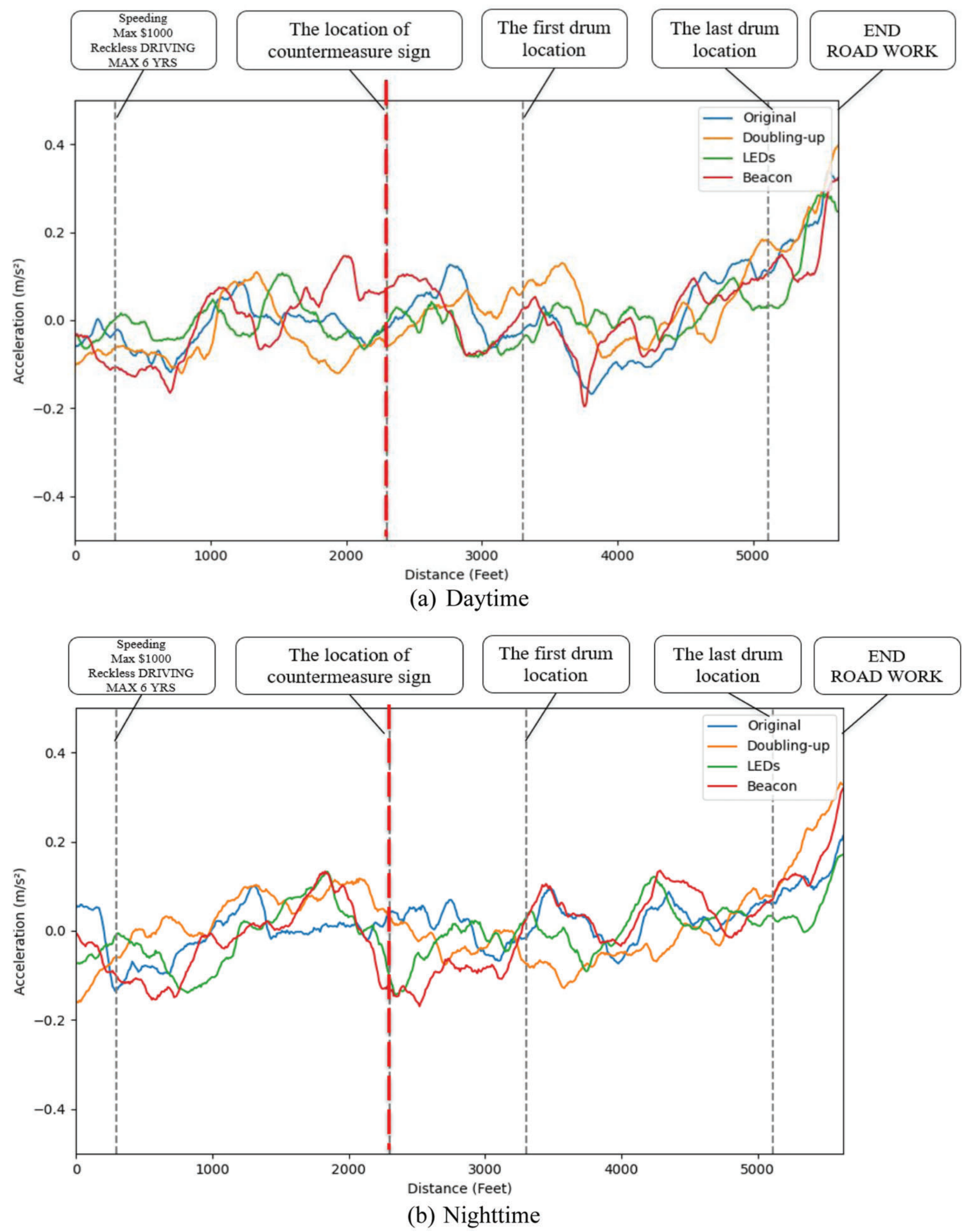
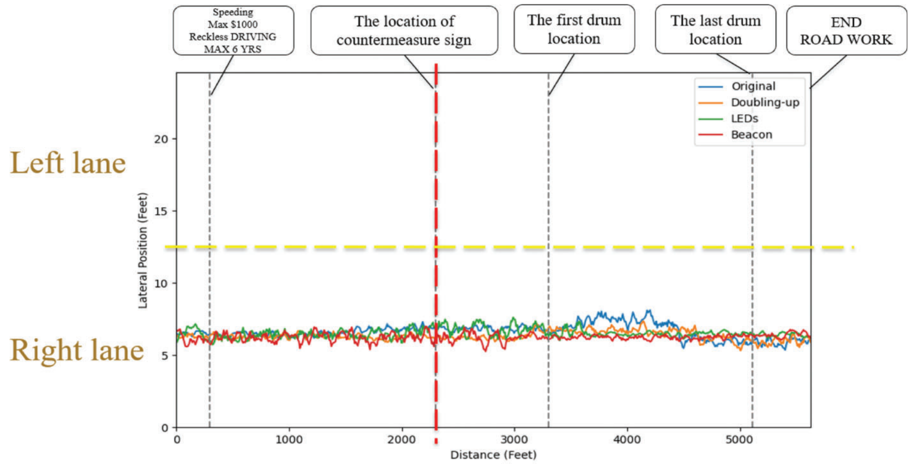
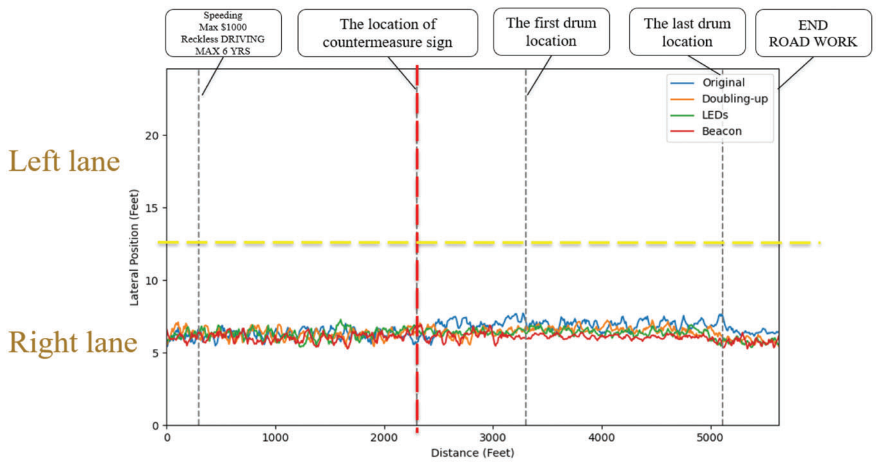


Figure 10.11 Relationship between vehicle acceleration and distance (shoulder work) during daytime and nighttime.



(a) Daytime



(b) Nighttime

Figure 10.12 Relationship between lateral position and distance (shoulder work) during daytime and nighttime.

10.2.3.2.2 Results of ANOVA test. As both P-values were larger than 0.05, no significant differences in speed reductions between countermeasures during both daytime and nighttime were identified in the ANOVA test. It suggests that the countermeasures did not impact drivers' speed reduction. Details of ANOVA test results are listed in Table E.42 in Appendix E.

10.2.3.2.3 Results of Paired T-test. The Paired t-test results reveal that both doubling-up (C2) and LEDs (C3) showed significant differences in vehicle speed reduction between daytime and nighttime scenarios (P-values were smaller than 0.05). Doubling-up (C2) exhibited a t-statistic of -2.6599, indicating greater speed reduction during daytime. Similarly, LEDs (C3) had a t-statistic of 1.848, suggesting significantly more speed reduction during nighttime. In contrast, the original design (C1) and beacon (C4) showed no significant differences in speed reduction between time scenarios, as their P-values were larger than 0.05. Details of Paired t-test results are listed in Table E.43 in Appendix E.

10.2.3.3 Mean acceleration. Figure 10.11 shows the relationship between vehicle acceleration and distance for shoulder work under different countermeasures.

During daytime, doubling-up (C2) demonstrated the most consistent and smooth acceleration patterns, indicating more controlled driving behaviors. LEDs (C3) and beacons (C4) showed moderate variability, with occasional acceleration peaks before the first drum location, while the original design (C1) exhibited fluctuations, suggesting less predictable speed adjustments by drivers. Acceleration increased steadily after the last drum location for all countermeasures as vehicles exited the work zone, with positive peaks near the End Road Work sign. During nighttime, vehicle acceleration patterns became more variable across all countermeasures. Beacon (C4) showed sharper peaks in acceleration, particularly near the countermeasure sign and drum locations. In contrast, doubling-up (C2) continued to promote smoother acceleration patterns, similar to its daytime behavior.

Then, the main results of descriptive analysis, ANOVA test, and Paired t-test related to the mean acceleration were introduced in the following subsections. Detailed tables and figures are listed in Appendix E.2.2.3.

10.2.3.3.1 Descriptive statistics. Table 10.25 presents the mean and standard deviation (SD) of vehicle acceleration. For both daytime and nighttime, Doubling-up (C2) consistently exhibited the highest mean acceleration (0.0443 for both time periods), indicating a slightly more pronounced tendency for drivers to increase acceleration compared to other countermeasures. However, this measure showed higher variability during the daytime (SD = 0.0701) than nighttime (SD = 0.0464). The original design (C1) and Beacons (C4) had comparable mean accelerations across both scenarios, with moderate variability. LEDs (C3) showed the lowest mean accelerations (0.0329 in daytime and 0.0236 at nighttime), suggesting a tendency for less aggressive driving behavior, though variability was comparable to other countermeasures. The boxplot (Figure E.19) and explanations are listed in Appendix E.

10.2.3.3.2 Results of ANOVA test. According to the ANOVA test results for mean acceleration, as both P-values were larger than 0.05, no significant differences in accelerations between countermeasures during both daytime and nighttime were identified. It suggests that the countermeasures did not impact drivers' acceleration behaviors. Details of ANOVA test results are listed in Table E.44 in Appendix E.

10.2.3.3.3 Results of Paired T-test. According to the Paired t-test results comparing the mean acceleration between daytime and nighttime for countermeasures, none of the comparisons showed statistically significant differences, with all P-values exceeding 0.05. Therefore, drivers' mean acceleration remained consistent between daytime and nighttime scenarios, regardless of the countermeasures. Details of Paired t-test results are listed in Table E.45 in Appendix E.

10.2.3.4 Lateral position. Figure 10.12 illustrates the relationship between vehicle lateral position and distance for shoulder work under different countermeasures during daytime (Figure 10.12a) and nighttime (Figure 10.12b).

During daytime, drivers maintained relatively stable lateral positions, centered within the right lane across all countermeasures. Minimal variations were observed near the countermeasure sign and drum locations, with slightly larger fluctuations for the original design (C1) compared to the other three countermeasures. During nighttime, vehicles continued to maintain stability within the right lane, but slightly larger variations were observed compared to daytime, particularly near the drum locations. The original design (C1) showed more lateral position fluctuations, suggesting less precise lane-keeping performance under nighttime conditions. LEDs (C3) and beacon (C4), on the other hand, exhibited more consistent patterns, indicating the two countermeasures may help drivers maintain their lane position more effectively.

Then, the main results of descriptive analysis, ANOVA test, and Paired t-test related to the lateral position were introduced in the following subsections. Detailed tables and figures are listed in Appendix E.2.2.4.

10.2.3.4.1 Descriptive statistics. Table 10.26 illustrates the mean and standard deviation (SD) of lateral position, indicating slightly higher mean lateral positions during daytime for all countermeasures. For example, the original design (C1) has a daytime mean of 6.6169 feet and a nighttime mean of 6.5298 feet, showing a small increase during daytime. Similarly, doubling-up (C2) and beacon (C4) had slight increases in lateral position during daytime, while for LEDs (C3), the mean lateral positions were almost the same

TABLE 10.24
Mean and Standard Deviation (SD) of Speed Reduction (Shoulder Work)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	-3.2074	7.4051	-4.2432	7.9185	-2.4326	4.2199	-2.4422	6.7506
Nighttime	-2.8510	6.7197	0.1007	6.4792	-2.8297	7.3108	-3.3742	5.5263

TABLE 10.25
Mean and Standard Deviation (SD) of Vehicle Acceleration (Shoulder Work)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	0.0367	0.0409	0.0443	0.0701	0.0329	0.0701	0.0356	0.0466
Nighttime	0.0316	0.0669	0.0443	0.0464	0.0236	0.0570	0.0277	0.0537

TABLE 10.26
Mean and Standard Deviation (SD) of Lateral Position (Shoulder Work)

Time Scenarios	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Daytime	6.6169	0.5923	6.5496	0.4848	6.5758	0.5397	6.6204	0.5372
Nighttime	6.5298	0.5898	6.5059	0.4897	6.5742	0.4978	6.5322	0.5929

between daytime and nighttime. The standard deviations show moderate variability within each condition, with no substantial differences between day and night. The boxplot (Figure E.20) and explanations are listed in Appendix E.

10.2.3.4.2 Results of ANOVA test. According to the ANOVA test results for lateral position, as both P-values are larger than 0.05, no significant differences in vehicle lateral position between countermeasures during both daytime and nighttime were identified. Thus, countermeasures did not impact drivers' lane-keeping/changing behaviors significantly. Details of ANOVA test results are listed in Table E.46 in Appendix E.

10.2.3.4.3 Results of Paired T-test. The Paired t-test results compared vehicle lateral position between daytime and nighttime for countermeasures. None of the comparisons showed statistically significant differences, with all P-values exceeding 0.05. Therefore, drivers' mean accelerations remained consistent between daytime and nighttime scenarios, regardless of the countermeasures. Details of Paired t-test results are listed in Table E.47 in Appendix E.

10.2.4 Synchronized Data

Regarding the results of synchronized data, five indicators introduced in Table 9.4 were discussed: first-fixation distance to countermeasure, gas pedal variation, steering variation, speed variation, and lateral position variation.

10.2.4.1 First-fixation distance to countermeasure. The results of the first-fixation distance to countermeasure indicator cover four parts: descriptive statistics, ANOVA test, Tukey's HSD test, and Paired t-test. Main results are summarized as follows. Detailed tables and figures are listed in Appendix E.2.3.1 First-fixation distance to countermeasure.

10.2.4.1.1 Description statistics. Table 10.27 summarizes the mean and standard deviation (SD) of the first-fixation distance to countermeasure under daytime and nighttime scenarios. Beacon (C4) had the mean first-fixation distance of 1,470.751 feet (SD = 359.648), indicating superior visibility, closely followed by LEDs (C3) with a mean of 1,469.998 feet (SD = 473.936). Doubling-up (C2) achieved a mean of 1,283.401 feet (SD = 541.235), while the original design (C1) demonstrated the lowest visibility with a mean distance of 1,254.783 feet (SD = 651.158). During nighttime, LEDs (C3) showed the highest mean first-fixation distance of 1,253.83 feet (SD = 497.328), followed by beacon (C4) with a mean of 1,170.594 feet (SD = 607.942). Doubling-up (C2) achieved a mean of 840.93 feet (SD = 495.919), while the original design (C1) again exhibited the least visibility, with a mean distance of 739.213 feet (SD = 445.713). The boxplot (Figure E.21) is listed in Appendix E.

10.2.4.1.2 Results of ANOVA test. According to the results of the ANOVA test for the first-fixation distance to countermeasure indicator, during daytime, there was no statistically significant difference in first-fixation distances between the countermeasures (P-value = 0.291). During nighttime, significant differences were observed among the countermeasures (P-value = 0.002), indicating that some countermeasures could be seen at longer distances than others during nighttime. Details of ANOVA test results are listed in Table E.48 in Appendix E.

10.2.4.1.3 Results of Tukey's HSD test. According to the results of Tukey's HSD test for the first-fixation distance to countermeasure in the shoulder work experiment, during the daytime scenario, no statistically significant differences were identified, which is consistent with the ANOVA results. During the nighttime scenario, significant differences were found between several pairs. LEDs (C3) had significantly greater first-fixation distances than the original design (C1) and doubling-up (C2), with mean differences of 514.617 feet (P-value = 0.007) and 412.9 feet (P-value = 0.027), respectively. This indicates that LEDs (C3) attracted drivers' attention better than the original design and doubling-up (C2). Beacon (C4) also had a significantly greater first-fixation distance compared to the original design (C1), with a mean difference of 431.382 feet (P-value = 0.035), suggesting improved attention-capture ability. More details of Tukey's HSD test results are listed in Table E.49 in Appendix E.

10.2.4.1.4 Results of Paired T-test. The Paired t-test results compared first-fixation distances to countermeasures C1–C4 between daytime and nighttime scenarios. The original design (C1) exhibited a significant increase in first-fixation distance to countermeasure during nighttime, with a P-value of 0.007. Similarly, doubling-up (C2) demonstrated a significant

TABLE 10.27
Mean and Standard Deviation (SD) of First-Fixation Distance to Countermeasure (Shoulder Work)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	1,254.783	651.158	1,283.401	541.235	1,469.998	473.936	1,470.751	359.648
Nighttime	739.213	445.713	840.93	495.919	1,253.83	497.328	1,170.594	607.942

TABLE 10.28
Mean and Standard Deviation (SD) of Gas Pedal Variation (Shoulder Work)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	0.013	0.09	0.012	0.124	-0.003	0.031	-0.024	0.065
Nighttime	0.019	0.059	-0.008	0.036	0.005	0.059	0.009	0.08

increase in first-fixation distance to countermeasure at nighttime (P-value = 0.004). Beacon (C4) also showed a statistically significant increase in nighttime first-fixation distances to countermeasure (P-value = 0.042). The results suggest that time scenarios impact the countermeasures' effectiveness in attracting drivers' attention. In contrast, LEDs (C3) did not exhibit any statistically significant differences between daytime and nighttime scenarios (P-value = 0.119). Details of Paired t-test results are listed in Table E.50 in Appendix E.

10.2.4.2 Gas pedal variation. For gas pedal variation, the results cover three parts: descriptive statistics, ANOVA test, and Paired T-test. Main results are summarized as follows. Detailed tables and figures are listed in Appendix E.2.3.2.

10.2.4.2.1 Description statistics. Table 10.28 summarizes the mean and standard deviation (SD) of gas pedal variation under daytime and nighttime scenarios. During daytime, the original design (C1) and doubling-up (C2) showed the highest mean values (0.013 and 0.012, respectively), indicating slight acceleration behaviors. In contrast, LEDs (C3) and beacon (C4) had negative mean variations (-0.003 and -0.024), suggesting drivers were releasing the gas pedal (deceleration). During nighttime, the original design (C1) showed the highest mean variation (0.019), showing acceleration behaviors, while doubling-up (C2) exhibited the lowest mean (-0.008), reflecting more deceleration. LEDs (C3) and beacon (C4) had mean variations of 0.005 and 0.009, indicating stable gas pedal behaviors before and after the first-fixation location of countermeasure. Figure E.22 in Appendix E shows the boxplot of gas pedal variation.

10.2.4.2.2 Results of ANOVA test. According to the results of the ANOVA test for gas pedal variation in the shoulder work experiment, during daytime and nighttime, no statistically significant difference in gas pedal variation was observed between the countermeasures (P-value = 0.365 and 0.485, respectively). It indicates similar gas pedal variations across all countermeasures. Details of ANOVA test results are listed in Table E.51 in Appendix E.

10.2.4.2.3 Results of Paired T-test. The Paired t-test results compared gas pedal variation for countermeasures C1–C4 between daytime and nighttime scenarios. None of the comparisons showed statistically significant differences, with all P-values exceeding 0.05. Therefore, gas pedal variation remained consistent between daytime and nighttime scenarios for all countermeasures. Details of Paired t-test results are listed in Table E.52 in Appendix E.

10.2.4.3 Steering variation. For steering variation, the results cover three parts: descriptive statistics, ANOVA test, and Paired T-test. Main results are summarized as follows. Detailed tables and figures are listed in Appendix E.2.3.3.

10.2.4.3.1 Description statistics. Table 10.29 summarizes the mean and standard deviation (SD) of steering variation under daytime and nighttime scenarios. During daytime, mean steering variation was negative for all countermeasures, with values ranging from -0.049° for beacon (C4) to -0.107° for LEDs (C3). The standard deviation (SD) varied more noticeably. Doubling-up (C2) had the highest variability (SD = 0.833) and beacon (C4) and the original design (C1) had the lowest SDs (0.251). At nighttime, the mean steering variation remained negative but closer to zero, ranging from -0.023° for LEDs (C3) to -0.153° for doubling-up (C2). Doubling-up (C2) and beacon (C4) exhibited higher variability (SD = 0.593 and 0.554, respectively), while the original design (C1) had the lowest variability (SD = 0.271). Figure E.23 in Appendix E shows the boxplot of steering variation.

TABLE 10.29
Mean and Standard Deviation (SD) of Steering Variation (Shoulder Work)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	-0.092	0.251	-0.105	0.833	-0.107	0.475	-0.049	0.251
Nighttime	-0.072	0.271	-0.153	0.593	-0.023	0.302	-0.059	0.554

10.2.4.3.2 Results of ANOVA test. According to the results of the ANOVA, during daytime and nighttime, no statistically significant difference was found between countermeasures (P-value = 0.976 and 0.781, respectively). It suggests consistent steering behavior variations before and after the first fixation location across countermeasures. Details of ANOVA test results are listed in Table E.53 in Appendix E.

10.2.4.3.3 Results of Paired T-test. According to the Paired t-test results, none of the comparisons showed statistically significant differences, with all P-values exceeding 0.05. Steering variations remained consistent between daytime and nighttime scenarios for all countermeasures. Details of Paired t-test results are listed in Table E.54 in Appendix E.

10.2.4.4 Speed variation. For speed variation, the results cover three parts: descriptive statistics, ANOVA test, and Paired T-test. Main results are summarized as follows. Detailed tables and figures are listed in Appendix E.2.3.4.

10.2.4.4.1 Description statistics. Table 10.30 summarizes the mean and standard deviation (SD) of speed variation under daytime and nighttime scenarios. During the daytime, doubling-up (C2) exhibited the highest positive speed variation (0.128 mph, SD = 1.575), indicating acceleration behavior after the first fixation location. In contrast, LEDs (C3) showed the lowest mean speed variation (-0.531 mph, SD = 1.341), suggesting deceleration behavior. The original design (C1) and beacon (C4) also exhibited negative speed variations of -0.137 mph (SD = 0.664) and -0.177 mph (SD = 1.085), respectively. At nighttime, doubling-up (C2) again displayed the highest positive speed variation (0.274 mph, SD = 1.343), while LEDs (C3) maintained the lowest negative speed variation (-0.472 mph, SD = 0.918). The original design (C1) and beacon (C4) showed moderate negative speed variations of -0.183 mph (SD = 1.094) and -0.335 mph (SD = 1.184), respectively. Figure E.24 in Appendix E shows the boxplot of speed variation.

10.2.4.4.2 Results of ANOVA test. During daytime and nighttime, no statistically significant difference was found between the countermeasures according to the ANOVA test (P-value = 0.309 and 0.115, respectively). Thus, speed variation before and after the first fixation location remained consistent across countermeasures. Details of ANOVA test results are listed in Table E.55 in Appendix E.

10.2.4.4.3 Results of Paired T-test. The Paired t-test results show no statistically significant differences for any countermeasure, with all P-values exceeding 0.05. Speed variation also remained consistent between daytime and nighttime scenarios across all countermeasures. Details of Paired t-test results are listed in Table E.56 in Appendix E.

10.2.4.5 Lateral position variation. For lateral position variation, the results cover three parts: descriptive statistics, ANOVA test, and Paired T-test. Main results are summarized as follows. Detailed tables and figures are listed in Appendix E.2.3.5.

10.2.4.5.1 Description statistics. Table 10.31 summarizes the mean and standard deviation (SD) of lateral position variation under daytime and nighttime scenarios. During daytime, doubling-up (C2) showed the highest mean lateral position variation (0.295 feet, SD = 1.147). Beacon (C4) exhibited the largest movement to the right lane with a negative mean variation (-0.395 feet, SD = 2.001). The original design (C1) also had a negative mean variation (-0.25 feet, SD = 1.616), while LEDs (C3) showed minimal variation (-0.071 feet, SD = 0.701). At nighttime, LEDs (C3) demonstrated the most stable lane position, with the smallest mean lateral position variation (0.027 feet, SD = 0.83). Beacon (C4) had a similar mean value (0.056 feet, SD = 0.83). Doubling-up (C2) and the original design (C1) showed slight shifts toward the right lane with negative mean variations of -0.325 feet (SD = 1.493) and -0.196 feet (SD = 1.219), respectively. Figure E.25 in Appendix E shows the boxplot of lateral position variation.

10.2.4.5.2 Results of ANOVA test. During daytime and nighttime, no statistically significant difference was found between the countermeasures according to the ANOVA test (P-value = 0.367 and 0.587, respectively). Lateral position variation was consistent across all countermeasures, indicating stable lane-keeping behaviors before and after the location of the first fixation on countermeasure. Details of ANOVA test results are listed in Table E.57 in Appendix E.

10.2.4.5.3 Results of Paired T-test. The Paired t-test results indicate no statistically significant differ-

TABLE 10.30
Mean and Standard Deviation (SD) of Speed Variation (Shoulder Work)

	Original Design (C1)		Doubling-up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	-0.137	0.664	0.128	1.575	-0.531	1.341	-0.177	1.085
Nighttime	-0.183	1.094	0.274	1.343	-0.472	0.918	-0.335	1.184

TABLE 10.31
Mean and Standard Deviation (SD) of Lateral Position Variation (Shoulder Work)

	Original Design (C1)		Doubling-Up (C2)		LEDs (C3)		Beacon (C4)	
Time Scenarios	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Daytime	-0.25	1.616	0.295	1.147	-0.071	0.701	-0.395	2.001
Nighttime	-0.196	1.219	-0.325	1.493	0.027	0.83	0.056	0.83

ences between daytime and nighttime scenarios for any of the countermeasures, with all P-values exceeding 0.05. Lateral position variation remains consistent between daytime and nighttime scenarios for all countermeasures. Details of Paired t-test results are listed in Table E.58 in Appendix E.

10.2.5 Self-Evaluation

Regarding the results of self-evaluation data from post-survey, the main results of descriptive analysis, ANOVA test, and Tukey's HSD test are discussed as follows. Detailed tables and figures are listed in Appendix E.2.4.

10.2.5.1 Descriptive statistics. Table 10.32 summarizes the participants' subjective evaluations of three countermeasures—doubling-up (C2), LEDs (C3), and beacons (C4)—based on a post-survey conducted after the shoulder work driving simulation experiment. It shows that LEDs (C3) consistently received the highest percentages across all questions, with values ranging from 78.13% to 90.63% and an average of 84.38%, indcating their best performance in perception, cognition, and action, based on participants' evaluation. Then, beacon (C4) showed moderate effectiveness, with percentages ranging from 34.38% to 65.63% and an average of 54.69%, while doubling-up (C2) was scored as the lowest, with percentages between 34.38% and 53.13% and an average of 46.35%. The results suggest that participants perceived LEDs (C3) countermeasure as the most effective one for shoulder work, followed by beacon (C4), while doubling-up (C2) was the least effective one. All results are based on participants' self-evaluation and perceived effectiveness instead of their real performance.

10.2.5.2 Results of ANOVA test. The ANOVA test results for participants' self-evaluation of the three countermeasures indicate that there were statistically significant differences in self-evaluation results between countermeasures (P-value < 0.01). Further tests should be performed to identify which countermeasure contributed to the differences. Details of ANOVA test results are listed in Table E.59 in Appendix E.

10.2.5.3 Results of Tukey's HSD test. Tukey's HSD test compared participants' self-evaluation scores across three countermeasures under the shoulder work experiment. It indicates that LEDs (C3) had significantly different evaluation results compared to beacon (C4) and doubling-up (C2) (with P-values smaller than 0.05), when beacon and doubling-up did not show significant differences (with P-value larger than 0.05). Participants perceived LEDs (C3) as a more effective countermeasure for all questions related to perception, cognition, and action than doubling-up and beacon countermeasures. Details of Tukey's HSD test results are listed in Table E.60 in Appendix E.

10.2.6 Comprehensive Analysis Results and Discussions

The comprehensive analysis of the shoulder work experiment provides insights into the effectiveness of the original design and three countermeasures considering various indicators, including eye movement, driving performance, synchronized data, and self-evaluation. Table 10.33 shows the summary of statistical hypothesis tests results. Figure 10.13 shows the findings across three stages of human information processing using objective data as well as the self-evaluation results based on subjective data.

According to the ANOVA tests, three countermeasures and one original design showed significant differences in fixation number, first-fixation distance to countermeasure, fixation duration, and self-evaluation, covering the perception and cognition stages of human information processing and combining objective and subjective data.

- For fixation number, LEDs countermeasure showed significantly better performance in attracting drivers'

TABLE 10.32
Results of Selection Percentages Based on the Post-Survey (Shoulder Work)

	Countermeasures		
Questions	**Doubling-up (%)**	**LEDs (%)**	**Beacon (%)**
Q1	50.00	87.50	81.25
Q2	43.75	90.63	65.63
Q3	34.38	78.13	34.38
Q4	53.13	87.50	40.63
Q5	50.00	84.38	56.25
Q6	46.88	78.13	50.00
Average Value	46.35	84.38	54.69

attention than the original design and doubling-up countermeasure under nighttime scenario only. Therefore, LEDs countermeasure was more effective in attracting attention under low-lighting conditions.

- As for first-fixation distance to countermeasure, the LEDs countermeasure could be seen by drivers at significantly longer distances than the original design (with a mean difference of 515 feet) and doubling-up countermeasures (with a mean difference of 413 feet) during nighttime. Beacon countermeasure also showed better performance than the original design at night, with an average longer first-fixation distance of 431 feet. Thus, LEDs and beacon countermeasures are more effective in attracting drivers' attention early during nighttime.
- Regarding fixation duration, LEDs countermeasure was also recognized as a more effective one in maintaining drivers' cognitive workload and focus during nighttime compared to doubling-up countermeasure, supporting the significant impacts of countermeasures in the cognition stage.
- The self-evaluation results show that LEDs countermeasure was perceived as the most effective countermeasure in all questions compared to doubling-up and beacon countermeasures.

Therefore, the results show that LEDs countermeasure is the most effective one in attracting drivers' attention (perception stage) and maintaining drivers' cognitive workload and focus (cognition stage) during nighttime. The results are consistent with drivers' self-evaluation results based on subjective data. Beacon countermeasure is also effective in attracting drivers' attention for longer distances at night.

Then, the Paired t-test results showed that, between daytime and nighttime, there were significant differences in fixation number, first-fixation distance to countermeasure, the left pupil diameter, and the right pupil diameter.

- For the fixation number, significant differences were identified between the daytime and the nighttime for LEDs countermeasure. It can attract drivers' attention better at night than in the daytime.
- The results of the first-fixation distance to countermeasure show that the original design, doubling-up countermeasure, and beacon countermeasure had significantly different performances between the daytime and the nighttime. They had longer first-fixation distances at night. LEDs countermeasure had similar first-fixation distances during daytime and nighttime.
- As for the left and right pupil diameters, there were significant differences between the daytime and the nighttime for all countermeasures, showing that lighting conditions, rather than countermeasure design, primarily influenced pupil dilation. Drivers had significantly larger pupil diameters during nighttime, highlighting the critical role of lighting conditions in influencing drivers' attention and cognitive workload.

Even though no significant results were found in the action stage, the relationships between the three stages of human information processing (Proctor & Van Zandt, 2018) indicate that the effectiveness of countermeasures in the perception and action stages will also influence the action stage. For example, LEDs countermeasure can be seen at longer distances by drivers and attract drivers' attention more, which helps drivers extract visual information from the sign. After assisting drivers extract information visually, LEDs countermeasure could also help maintain drivers' cognitive workload and focus, showing that it can also facilitate the information analysis and decision-making process. The effectiveness of countermeasures in the perception and cognition stages could contribute to the action stage by reducing potential reaction time, improving driving behaviors, etc.

In addition, there are several potential reasons for the insignificant results in the action stage. The first potential reason is the learning effects for participants during the experiment. In the driving simulation experiment, each participant finished eight trials (four countermeasures under daytime and nighttime) with the same road and work zone settings. Even though we used the Latin Square design to balance daytime and nighttime and random orders of four countermeasures to reduce the learning effects, drivers may still learn more about the situation after driving through it several times and take relevant behaviors based on the previous trials. For example, some participants changed lanes to the left at the beginning of the trial for the lane closure experiment based on their experiences of previous trials, when they actually did not see any signs or work zone elements. Existing studies also indicate that repeated trials/scenarios will impact reaction time and driving behaviors (de Groot et al., 2011; Winkler et al., 2018; Zangi et al., 2022). Thus, the learning effects during the experiment may cause drivers' driving behaviors to not change significantly due to their familiarity with the

TABLE 10.33
Summary of Statistical Hypothesis Tests Results (Shoulder Work)

Category	Indicators	Meanings	ANOVA Test on Countermeasures	Paired T-Test on Time Scenarios
Drivers' Perception	Fixation Number	More fixations → higher level of attention → better countermeasure	√ (nighttime only)	√
	First-fixation Distance to Countermeasure	Higher value → the driver could see the countermeasure at a longer distance (more effective in attracting the driver's attention)	√ (nighttime only)	√
Drivers' Cognition	Fixation Duration	Longer duration → higher mental/ cognitive workload → greater concern and focus → better countermeasure	√ (nighttime only)	×
	Left Pupil Diameter[1]	Larger → higher level of attention and mental workload → more attention, concern, and focus → better countermeasure	×	√
	Right Pupil Diameter[1]		×	√
Driving Performance (Drivers' Action)	Mean Speed	Lower mean speed (average driving speed across the entire road section) → better driving performance	×	×
	Speed Reduction	Higher value of speed reduction (speed of sign with countermeasures minus speed of the speeding penalty sign) → better driving performance	×	×
	Mean Acceleration	Lower mean acceleration (average acceleration during the entire road section) → better speed control and better driving performance	×	×
	Lateral Position	Higher lateral position (distance from the center of the vehicle to the right lane edge line) → the driver changes lanes earlier and has better driving performance	×	×
Driving performance (Drivers' action)	Gas Pedal Variation	Negative value → the driver is releasing the gas pedal (deceleration); Higher absolute value → greater gas pedal behavior variation before and after the driver's first fixation on the countermeasure	×	×
	Steering Variation	Negative value → the driver is turning the steering wheel to the right (moving closer to the right lane); Higher absolute value → greater variation in steering behavior	×	×
	Speed Variation	Negative value → the driver is decelerating; A higher absolute value → greater speed variation	×	×
	Lateral Position Variation	Negative value → the vehicle is moving closer to the right lane; Higher absolute value → greater variation in the lateral position	×	×
Self-evaluation	Average Selection Percentage	Higher average percentage → better countermeasure	√	–

Note: √ = significant difference; × = non-significant difference; – = did not examine the impacts.

road section. Second, simulation scenarios are not exactly the same as the real-life scenarios. Even though we put much effort into simulating the road section, work zones, traffic signs, etc., simulation cannot 100% reproduce real-world scenarios. Therefore, drivers' behaviors might be different between driving simulation and real-world driving, which may impact the potential effectiveness of countermeasures. Third, the changes in the perception and cognition stages may not lead to changes in behaviors. Even though the human informa-

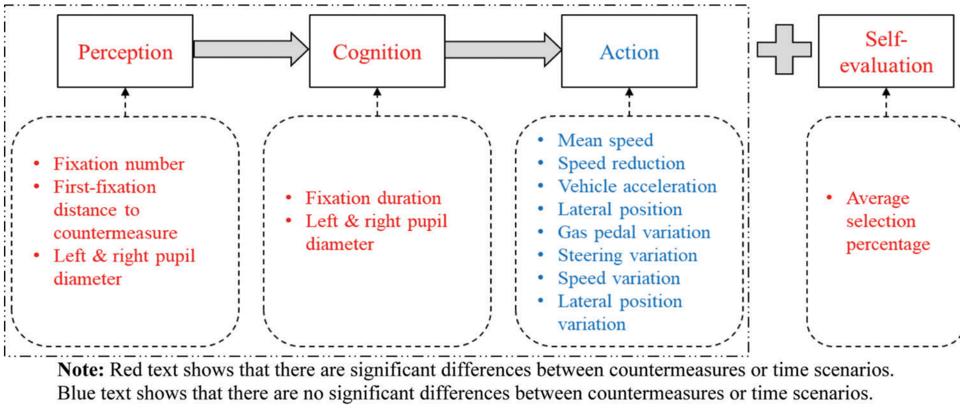


Figure 10.13 Summary of findings in shoulder work experiment.

tion processing theory illustrates that differences in drivers' perception and cognition will lead to changes in the action stage, in real driving, drivers may not change their behaviors even if there are improvements in their perception and cognition stages. For example, drivers may see the countermeasures several hundred feet ahead and process the information earlier, they may decide not to reduce speed because the current speed is within the speed limit, or they feel the situation is under their control. Traffic signs with countermeasures could only provide warning information ahead and facilitate drivers' understanding of the information, instead of forcing drivers to take necessary actions. Many other factors may influence drivers' decisions, such as drivers' age, gender, driving experience, and education (McGwin & Brown, 1999; Singh & Kathuria, 2021), drivers' emotions and personalities (Jafarpour & Rahimi-Movaghar, 2014; Singh & Kathuria, 2021), and other distractions (Kountouriotis & Merat, 2016; Stutts et al., 2001; Stutts & Hunter, 2003). For example, investigating the differences in behaviors between drivers who exceed the speed limit or have distracted driving and normal drivers could provide valuable insights into the action stages of different drivers. Future studies could explore how to address those reasons to further explore the effectiveness of countermeasures, such as reducing learning effects by recruiting more participants, conducting field experiments in real-world work zones, and considering other factors that may influence driving behaviors in the process.

11. SUMMARY AND RECOMMENDATIONS

11.1 Summary and Limitations

Work zone safety remains a persistent concern in the United States, with 20%–30% more crashes than normal roads (Ullman et al., 2008). Color patterns are an effective way to provide visual information for drivers, especially in work zones. This study aims to systematically investigate color patterns considering various work zone elements and human information processing theory to improve the overall safety and perception of INDOT work zones. Methodology used in this study covers the following parts: (1) a literature review to summarize the current efforts related to work zone crashes as well as color-related factors; (2) crash data analysis to identify the representative work zones in Indiana; (3) crash data analysis using NLP method to explore color-related root causes of Indiana work zone crashes; (4) interviews and literature review to propose color-related countermeasures to reduce work zone crashes in Indiana; and (5) driving simulation experiment to evaluate the effectiveness of proposed countermeasures in representative work zones. Several key findings were summarized in this study as follows.

First, the color-related root causes of work zone crashes in Indiana were proposed as follows: (1) poor visibility and brightness of color for work zone elements (e.g., traffic signs, channelizing devices, pavement markings, etc.); (2) insufficient color contrast between work zone elements and the overall environment, especially in the areas of road geometry change (e.g., turn directions, intersections with traffic lights) and road surface conditions change (e.g., slippery roads); and (3) lack of changes in color for work zone elements in dangerous areas (e.g., entering the work zone, transition area, road geometry change and road surface conditions change).

Moreover, the effectiveness of the proposed countermeasures was identified as follows.

- For lane closure scenario, the proposed countermeasures had significant impacts on all three stages of human information processing for drivers (perception, cognition, and action stages). Fluorescent orange sign with orange LEDs was the most effective countermeasure in attracting drivers' attention more and at longer distances in the perception stage (with mean differences of 164 feet and 153 feet than the original design during daytime and nighttime, respectively), maintaining drivers' cognitive workload better in the cognition stage, and influencing drivers' steering behaviors in the action stage by moving vehicles more to the left as there was a lane closure work zone on the right lane. The significant impacts on perception and cognition stages are during both daytime and nighttime, while the significant changes at the action stage are during daytime only. Fluorescent orange sign with orange beacon countermeasure also helped attract drivers' attention more and at longer distances during nighttime (with a mean difference of 185 feet than the original design) and maintain drivers' cognitive workload and focus better during daytime. The two countermeasures were also ranked as more effective ones according to drivers' self-perception.

- For shoulder work scenario, the proposed countermeasures had significant impacts on both perception and cognition stages of human information processing for drivers, while no significant differences were found in the action stage. Fluorescent orange sign with orange LEDs was the most effective countermeasure in attracting drivers' attention more and at longer distances (with a mean difference of 515 feet than the original design) and maintaining drivers' cognitive workload more at nighttime. It was also ranked as the most effective countermeasure based on drivers' self-evaluation. The fluorescent orange sign with orange beacon countermeasure also helped attract drivers' attention at longer distances during nighttime (with a mean difference of 431 feet than the original design).
- Time scenarios (with major differences in lighting conditions) had a significant impact on drivers' attention and cognitive workload under both lane closure and shoulder work experiments, emphasizing the importance of considering time scenarios when proposing and applying countermeasures to improve work zone safety.

In addition, this study has several limitations.

- First, there are potential learning effects for participants during the driving simulation experiments. In both driving simulation experiments, each participant finished eight trials (four countermeasures during daytime and nighttime) using the same road and work zone settings, with only the countermeasures differing across trials. Even though we used the Latin Square design to balance daytime and nighttime and random orders of four countermeasures to reduce the learning effects, drivers may still learn after driving through it several times and take relevant behaviors based on the previous trials. It may influence the experiment results, especially the action stage. Existing studies also indicate that repeated trials/scenarios will impact reaction time and driving behaviors (de Groot et al., 2011; Winkler et al., 2018; Zangi et al., 2022). Future studies should address this limitation by recruiting more participants and allowing each participant to finish fewer trials to reduce the learning effects.
- Second, simulation cannot be the same as the real world because simulation cannot 100% reproduce real-world scenarios. Existing studies showed that even though driving simulation is a useful tool for research on driving behaviors, simulation is a more relaxed environment for drivers to experiment, resulting in more variations in driving behaviors and underestimation of speed (Ekanayake et al., 2013; Hussain et al., 2019). Differences in drivers' behaviors between driving simulation and real-world driving may impact the measurement of countermeasures' effectiveness. Future work should consider combining simulation results with field tests to further explore the effectiveness of countermeasures.
- Third, other potential factors influencing driving behaviors should be considered. Even though the human information processing theory illustrates that differences in drivers' perception and cognition will lead to changes in the action stage, in real driving, drivers may change their behaviors even if there are improvements in their perception and cognition stages. Because many other factors may influence their decisions and behaviors, such as drivers' age, gender, driving experience, and education (McGwin & Brown, 1999; Singh & Kathuria, 2021), emotions and personalities (Jafarpour & Rahimi-Movaghar, 2014; Singh & Kathuria, 2021), and other distractions (Kountouriotis & Merat, 2016; Stutts et al., 2001; Stutts & Hunter, 2003). Future studies could explore the factors that may influence driving behaviors in the process to better understand the effectiveness of countermeasures.

11.2 Recommendations

Based on comprehensive analysis, recommendations to improve work zone safety for both lane closure and shoulder work scenarios were provided.

For lane closure scenario, fluorescent orange sign with orange LEDs countermeasure is recommended as the most effective solution due to its strong ability to attract drivers' attention more and at longer distances and maintain drivers' cognitive workload during both daytime and nighttime as well as improve drivers' steering behaviors during daytime, which may contribute to the reduction of work zone crashes. Moreover, fluorescent orange sign with orange beacon countermeasure is also recommended as an effective solution for improving work zone safety, which demonstrated strong performance in attracting drivers' attention early during nighttime and maintaining drivers' cognitive workload during daytime.

For shoulder work scenario, fluorescent orange sign with orange LEDs countermeasure is also the most effective countermeasure during nighttime scenario. LEDs countermeasure was more effective in capturing drivers' attention more and at longer distances and maintaining drivers' cognitive workload at night. In addition, fluorescent orange sign with orange beacon countermeasure is also recommended as an effective one as it can attract drivers' attention at longer distances at night.

The results also show that time scenarios (with major differences in lighting conditions) significantly influence drivers' attention and cognitive workload. When proposing and adopting the countermeasures, time scenarios should be considered. During daytime, some countermeasures might not be as effective as nighttime, more effort should be devoted to exploring other potential countermeasures. During nighttime, even though effective countermeasures were identified, it is also important to consider the combination of multiple lighting sources in the work zones to avoid potential distractions.

In addition, the study proposed a comprehensive research method to evaluate new countermeasures in work zones in a virtual environment considering drivers' perception, cognition, and action stages. It can be applied to evaluate new countermeasures, especially the ones that are not included in standards (e.g., MUTCD). The results of the driving simulation experiment could provide preliminary evidence about the effectiveness of new countermeasures before potential field tests.

REFERENCES

Ackerman, M. L., Edwards, J. D., Ross, L. A., Ball, K. K., & Lunsman, M. (2008). Examination of cognitive and instrumental functional performance as indicators for driving cessation risk across 3 years. *Gerontologist*, *48*(6), 802–810. https://doi.org/10.1093/geront/48.6.802

Ahlström, C., Kircher, K., Nyström, M., & Wolfe, B. (2021). Eye tracking in driver attention research—How gaze data interpretations influence what we learn. *Frontiers in Neuroergonomics*, 2. https://doi.org/10.3389/fnrgo.2021.778043

Alhomaidat, F., Hasan, R. A., Hanandeh, S., & Alhajyaseen, W. (2023). Using driving simulator to study the effect of crash fact signs on speeding behaviour along freeways. *International Journal of Injury Control and Safety Promotion*, *30*(1), 15–25. https://doi.org/10.1080/17457300.2022.2097698

Almallah, M., Hussain, Q., Alhajyaseen, W. K. M., Pirdavani, A., Brijs, K., Dias, C., & Brijs, T. (2021). Improved traffic safety at work zones through animation-based variable message signs. *Accident Analysis & Prevention*, *159*, 106284. https://doi.org/10.1016/j.aap.2021.106284

Alonso, P., Shridhar, K., Kleyko, D., Osipov, E., & Liwicki, M. (2021). HyperEmbed: Tradeoffs between resources and performance in NLP tasks with hyperdimensional computing enabled embedding of n-gram statistics. *Proceedings of the International Joint Conference on Neural Networks*. https://doi.org/10.1109/IJCNN52387.2021.9534359

Alsghan, I. (2018). *The effect of truck platooning on sign occlusion and native tools to assess sign occlusion* [Doctoral dissertation, University of Wisconsin-Madison]. UW Digital Collections. https://asset.library.wisc.edu/1711.dl/N7XUA3VC4EJDJ8U/R/file-ceb87.pdf?dl

Anani, S. (2015). *Work zone illumination design: Guidance strategies to specify appropriate work zone lighting plan* [Master's thesis, University of Wisconsin Milwaukee]. MINDS@UW. http://digital.library.wisc.edu/1793/94362

Andrews, E. C., & Westerman, S. J. (2012). Age differences in simulated driving performance: Compensatory processes. *Accident Analysis and Prevention*, *45*, 660–668. https://doi.org/10.1016/j.aap.2011.09.047

Atchley, P., & Dressel, J. (2006). *The effect of fluorescent yellow-green background for vehicle-mounted work zone signs on attention and eye-movements*. http://www.ctre.iastate.edu/smartwz/

Awan, H. H., Pirdavani, A., Houben, A., Westhof, S., Adnan, M., & Brijs, T. (2019). Impact of perceptual countermeasures on driving behavior at curves using driving simulator. *Traffic Injury Prevention*, *20*(1), 93–99. https://doi.org/10.1080/15389588.2018.1532568

Babić, D., Babić, D., Cajner, H., Sruk, A., & Fiolić, M. (2020). Effect of road markings and traffic signs presence on young driver stress level, eye movement and behaviour in night-time conditions: A driving simulator study. *Safety*, *6*(2), 24. https://doi.org/10.3390/safety6020024

Bai, Y., & Li, Y. (2006). *Determining major causes of highway work zone accidents in Kansas* (Report No. K-TRAN: KU-05-1). University of Kansas. https://kuscholarworks.ku.edu/entities/publication/0e94bf95-0c6c-4251-9b16-3b808376583a

Baron, W., & daSilva, M. (2019, June). *Effectiveness of LED-enhanced signs in reducing incidents of vehicles stopping on tracks* (Report No. DOT-VNTSC-FRA-19-06). U.S. Department of Transportation. https://railroads.dot.gov/sites/fra.dot.gov/files/fra_net/18806/LED-Enhanced%20Signs_A.PDF

Brewer, M. A., Pesti, G., & Schneider, W., IV. (2006). Improving compliance with work zone speed limits: Effectiveness of selected devices. *Transportation Research Record*, *1948*(1), 67–76. https://doi.org/10.1177/0361198106194800108

Calvi, A., D'Amico, F., Bianchini Ciampoli, L., & Ferrante, C. (2019). Evaluating the effectiveness of perceptual treatments on sharp curves: A driving simulator study. *Traffic Injury Prevention*, *20*(sup2), S13–S19. https://doi.org/10.1080/15389588.2019.1669789

Carlson, P. J., Rose, E. R., Chrysler, S. T., & Bischoff, A. L. (2004). *Simplifying delineator and chevron applications for horizontal curves*. Texas Transportation Institute. https://www.researchgate.net/publication/238768673

Centers for Disease Control and Prevention. (2024, November 6). *Highway work zone safety* [Webpage]. National Institute for Occupational Safety and Health. https://www.cdc.gov/niosh/topics/highwayworkzones/default.html#:~:text=Fast%20Facts&text=The%20Federal%20Highway%20Administration%20reports,lives%20in%20work%20zone%20crashes

Christ, R. E. (1975). Review and analysis of color coding research for visual displays. *Human Factors*, *17*(6), 542–570. https://doi.org/10.1177/001872087501700602

Clark, J. B., & Fontaine, M. D. (2015). Exploration of work zone crash causes and implications for safety performance measurement programs. *Transportation Research Record*, *2485*, 61–69. https://doi.org/10.3141/2485-08

Costa, M., Simone, A., Vignali, V., Lantieri, C., & Palena, N. (2018). Fixation distance and fixation duration to vertical road signs. *Applied Ergonomics*, *69*, 48–57. https://doi.org/10.1016/j.apergo.2017.12.017

Das, S., Dutta, A., & Tsapakis, I. (2021). Topic models from crash narrative reports of motorcycle crash causation study. *Transportation Research Record*, *2675*(9), 449–462. https://doi.org/10.1177/03611981211002523

de Greef, T., Lafeber, H., van Oostendorp, H., & Lindenberg, J. (2009). Eye movement as indicators of mental workload to trigger adaptive automation. D. D. Schmorrow, I.V. Estabrooke, and M. Grootjen (Eds.), *International Conference on Foundations of Augmented Cognition* (pp. 219–228). Springer.

de Groot, S., de Winter, J. C. F., García, J. M. L., Mulder, M., & Wieringa, P. A. (2011). The effect of concurrent bandwidth feedback on learning the lane-keeping task in a driving simulator. *Human Factors*, *53*(1), 50–62. https://doi.org/10.1177/0018720810393241

Deng, Q., Wang, J., Hillebrand, K., Benjamin, C. R., & Söffker, D. (2020). Prediction performance of lane changing behaviors: A study of combining environmental and eye-tracking data in a driving simulator. *IEEE Transactions on Intelligent Transportation Systems*, *21*(8), 3561–3570. https://doi.org/10.1109/TITS.2019.2937287

Ding, D., Lawson, K. D., Kolbe-Alexander, T. L., Finkelstein, E. A., Katzmarzyk, P. T., van Mechelen, W., & Pratt, M. (2016). The economic burden of physical inactivity: a global analysis of major non-communicable diseases. *The Lancet*, *388*(10051), 1311–1324. https://doi.org/10.1016/S0140-6736(16)30383-X

Domenichini, L., La Torre, F., Branzi, V., & Nocentini, A. (2017). Speed behaviour in work zone crossovers. A driving simulator study. *Accident Analysis & Prevention*, *98*, 10–24. https://doi.org/10.1016/j.aap.2016.09.018

DuPont, B., & DeDene, C. D. (2017). Orange work zone pavement markings: Experience gained from early field trials. *Transportation Research Board 96th Annual Meeting*. The National Academies Press. https://trid.trb.org/view/1437876

Eboli, L., Mazzulla, G., & Pungillo, G. (2016). Combining speed and acceleration to define car users' safe or unsafe driving behaviour. *Transportation Research Part C: Emerging Technologies*, *68*, 113–125. https://doi.org/10.1016/j.trc.2016.04.002

Ekanayake, H. B., Backlund, P., Ziemke, T., Ramberg, R., Hewagamage, K. P., & Lebram, M. (2013). Comparing expert driving behavior in real world and simulator contexts. *International Journal of Computer Games Technology*, *2013*(1), 891431. https://doi.org/10.1155/2013/891431

El-Rayes, K., Liu, L., El-Gohary, N., & Abdelmohsen, A. Z. (2014). *Effect of flaggers and spotter in directing work zone traffic for Illinois expressways and freeways* (Research Report No. FHWA-ICT-14-001). Illinois Center for Transportation. https://www.ideals.illinois.edu/items/50011

Federal Highway Administration. (2022). *FHWA work zone facts and statistics* [Webpage]. https://ops.fhwa.dot.gov/wz/resources/facts_stats.htm

Federal Highway Administration. (2023a). *Highway statistics 2021* [Webpage]. https://www.fhwa.dot.gov/policyinformation/statistics/2021/

Federal Highway Administration. (2023b). *Manual on uniform traffic control devices (MUTCD) for streets and highways* (11th ed.). https://mutcd.fhwa.dot.gov/pdfs/11th_Edition/mutcd11thedition.pdf

Fitzpatrick, C. D., Rakasi, S., & Knodler, M. A., Jr. (2017). An investigation of the speeding-related crash designation through crash narrative reviews sampled via logistic regression. *Accident Analysis and Prevention*, *98*, 57–63. https://doi.org/10.1016/j.aap.2016.09.017

Fitzpatrick, K., & Park, E. S. (2021). Nighttime effectiveness of the pedestrian hybrid beacon, rectangular rapid flashing beacon, and LED-embedded crossing sign. *Journal of Safety Research*, *79*, 273–286. https://doi.org/10.1016/j.jsr.2021.09.009

Fitzpatrick, K., Park, E. S., & Johnson, N. (2022). Multistate analysis investigating roadway characteristics that affect driver yielding at LED-embedded pedestrian-and school-crossing signs. *Transportation Research Record*, *2676*(8), 714–723. https://doi.org/10.1177/03611981221085513

Fitzpatrick, K., Park, E. S., Johnson, N., & Falk, K. (2023). *Driver yielding with LED-embedded pedestrian- and school-crossing signs* (Report No. FHWA-HRT-23-038). Texas A&M Transportation Institute.

Fugiglando, U., Massaro, E., Santi, P., Milardo, S., Abida, K., Stahlmann, R., Netter, F., & Ratti, C. (2019). Driving behavior analysis through CAN bus data in an uncontrolled environment. *IEEE Transactions on Intelligent Transportation Systems*, *20*(2), 737–748. https://doi.org/10.1109/TITS.2018.2836308

Garber, N. J., & Zhao, M. (2002). Distribution and characteristics of crashes at different locations within work zones in Virginia. *Transportation Research Record*, *1794* (02–2132), 19–25.

Harb, R., Radwan, E., Yan, X., Pande, A., & Abdel-Aty, M. (2008). Freeway work-zone crash analysis and risk identification using multiple and conditional logistic regression. *Journal of Transportation Engineering*, *134*(5), 203–214. https://doi.org/10.1061/ASCE0733-947X2008134:5203

Hellman, A. (2021). *LED-enhanced sign research to reduce vehicle queuing at highway-rail grade crossings*. https://railroads.dot.gov/sites/fra.dot.gov/files/2021-02/MTA%20LED%20Signs-A.pdf

Holmqvist, K., Örbom, S. L., Hooge, I. T. C., Niehorster, D. C., Alexander, R. G., Andersson, R., Benjamins, J. S., Blignaut, P., Brouwer, A.-M., Chuang, L. L., Dalrymple, K. A., Drieghe, D., Dunn, M. J., Ettinger, U., Fiedler, S., Foulsham, T., van der Geest, J. N., Hansen, D. W., Hutton, S. B., … Hessels, R. S. (2022). Eye tracking: empirical foundations for a minimal reporting guideline. *Behavior Research Methods*, *55*(1), 364–416. https://doi.org/10.3758/s13428-021-01762-8

Huang, Y., & Bai, Y. (2019). Driver responses to graphic-aided portable changeable message signs in highway work zones. *Journal of Transportation Safety & Security*, *11*(6), 661–682. https://doi.org/10.1080/19439962.2018.1463336

Hummer, J. E., & Scheffler, C. R. (1999). Driver performance comparison of fluorescent orange to standard orange work zone traffic signs. *Transportation Research Record*, *1657*(1), 55–62.

Hussain, Q., Alhajyaseen, W. K. M., Brijs, K., Pirdavani, A., & Brijs, T. (2020). Innovative countermeasures for red light running prevention at signalized intersections: A driving simulator study. *Accident Analysis and Prevention*, *134*. https://doi.org/10.1016/j.aap.2019.105349

Hussain, Q., Alhajyaseen, W. K., Pirdavani, A., Reinolsmann, N., Brijs, K., & Brijs, T. (2019). Speed perception and actual speed in a driving simulator and real-world: A validation study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *62*, 637–650. https://doi.org/10.1016/j.trf.2019.02.019

Imprialou, M., & Quddus, M. (2019). Crash data quality for road safety research: Current state and future directions. *Accident Analysis and Prevention*, *130*, 84–90. https://doi.org/10.1016/j.aap.2017.02.022

Indiana Department of Labor. (2022). *Work zone safety* [Webpage]. https://www.in.gov/dol/iosha/worker-safety-initiatives/work-zone-safety/

Indiana Department of Transportation. (2016). *Indiana manual on uniform traffic control devices (MUTCD)* (2011 ed.). https://www.in.gov/dot/div/contracts/design/mutcd/2011rev3/2011%20IMUTCD%20with%20Revisions%201%202%20and%203%20-Whole%20Document.pdf

Indiana Department of Transportation. (2022). *2022 standard drawings* [Webpage]. https://www.in.gov/dot/div/contracts/standards/drawings/sep22/sep.htm

Indiana Department of Transportation. (2023). *Work zone traffic control guidelines*. https://www.in.gov/indot/doing-business-with-indot/files/WorkZoneTCH.pdf

Indiana Department of Transportation. (2024). *Work zone safety* [Webpage]. https://www.in.gov/indot/safety/work-zone-safety/

Indiana State Police. (2022). *ARIES crash data*. https://www.ariesportal.com/

Jafarpour, S., & Rahimi-Movaghar, V. (2014). Determinants of risky driving behavior: a narrative review. *Medical Journal of the Islamic Republic of Iran*, *28*(142).

Jenssen, G. D., & Brekke, B. (1998). A study of the visibility and effectiveness of fluorescent retroreflective traffic control signing in work zone applications. *Traffic Safety on Two Continents* (pp. 63–80). https://trid.trb.org/view/504581

Jimenéz, P., Bergasa, L. M., Nuevo, J., Hernández, N., & Daza, I. G. (2012). Gaze fixation system for the evaluation of driver distractions induced by IVIS. *IEEE Transactions on Intelligent Transportation Systems*, *13*(3), 1167–1178. https://doi.org/10.1109/TITS.2012.2187517

Kang, H., Kim, J., Park, S., Lee, C.-S., & Pak, H. (2023). Visibility of the phantom array effect at different LED colour temperatures under high-frequency temporal light modulation. *Lighting Research & Technology*, *55*(1), 36–46. https://doi.org/10.1177/14771535221101558

Kountouriotis, G. K., & Merat, N. (2016). Leading to distraction: Driver distraction, lead car, and road environment. *Accident Analysis and Prevention*, *89*, 22–30. https://doi.org/10.1016/j.aap.2015.12.027

Kwayu, K. M., Kwigizile, V., Lee, K., & Oh, J.-S. (2021). Discovering latent themes in traffic fatal crash narratives using text mining analytics and network topology. *Accident Analysis and Prevention*, 150. https://doi.org/10.1016/j.aap.2020.105899

Kwayu, K. M., Kwigizile, V., Zhang, J., & Oh, J.-S. (2020). Semantic N-Gram feature analysis and machine learning–based classification of drivers' hazardous actions at signal-controlled intersections. *Journal of Computing in Civil Engineering*, *34*(4), 04020015. https://doi.org/10.1061/(asce)cp.1943-5487.0000895

Lai, C.-J. (2010). Effects of color scheme and message lines of variable message signs on driver performance. *Accident Analysis and Prevention*, *42*(4), 1003–1008. https://doi.org/10.1016/j.aap.2009.12.002

Lammers-Staats, E., Staats, W., & Agent, K. (2021). *Evaluation of orange pavement striping for use in work zones* (Kentucky Transportation Center Report No. KTC–21–03/FRT–227–1F). University of Kentucky. https://doi.org/10.13023/ktc.rr.2021.03

Lee, H. C., Cameron, D., & Lee, A. H. (2003). Assessing the driving performance of older adult drivers: on-road versus simulated driving. *Accident Analysis & Prevention*, *35*(5), 797–803. https://doi.org/10.1016/S0001-4575(02)00083-0

Lehtonen, E., Lappi, O., Koirikivi, I., & Summala, H. (2014). Effect of driving experience on anticipatory look-ahead fixations in real curve driving. *Accident Analysis and Prevention*, *70*, 195–208. https://doi.org/10.1016/j.aap.2014.04.002

Li, Y., & Bai, Y. (2009). Highway work zone risk factors and their impact on crash severity. *Journal of Transportation Engineering*, *135*(10), 694–701. https://doi.org/10.1061/ASCETE.1943-5436.0000055

Li, Z., Wang, W., Chen, R., Liu, P., & Xu, C. (2013). Evaluation of the impacts of speed variation on freeway traffic collisions in various traffic states. *Traffic Injury Prevention*, *14*(8), 861–866. https://doi.org/10.1080/15389588.2013.775433

Liang, Y., & Lee, J. D. (2008). Driver cognitive distraction detection using eye movements. In *Passive Eye Monitoring* (pp. 285–300). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-75412-1_13

McAvoy, D. S., Duffy, S., & Whiting, H. S., II (2011). Simulator study of primary and precipitating factors in work zone crashes. *Transportation Research Record*, *2258*(1), 32–39. https://doi.org/10.3141/2258-04

McGwin, J. G., Jr., & Brown, D. B. (1999). Characteristics of traffic crashes among young, middle-aged, and older drivers. *Accident Analysis & Prevention*, *31*(3), 181–198. https://doi.org/https://doi.org/10.1016/S0001-4575(98)00061-X

Meyer, E. (2002). *Reflectorized sleeves for barrel delineators*. http://www.matc.unl.edu/research/MwSWZDI/

Nadkarni, P. M., Ohno-Machado, L., & Chapman, W. W. (2011). Natural language processing: an introduction. *Journal of the American Medical Informatics Association*, *18*(5), 544–551. https://doi.org/10.1136/amiajnl-2011-000464

Najar, S. A., & Sanjram, P. K. (2018). Gaze behavior and human error in distracted driving: Unlocking the complexity of articulatory rehearsal mechanism. *Transportation Research Part F: Traffic Psychology and Behaviour*, *59*(November), 12–23. https://doi.org/10.1016/j.trf.2018.08.005

Nyström, M., & Holmqvist, K. (2010). An adaptive algorithm for fixation, saccade, and glissade detection in eyetracking data. *Behavior Research Methods*, *42*(1), 188–204. https://doi.org/10.3758/BRM.42.1.188

Proctor, R. W., & Van Zandt, T. (2018). *Human factors in simple and complex systems* (3rd ed.). CRC Press.

Qin, L., Dong, L.-L., Xu, W.-H., Zhang, L.-D., & Leon, A. (2018). Influence of vehicle speed on the characteristics of driver's eye movement at a highway tunnel entrance during day and night conditions: A pilot study. *International Journal of Environmental Research and Public Health*, *15*(4), 656. https://doi.org/10.3390/ijerph15040656

Radhakrishnan, V., Louw, T., Cirino Gonçalves, R., Torrao, G., Lenné, M. G., & Merat, N. (2023). Using pupillometry and gaze-based metrics for understanding drivers' mental workload during automated driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, *94*, 254–267. https://doi.org/10.1016/j.trf.2023.02.015

Rahman, M. M., Strawderman, L., Garrison, T., Eakin, D., & Williams, C. C. (2017). Work zone sign design for increased driver compliance and worker safety. *Accident Analysis & Prevention*, *106*, 67–75. https://doi.org/10.1016/j.aap.2017.05.023

Rista, E., & Fitzpatrick, K. (2020). Comparison of LED-embedded pedestrian crossing signs with rectangular rapid flashing beacons and pedestrian hybrid beacons. *Transportation Research Record*, *2674*(11), 856–866. https://doi.org/10.1177/0361198120941849

Sagaspe, P., Taillard, J., Bayon, V., Lagarde, E., Moore, N., Boussuge, J., Chaumet, G., Bioulac, B., & Philip, P. (2010). Sleepiness, near-misses and driving accidents among a representative population of French drivers. *Journal of Sleep Research*, *19*(4), 578–584. https://doi.org/10.1111/j.1365-2869.2009.00818.x

Sayer, J. R., & Mefford, M. L. (2004). High visibility safety apparel and nighttime conspicuity of pedestrians in work zones. *Journal of Safety Research*, *35*(5), 537–546. https://doi.org/10.1016/j.jsr.2004.08.007

Schrock, S. D., Ullman, G. L., Cothron, A. S., Kraus, E., & Voigt, A. P. (2004). *An analysis of fatal work zone crashes in Texas* (Report No. FHWA/TX-05/0-4028-1). Texas Transportation Institute. https://static.tti.tamu.edu/tti.tamu.edu/documents/0-4028-1.pdf

Shaw, J. W., Chitturi, M. V., Santiago-Chaparro, K. R., Qin, L., Bill, A. R., & Noyce, D. A. (2018). *Orange work zone pavement marking Midwest field test*. University of Wisconsin – Madison. https://www.intrans.iastate.edu/

research/completed/orange-work-zone-pavement-marking-midwest-field-test/

Sheikholeslami, S., Boroujerdian, A. M., & Asadamraji, M. (2020). A rural road accident probability model based on single-vehicle hazard properties including hazard color and mobility: A driving simulator study. *Journal of Advanced Transportation*, *2020*(1), 1–8. https://doi.org/10.1155/2020/8826374

Shen, J., Gao, W., Chen, Y., & Wu, H. (2021). *Cognitive attention and its application in countermeasures on a curve section* (Report No. FHWA-GA-21-1912). Georgia Southern University. https://g92018.eos-intl.net/eLibSQL14_G92018_Documents/19-12.pdf

Simulation of Urban Mobility. (2025, July 8). *SUMO user documentation*. https://sumo.dlr.de/docs/index.html

Singh, H., & Kathuria, A. (2021). Analyzing driver behavior under naturalistic driving conditions: A review. *Accident Analysis & Prevention*, *150*, 105908. https://doi.org/10.1016/j.aap.2020.105908

Stutts, J. C., & Hunter, W. W. (2003). Driver inattention, driver distraction and traffic crashes. *ITE Journal*, *73*(7), 34.

Stutts, J. C., Reinfurt, D. W., Staplin, L., & Rodgman, E. (2001, May 1). *The role of driver distraction in traffic crashes*. University of North Carolina Highway Safety Research Center. https://rosap.ntl.bts.gov/view/dot/17717

Sun, C., Edara, P., & Zhu, Z. (2013). Evaluation of temporary ramp metering for work zones. *Transportation Research Record*, *2337*(1), 17–24. https://doi.org/10.3141/2337-03

Sze, N. N., & Song, Z. (2019). Factors contributing to injury severity in work zone related crashes in New Zealand. *International Journal of Sustainable Transportation*, *13*(2), 148–154. https://doi.org/10.1080/15568318.2018.1452083

Thelin, R., Rukes, K., & Jamie Palmer. (2020). *Indiana crash facts 2019*. Indiana University Public Policy Institute. https://www.in.gov/cji/research/files/Indiana-Crash-Fact-Book-2019.pdf

Turner, J. D., Simmons, C. J., & Graham, J. R. (1997). High-visibility clothing for daytime use in work zones. *Transportation Research Record*, *1585*(1), 1–8. https://doi.org/10.3141/1585-01

Ullman, G. L., Finley, M. D., Bryden, J. E., Srinivasan, R., & Council, F. M. (2008). *Traffic safety evaluation of nighttime and daytime work zones*. The National Academies Press. https://doi.org/10.17226/14196

Ullman, G. L., & Scriba, T. A. (2004). Revisiting the influence of crash report forms on work zone crash data. *Transportation Research Record*, *1897*(1), 180–182. www.nhtsa.dot.gov/people/perform/

U.S. Bureau of Labor Statistics. (2023). *Occupational employment and wage statistics* [Webpage]. https://www.bls.gov/oes/current/oes_nat.htm

Vignali, V., Bichicchi, A., Simone, A., Lantieri, C., Dondi, G., & Costa, M. (2019). Road sign vision and driver behaviour in work zones. *Transportation Research Part F: Traffic Psychology and Behaviour*, *60*, 474–484. https://doi.org/10.1016/j.trf.2018.11.005

Winkler, S., Kazazi, J., & Vollrath, M. (2018). Practice makes better – Learning effects of driving with a multi-stage collision warning. *Accident Analysis & Prevention*, *117*, 398–409. https://doi.org/10.1016/j.aap.2018.01.018

Wu, H., Chen, Y., Zhang, J., & Jenkins, J. L. (2024). Key factors and representative scenarios in work zone safety: Indiana crash data analysis. In Proceedings of 60th Annual Associated Schools of Construction International Conference. *EPiCSeries in Built Environment*, *Volume 5*, 939–947.

Wu, H., Guo, X., Tian, C., Chen, Y., Zhang, J., & Jenkins, J. L. (2024). Understanding the causes of work zone crashes from the color-related perspective: Indiana crash data analysis using natural language processing. *Transportation Research Board 103rd Annual Meeting*. The National Academies Press. https://annualmeeting.mytrb.org/OnlineProgramArchive/Details/21374

Wu, Y.-N., Han, Y.-Z., & Chen, Z. (2020). Traffic safety evaluation of asphalt pavement based on color information. In *2020 5th International Conference on Electromechanical Control Technology and Transportation (ICECTT)* (pp. 469–473). https://doi.org/10.1109/ICECTT50890.2020.00108

Wynne, R. A., Beanland, V., & Salmon, P. M. (2019). Systematic review of driving simulator validation studies. *Safety Science*, *117*, 138–151. https://doi.org/10.1016/j.ssci.2019.04.004

Xue, X., & Zhang, J. (2021). Part-of-speech tagging of building codes empowered by deep learning and transformational rules. *Advanced Engineering Informatics*, *47*, 101235. https://doi.org/10.1016/j.aei.2020.101235

Yan, X., Radwan, E., Guo, D., & Richards, S. (2009). Impact of "signal ahead" pavement marking on driver behavior at signalized intersections. *Transportation Research Part F: Psychology and Behaviour*, *12*(1), 50–67. https://doi.org/10.1016/j.trf.2008.07.002

Yang, H., Ozbay, K., Ozturk, O., & Xie, K. (2015). Work zone safety analysis and modeling: A state-of-the-art review. *Traffic Injury Prevention*, *16*(4), 387–396. https://doi.org/10.1080/15389588.2014.948615

Yi, J.-S., Kim, Y.-W., Kim, K.-A., & Koo, B. (2012). A suggested color scheme for reducing perception-related accidents on construction work sites. *Accident Analysis and Prevention*, *48*, 185–192. https://doi.org/10.1016/j.aap.2011.04.022

Zangi, N., Srour-Zreik, R., Ridel, D., Chassidim, H., & Borowsky, A. (2022). Driver distraction and its effects on partially automated driving performance: A driving simulator study among young-experienced drivers. *Accident Analysis & Prevention*, *166*, 106565. https://doi.org/10.1016/j.aap.2022.106565

Zhang, C., Tian, C., Tianfang, H., Chen, Y., Zhang, J., & Feng, Y. (2025). Examining driving behaviors and trust in an in-vehicle warning system under uncertainty: A driving simulator study. *Transportation Research Board 104th Annual Meeting*. The National Academies Press.

Zhang, C., Tian, C., Tianfang, H., Li, H., Feng, Y., Che, Y., Proctor, R. W., & Zhang, J. (2024). Evaluation of infrastructure-based warning system on driving behaviors–A roundabout study. *Transportation Research Board 103rd Annual Meeting*. The National Academies Press.

Zhang, J., & El-Gohary, N. M. (2016). Semantic NLP-based information extraction from construction regulatory documents for automated compliance checking. *Journal of Computing in Civil Engineering*, *30*(2), 04015014. https://doi.org/10.1061/(asce)cp.1943-5487.0000346

Zhang, J., Kwigizile, V., & Oh, J.-S. (2016). Automated hazardous action classification using Natural Language Processing and machine-learning techniques. *CICTP 2016 - Green and Multimodal Transportation and Logistics - Proceedings of the 16th COTA International Conference of Transportation Professionals* (pp. 1579–1590). https://doi.org/10.1061/9780784479896.144

Zhang, K., Hassan, M., Yahaya, M., & Yang, S. (2018). Analysis of work-zone crashes using the ordered probit model with factor analysis in Egypt. *Journal of Advanced*

Transportation, *2018*(1), 8570207. https://doi.org/10.1155/2018/8570207

Zockaie, A., Saedi, R., Fakhrmoosavi, F., Jazlan, F., Ghamami, M., Gates, T., Savolainen, P., Brascamp, J., & Schneider, B. (2020). *Effectiveness of green strobes on winter maintenance vehicles and equipment*. Michigan State University. https://www.michigan.gov/mdot/-/media/Project/Websites/MDOT/Programs/Research-Administration/Final-Reports/SPR-1692-Report.pdf

APPENDICES

Appendix A. Interview Questions

Appendix B. Pre-Survey of Driving Experiment

Appendix C. Post-Survey of Driving Experiment

Appendix D. Supplementary Figures and Tables

Appendix E. Supplementary Information for Session 10

APPENDIX A. INTERVIEW QUESTIONS

Part 1: Basic information

1. What institute/organization are you working for?

2. What is your working title/position?

3. How many years of working experience related to **work zones** do you have?

4. How many years of working experience related to **Indiana work zones** do you have?

5. Please provide more details about your working experience related to **work zones**.

6. How would you rate your **level of expertise** in the following topics using a 5-point scale?

	Beginner	Novice	Intermediate	Advanced	Expert
Application of traffic signs in work zones					
Color code of traffic control devices (e.g., *Section 1A.12 in MUTCD)*					
Design of traffic signs in work zones					
Design of channelizing devices in work zones					
Design of pavement markings in work zones					
Design of personal protective equipment (PPE) for workers					

Part 2: Traffic signs

1. Please rank the following 8 traffic signs that are usually used when entering the work zone based on the listed criteria.

No.	Sign	Figure	Commonly Used	Effectiveness to Reduce Crashes	Driver's Attention	Reduce Speed	Overall Importance
1	Speeding Max $1000 Reckless Driving Max 8 yrs (XW2-6)						
2	Lane(s) Closed (with distance) (W20-5)						
3	One Lane Road (with distance) (W20-4)						
4	Yield Ahead (W3-2)						
5	Road Work (with distance/ahead) (W20-1)						
6	Flagger (W20-7)						
7	Shoulder Work (W21-5)						
8	Detour (with distance) (W20-2)						

2. According to Work Zone Traffic Control Guideline, 4 signs can be used instead of Road Work Ahead sign. Please select the top one from the following 4 signs and Road Work Ahead sign based on the listed criteria.

No.	Sign	Figure	Commonly Used	Effectiveness to Reduce Crashes	Driver's Attention	Reduce Speed	Overall Importance
1	Road Work (with distance/ahead) (W20-1)						
2	Workers (W21-1)						
3	Slow Traffic Ahead (W23-1)						
4	Utility Work Ahead (W21-7)						
5	Road Machinery Ahead (W21-3)						

3. Please select the top one from the following two signs with similar meanings based on the listed criteria.

No.	Sign	Figure	Commonly Used	Effectiveness to Reduce Crashes	Driver's Attention	Reduce Speed	Overall Importance
1	Be Prepared To Stop (W3-4)						
2	Yield Ahead (W3-2)						

4. Please select the top one from the following two signs with similar meanings based on the listed criteria.

No.	Sign	Figure	Commonly Used	Effectiveness to Reduce Crashes	Driver's Attention	Reduce Speed	Overall Importance
1	Detour (with distance) (W20-2)						
2	Road (Street) Closed (with distance) (W20-3)						

5. Please rank the following 2 traffic signs that are usually used at the end of the work zone (when the drivers leave the work zone) based on the listed criteria.

No.	Sign	Figure	Commonly Used	Effectiveness to Reduce Crashes	Driver's Attention	Reduce Speed	Overall Importance
1	End Road Work (G20-2)						
2	Exit Open (E5-2)						

6. Please rank the following 7 traffic signs that are used both in general road and work zones (changed to be orange) based on the listed criteria.

No.	Sign	Figure	Commonly Used	Effectiveness to Reduce Crashes	Driver's Attention	Reduce Speed	Overall Importance
1	Lane Ends (W4-2)						
2	Advisory Speed (W13-1P)						
3	Two-Way Traffic (XW6-3)						
4	On Ramp (W13-4P)						
5	One-Direction Large Arrow (W1-6)						
6	Turn and Curve Sign (Reverse curve W1-4)						
7	Road Narrows (W5-1)						

7. Please provide any other work zone signs/plaques that you think are important but are not listed above:

Part 3: Color-related countermeasures

1. Which of the following 11 color designs of traffic signs could be used in work zones based on your experience? Please select all that apply.

No.	Countermeasure	Example	No.	Countermeasure	Example
1	Fluorescent orange sign with fluorescent yellow-green border		6	Fluorescent orange sign with white LED units	
2	Doubling-up of fluorescent orange sign		7	Fluorescent orange sign with yellow LED units	
3	Fluorescent orange sign with retroreflective aluminum orange flags		8	Fluorescent orange sign with orange LED units	
4	Fluorescent orange sign with yellow warning beacon		9	Fluorescent orange sign with orange retroreflective strip on support	
5	Fluorescent orange sign with orange warning beacon		10	Fluorescent orange sign with yellow flash warning light	
			11	Fluorescent orange sign with orange flash warning light	

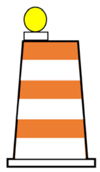
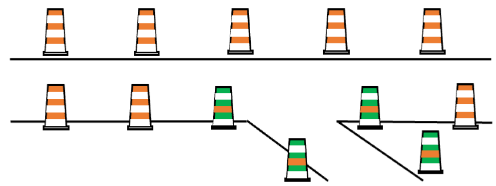
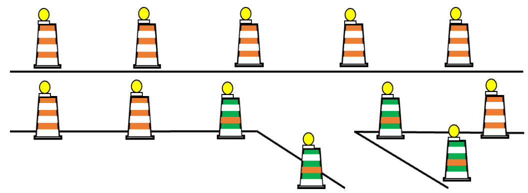
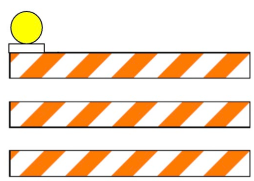
2. Which of the following 11 color designs of traffic signs would be effective to reduce work zone crashes based on your experience? Please select all that apply.

No.	Countermeasure	Example	No.	Countermeasure	Example
1	Fluorescent orange sign with fluorescent yellow-green border		6	Fluorescent orange sign with white LED units	
2	Doubling-up of fluorescent orange sign		7	Fluorescent orange sign with yellow LED units	
3	Fluorescent orange sign with retroreflective aluminum orange flags		8	Fluorescent orange sign with orange LED units	
4	Fluorescent orange sign with yellow warning beacon		9	Fluorescent orange sign with orange retroreflective strip on support	
5	Fluorescent orange sign with orange warning beacon		10	Fluorescent orange sign with yellow flash warning light	
			11	Fluorescent orange sign with orange flash warning light	

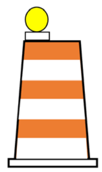
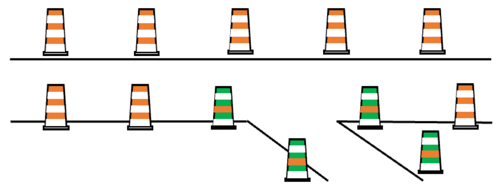
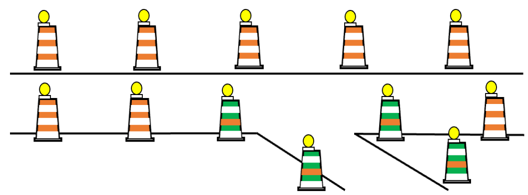
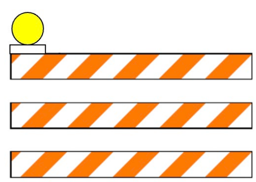
3. Please suggest any other new color designs of traffic signs that you think are feasible in work zones but are not listed above:

4. Please suggest any other new color designs of traffic signs that you think are effective in work zones but are not listed above:

5. Which of the following 4 color designs of channelizing devices could be used in work zones based on your experience? Please select all that apply.

No.	Countermeasure	Example
1	Fluorescent orange and white drum with yellow warning light	
2	Fluorescent orange, white, and green drum for exit ramp	
3	Fluorescent orange, white, and green drum for exit ramp with warning lights	
4	Fluorescent orange and white barricade with yellow warning light	

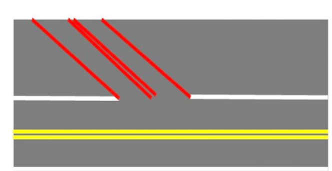
6. Which of the following 4 color designs of channelizing devices would be effective to reduce work zone crashes based on your experience? Please select all that apply.

No.	Countermeasure	Example
1	Fluorescent orange and white drum with yellow warning light	
2	Fluorescent orange, white, and green drum for exit ramp	
3	Fluorescent orange, white, and green drum for exit ramp with warning lights	
4	Fluorescent orange and white barricade with yellow warning light	

7. Please suggest any other new color designs of channelizing devices that you think are feasible in work zones but are not listed above:

8. Please suggest any other new color designs of channelizing devices that you think are effective in work zones but are not listed above:

9. Which of the following 2 color designs of pavement markings could be used in work zones based on your experience? Please select all that apply.

No.	Countermeasure	Example	No.	Countermeasure	Example
1	Orange pavement markings		2	Red pavement markings for one-way roadways, ramps, or travel lanes that shall not be entered	

10. Which of the following 2 color designs of pavement markings would be effective to reduce work zone crashes based on your experience? Please select all that apply.

No.	Countermeasure	Example	No.	Countermeasure	Example
1	Orange pavement markings		2	Red pavement markings for one-way roadways, ramps, or travel lanes that shall not be entered	

11. Please suggest any other new color designs of pavement markings that you think are feasible in work zones but are not listed above:

12. Please suggest any other new color designs of pavement markings that you think are effective in work zones but are not listed above:

13. Which of the following 8 color designs of personal protective equipment (PPE) for workers could be used in work zones based on your experience? Please select all that apply.

No.	Countermeasure	Example	No.	Countermeasure	Example
1	Fluorescent yellow-green with yellow and silver strips		5	Fluorescent orange-red with white and silver strips	
2	Fluorescent yellow-green with white and silver strips		6	Red hard hat	
3	Fluorescent orange-red with yellow-green and silver strips		7	Yellow hard hat	
4	Fluorescent orange-red with yellow and silver strips		8	Blue hard hat	

14. Which of the following 8 color designs of personal protective equipment (PPE) for workers would be effective to reduce work zone crashes based on your experience? Please select all that apply.

No.	Countermeasure	Example	No.	Countermeasure	Example
1	Fluorescent yellow-green with yellow and silver strips		5	Fluorescent orange-red with white and silver strips	
2	Fluorescent yellow-green with white and silver strips		6	Red hard hat	
3	Fluorescent orange-red with yellow-green and silver strips		7	Yellow hard hat	
4	Fluorescent orange-red with yellow and silver strips		8	Blue hard hat	

15. Please suggest any other new color designs of PPE of workers that you think are feasible but are not listed above:

16. Please suggest any other new color designs of PPE of workers that you think are effective but are not listed above:

17. Please provide any other color-related countermeasures in work zones that you think are feasible but are not listed above:

18. Please provide any other color-related countermeasures in work zones that you think are effective but are not listed above:

Part 4: Comments

1. Please provide any comments or suggestions for the study, if applicable:

APPENDIX B. PRE-SURVEY OF DRIVING EXPERIMENT

Welcome and thank you for your interest in the driving simulation experiment!

The survey will collect your basic information, driving experience, and available time slots for the experiment. It should take no longer than **10 minutes** to complete. If you are selected, the research team will contact you by email soon.

If you have any questions, please contact Yunfeng Chen at chen428@purdue.edu or Hongyue Wu at wu1513@purdue.edu.

By clicking "Yes" below you are offering consent to participate in this survey.

- Yes, proceed to the survey
- No, quit the survey

Part 1: Basic information

1. Do you have a valid **Indiana driver's license**?
    - Yes
    - No (quit the survey)

2. What is your gender?
    - Male
    - Female
    - Others (please specify):________________________
    - Prefer not to disclose

3. What is your age?

    ____

4. What is your highest level of education?
    - High school
    - Some college
    - Associate
    - Bachelor
    - Master
    - Doctorate
    - Others (please specify):________________________
    - Prefer not to disclose

5. What is your occupation?

    ____

6. What is your major/industry?

    ____

7. What is your ethnicity?
   - White
   - Hispanic or Latino
   - Black or African American
   - Native American or American Indian
   - Asian
   - Pacific Islander
   - Other (please specify)
   - Prefer not to disclose

8. What is your marital status?
   - Single, never married
   - Married or domestic partnership
   - Widowed
   - Divorced
   - Separated
   - Prefer not to disclose

9. What is your annual household income (AHI) (after tax)?
   - AHI ≤ $20,000
   - $20,000 < AHI ≤ $40,000
   - $40,000 < AHI ≤ $60,000
   - $60,000 < AHI ≤ $80,000
   - $80,000 < AHI ≤ $100,000
   - $100,000 < AHI ≤ $120,000
   - AHI > $120,000
   - Prefer not to disclose

10. What is your visual ability (select all the items that you meet)?
    - Myopia
    - Hypermetropia
    - Normal
    - Color blindness
    - Other (please specify)

11. Do you wear glasses when driving?
    - Yes
    - No

12. Do you have color blindness?
    - Red-green color blindness
    - Blue-yellow color blindness
    - Complete color blindness
    - Other types of color blindness (please specify):_______________________
    - No
    - Prefer not to disclose

Part 2: Driving experience

13. How many years have you been driving?

    ____

14. How many years have you been driving in **Indiana**?

    ____

15. How often do you drive?
    - Everyday
    - 3 to 6 days per week
    - 1 to 2 days per week
    - Fewer than once per week

16. How many miles do you drive per year?

    ____

17. Did you have any crashes or near-miss crashes **in work zones**?
    - No (to Q19)
    - Yes (to Q18)

18. Please specify the reasons of the crashes or near-miss crashes in work zones:

    ____

19. Please evaluate your driving ability in work zones using a five-point Likert scale:
    - 1: Poor
    - 2: Fair
    - 3: Good
    - 4: Very good
    - 5: Excellent

Part 3: Experiment time slots

20. Please provide your **name and email** for the research team to contact you. **Your information will be kept confidential and will not be used for any other purposes.**
    Name:____
    Email address:____

Please provide **all available time slots** for the experiment through the link. Please provide your **name or email** when submitting the availability for researchers to track your response.
https://whenisgood.net/driving

If you are selected, the research team will contact you by email soon. Thank you very much for your time and support!

APPENDIX C. POST-SURVEY OF DRIVING EXPERIMENT

Participant No. (provided by the research team): _________

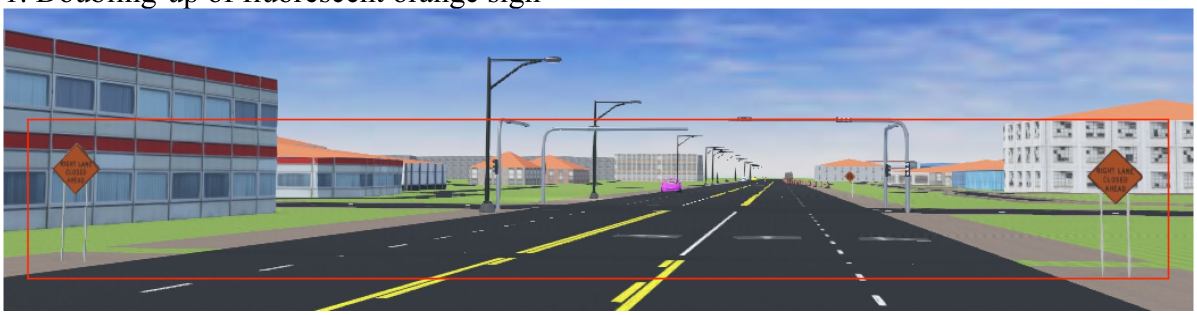
Work zone scenario:

- Lane closure
- Shoulder work

For Lane closure:

In this experiment, we have the following three countermeasures (red box in the figures below).

1. Doubling-up of fluorescent orange sign



2. Fluorescent orange sign with orange warning beacon

3. Fluorescent orange sign with orange LEDs

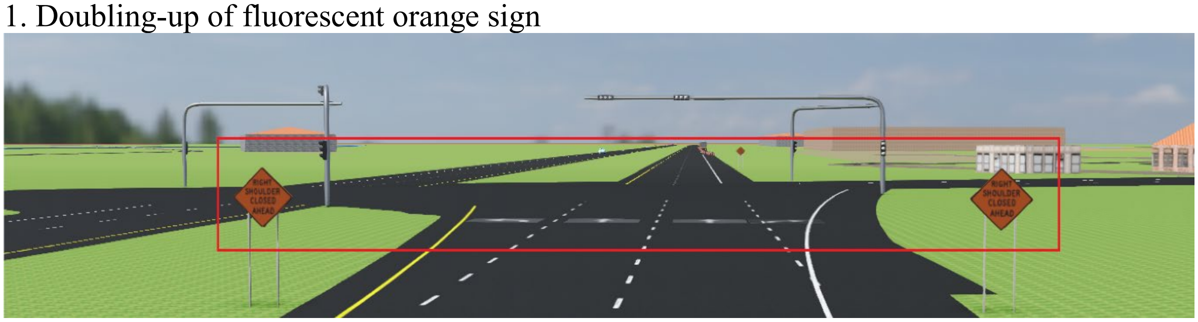
Please select the countermeasures based on the listed sub-questions (select all that apply).

Questions	**Doubling-Up of Fluorescent Orange Sign**	**Fluorescent Orange Sign with Orange Warning Beacon**	**Fluorescent Orange Sign with Orange LEDs**	**None of Them**
Which countermeasure(s) did you notice during the driving? (select all that apply)				
Which countermeasure(s) attracts your attention? (select all that apply)				
Which countermeasure(s) helps you understand the sign more quickly? (select all that apply)				
Which countermeasure(s) makes you more aware of the work zone? (select all that apply)				
Which countermeasure(s) better helps you make decisions about driving behaviors? (select all that apply)				
Which countermeasure(s) helps you improve your driving performance? (select all that apply)				

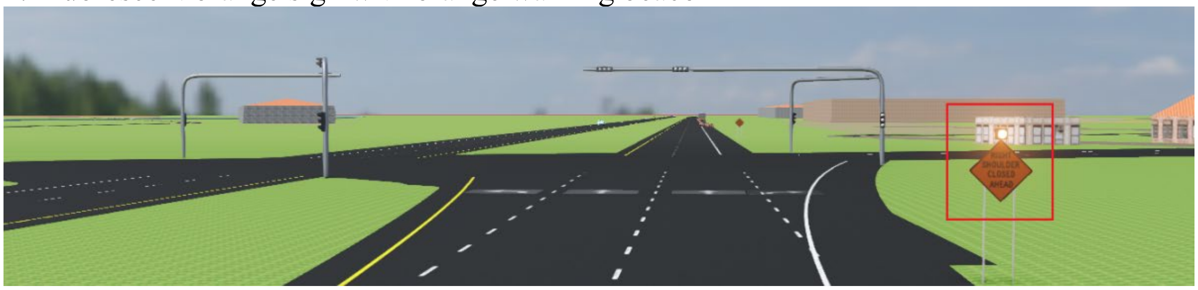
For Shoulder work:

In this experiment, we have the following three countermeasures (red box in the figures below).

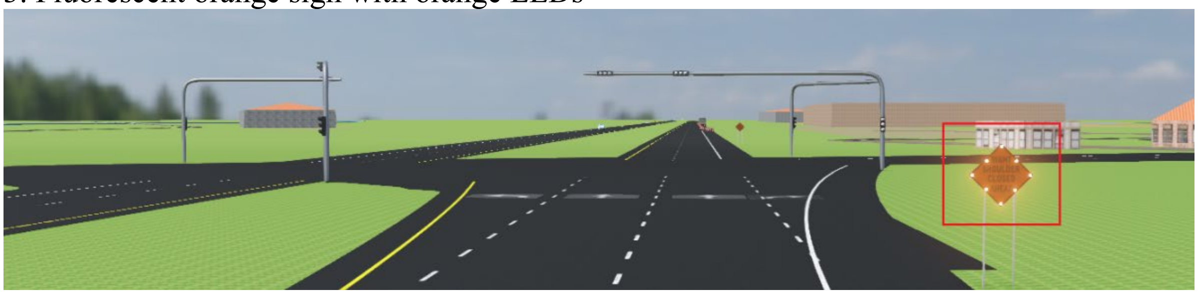
1. Doubling-up of fluorescent orange sign



2. Fluorescent orange sign with orange warning beacon



3. Fluorescent orange sign with orange LEDs



Please select the countermeasures based on the listed sub-questions (select all that apply).

Questions	**Doubling-Up of Fluorescent Orange Sign**	**Fluorescent Orange Sign with Orange Warning Beacon**	**Fluorescent Orange Sign with Orange LEDs**	**None of Them**
Which countermeasure(s) did you notice during the driving? (select all that apply)				
Which countermeasure(s) attracts your attention? (select all that apply)				
Which countermeasure(s) helps you understand the sign more quickly? (select all that apply)				
Which countermeasure(s) makes you more aware of the work zone? (select all that apply)				
Which countermeasure(s) better helps you make decisions about driving behaviors? (select all that apply)				
Which countermeasure(s) helps you improve your driving performance? (select all that apply)				

2. Please rate your level of fatigue after the driving task using the Stanford Sleepiness Scale.

1	Feel active and vital; alert, wide awake
2	Functioning at a high level, but not at peak, able to concentrate
3	Relaxed; awake; not at full alertness, responsive
4	A little foggy, not at peak; let down
5	Fogginess; beginning to lose interest in remaining awake; slowed down
6	Sleepiness; prefer to be lying down; fighting sleep; woozy
7	Almost in reverie; sleep onset soon; lost; struggle to remain awake

3. Please rate your level of motion sickness after the driving task using the global sickness rating scale.

1	No symptoms
2	Initial symptoms of motion sickness but no nausea
3	Mild nausea
4	Moderate nausea
5	Severe nausea and/or retching
6	Vomiting

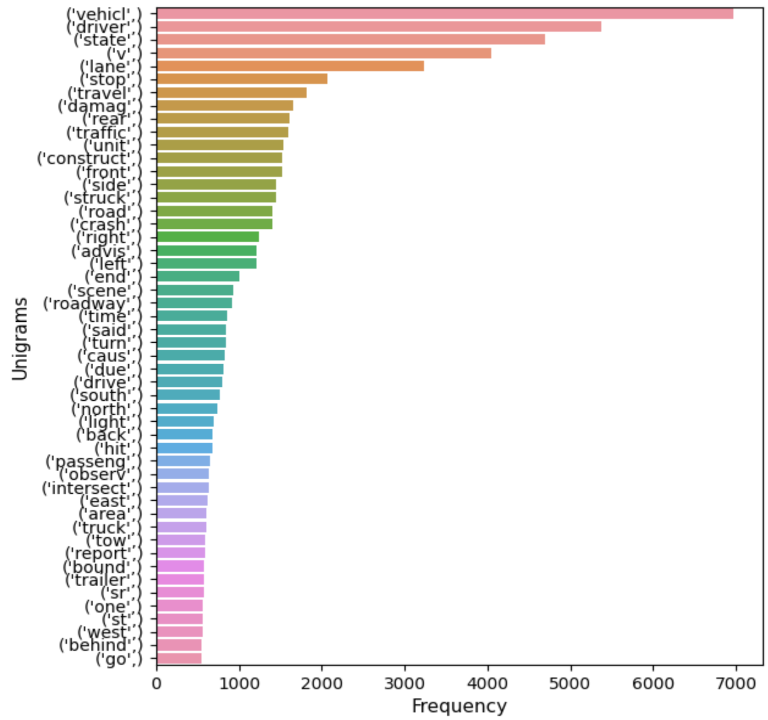
4. Please evaluate your driving style in the listed scenarios.
   Note: A higher number indicates a more aggressive driving style.

	1	2	3	4	5	6	7	8	9
Daytime with original fluorescent orange sign									
Daytime with fluorescent orange sign having orange warning beacon									
Daytime with fluorescent orange sign having orange LEDs									
Daytime with doubling-up of fluorescent orange sign									
Nighttime with original fluorescent orange sign									
Nighttime with fluorescent orange sign having orange warning beacon									
Nighttime with fluorescent orange sign having orange LEDs									
Nighttime with doubling-up of fluorescent orange sign									

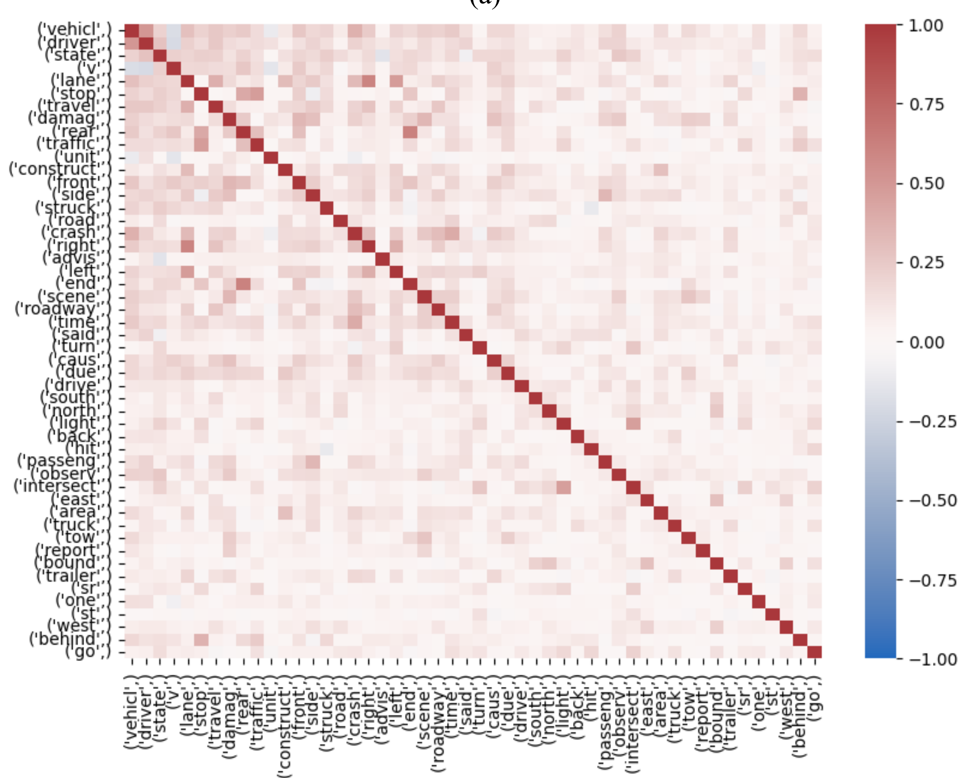
5. Please provide any comments or suggestions on the driving experiment, if applicable:
   ____

Thank you very much for your time and support!

APPENDIX D. SUPPLEMENTARY FIGURES AND TABLES

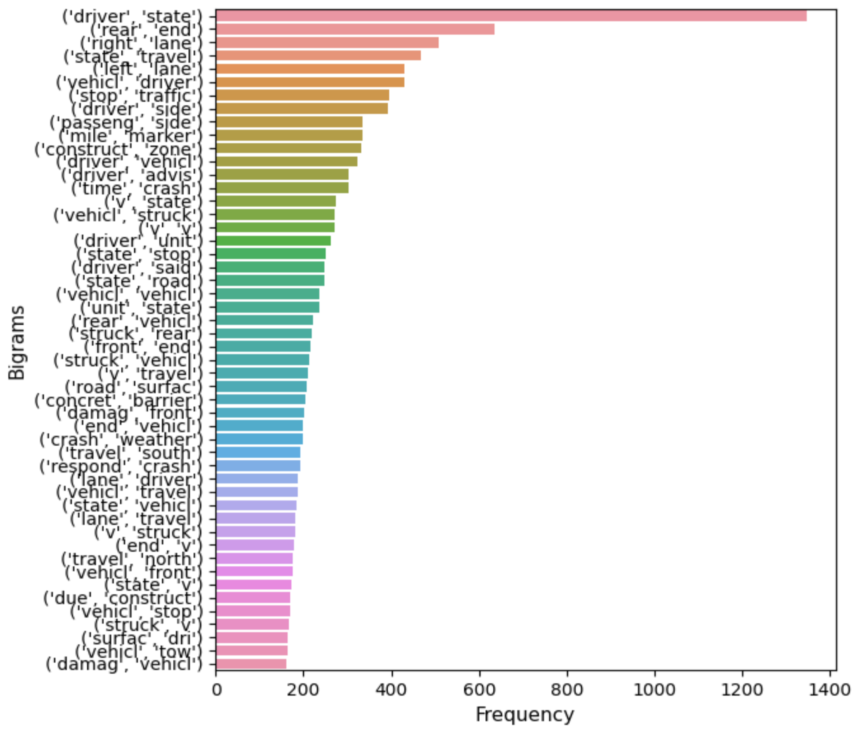


(a)

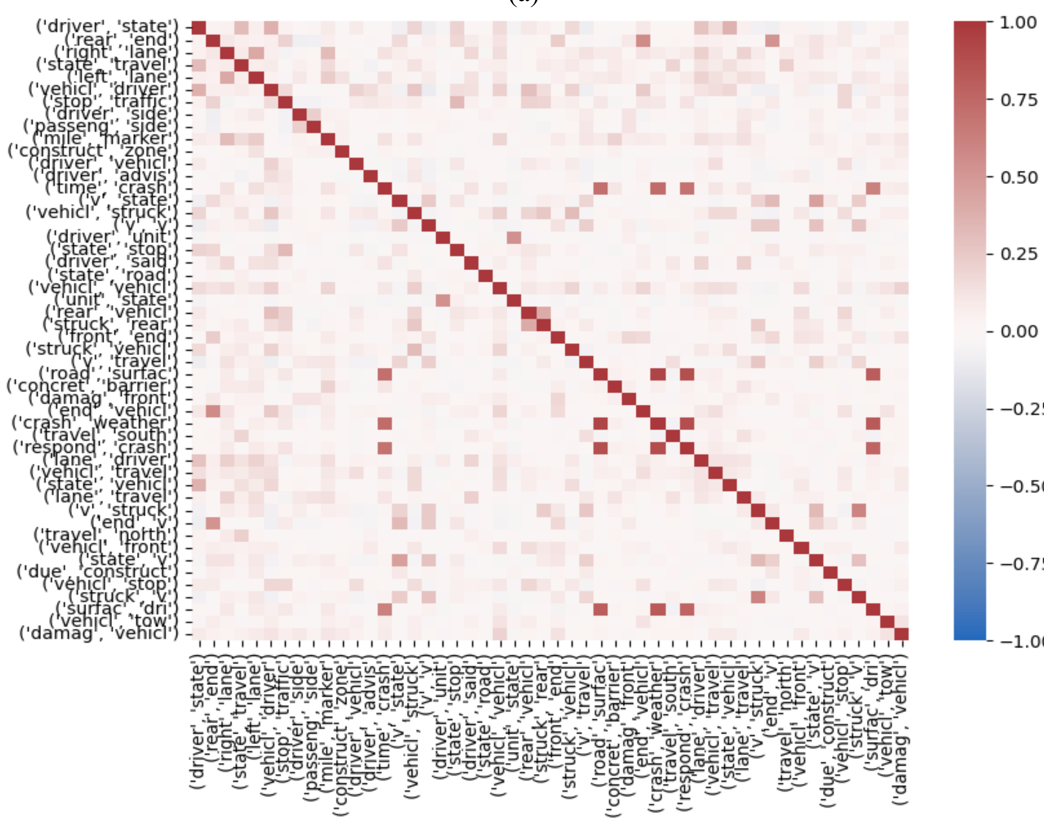


(b)

Figure D.1 Frequency and correlation heatmap of top 50 unigrams (ARIES crash reports).

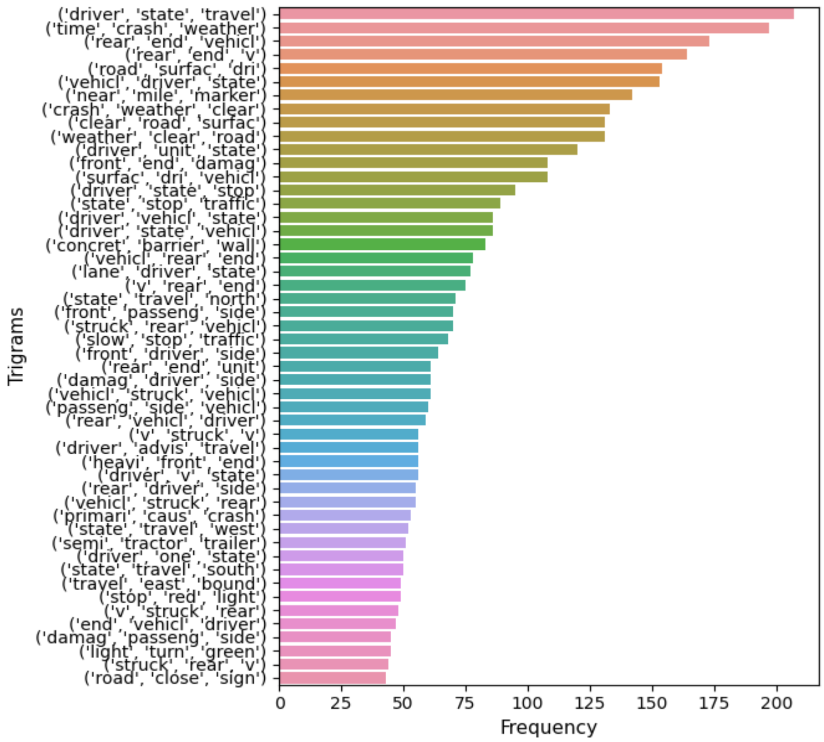


(a)

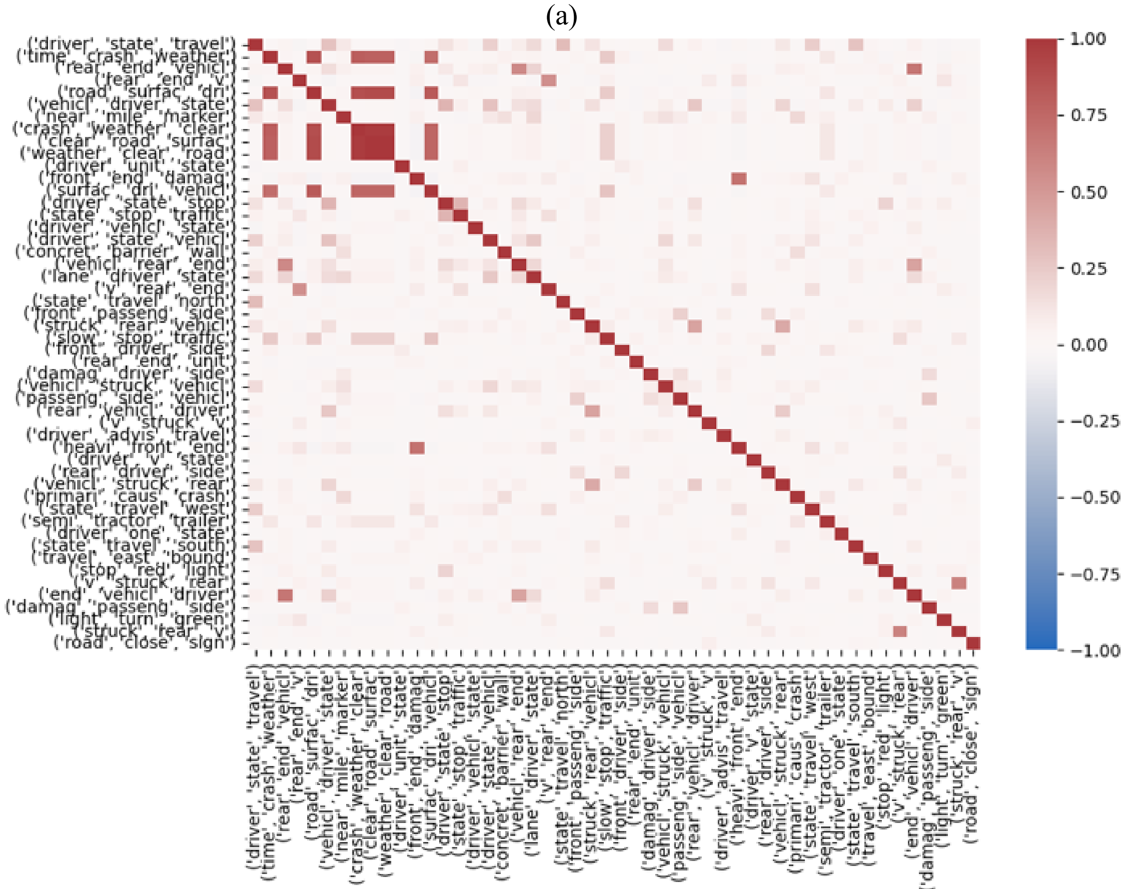


(b)

Figure D.2 Frequency and correlation heatmap of top 50 bigrams (ARIES crash reports).



(a)



(b)

Figure D.3 Frequency and correlation heatmap of top 50 trigrams (ARIES crash reports).

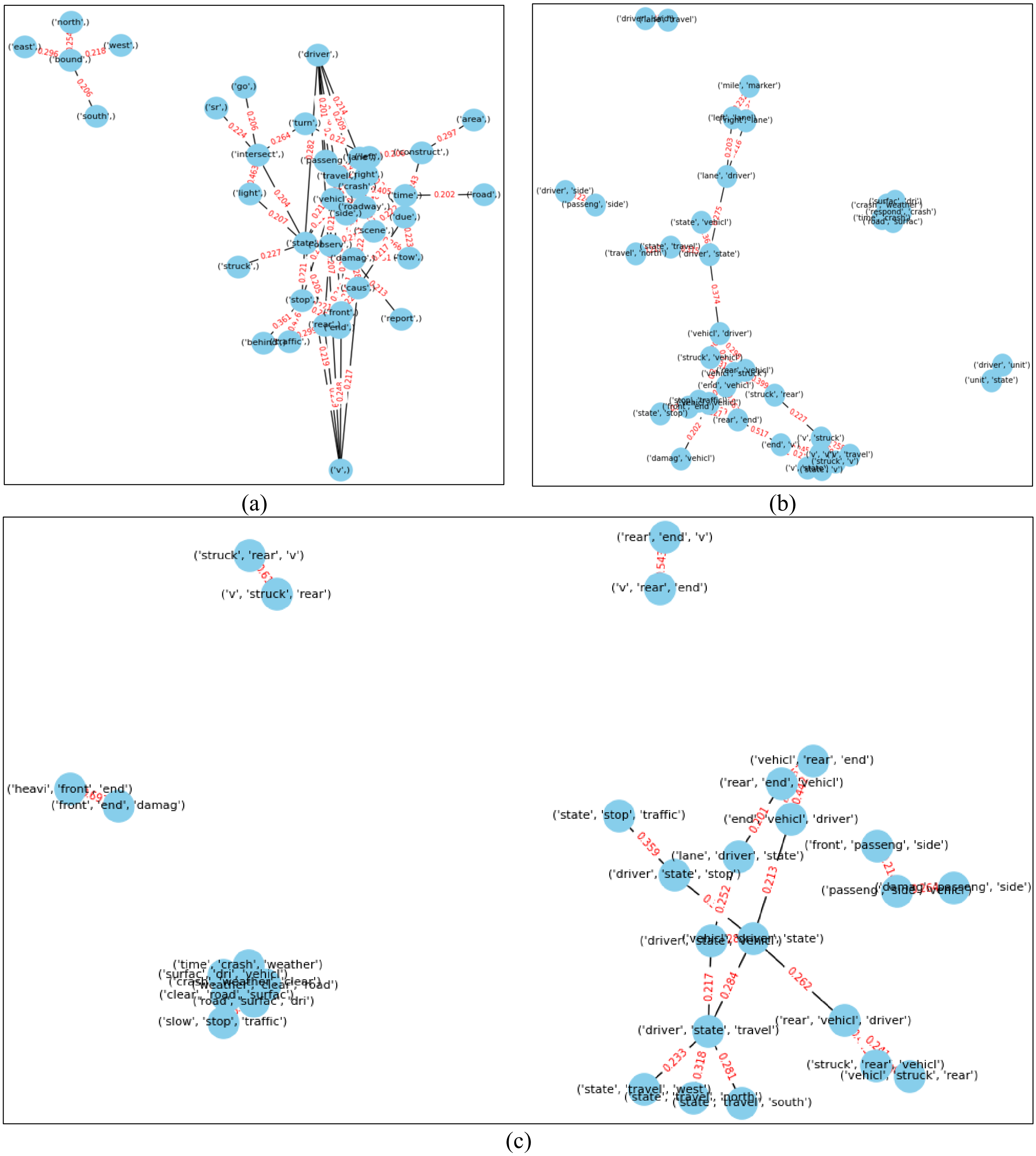


Figure D.4 Network graph of top N-grams (ARIES crash reports).

Table D.1 Ranks of Traffic Signs

Signs	Commonly Used		Attracting Drivers' Attention		Reducing Speed		Effectiveness In Reducing Crashes		Overall Importance	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Signs when entering work zones										
Road Work (with distance/ahead) (W20-1)	1.18	0.40	3.67	2.24	4.00	2.67	3.82	2.23	2.82	2.44
Flagger (W20-7)	4.00	1.48	3.25	1.83	4.71	2.93	3.80	2.39	2.10	1.29
Shoulder Work (W21-5)	5.18	1.60	6.25	1.49	6.86	1.35	5.60	1.65	5.30	2.31
Speeding Max $1000 Reckless Driving Max 6 yrs (XW2-6)	2.91	2.21	4.78	2.82	2.50	2.45	4.91	2.34	4.40	2.21
Lane(s) Closed (with distance) (W20-5)	3.18	1.25	3.67	1.80	4.88	1.89	3.09	1.45	3.00	1.34
One Lane Road (with distance) (W20-4)	4.09	1.58	4.38	1.69	5.43	1.51	4.09	1.81	4.50	2.17
Yield Ahead (W3-2)	6.91	2.02	5.50	2.56	5.43	2.82	5.20	2.94	4.90	2.73
Detour (with distance) (W20-2)	6.18	1.60	3.50	1.20	4.71	2.50	4.50	2.01	5.20	2.25
Signs at the end of the work zone or leaving the work zone										
End Road Work (G20-2)	1.00	0.00	1.71	0.49	1.71	0.49	1.56	0.53	1.70	0.48
Exit Open (E5-2)	2.00	0.00	1.29	0.49	1.29	0.49	1.44	0.53	1.30	0.48
Signs used in general road and work zones										
Lane Ends (W4-2)	1.45	0.52	2.00	1.41	2.13	0.83	1.70	1.25	1.80	1.48
Turn and Curve Sign (Reverse curve W1-4)	2.90	1.97	2.75	1.58	3.00	1.51	3.30	1.77	3.60	1.51
One-Direction Large Arrow (W1-6)	4.60	1.43	3.25	1.83	3.13	1.89	3.70	1.42	4.10	1.37
Two-Way Traffic (W6-3)	4.60	1.17	4.00	1.31	4.50	1.41	4.50	1.51	4.60	1.78
Advisory Speed (W13-1P)	4.50	2.22	6.00	1.31	4.00	2.67	5.10	2.13	4.30	2.54
On Ramp (W13-4P)	6.30	2.06	6.00	2.07	6.88	0.83	6.30	2.06	6.30	1.70
Road Narrows (W5-1)	4.00	1.41	4.88	1.81	4.38	0.92	4.10	1.60	4.10	1.79

Note: A smaller value of Mean indicates a higher rank. There is missing data for the last four criteria. And for the Attracting drivers' attention and Reducing speed, there were only 9 responses.

Table D.2 Results of Color-related Countermeasures

Countermeasures	Feasibility			Effectiveness			Comments from Participants
	Yes	No	Not sure	Yes	No	Not sure	
Traffic Signs							
Fluorescent orange sign with fluorescent yellow-green border	5	5	1	6	3	2	This will cause confusion because this color is for school zones and pedestrians; It is difficult to get approval; Can be specifically used for signs related to people (e.g., worker and flagger signs).
Doubling-up of fluorescent orange sign	9	2	0	8	3	0	Required on divided highways and multiple lanes; Recommended for yield conditions on entrance ramp; Might cause more distractions; Have been there for a long time and people may not pay attention to it; Can provide minor benefits.
Fluorescent orange sign with retroreflective orange flags	10	1	0	7	3	1	It is weather dependent (e.g., impacted by wind); Aluminum flag is a possible option; Would be bleached with sunlight; Have been there for a long time and people may not pay attention to it.
Fluorescent orange sign with yellow warning beacon	8	2	1	8	2	1	Prefer orange because it is the work zone color; Can be effective during both day and night; Can be used for very explicit signs.
Fluorescent orange sign with orange warning beacon	9	1	1	8	2	1	
Fluorescent orange sign with white LED units	8	2	1	8	1	2	It is the most effective one that could attract attention, which is very impressed; Prefer orange because it is the work zone color; Yellow stands out; White may not be a good color; It is a good way to denounce signs and should be used for some specific signs; Can be turned on at night as an accomplishment; Do not do it for every sign.
Fluorescent orange sign with yellow LED units	8	2	1	9	0	2	
Fluorescent orange sign with orange LED units	10	1	0	10	0	1	
Fluorescent orange sign with orange retroreflective strip on support	9	2	0	7	3	0	Should be sparingly used; It is the least effective one; May cause extra distraction; Have been there for a long time and people may not pay attention to it.
Fluorescent orange sign with yellow flash warning light	9	1	1	4	5	2	It is current standard practice; Provide nighttime visibility only; Prefer orange because it is the work zone color; Have been there for a long time and people may not pay attention to it.
Fluorescent orange sign with orange flash warning light	10	0	1	4	5	2	

Channelizing Devices							
Fluorescent orange and white drum with yellow warning light	9	2	0	9	2	0	It is the standard requirement; Should use steady burned lights; Lights are only effective at night; Drums are more effective than other devices; Had lights a long time ago but stopped using them because of more maintenance needs; Use solar to reduce maintenance; Adding lights for merging situations only.
Fluorescent orange, white, and green drum for exit ramp	9	1	1	9	2	0	Should use fluorescent green rather than fluorescent yellow-green; Adding light would be more effective at night; Set-up of drums is more effective than color; Would only go with orange; Need to educate people; Adding 10 more drums to warning ahead; Use the same green as guide signs; Use drums without lights for general location and have the green drum with the lights at the exit.
Fluorescent orange, white, and green drum for exit ramp with warning lights	9	2	0	8	3	0	
Fluorescent orange and white barricade with yellow warning light	9	2	0	9	2	0	It is the standard requirement; Barricade has specific utilization for road closure.
Pavement Markings							
Orange pavement markings	9	1	1	8	2	1	Use orange as complimentary with existing white and yellow rather than orange only, which could make the line wider and enhance color contrast; The design makes people center up and causes a slight reduction in speed; It will become dark in 2-3 weeks and lose the contrast and retro-reflectivity; Orange color does not seem consistent during daytime and nighttime; Same orange color as other work zone elements will not let people be alerted to it; Can use it in transition areas.
Red pavement markings for one-way roadways, ramps, or travel lanes that shall not be entered	9	2	0	6	4	1	Red is too dark and less retroreflective; Cannot see it unless you are almost on top of it; Red pavement is for public vehicle transit lanes; Should be used for lane closure rather than closed ramp.

PPE for Workers							
Fluorescent yellow-green with yellow and silver stripes	11	0	0	10	1	0	The current design (fluorescent yellow-green with orange and silver strops) is the most effective and safe one; Fluorescent yellow-green stands out better; Could provide great conspicuity, especially at night.
Fluorescent yellow-green with white and silver stripes	11	0	0	10	1	0	
Fluorescent orange-red with yellow-green and silver stripes	8	3	0	3	8	0	Blend in the orange background (make people look like a barrel); It is the INDOT's past practice (prefer not to go back); Orange and red would be effective; More orange lets people get lost.
Fluorescent orange-red with yellow and silver stripes	8	3	0	3	8	0	
Fluorescent orange-red with white and silver stripes	8	3	0	3	8	0	
Red hard hat	6	4	1	4	6	1	May have other meanings (e.g., fire chief); Look similar to the orange background.
Yellow hard hat	8	2	1	6	4	1	Yellow is more effective and stands out from the background.
Blue hard hat	5	3	2	3	7	1	May have other meanings (e.g., police); Blend in a little bit more; Prefer not to use this calming color.

Note: The table shows the number of participants for each answer.

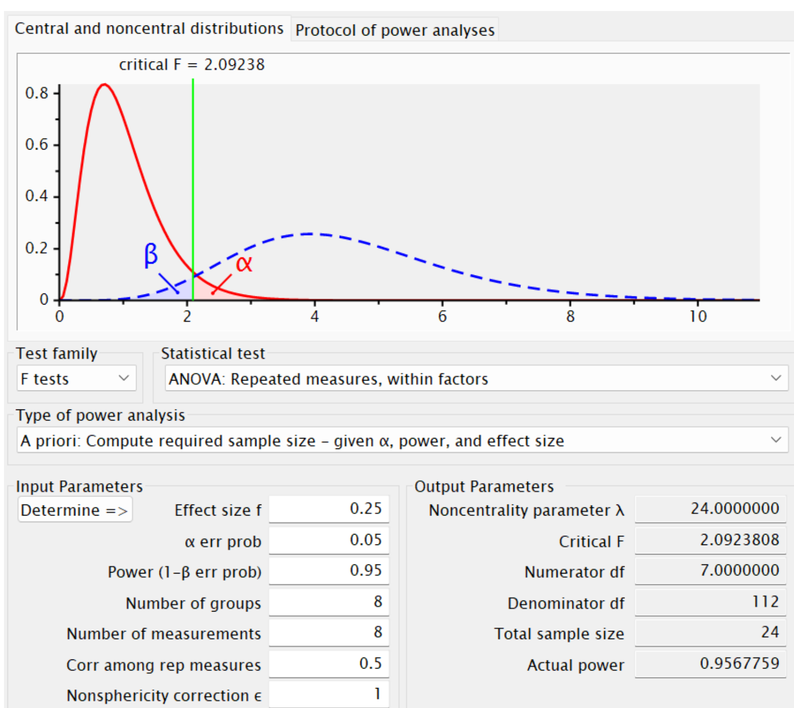


Figure D.5 Power analysis for driving experiment sample size.

Table D.3 The List of Participants

Participant	Work zone Scenario	Time Scenarios and Countermeasures									
1	Lane closure	Day	C3	C4	C1	C2	Night	C4	C3	C2	C1
2	Lane closure	Night	C4	C2	C3	C1	Day	C4	C1	C3	C2
3	Lane closure	Day	C1	C4	C2	C3	Night	C3	C4	C1	C2
4	Lane closure	Night	C4	C3	C1	C2	Day	C4	C1	C3	C2
5	Lane closure	Day	C3	C4	C2	C1	Night	C2	C4	C1	C3
6	Lane closure	Night	C4	C1	C2	C3	Day	C3	C2	C1	C4
7	Lane closure	Day	C1	C3	C2	C4	Night	C2	C4	C1	C3
8	Lane closure	Night	C1	C2	C3	C4	Day	C2	C3	C1	C4
9	Lane closure	Day	C3	C4	C2	C1	Night	C1	C3	C2	C4
10	Lane closure	Night	C1	C3	C4	C2	Day	C3	C2	C1	C4
11	Lane closure	Day	C3	C1	C2	C4	Night	C1	C3	C4	C2
12	Lane closure	Night	C3	C1	C4	C2	Day	C1	C3	C4	C2
13	Lane closure	Day	C3	C4	C1	C2	Night	C3	C1	C2	C4
14	Lane closure	Night	C1	C2	C4	C3	Day	C4	C2	C3	C1
15	Lane closure	Day	C1	C2	C4	C3	Night	C2	C1	C3	C4
16	Lane closure	Night	C4	C1	C2	C3	Day	C3	C1	C2	C4
17	Lane closure	Day	C1	C3	C4	C2	Night	C3	C4	C1	C2
18	Lane closure	Night	C1	C2	C3	C4	Day	C4	C2	C1	C3
19	Lane closure	Day	C4	C2	C1	C3	Night	C3	C4	C2	C1
20	Lane closure	Night	C3	C4	C1	C2	Day	C1	C2	C3	C4
21	Lane closure	Day	C3	C4	C2	C1	Night	C2	C4	C3	C1
22	Lane closure	Night	C3	C1	C2	C4	Day	C1	C3	C4	C2
23	Lane closure	Day	C4	C3	C2	C1	Night	C2	C1	C4	C3
24	Lane closure	Night	C4	C2	C1	C3	Day	C4	C1	C3	C2
25	Lane closure	Day	C4	C1	C3	C2	Night	C4	C3	C2	C1
26	Lane closure	Night	C3	C1	C2	C4	Day	C4	C2	C3	C1
27	Lane closure	Day	C4	C1	C2	C3	Night	C1	C3	C2	C4
28	Lane closure	Night	C3	C2	C4	C1	Day	C4	C2	C3	C1
29	Lane closure	Day	C4	C3	C2	C1	Night	C3	C1	C2	C4
30	Lane closure	Night	C3	C4	C1	C2	Day	C4	C2	C1	C3
31	Lane closure	Day	C4	C3	C2	C1	Night	C1	C2	C3	C4
32	Lane closure	Night	C1	C2	C3	C4	Day	C3	C4	C2	C1
33	Shoulder work	Day	C3	C4	C1	C2	Night	C4	C3	C2	C1
34	Shoulder work	Night	C4	C2	C3	C1	Day	C4	C1	C3	C2
35	Shoulder work	Day	C1	C4	C2	C3	Night	C3	C4	C1	C2
36	Shoulder work	Night	C4	C3	C1	C2	Day	C4	C1	C3	C2
37	Shoulder work	Day	C3	C4	C2	C1	Night	C2	C4	C1	C3
38	Shoulder work	Night	C4	C1	C2	C3	Day	C3	C2	C1	C4
39	Shoulder work	Day	C1	C3	C2	C4	Night	C2	C4	C1	C3
40	Shoulder work	Night	C1	C2	C3	C4	Day	C2	C3	C1	C4
41	Shoulder work	Day	C3	C4	C2	C1	Night	C1	C3	C2	C4
42	Shoulder work	Night	C1	C3	C4	C2	Day	C3	C2	C1	C4
43	Shoulder work	Day	C3	C1	C2	C4	Night	C1	C3	C4	C2

44	Shoulder work	Night	C3	C1	C4	C2	Day	C1	C3	C4	C2
45	Shoulder work	Day	C3	C4	C1	C2	Night	C3	C1	C2	C4
46	Shoulder work	Night	C1	C2	C4	C3	Day	C4	C2	C3	C1
47	Shoulder work	Day	C1	C2	C4	C3	Night	C2	C1	C3	C4
48	Shoulder work	Night	C4	C1	C2	C3	Day	C3	C1	C2	C4
49	Shoulder work	Day	C1	C3	C4	C2	Night	C3	C4	C1	C2
50	Shoulder work	Night	C1	C2	C3	C4	Day	C4	C2	C1	C3
51	Shoulder work	Day	C4	C2	C1	C3	Night	C3	C4	C2	C1
52	Shoulder work	Night	C3	C4	C1	C2	Day	C1	C2	C3	C4
53	Shoulder work	Day	C3	C4	C2	C1	Night	C2	C4	C3	C1
54	Shoulder work	Night	C3	C1	C2	C4	Day	C1	C3	C4	C2
55	Shoulder work	Day	C4	C3	C2	C1	Night	C2	C1	C4	C3
56	Shoulder work	Night	C4	C2	C1	C3	Day	C4	C1	C3	C2
57	Shoulder work	Day	C4	C1	C3	C2	Night	C4	C3	C2	C1
58	Shoulder work	Night	C3	C1	C2	C4	Day	C4	C2	C3	C1
59	Shoulder work	Day	C4	C1	C2	C3	Night	C1	C3	C2	C4
60	Shoulder work	Night	C3	C2	C4	C1	Day	C4	C2	C3	C1
61	Shoulder work	Day	C4	C3	C2	C1	Night	C3	C1	C2	C4
62	Shoulder work	Night	C3	C4	C1	C2	Day	C4	C2	C1	C3
63	Shoulder work	Day	C4	C3	C2	C1	Night	C1	C2	C3	C4
64	Shoulder work	Night	C1	C2	C3	C4	Day	C3	C4	C2	C1

Note: C1: Original design of traffic sign (fluorescent orange sign); C2: Doubling-up of fluorescent orange sign (setting signs on both sides of the road); C3: Fluorescent orange sign with orange LEDs; C4: Fluorescent orange sign with orange beacon.

APPENDIX E. SUPPLEMENTARY INFORMATION FOR SESSION 10

E.1 Lane Closure Experiment

E.1.1 Eye Movement

E.1.1.1 Fixation duration

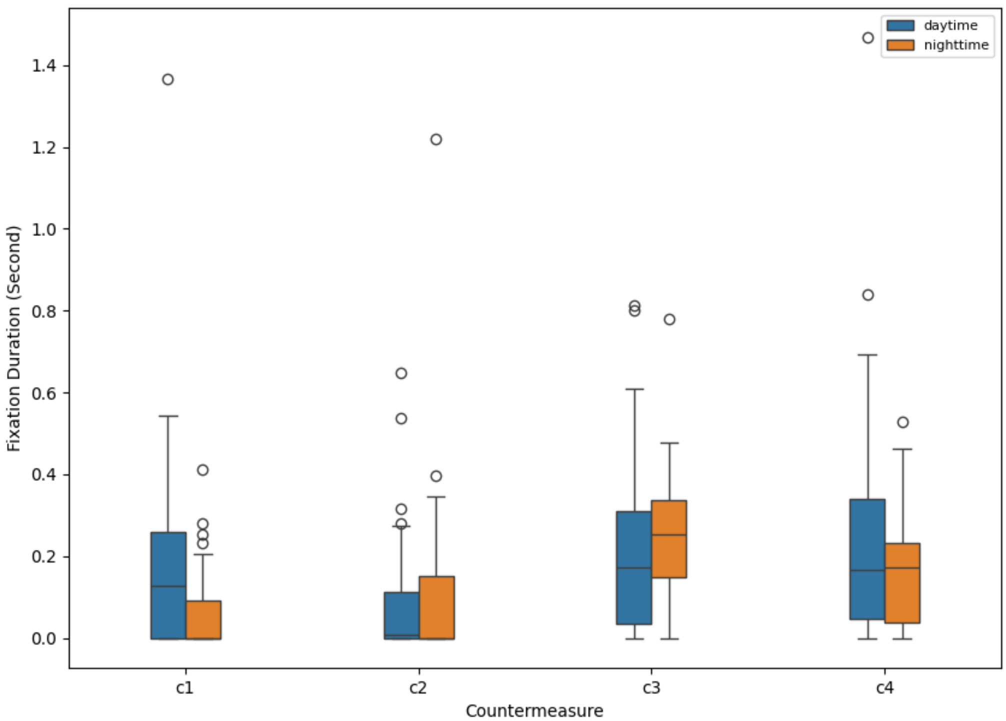


Figure E.1 Boxplot of fixation duration (lane closure).

Table E.1 ANOVA Test Results for Fixation Duration (Lane Closure)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	0.4372	0.1457	3.3984	0.0312
	Error	124	7.5346	0.0608	–	–
	Corrected Total	127	7.9718	–	–	–
Nighttime	Model	3	0.6135	0.2045	7.0741	<0.01
	Error	124	3.5845	0.0289	–	–
	Corrected Total	127	4.1980	–	–	–

Table E.2 Tukey's HSD Test Results for Fixation Duration (Lane Closure)

Time Scenarios	Group 1	Group 2	Mean Difference	P-value	Lower	Upper	Reject
Daytime	Original design (C1)	Doubling-up (C2)	-0.0931	0.4339	-0.2536	0.0674	FALSE
	Original design (C1)	LEDs (C3)	0.0269	0.9722	-0.1336	0.1874	FALSE
	Original design (C1)	Beacon (C4)	0.0653	0.7144	-0.0952	0.2258	FALSE
	Doubling-up (C2)	LEDs (C3)	0.1776	0.0439	-0.0405	0.2805	TRUE
	Doubling-up (C2)	Beacon (C4)	0.1685	0.0413	-0.0020	0.3189	TRUE
	LEDs (C3)	Beacon (C4)	0.0385	0.9242	-0.1220	0.1989	FALSE
Nighttime	Original design (C1)	Doubling-up (C2)	0.0475	0.6798	-0.0632	0.1582	FALSE
	Original design (C1)	LEDs (C3)	0.1857	0.0002	0.0750	0.2964	TRUE
	Original design (C1)	Beacon (C4)	0.1049	0.0699	-0.0057	0.2156	FALSE
	Doubling-up (C2)	LEDs (C3)	0.1382	0.0079	0.0275	0.2489	TRUE
	Doubling-up (C2)	Beacon (C4)	0.0575	0.5318	-0.0532	0.1682	FALSE
	LEDs (C3)	Beacon (C4)	-0.0808	0.2334	-0.1915	0.0299	FALSE

Table E.3 Paired T-test Results for Fixation Duration (Lane Closure)

Countermeasures	T-Statistic	P-value
Original design (C1)	1.9023	0.0782
Doubling-up (C2)	-0.2857	0.7770
LEDs (C3)	-0.6669	0.5098
Beacon (C4)	1.5300	0.1362

E.1.1.2 Left pupil diameter

Figure E.2 shows the boxplot of left pupil mean diameter for the original design (C1) and three countermeasures (doubling-up of fluorescent orange sign (C2), fluorescent orange sign with orange LEDs (C3), and fluorescent orange sign with orange beacon (C4)) under daytime and nighttime conditions. For all countermeasures (including the original design group), the left pupil mean diameters were higher during nighttime compared to daytime. It indicates that there were increased left pupil diameters under low-lighting conditions. The distribution of data (interquartile range) was also wider for some nighttime scenarios, suggesting greater variability in pupil response. Outliers are observed in a few cases, indicating that some participants had different left pupil diameters from the majority.

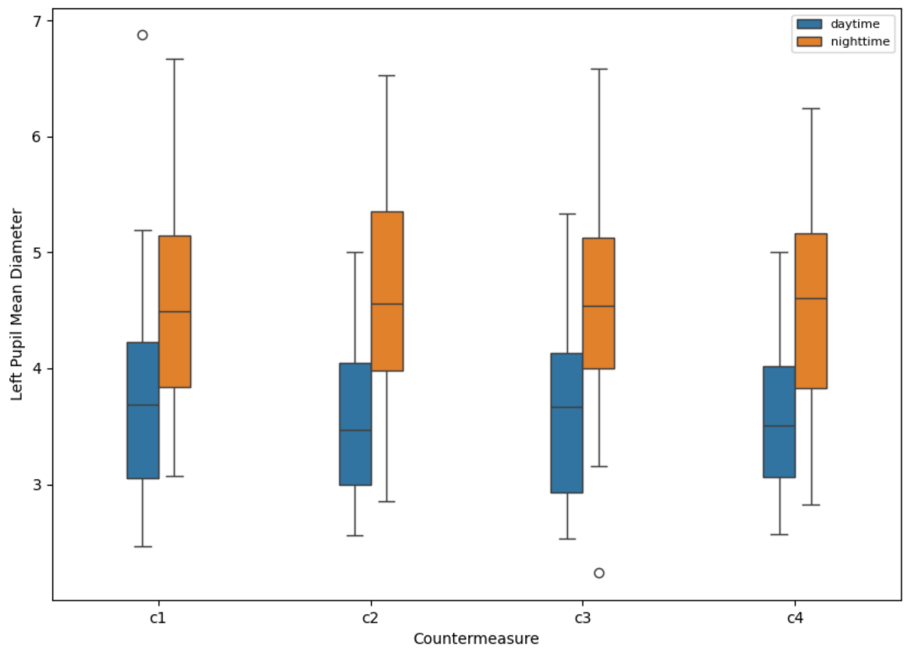


Figure E.2 Boxplot of left pupil mean diameter (lane closure).

Table E.4 ANOVA Test Results for Left Pupil Mean Diameter (Lane Closure)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	0.4602	0.2301	0.2519	0.8599
	Error	124	75.5282	4.1960	–	–
	Corrected Total	127	75.9884	–	–	–
Nighttime	Model	3	0.3941	0.1971	0.1403	0.9357
	Error	124	116.1403	6.4522	–	–
	Corrected Total	127	116.5344	–	–	–

Table E.5 Paired T-test Results for Left Pupil Mean Diameter (Lane Closure)

Countermeasures	T-Statistic	P-value
Original design (C1)	-4.9087	<0.01
Doubling-up (C2)	-7.8887	<0.01
LEDs (C3)	-9.2670	<0.01
Beacon (C4)	-7.1153	<0.01

E.1.1.3 Right pupil diameter

Figure E.3 shows the boxplot of right pupil mean diameter for C1–C4. Similar as the left pupil mean diameter, for all countermeasures (including the original design group), the right pupil mean diameters were higher during nighttime compared to daytime, possibly due to the natural dilation response in low-light environments. The interquartile ranges were generally larger for nighttime than for daytime across most countermeasures, indicating more variability in pupil diameter in low-lighting conditions. Outliers are obvious at nighttime, suggesting individual differences in adaptation to nighttime conditions.

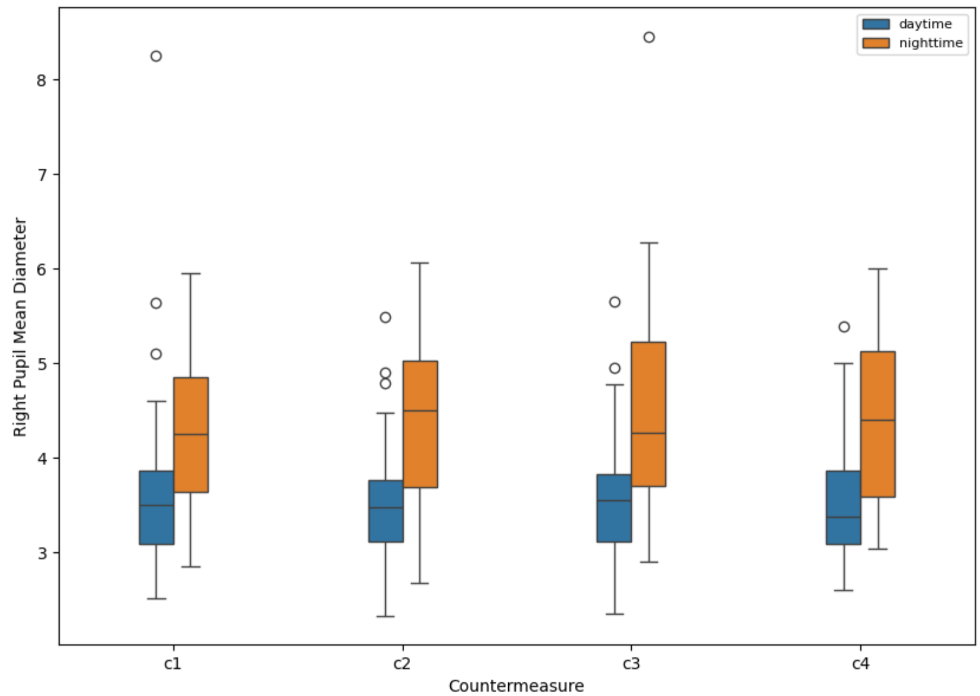


Figure E.3 Boxplot of right pupil mean diameter (lane closure).

Table E.6 ANOVA Test Results for Right Pupil Mean Diameter (Lane Closure)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	0.5802	0.2901	0.2777	0.8414
	Error	124	86.368	4.7982	–	–
	Corrected Total	127	86.9482	–	–	–
Nighttime	Model	3	1.2406	0.6203	0.4756	0.6998
	Error	124	107.8151	5.9897	–	–
	Corrected Total	127	109.0557	–	–	–

Table E.7 Paired T-test Results for Right Pupil Mean Diameter (Lane Closure)

Countermeasures	T-Statistic	P-value
Original design (C1)	-3.0716	<0.01
Doubling-up (C2)	-8.3513	<0.01
LEDs (C3)	-5.4875	<0.01
Beacon (C4)	-6.8882	<0.01

E.1.2 Driving Performance

E.1.2.1 Mean speed

Figure E.4 shows the vehicle speed data for the original design (C1) and three countermeasures (doubling-up (C2), LEDs (C3), and beacon (C4)) under daytime and nighttime conditions. Median speeds were fairly consistent across all countermeasures, with small differences between daytime and nighttime conditions, suggesting that drivers generally maintained similar speeds regardless of time scenarios.

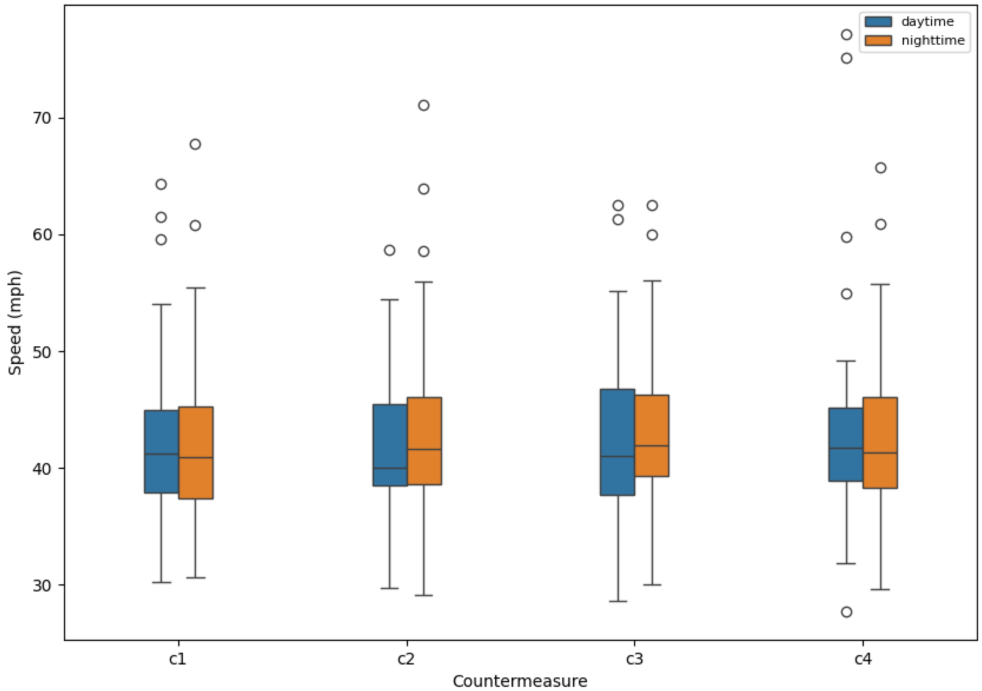


Figure E.4 Boxplot of vehicle speed (lane closure).

Table E.8 ANOVA Test Results for Mean Speed (Lane Closure)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	64.7357	21.5786	0.3150	0.8145
	Error	124	8,494.3543	68.5029	–	–
	Corrected Total	127	8,559.0900	–	–	–
Nighttime	Model	3	14.0433	4.6811	0.0719	0.9749
	Error	124	8,075.8426	65.1278	–	–
	Corrected Total	127	8,089.8859	–	–	–

Table E.9 Paired T-test Results for Mean Speed (Lane Closure)

Countermeasures	T-Statistic	P-value
Original design (C1)	0.1141	0.9099
Doubling-up (C2)	-1.9010	0.0666
LEDs (C3)	-0.8715	0.3902
Beacon (C4)	1.1563	0.2564

E.1.2.2 Speed reduction

Figure E.5 shows the speed reduction data for the original design (C1) and three countermeasures (doubling-up (C2), LEDs (C3), and beacon (C4)) under both daytime and nighttime conditions. It indicates that speed reductions were larger during nighttime across all countermeasures, suggesting drivers' cautious behaviors at nighttime.

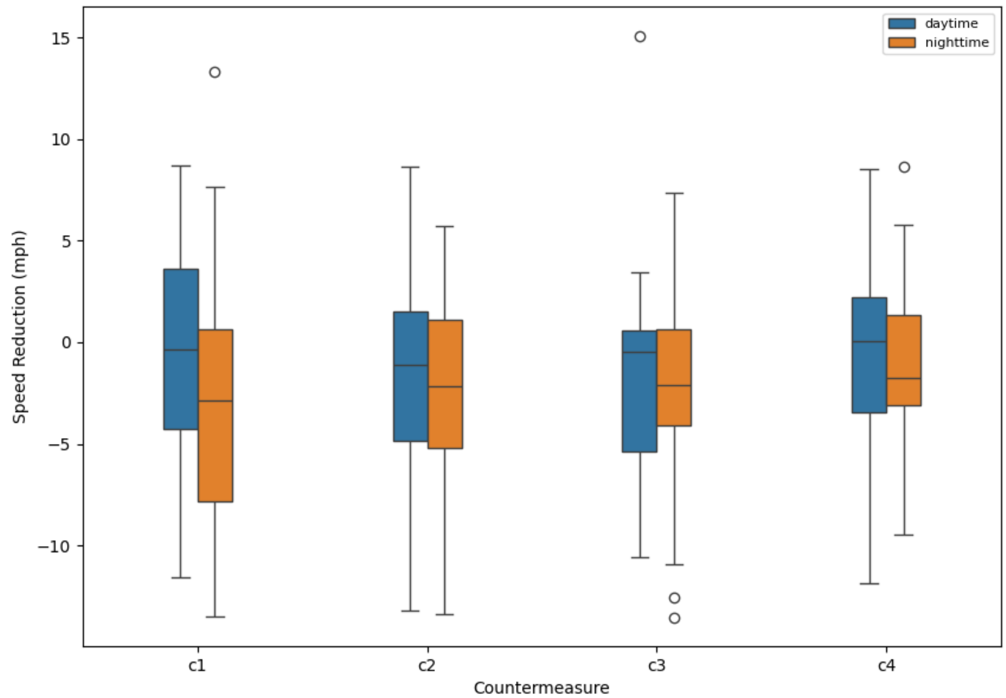


Figure E.5 Boxplot of speed reduction (lane closure).

Table E.10 ANOVA Test Results for Speed Reduction (Lane Closure)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	49.6115	16.5372	0.6258	0.5996
	Error	124	3,276.5703	26.4240	–	–
	Corrected Total	127	3,326.1818	–	–	–
Nighttime	Model	3	48.5640	16.1880	0.6318	0.5959
	Error	124	3,177.1926	25.6225	–	–
	Corrected Total	127	3,225.7566	–	–	–

Table E.11 Paired T-test Results for Speed Reduction (Lane Closure)

Countermeasures	T-Statistic	P-value
Original design (C1)	1.8197	0.0785
Doubling-up (C2)	1.1290	0.2676
LEDs (C3)	0.3835	0.7040
Beacon (C4)	0.4088	0.6855

E.1.2.3 Mean acceleration

Figure E.6 shows a boxplot of vehicle acceleration for C1–C4 under daytime and nighttime scenarios. For the original design, doubling-up, and beacon, acceleration was larger during daytime compared to nighttime, while LEDs (C3) showed the opposite result. Outliers were presented in all countermeasures, with slightly more variability in acceleration observed during nighttime scenario for doubling-up and beacon countermeasures.

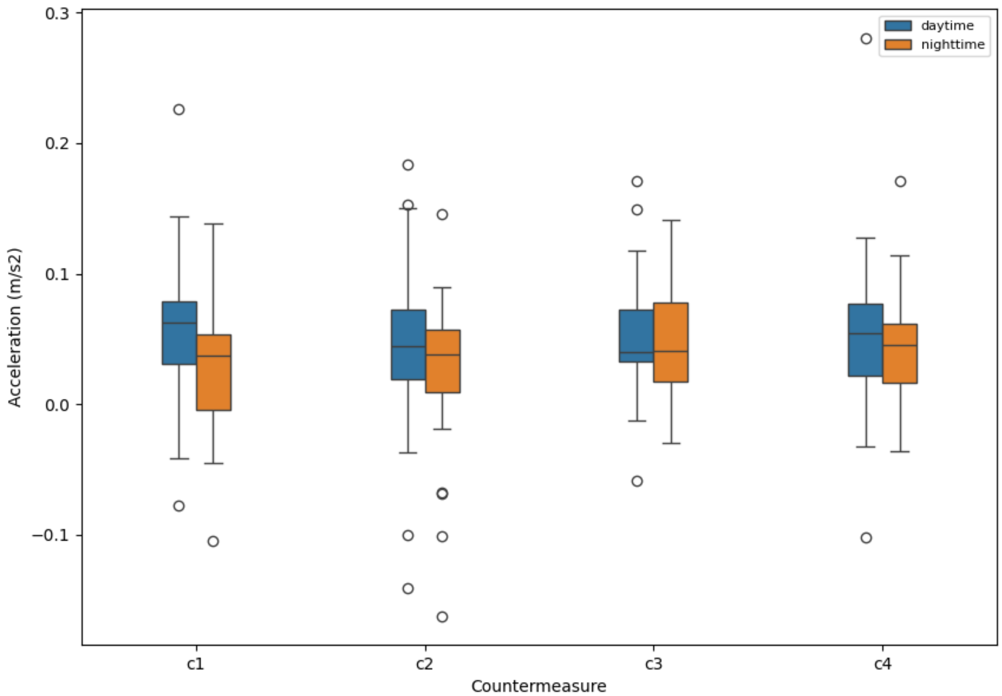


Figure E.6 Boxplot of vehicle acceleration (lane closure).

Table E.12 ANOVA Test Results for Mean Acceleration (Lane Closure)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	0.0021	0.0007	0.2001	0.8961
	Error	124	0.4213	0.0034	–	–
	Corrected Total	127	0.4234	–	–	–
Nighttime	Model	3	0.0099	0.0033	1.3153	0.2725
	Error	124	0.3111	0.0025	–	–
	Corrected Total	127	0.3210	–	–	–

Table E.13 Paired T-test Results for Mean Acceleration (Lane Closure)

Countermeasures	T-Statistic	P-value
Original design (C1)	1.4344	0.1618
Doubling-up (C2)	1.0688	0.2937
LEDs (C3)	0.5496	0.5867
Beacon (C4)	0.6316	0.5324

E.1.2.4 Lateral position

Figure E.7 displays the distribution of vehicle lateral position (in feet) for C1 – C4 under both daytime and nighttime scenarios. Overall, the lateral positions were consistent across conditions, with a slight increase in median position during nighttime. There were some lower outliers, particularly during the daytime, indicating instances where the vehicle position was closer to the right lane edge.

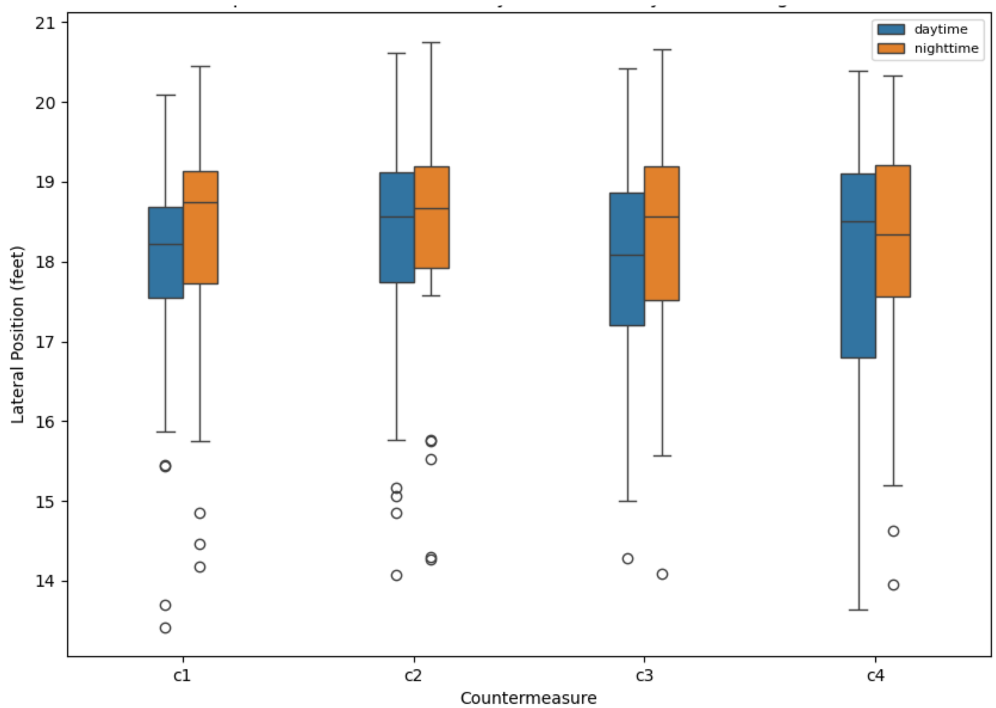


Figure E.7 Boxplot of lateral position (lane closure).

Table E.14 ANOVA Test Results for Lateral Position (Lane Closure)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	1.6657	0.5552	0.2104	0.8891
	Error	124	327.2422	2.6391	–	–
	Corrected Total	127	328.9079	–	–	–
Nighttime	Model	3	0.4618	0.1539	0.0642	0.9787
	Error	124	297.1840	2.3966	–	–
	Corrected Total	127	297.6458	–	–	–

Table E.15 Paired T-test Results for Lateral Position (Lane Closure)

Countermeasures	T-Statistic	P-value
Original design (C1)	-1.6713	0.1047
Doubling-up (C2)	-0.6399	0.5269
LEDs (C3)	-1.7696	0.0866
Beacon (C4)	-1.1733	0.2496

E.1.3 Synchronized Data

E.1.3.1 First-fixation distance to countermeasure

Figure E.8 shows the boxplot of the first-fixation distance to countermeasure indicator for C1–C4 under the lane closure scenario. It shows that LEDs (C3) and beacon (C4) had longer average first-fixation distance to countermeasure than the original design (C1) and doubling-up (C2).

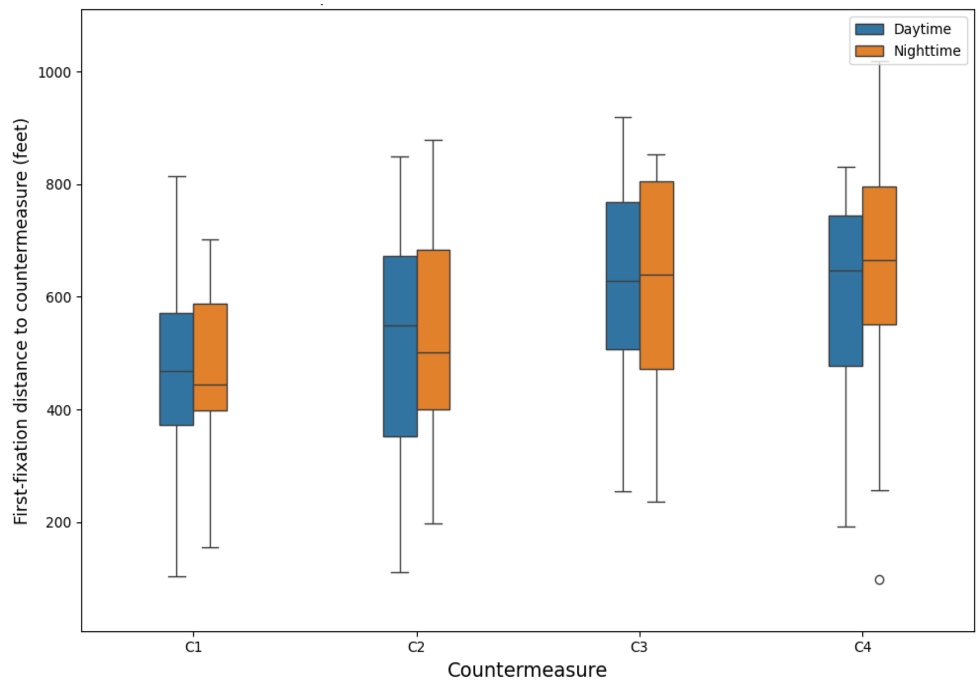


Figure E.8 Boxplot of first-fixation distance to countermeasure (lane closure).

Table E.16 ANOVA Test Results for First-fixation Distance to Countermeasure (Lane Closure)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	337,233.466	112,411.155	3.111	0.03
	Error	87	3,143,418.15	36,131.243	–	–
	Corrected Total	90	3,480,651.616	–	–	–
Nighttime	Model	3	414,067.311	138,022.437	3.815	0.013
	Error	79	2,858,262.271	36,180.535	–	–
	Corrected Total	82	3,272,329.582	–	–	–

Table E.17 Tukey's HSD Test Results for First-fixation Distance to Countermeasure (Lane Closure)

Time Scenarios	Group 1	Group 2	Mean difference	P-value	Lower	Upper	Reject
Daytime	Original design (C1)	Doubling-up (C2)	68.701	0.675	-91.228	228.630	FALSE
	Original design (C1)	LEDs (C3)	163.538	0.021	18.671	308.405	TRUE
	Original design (C1)	Beacon (C4)	113.635	0.189	-33.746	261.015	FALSE
	Doubling-up (C2)	LEDs (C3)	94.837	0.362	-56.669	246.343	FALSE
	Doubling-up (C2)	Beacon (C4)	44.934	0.870	-108.977	198.845	FALSE
	LEDs (C3)	Beacon (C4)	-49.904	0.780	-188.098	88.291	FALSE
Nighttime	Original design (C1)	Doubling-up (C2)	72.900	0.719	-108.806	254.605	FALSE
	Original design (C1)	LEDs (C3)	152.553	0.044	2.754	302.352	TRUE
	Original design (C1)	Beacon (C4)	184.830	0.015	27.726	341.934	TRUE
	Doubling-up (C2)	LEDs (C3)	79.654	0.594	-86.975	246.282	FALSE
	Doubling-up (C2)	Beacon (C4)	111.930	0.333	-61.296	285.155	FALSE
	LEDs (C3)	Beacon (C4)	32.276	0.929	-107.115	171.667	FALSE

Table E.18 Paired T-test Results for First-fixation Distance to Countermeasure (Lane Closure)

Countermeasures	T-Statistic	P-value
Original design (C1)	-0.024	0.981
Doubling-up (C2)	-0.072	0.943
LEDs (C3)	0.201	0.842
Beacon (C4)	-1.240	0.222

E.1.3.2 Gas pedal variation

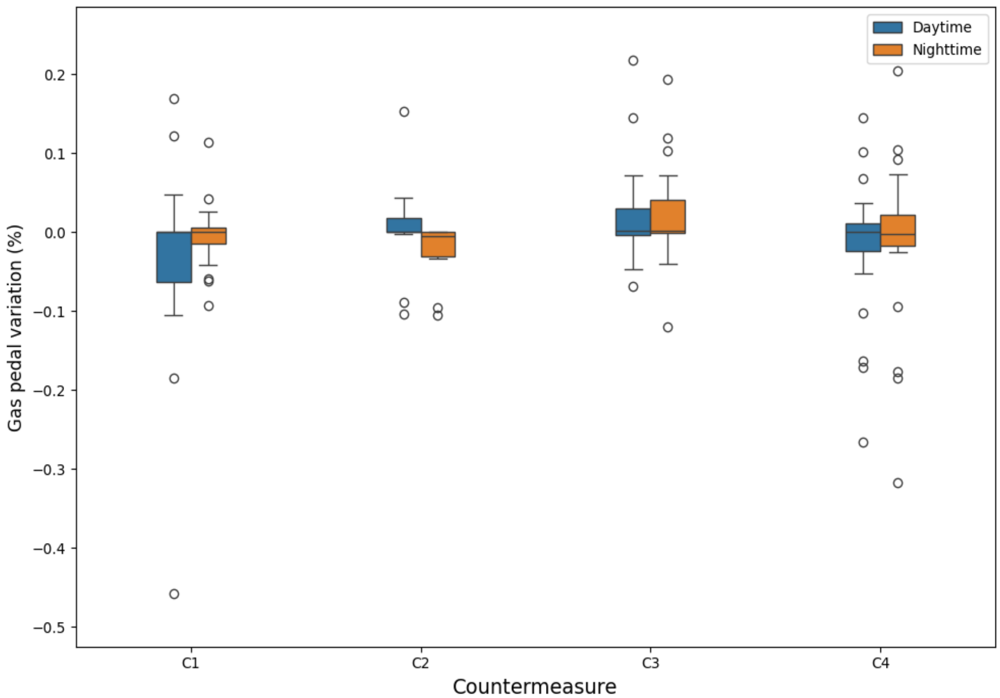


Figure E.9 Boxplot of gas pedal variation (lane closure).

Table E.19 ANOVA Test Results for Gas Pedal Variation (Lane Closure)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	0.032	0.011	1.549	0.208
	Error	87	0.6	0.007	–	–
	Corrected Total	90	0.632	–	–	–
Nighttime	Model	3	0.019	0.006	1.283	0.286
	Error	79	0.382	0.005	–	–
	Corrected Total	82	0.401	–	–	–

Table E.20 Paired T-test Results for Gas Pedal Variation (Lane Closure)

Countermeasures	T-Statistic	P-value
Original design (C1)	-0.878	0.388
Doubling-up (C2)	1.829	0.078
LEDs (C3)	0.055	0.957
Beacon (C4)	-0.210	0.835

E.1.3.3 Steering variation

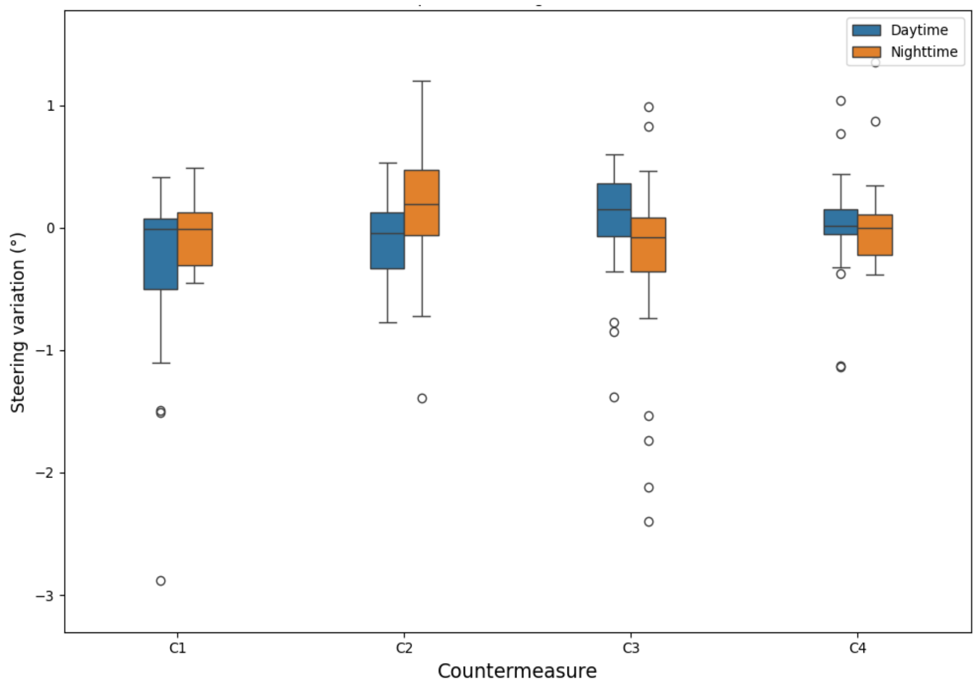


Figure E.10 Boxplot of steering variation (lane closure).

Table E.21 ANOVA Test Results for Steering Variation (Lane Closure)

Time Scenarios	**Source**	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**P-value**
Daytime	Model	3	2.871	0.957	3.244	0.026
	Error	87	25.664	0.295	–	–
	Corrected Total	90	28.535	–	–	–
Nighttime	Model	3	1.550	0.517	1.512	0.218
	Error	79	27.003	0.342	–	–
	Corrected Total	82	28.553	–	–	–

Table E.22 Tukey's HSD Test Results for Steering Variation (Lane Closure)

Time Scenarios	Group 1	Group 2	Mean difference	P-value	Lower	Upper	Reject
Daytime	Original design (C1)	Doubling-up (C2)	0.307	0.301	-0.150	0.764	FALSE
	Original design (C1)	LEDs (C3)	0.463	0.022	0.049	0.877	TRUE
	Original design (C1)	Beacon (C4)	0.404	0.065	-0.017	0.826	FALSE
	Doubling-up (C2)	LEDs (C3)	0.156	0.781	-0.277	0.589	FALSE
	Doubling-up (C2)	Beacon (C4)	0.098	0.937	-0.342	0.538	FALSE
	LEDs (C3)	Beacon (C4)	-0.058	0.980	-0.453	0.337	FALSE
Nighttime	Original design (C1)	Doubling-up (C2)	0.456	0.827	-0.940	1.852	FALSE
	Original design (C1)	LEDs (C3)	0.319	0.886	-0.832	1.471	FALSE
	Original design (C1)	Beacon (C4)	0.055	0.999	-1.152	1.263	FALSE
	Doubling-up (C2)	LEDs (C3)	-0.137	0.992	-1.417	1.144	FALSE
	Doubling-up (C2)	Beacon (C4)	-0.401	0.859	-1.732	0.930	FALSE
	LEDs (C3)	Beacon (C4)	-0.264	0.916	-1.336	0.807	FALSE

Table E.23 Paired T-test Results for Steering Variation (Lane Closure)

Countermeasures	T-Statistic	P-value
Original design (C1)	-1.979	0.059
Doubling-up (C2)	-1.036	0.314
LEDs (C3)	1.762	0.085
Beacon (C4)	-0.276	0.784

E.1.3.4 Speed variation

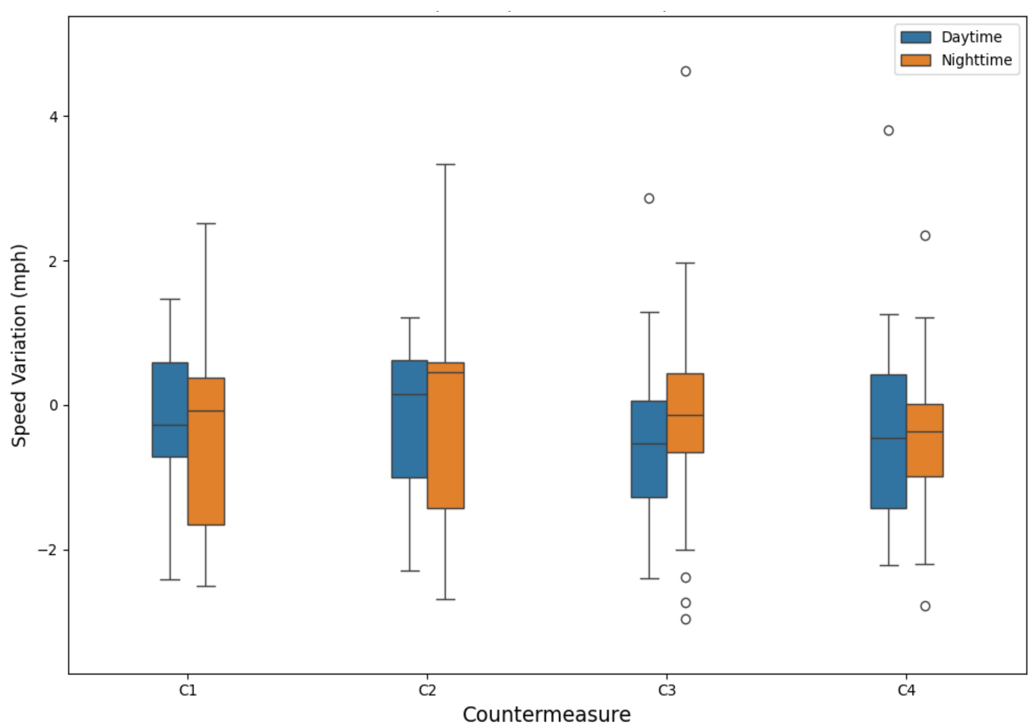


Figure E.11 Boxplot of speed variation (lane closure).

Table E.24 ANOVA Test Results for Speed Variation (Lane Closure)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	1.6	0.533	0.386	0.763
	Error	87	120.264	1.382	–	–
	Corrected Total	90	121.864	–	–	–
Nighttime	Model	3	2.468	0.823	0.385	0.764
	Error	79	168.802	2.137	–	–
	Corrected Total	82	171.27	–	–	–

Table E.25 Paired T-test Results for Speed Variation (Lane Closure)

Countermeasures	T-Statistic	P-value
Original design (C1)	0.721	0.477
Doubling-up (C2)	-0.304	0.765
LEDs (C3)	-1.003	0.320
Beacon (C4)	0.270	0.788

E.1.3.5 Lateral position variation

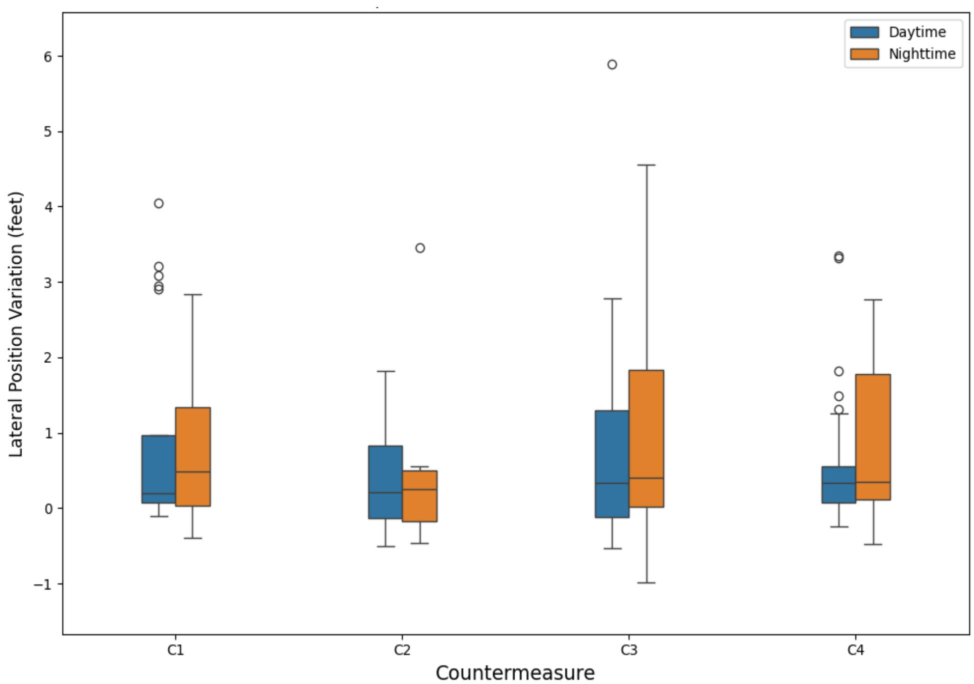


Figure E.12 Boxplot of lateral position variation (lane closure).

Table E.26 ANOVA Test Results for Lateral Position Variation (Lane Closure)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	2.747	0.916	0.679	0.567
	Error	87	117.394	1.349	–	–
	Corrected Total	90	120.141	–	–	–
Nighttime	Model	3	3.777	1.259	0.854	0.468
	Error	79	116.398	1.473	–	–
	Corrected Total	82	120.175	–	–	–

Table E.27 Paired T-test Results for Lateral Position Variation (Lane Closure)

Countermeasures	T-Statistic	P-value
Original design (C1)	0.289	0.774
Doubling-up (C2)	0.101	0.920
LEDs (C3)	0.614	0.544
Beacon (C4)	-0.876	0.386

E.1.4 Self-evaluation

Table E.28 ANOVA Test Results for Participants' Self-Evaluation (Lane Closure)

Source	DF	Sum of Squares	Mean Square	F Value	P-value
Model	2	8,301.1545	4,150.5773	50.4636	< 0.01
Error	15	1,233.7345	82.2490	–	–
Corrected Total	17	9,534.8890	–	–	–

Table E.29 Results of the Tukey's HSD Test for Participants' Self-Evaluation (Lane Closure)

Group 1	Group 2	Mean Difference	P-value	Lower	Upper	Reject
Beacon (C4)	Doubling-up (C2)	-48.9567	<0.01	-62.557	-35.356	TRUE
Beacon (C4)	LEDs (C3)	-7.8133	0.3223	-21.413	5.787	FALSE
Doubling-up (C2)	LEDs (C3)	41.1433	<0.01	27.542	54.743	TRUE

E.2 Shoulder Work Experiment

E.2.1 Eye Movement

E.2.1.1 Fixation number

Figure E.13 shows the boxplot of fixation number for C1–C4 in the shoulder work experiment. The boxplot shows that during daytime, doubling-up (C2) had a higher median and wider spread of fixation numbers compared to the other countermeasures, suggesting increased drivers' attention. In contrast, LEDs (C3) exhibited the highest variability during nighttime, with several outliers indicating a diverse response from participants. The original design (C1) and beacon (C4) had relatively low and consistent fixation numbers.

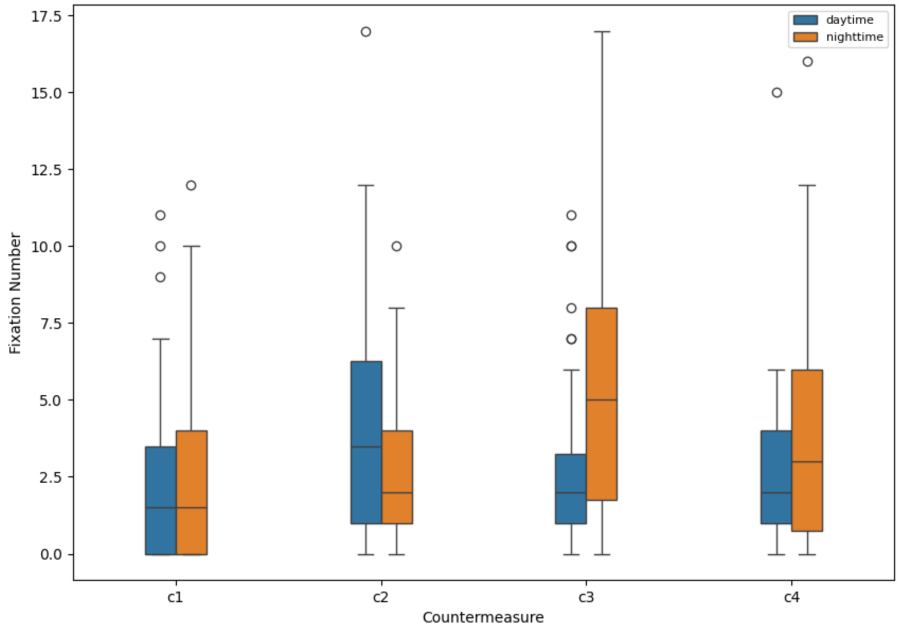


Figure E.13 Conditions boxplot of fixation number (shoulder work).

Table E.30 ANOVA Test Results for Fixation Number (Shoulder Work)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	54.3359	18.1120	1.6015	0.1925
	Error	124	1,402.4062	11.3097	–	–
	Corrected Total	127	1,456.7421	–	–	–
Nighttime	Model	3	226.9375	75.6458	5.1371	0.0022
	Error	124	1,825.9375	14.7253	–	–
	Corrected Total	127	2,052.8750	–	–	–

Table E.31 Tukey's HSD Test Results for Fixation Number (Shoulder Work)

Time Scenarios	Group 1	Group 2	Mean Difference	P-value	Lower	Upper	Reject
Daytime	Original design (C1)	Doubling-up (C2)	1.6875	0.1909	-0.5020	3.8770	FALSE
	Original design (C1)	LEDs (C3)	0.5000	0.9335	-1.6895	2.6895	FALSE
	Original design (C1)	Beacon (C4)	0.2188	0.9938	-1.9707	2.4082	FALSE
	Doubling-up (C2)	LEDs (C3)	-1.1875	0.494	-3.3770	1.0020	FALSE
	Doubling-up (C2)	Beacon (C4)	-1.4688	0.3041	-3.6582	0.7207	FALSE
	LEDs (C3)	Beacon (C4)	-0.2812	0.9870	-2.4707	1.9082	FALSE
Nighttime	Original design (C1)	Doubling-up (C2)	0.1562	0.9985	-2.3421	2.6546	FALSE
	Original design (C1)	LEDs (C3)	3.3125	0.0042	0.8142	5.8108	TRUE
	Original design (C1)	Beacon (C4)	1.5312	0.3846	-0.9671	4.0296	FALSE
	Doubling-up (C2)	LEDs (C3)	3.1562	0.0071	0.6579	5.6546	TRUE
	Doubling-up (C2)	Beacon (C4)	1.3750	0.4811	-1.1233	3.8733	FALSE
	LEDs (C3)	Beacon (C4)	-1.7812	0.2522	-4.2796	0.7171	FALSE

Table E.32 Paired T-test Results for Fixation Number (Shoulder Work)

Countermeasures	T-Statistic	P-value
Original design (C1)	0.2065	0.8378
Doubling-up (C2)	1.9841	0.0562
LEDs (C3)	-3.2926	0.0025
Beacon (C4)	-1.6451	0.1100

E.2.1.2 Fixation duration

Figure E.14 shows the boxplot of fixation durations for C1 – C4 under daytime and nighttime scenarios. The figure shows that, for all countermeasures, the median fixation duration was relatively consistent between daytime and nighttime, but variability was noticeably higher for beacon (C4) during daytime. Outliers were observed, particularly for LEDs (C3) and beacon (C4), suggesting that some participants exhibited longer fixation durations compared to others.

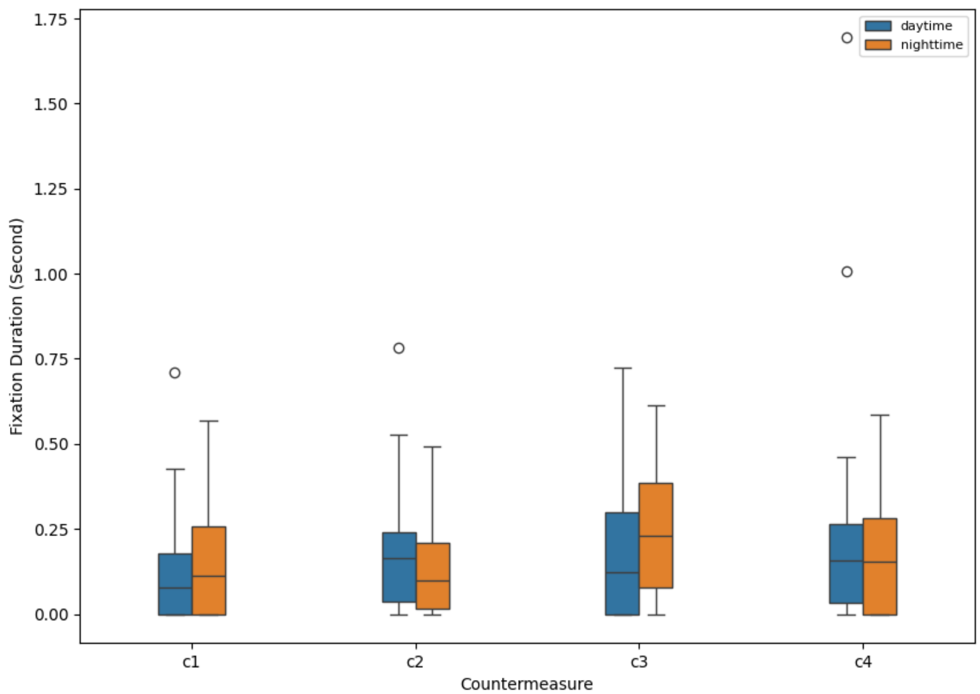


Figure E.14 Boxplot of fixation duration (shoulder work).

Table E.33 ANOVA Test Results for Fixation Duration (Shoulder Work)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	0.2283	0.0761	1.5316	0.2096
	Error	124	6.1603	0.0497	–	–
	Corrected Total	127	6.3886	–	–	–
Nighttime	Model	3	0.2124	0.0708	2.9389	0.0359
	Error	124	2.9867	0.0241	–	–
	Corrected Total	127	3.1991	–	–	–

Table E.34 Tukey's HSD Test Results for Fixation Duration (Shoulder Work)

Time Scenarios	Group 1	Group 2	Mean Difference	P-value	Lower	Upper	Reject
Daytime	Original design (C1)	Doubling-up (C2)	0.0616	0.6871	-0.0835	0.2067	FALSE
	Original design (C1)	LEDs (C3)	0.0614	0.6888	-0.0837	0.2065	FALSE
	Original design (C1)	Beacon (C4)	0.1194	0.1454	-0.0257	0.2645	FALSE
	Doubling-up (C2)	LEDs (C3)	-0.0002	1.0000	-0.1453	0.1450	FALSE
	Doubling-up (C2)	Beacon (C4)	0.0578	0.7275	-0.0873	0.2029	FALSE
	LEDs (C3)	Beacon (C4)	0.0580	0.7258	-0.0871	0.2031	FALSE
Nighttime	Original design (C1)	Doubling-up (C2)	-0.0074	0.9975	-0.1085	0.0936	FALSE
	Original design (C1)	LEDs (C3)	0.0949	0.0738	-0.0061	0.1960	FALSE
	Original design (C1)	Beacon (C4)	0.0420	0.7008	-0.0590	0.1430	FALSE
	Doubling-up (C2)	LEDs (C3)	0.1023	0.0459	0.0013	0.2034	TRUE
	Doubling-up (C2)	Beacon (C4)	0.0494	0.5814	-0.0516	0.1505	FALSE
	LEDs (C3)	Beacon (C4)	-0.0529	0.5244	-0.1540	0.0481	FALSE

Table E.35 Paired T-test Results for Fixation Duration (Shoulder Work)

Countermeasure	T-Statistic	P-value
Original design (c1)	-0.8777	0.3868
Doubling-up (c2)	1.2489	0.2211
LEDs (c3)	-1.5863	0.1228
Beacon (c4)	0.9633	0.3428

E.2.1.3 Left pupil diameter

Figure E.15 shows the boxplot of left pupil mean diameter for C1–C4 under daytime and nighttime. It indicates that across all conditions, nighttime pupil diameters were consistently higher than daytime, indicating increased pupil dilation under low-lighting conditions. Also, the variability was greater at nighttime, as shown by wider interquartile ranges and more outliers. Among all countermeasures, the nighttime condition for the original design (C1) exhibited the largest range, suggesting diverse pupil dilation responses.

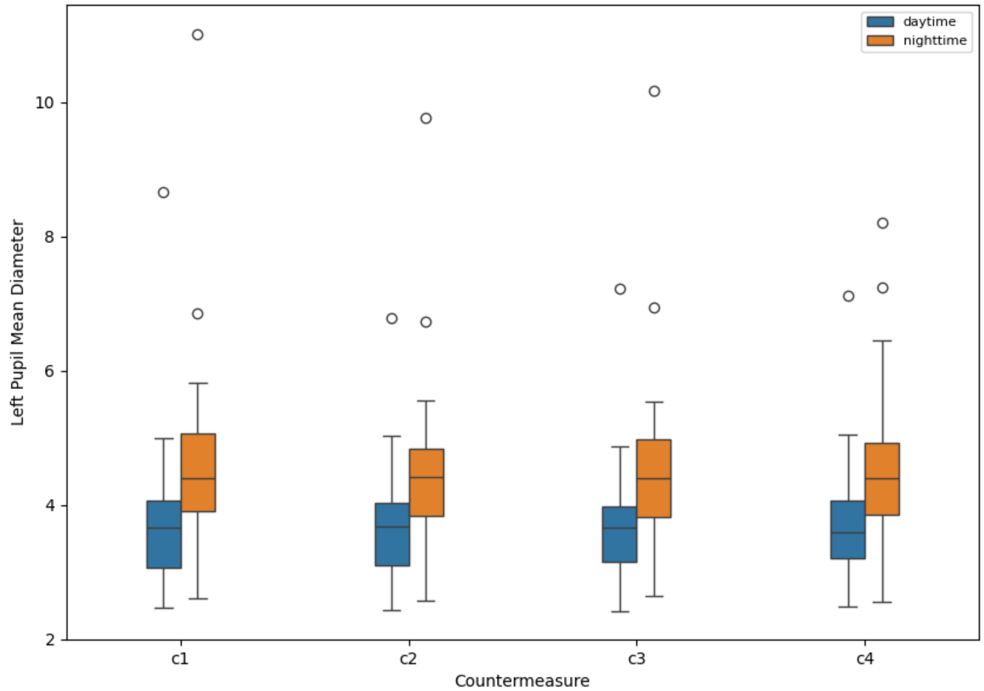


Figure E.15 Boxplot of left pupil mean diameter (shoulder work).

Table E.36 ANOVA Test Results for Left Pupil Mean Diameter (Shoulder Work)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	0.1559	0.0520	0.0570	0.9820
	Error	124	113.0602	0.9118	–	–
	Corrected Total	127	113.2161	–	–	–
Nighttime	Model	3	0.2375	0.0792	0.0446	0.9874
	Error	124	220.0631	1.7747	–	–
	Corrected Total	127	220.3006	–	–	–

Table E.37 Paired T-test Results for Left Pupil Mean Diameter (Shoulder Work)

Countermeasures	T-Statistic	P-value
Original design (C1)	-8.6476	<0.01
Doubling-up (C2)	-8.0761	<0.01
LEDs (C3)	-7.2776	<0.01
Beacon (C4)	-8.3693	<0.01

E.2.1.4 Right pupil diameter

Figure E.16 shows the boxplot of right pupil mean diameter for C1–C4. The boxplot shows a consistent trend of larger pupil diameters during nighttime compared to daytime across all countermeasures, suggesting a higher level of attention or cognitive load at night.

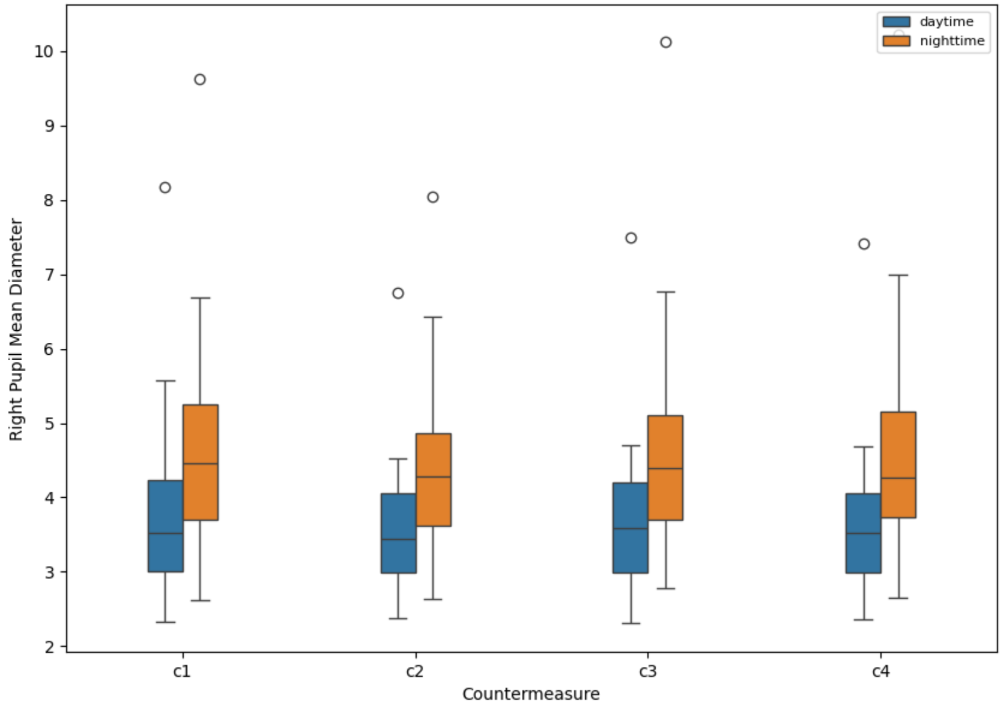


Figure E.16 Boxplot of right pupil mean diameter (shoulder work).

Table E.38 ANOVA Test Results for Right Pupil Mean Diameter (Shoulder Work)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	0.3036	0.1012	0.1046	0.9572
	Error	124	119.9442	0.9673	–	–
	Corrected Total	127	120.2478	–	–	–
Nighttime	Model	3	0.7375	0.2458	0.1400	0.9359
	Error	124	217.7442	1.7560	–	–
	Corrected Total	127	218.4817	–	–	–

Table E.39 Paired T-test Results for Right Pupil Mean Diameter (Shoulder Work)

Countermeasures	T-Statistic	P-value
Original design (C1)	-8.1646	<0.01
Doubling-up (C2)	-9.3333	<0.01
LEDs (C3)	-7.7875	<0.01
Beacon (C4)	-8.3617	<0.01

E.2.2 Driving Performance

E.2.2.1 Mean speed

Figure E.17 shows a boxplot of mean speed. Among all countermeasures, vehicle speed was generally consistent between daytime and nighttime, with similar medians and interquartile ranges. Nighttime conditions exhibited slightly wider variability in some countermeasures, particularly LEDs (C3) and beacon (C4), as indicated by a larger spread and the presence of more outliers.

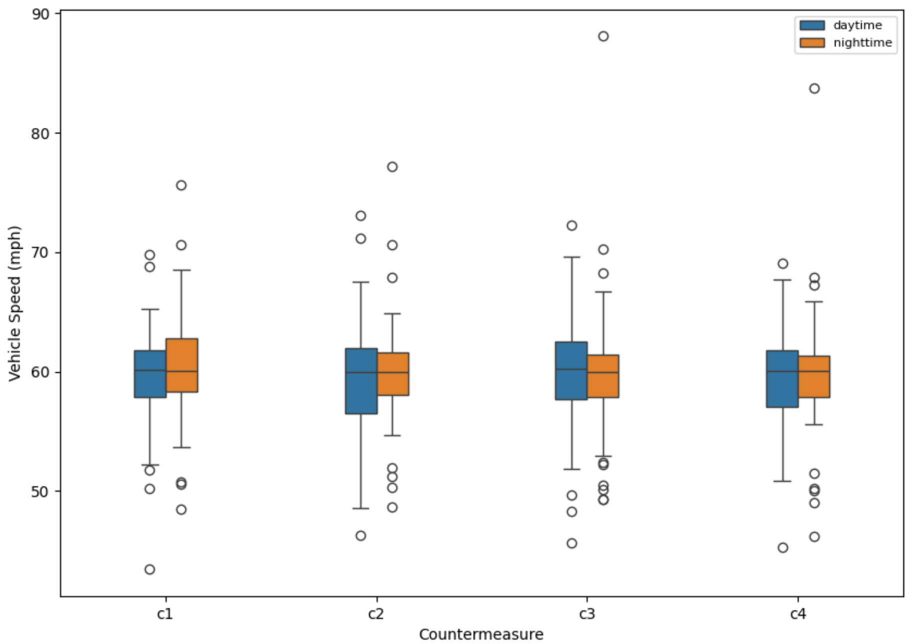


Figure E.17 Boxplot of vehicle speed (shoulder work).

Table E.40 ANOVA Test Results for Mean Speed (Shoulder Work)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	9.0439	3.0146	0.0991	0.9604
	Error	124	3,773.2906	30.4298	–	–
	Corrected Total	127	3,782.3345	–	–	–
Nighttime	Model	3	3.5214	1.1738	0.0292	0.9933
	Error	124	4,987.5904	40.2225	–	–
	Corrected Total	127	4,991.1118	–	–	–

Table E.41 Paired T-test Results for Mean Speed (Shoulder Work)

Countermeasures	T-Statistic	P-value
Original design (C1)	-1.2226	0.2307
Doubling-up (C2)	-1.1814	0.2464
LEDs (C3)	0.0146	0.9884
Beacon (C4)	-0.5981	0.5541

E.2.2.2 Speed reduction

Figure E.18 presents a boxplot for vehicle speed reduction. The speed reduction was small for all countermeasures and considering both daytime and nighttime, with most values centered around zero. However, greater variability was observed for doubling-up (C2) and beacon (C4), with wider interquartile ranges and several outliers, particularly during daytime. For most countermeasures, speed reductions were slightly larger during daytime compared to nighttime, except for doubling-up (C2), where speed increased a little bit during nighttime.

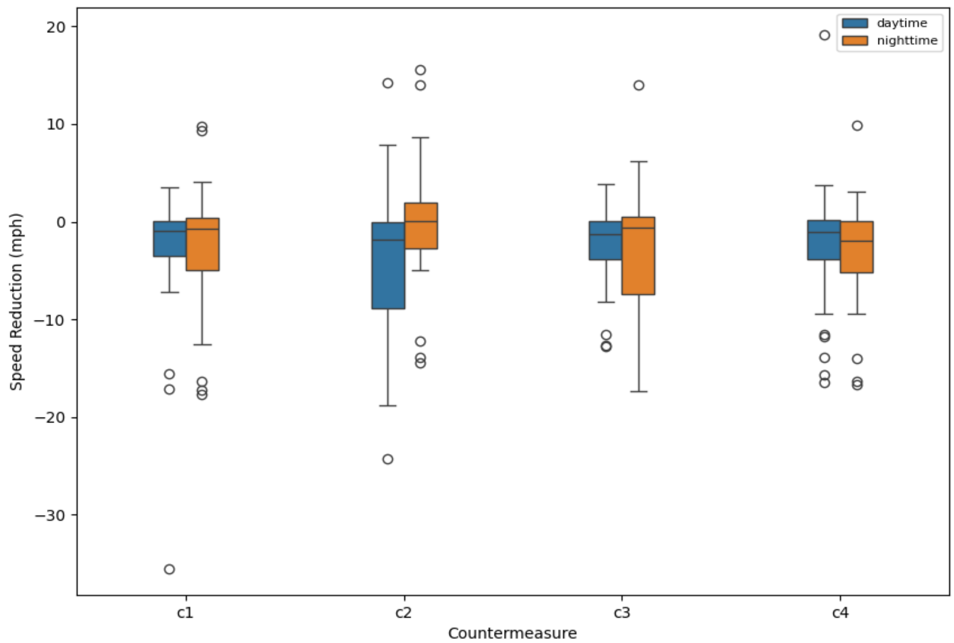


Figure E.18 Boxplot of speed reduction (shoulder work).

Table E.42 ANOVA Test Results for Speed Reduction (Shoulder Work)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	70.2438	23.4146	0.5177	0.6709
	Error	124	5,608.4019	45.2290	–	–
	Corrected Total	127	5,678.6457	–	–	–
Nighttime	Model	3	239.5678	79.8559	1.8666	0.1387
	Error	124	5,304.7787	42.7805	–	–
	Corrected Total	127	5,544.3465	–	–	–

Table E.43 Paired T-test Results for Speed Reduction (Shoulder Work)

Countermeasures	T-Statistic	P-value
Original design (C1)	-0.2226	0.8253
Doubling-up (C2)	-2.6599	0.0123
LEDs (C3)	1.8480	0.0377
Beacon (C4)	0.6126	0.5446

E.2.2.3 Mean acceleration

Figure E.19 shows boxplots of vehicle acceleration. It shows that acceleration values were generally small and stable across all countermeasures, with medians close to 0. Outliers were observed for all countermeasures, indicating occasional instances of higher or lower acceleration, particularly for nighttime conditions. Among countermeasures, doubling-up (C2) showed a wider interquartile range, suggesting slightly higher variability in acceleration. In contrast, the original design (C1) and beacon (C4) exhibited more compacted distributions, implying greater stability.

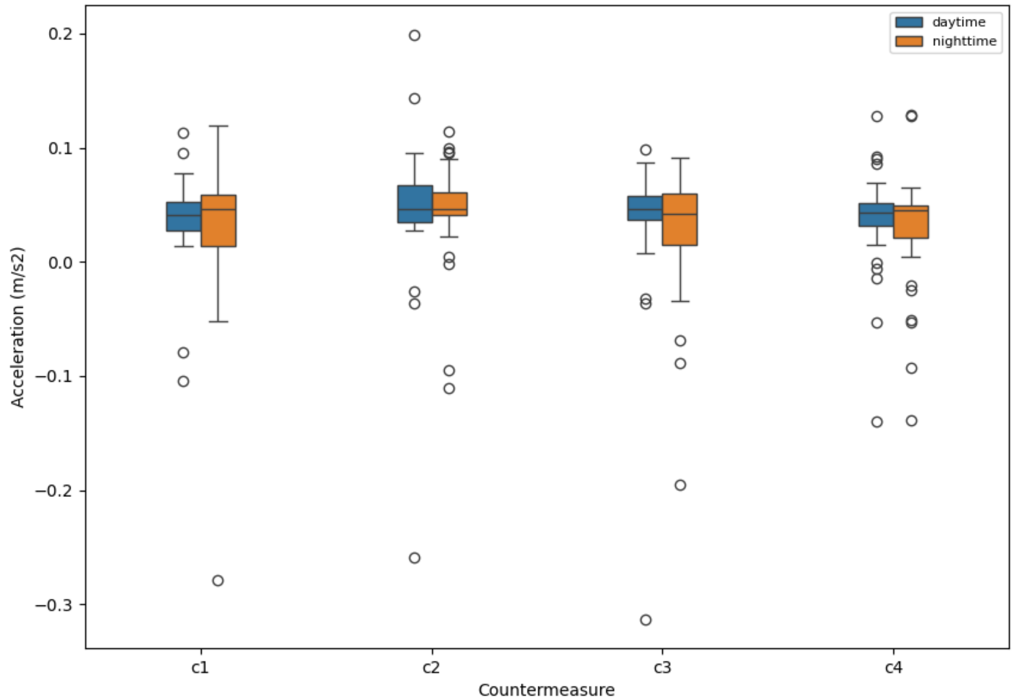


Figure E.19 Boxplot of vehicle acceleration (shoulder work).

Table E.44 ANOVA Test Results for Mean Acceleration (Shoulder Work)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	0.0022	0.0007	0.2190	0.8831
	Error	124	0.4098	0.0033	–	–
	Corrected Total	127	0.4120	–	–	–
Nighttime	Model	3	0.0077	0.0026	0.8069	0.4923
	Error	124	0.3956	0.0032	–	–
	Corrected Total	127	0.4033	–	–	–

Table E.45 Paired T-test Results for Mean Acceleration (Shoulder Work)

Countermeasures	T-Statistic	P-value
Original design (C1)	0.5837	0.5638
Doubling-up (C2)	0.1202	0.9052
LEDs (C3)	0.6949	0.4925
Beacon (C4)	0.6032	0.5509

E.2.2.4 Lateral position

Figure E.20 shows a boxplot of the vehicle's lateral position. It reveals similar distributions in lateral position across all countermeasures, with minor variations between daytime and nighttime. The original design (C1) and beacon (C4) showed a larger scale of distribution during both daytime and nighttime.

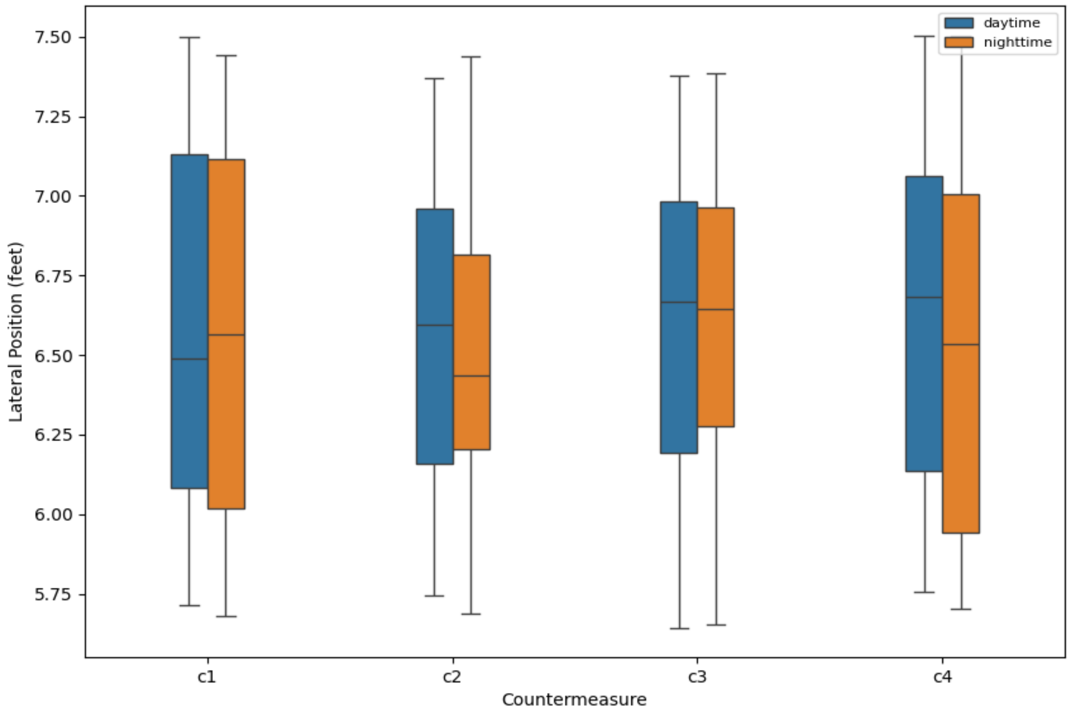


Figure E.20 Boxplot of lateral position (shoulder work).

Table E.46 ANOVA Test Results for Lateral Position (Shoulder Work)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	0.1113	0.0371	0.1273	0.9438
	Error	124	36.1396	0.2914	–	–
	Corrected Total	127	36.2509	–	–	–
Nighttime	Model	3	0.0774	0.0258	0.0870	0.9671
	Error	124	36.7977	0.2968	–	–
	Corrected Total	127	36.8751	–	–	–

Table E.47 Paired T-test Results for Lateral Position (Shoulder Work)

Countermeasures	T-Statistic	P-value
Original design (C1)	0.5588	0.5803
Doubling-up (C2)	0.3563	0.7240
LEDs (C3)	0.0121	0.9904
Beacon (C4)	0.5447	0.5898

E.2.3 Synchronized Data

E.2.3.1 First-fixation distance to countermeasure

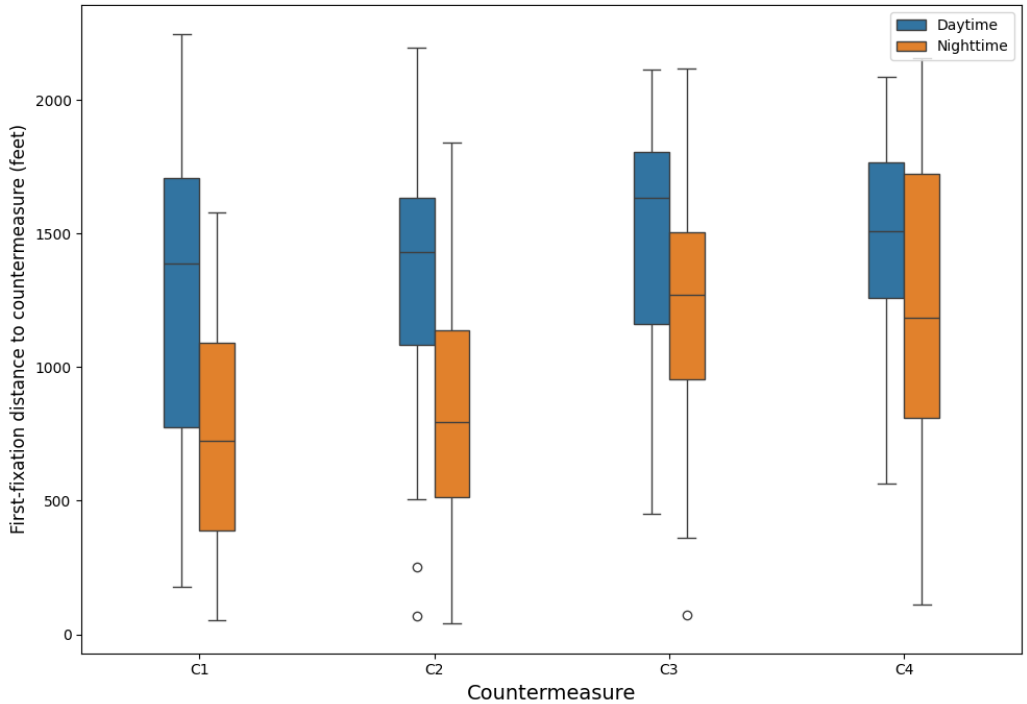


Figure E.21 Boxplot of first-fixation distance to countermeasure (shoulder work).

Table E.48 ANOVA Test Results for First-fixation Distance to Countermeasure (Shoulder Work)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	964146.549	321382.183	1.264	0.291
	Error	93	23640949.89	254203.762	–	–
	Corrected Total	96	24605096.44	–	–	–
Nighttime	Model	3	4314811.871	1438270.624	5.373	0.002
	Error	91	24359630.14	267688.243	–	–
	Corrected Total	94	28674442.01	–	–	–

Table E.49 Tukey's HSD Test Results for First-fixation Distance to Countermeasure (Shoulder Work)

Time Scenarios	Group 1	Group 2	Mean Difference	P-value	Lower	Upper	Reject
Daytime	Original design (C1)	Doubling-up (C2)	28.619	0.998	-372.825	430.062	FALSE
	Original design (C1)	LEDs (C3)	215.215	0.494	-182.881	613.310	FALSE
	Original design (C1)	Beacon (C4)	215.969	0.484	-179.002	610.939	FALSE
	Doubling-up (C2)	LEDs (C3)	186.596	0.552	-182.869	556.061	FALSE
	Doubling-up (C2)	Beacon (C4)	187.350	0.541	-178.746	553.445	FALSE
	LEDs (C3)	Beacon (C4)	0.754	1.000	-361.668	363.175	FALSE
Nighttime	Original design (C1)	Doubling-up (C2)	101.718	0.911	-301.018	504.453	FALSE
	Original design (C1)	LEDs (C3)	514.617	0.007	108.395	920.839	TRUE
	Original design (C1)	Beacon (C4)	431.382	0.035	21.416	841.348	TRUE
	Doubling-up (C2)	LEDs (C3)	412.900	0.027	33.610	792.189	TRUE
	Doubling-up (C2)	Beacon (C4)	329.664	0.118	-53.633	712.961	FALSE
	LEDs (C3)	Beacon (C4)	-83.235	0.943	-470.194	303.724	FALSE

Table E.50 Paired T-test Results for First-fixation Distance to Countermeasure (Shoulder Work)

Countermeasures	T-Statistic	P-value
Original design (C1)	2.871	0.007
Doubling-up (C2)	3.041	0.004
LEDs (C3)	1.588	0.119
Beacon (C4)	2.112	0.042

E.2.3.2 Gas pedal variation

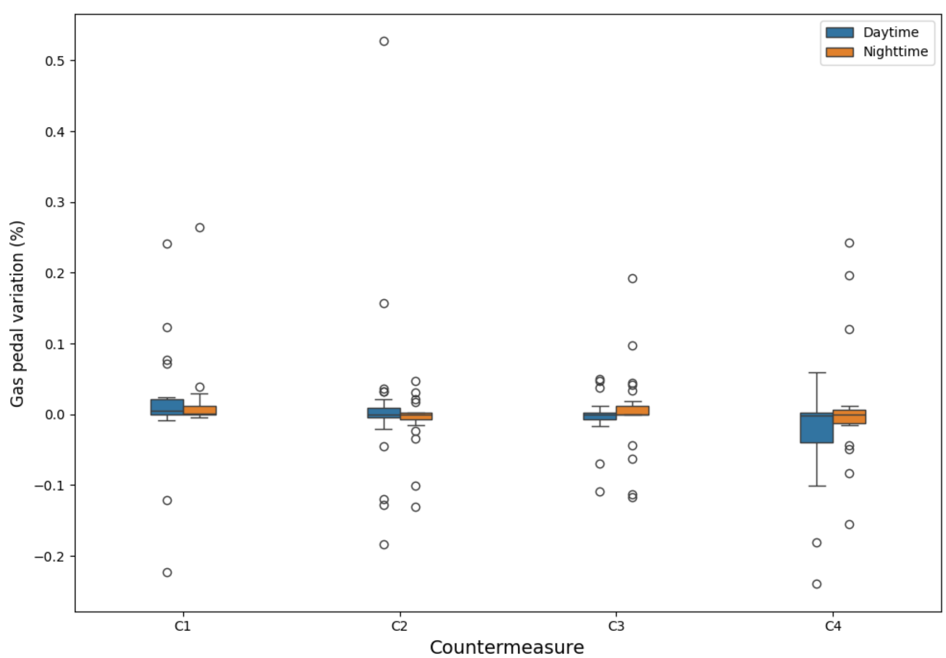


Figure E.22 Boxplot of gas pedal variation (shoulder work).

Table E.51 ANOVA Test Results for Gas Pedal Variation (Shoulder Work)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	0.022	0.007	1.071	0.365
	Error	93	0.651	0.007	–	–
	Corrected Total	96	0.673	–	–	–
Nighttime	Model	3	0.009	0.003	0.821	0.485
	Error	91	0.328	0.004	–	–
	Corrected Total	94	0.337	–	–	–

Table E.52 Paired T-test Results for Gas Pedal Variation (Shoulder Work)

Countermeasures	T-Statistic	P-value
Original design (C1)	-0.261	0.796
Doubling-up (C2)	0.791	0.435
LEDs (C3)	-0.635	0.529
Beacon (C4)	-1.606	0.115

E.2.3.3 Steering variation

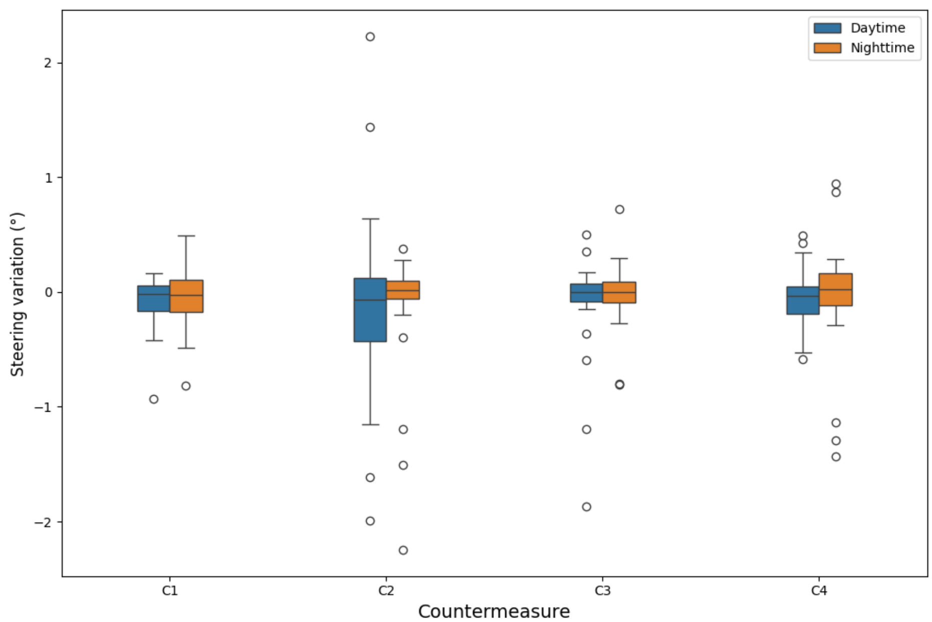


Figure E.23 Boxplot of steering variation (shoulder work).

Table E.53 ANOVA Test Results for Steering Variation (Shoulder Work)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	0.057	0.019	0.071	0.976
	Error	93	25.056	0.269	–	–
	Corrected Total	96	25.113	–	–	–
Nighttime	Model	3	0.232	0.077	0.362	0.781
	Error	91	19.434	0.214	–	–
	Corrected Total	94	19.666	–	–	–

Table E.54 Paired T-test Results for Steering Variation (Shoulder Work)

Countermeasures	T-Statistic	P-value
Original design (C1)	-0.233	0.817
Doubling-up (C2)	0.239	0.812
LEDs (C3)	-0.753	0.456
Beacon (C4)	0.080	0.937

E.2.3.4 Speed variation

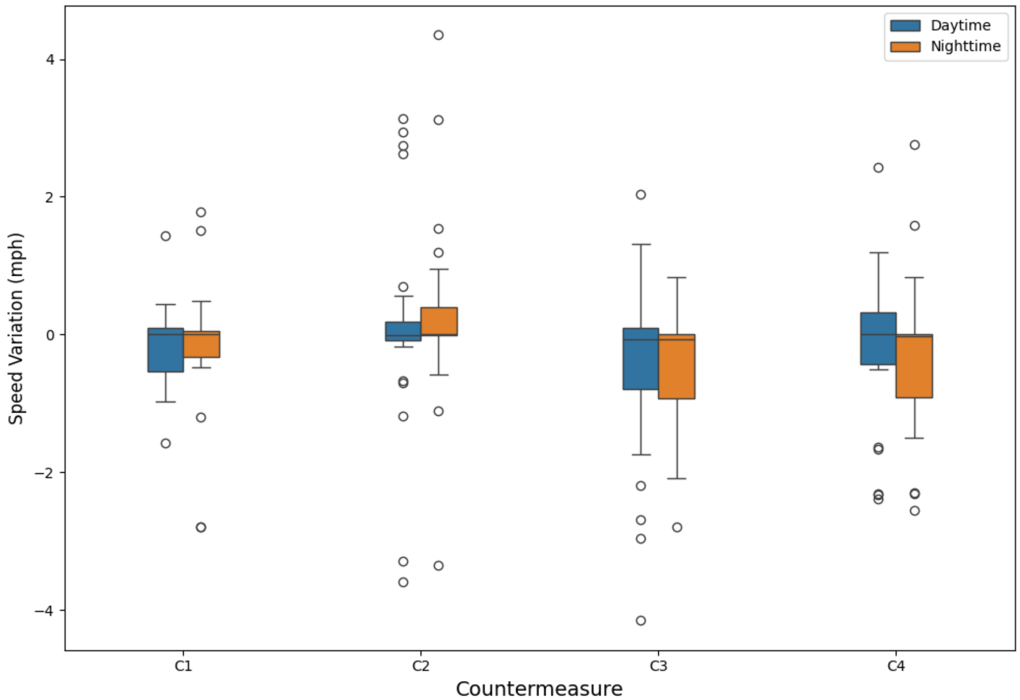


Figure E.24 Boxplot of speed variation (shoulder work).

Table E.55 ANOVA Test Results for Speed Variation (Shoulder Work)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	5.599	1.866	1.214	0.309
	Error	93	142.991	1.538	–	–
	Corrected Total	96	148.59	–	–	–
Nighttime	Model	3	8.066	2.689	2.034	0.115
	Error	91	120.298	1.322	–	–
	Corrected Total	94	128.364	–	–	–

Table E.56 Paired T-test Results for Speed Variation (Shoulder Work)

Countermeasures	T-Statistic	P-value
Original design (C1)	0.159	0.874
Doubling-up (C2)	-0.357	0.723
LEDs (C3)	-0.184	0.855
Beacon (C4)	0.495	0.623

E.2.3.5 Lateral position variation

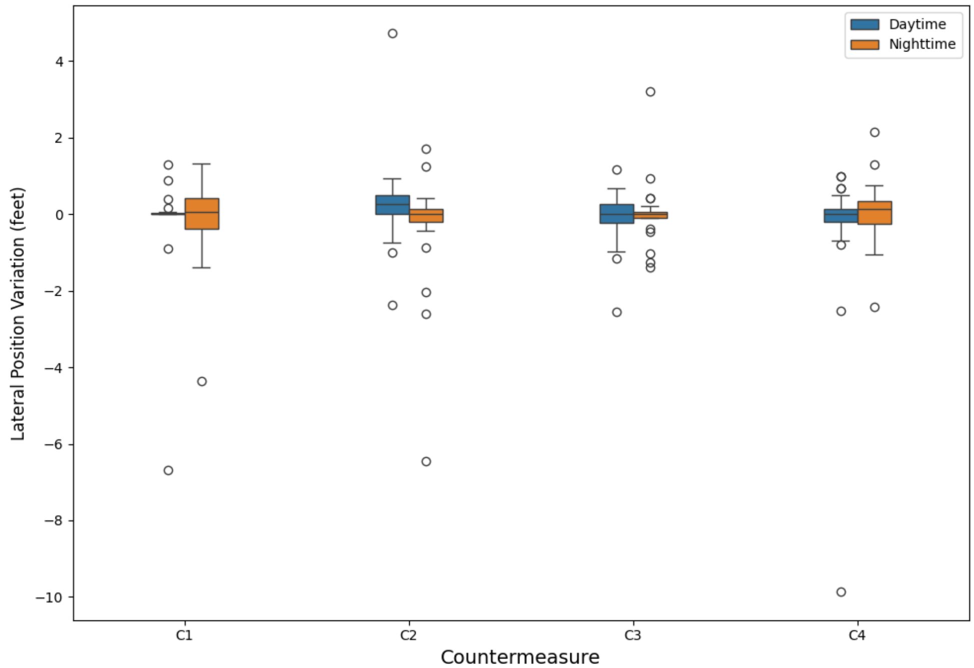


Figure E.25 Boxplot of lateral position variation (shoulder work).

Table E.57 ANOVA Test Results for Lateral Position Variation (Shoulder Work)

Time Scenarios	Source	DF	Sum of Squares	Mean Square	F Value	P-value
Daytime	Model	3	6.711	2.237	1.067	0.367
	Error	93	195.045	2.097	–	–
	Corrected Total	96	201.756	–	–	–
Nighttime	Model	3	2.484	0.828	0.647	0.587
	Error	91	116.359	1.279	–	–
	Corrected Total	94	118.843	–	–	–

Table E.58 Paired T-test Results for Lateral Position Variation (Shoulder Work)

Countermeasures	T-Statistic	P-value
Original design (C1)	-0.118	0.907
Doubling-up (C2)	1.668	0.102
LEDs (C3)	-0.453	0.652
Beacon (C4)	-1.074	0.290

E.2.4 Self-Evaluation

Table E.59 ANOVA Test Results for Participants' Self-Evaluation (Shoulder Work)

Source	DF	Sum of Squares	Mean Square	F Value	P-value
Model	2	4,792.9774	2,396.4887	19.7587	< 0.01
Error	15	1,819.3178	121.2879	–	–
Corrected Total	17	6,612.2952	–	–	–

Table E.60 Tukey's HSD Test Results for Participants' Self-Evaluation (Shoulder Work)

Group 1	**Group 2**	**Mean Difference**	**P-value**	**Lower**	**Upper**	**Reject**
Beacon (C4)	Doubling-up (C2)	-8.3333	0.4111	-24.849	8.1824	FALSE
Beacon (C4)	LEDs (C3)	29.6883	0.0008	13.172	46.204	TRUE
Doubling-up (C2)	LEDs (C3)	38.0217	0.0001	21.505	54.537	TRUE

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at https://docs.lib.purdue.edu/jtrp/.

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