MDOT State Study 324:

Assessing the Effectiveness of Blue Lights on Work Zone Safety

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16. Abstract

This project investigated the effectiveness of blue lights in work zones following the enactment of Mississippi's "Blue Light Law". The methodology combined a systematic literature review, a nationwide survey, and field data analysis. The literature review indicated a lack of standardized guidance. The survey findings showed that practitioners perceived blue lights as effective in improving alertness. The field data analysis suggested that blue lights were associated with changes in driver behavior, including shifts away from the lane closest to the construction and more consistent nighttime speed reductions. Overall, blue lights may function as a visual signal that supports safer driving behavior, especially at night. This highlighted the need for further evaluation and development of standardized deployment strategies in work zones.

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The contents, conclusions, and opinions expressed in this report are solely those of the authors and do not necessarily reflect the views of MDOT, the individuals, or organizations acknowledged above.

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List of Abbreviations

AASHTO RAC- the American Association of State Highway and Transportation Officials Research Advisory Committee

ART ANOVA- Aligned Rank Test ANOVA

DOT- Department of Transportation

FHWA - Federal Highway Administration

IQR - Interquartile Range

L1_WB_1stH - Lane 1 With Blue Light First Half

L1_WB_2ndH- Lane 1 With Blue Light Second Half

L1_WB_Beg - Lane 1 With Blue Lights Beginning

L1_WOB_1stH - Lane 1 Without Blue Light First Half

L1_WOB_2ndH - Lane 1 Without Blue Light Second Half

L1_WOB_Beg - Lane 1 Without Blue Lights Beginning

L2_WB_1stH - Lane 2 With Blue Light First Half

L2_WB_2ndH - Lane 2 With Blue Light Second Half

L2_WB_Beg - Lane 2 With Blue Lights Beginning

L2_WOB_1stH - Lane 2 With Blue Light First Half

L2_WOB_2ndH - Lane 2 Without Blue Light Second Half

L2_WOB_Beg - Lane 2 With Blue Lights Beginning

MDOT - Mississippi Department of Transportation

MnDOT- Minnesota Department of Transportation

NAATSHO - North American Association of Transportation Safety & Health Officials

NZWS - National Work Zone Safety

PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses

WB_1stH - With Blue Light First Half

WB_2ndH - With Blue Light Second Half

WB_Beg - With Blue Light Beginning

WOB_1stH - Without Blue Light First Half

WOB_2ndH - Without Blue Light Second Half

WOB_Beg - Without Blue Light Beginning

Executive Summary

Crashes, injuries, and fatalities in work zones remain a persistent safety concern despite the wide use of warning devices. In 2019, Mississippi's "Blue Light Law" was enacted, which allowed law enforcement vehicles to use flashing blue lights in work zones, aiming to enhance work zone safety. In response to the "Blue Light Law", this project examined the current implementation practices of blue lights and their effectiveness on work zone safety.

This project employed a three-part methodology consisting of a systematic literature review, a nationwide survey of transportation professionals, and field data collection at an active Mississippi work zone. The literature review synthesized prior research and agency reports to identify existing applications, effectiveness, and gaps related to blue light deployment as a warning sign in work zones. Building on these findings, a nationwide survey was designed that compiled the implementation practices, perceptions of effectiveness, and operational challenges of using blue light for work zone safety. Afterward, field data, including traffic volume and average vehicle speed under construction conditions with blue lights as well as without blue lights, were collected from a work zone using radars and statistically analyzed. This helped gather on-site data, allowing for an empirical evaluation of driver behavior in real work zone environments with and without using blue lights.

The combined findings suggested that blue lights may serve as an effective visual tool for enhancing work zone safety, particularly by influencing lane choice and reducing vehicle speeds under certain conditions. The literature review and survey results highlighted strong associations between blue lights and perceived law enforcement presence. Also, the collected field data indicated that the presence of blue light in the work zone had a significant effect on the driving behavior. The drivers tended to drive in the lane that was farthest from the work zone and also reduced speed when there was the presence of blue lights. This pattern was more consistent during nighttime when construction was ongoing in the work zone. Overall, the results highlighted the importance of standardized deployment practices, strategic placement, and coordination with law enforcement to maximize the effectiveness of blue light implementation. Based on the findings, this project recommended that MDOT consider developing deployment guidance, supporting expanded pilot testing, and strengthening inter-agency coordination for blue light use in work zones.

Chapter 1. Introduction

1.1 Background

Ensuring work zone safety has always been vital to construction, transportation, and the public. In 2020, among the work zone fatalities, about 37% were caused by speeding motorists, 27% were caused by commercial motor vehicles, and 20% were due to rear-end collisions between vehicles (FHWA, 2022). In 2021, about 60% of the total work zone contractors reported having work zone crashes on their sites (WZB, 2022). There were 106,000 crashes, 42,000 injuries, and 956 fatalities in the U.S. work zones in 2021 (NWZS, 2022). Errant vehicles entering work zones, primarily due to the inattentiveness of drivers and overspeeding, are a significant reason leading to the high number of injuries in these areas (Paaswell and Baker, 2006). Therefore, effective implementation of innovative methods is needed to minimize work zone injuries and fatalities.

Warning lights, such as those on stationary police vehicles or temporary work zone lights, have been explored as a way to enhance work zone safety. Existing studies indicate that portable solutions such as rumble strips reduce average vehicle speeds by 6-14 mph, while warning and work zone lights improve object detection distances and encourage earlier speed reduction (Bhagavathula and Gibbons, 2017; Finley et al., 2014). Among the warning lights used in work zones, amber, yellow, and red lights are prominent. However, the use of allowable colors for warning lights in the U.S. work zones differs according to the legislation of state Department of Transportation (DOTs). In terms of the Mississippi DOT (MDOT), the "Blue Light Law" was officially signed in 2019 (MDOT, 2019). This law allows road users and construction contractors to look to state and local police departments for a presence with blue lights in work zones. Such implementation of blue lights in Mississippi work zones is intended to help ensure the safety of workers and road users.

As transportation agencies explore innovative safety solutions, blue lights have increasingly drawn attention due to their potential to influence driver behavior and enhance visibility in high-risk environments (Gan et al., 2018). Their presence, particularly when used in combination with law enforcement, has been associated with reductions in vehicle speed and increased driver awareness (Gambatese et al., 2019). However, the effectiveness of blue lights for work zone safety remains unclear and may vary depending on factors such as placement, operational context, and color configuration (MnDOT, 2013; Ahmed et al., 2021; Ullman, 2000). Moreover, there is no unified standard guiding their deployment across states in the U.S., and little is known about how transportation agencies implement these systems in practice. These uncertainties have led to growing interest in investigating how blue lights are currently being used and what strategies agencies are adopting or can adopt to implement them effectively. Moreover, field data collected from active work zones is essential for understanding the true impact of blue lights on driver behavior. Unlike surveys or reported experiences, field observations provide direct evidence of how motorists respond under real traffic and environmental conditions. By analyzing factors including vehicle speed, traffic volume, and lane distribution, these data offer critical insights into

the effectiveness of blue lights as a safety measure. The empirical evidence is expected to help validate agency perspectives, address uncertainties in existing studies, and guide transportation agencies in developing more effective work zone safety strategies.

1.2 Project Needs

The enactment of Mississippi's "Blue Light Law" created new opportunities for enhancing work zone safety through the use of law enforcement vehicles equipped with blue lights. However, limited guidance was available regarding how blue lights should be implemented, where they should be deployed, and under what conditions they would be most effective. Although other state DOTs have explored blue light applications, implementation practices remain inconsistent and not well-documented.

For MDOT, this created a practical need to better understand how blue lights are currently being used, what implementation challenges exist, and whether their deployment meaningfully influences driver behavior in work zones. The absence of standardized deployment strategies, limited policy frameworks, and insufficient field-based evidence on effectiveness highlighted a gap between theoretical knowledge and practical implementation.

Thus, this project sought to contribute to this body of knowledge by evaluating current implementation practices and assessing the effectiveness of blue light deployment in work zones to support informed decision-making and future policy development.

1.3 Project Objectives

To address the above-mentioned problem and following the enactment of the "Blue Light Law" in Mississippi, this project was undertaken to examine implementation practices and initiatives for blue lights in work zones. The project is focused on generating practical insights on blue light implementation in Mississippi work zones. The key objectives are:

1) Conduct a systematic review to identify warning and blue light implementation practices and initiatives documented in the literature.
2) Conduct a nationwide survey to collect and investigate blue light implementation practices and initiatives across U.S. transportation agencies.
3) Collect and analyze traffic volume and speed data from Mississippi work zone in the presence of blue lights to evaluate their effectiveness in influencing driver behavior and safety.

1.4 Organization of the Report

The following chapters of this report are organized based on the above-discussed objectives. Chapter 2 discusses the literature review conducted for this project; Chapter 3 outlines the methodology; Chapter 4 discusses the systematic literature review on warning lights and blue light implementation practices with their results; Chapter 5 includes the survey that was designed based on the results of the systematic literature review, along with the results of the survey analysis;

Chapter 6 discusses the field data collection and analysis part, which includes the details of the work zone used for this project, the setup of the instrument to collect the data, the details of the collected data, and the analysis results; Chapter 7 includes a comprehensive discussion section, which discusses the findings of this project; Chapter 8 includes the conclusions, followed by limitations and future implementation recommendations for MDOT.

Chapter 2. Literature Review

2.1 Applications of Blue Light by State DOTs

The use of blue lights in work zones in the United States has been gaining attention in recent years. The Minnesota DOT evaluated several lighting configurations by conducting field experiments using the Comprehensive Intersection Collision Avoidance System to track vehicle speed and lane choice in real time. The evaluation measured changes in average speed and the proportion of vehicles that shifted to the left lane when approaching a patrol vehicle. The results showed that configurations combining amber and blue lights were most effective, producing average speed reductions of nearly six miles per hour and shifting almost all vehicles into the left lane compared to a much smaller percentage in the control condition (MnDOT, 2013). The Oregon DOT sponsored three case studies in which flashing blue lights were tested at work zones. Vehicle speeds were measured in the field both before and after the deployment of the lights. In all three cases, reductions in average vehicle speed were observed, confirming the ability of blue lights to influence driver behavior (Gambatese et al., 2019). A study funded by the Florida DOT used a controlled before, during, and after field evaluation at two freeway work zones. Speed and lane use data were collected with radar-based monitoring equipment and pneumatic road tubes for six weeks, covering baseline, deployment, and post-deployment periods. The evaluation measured changes in average speed, the percentage of vehicles exceeding the work zone speed limit, and lane use distribution. The results indicated that stationary police vehicles with flashing blue lights reduced average speeds by about three to four miles per hour and decreased the proportion of speeding vehicles by up to twenty percent (Gan et al., 2018). The Texas DOT permitted certain vehicles to use combined yellow and blue lights in hazardous areas of work zones. Evaluations relied on field observations of traffic flow and speed patterns near these vehicles. The findings suggested that the combined color configuration improved visibility and encouraged safer driver behavior (Ullman and Lewis, 1998). Overall, these studies showed that blue lights can reduce speeds and influence lane choice, but most emphasized outcomes such as speed reduction rather than documenting the details of how the lights were implemented. As a result, effective practices and initiatives for deploying blue lights in work zones remain unclear.

2.2 Research on Work Zone Safety

Apart from warning lights, including blue lights, many state DOTs and transportation research centers in the United States worked on developing and testing innovative tools that could be integrated into work zones to mitigate safety risks. The Virginia DOT implemented temporary rumble strips on one-lane and two-lane roads and evaluated their impact on reducing cross-over the centerline crashes. The analysis relied on statewide crash data from 2001 through 2003 and focused on crash frequency, density, and rates on rural highways. The results demonstrated that centerline rumble strips were effective in lowering head-on and sideswipe opposite direction crashes and that the benefit-to-cost ratio of these installations was favorable (Chen and Cottrell, 2005). The Missouri DOT investigated several countermeasures. Rumble strips were used for merging lanes, shifting lanes, and promoting speed reduction zones, and their effectiveness was

measured through observed changes in merge distance, driver reaction points, and vehicle speeds at conflict areas. In another initiative, LiDAR sensors were installed in work zones to detect vehicle passing distances and update safety databases in real time. These sensors provided continuous measures of vehicle trajectories and proximity, which allowed the identification of high-risk behaviors and potential conflicts (Brown et al., 2018). The California DOT tested portable rumble strips during flagging operations. The evaluation included integration with signage, flagger positioning, and channelizing devices. The study measured worker response times to alarms, sound levels of the systems, and driver reactions. The findings indicated that portable rumble strips, when combined with proper signage and channelization, enhanced driver awareness and improved worker safety (Sanni, 2019). The Oregon DOT deployed NC 350 portable traffic sensors in work zones at regular intervals of approximately a quarter mile. These sensors captured detailed traffic data, including speed, vehicle length, headway, and following distance. The data were validated using controlled vehicle runs to ensure accuracy. The results demonstrated that the sensors could reliably record real-time traffic behavior and provide valuable input for assessing the effectiveness of safety interventions in work zones (Ahmed et al., 2021). The Indiana DOT studied the role of traffic cameras and police patrols in improving safety in active work zones. Data were collected at three locations representing the beginning, middle, and end of work zones. The cameras provided continuous records of vehicle speed, density, and lane use, while field experiments involving police patrols measured driver compliance and speed reduction. Statistical models were used to estimate the effects of enforcement strategies, which were later converted into crash modification factors. These findings supported the development of an optimization tool for programming police enforcement in work zones (Chen and Tarko, 2012). The University of Vermont Transportation Research Center tested two off road sensor systems to support work zone safety analysis. The first system, iCones, recorded vehicle speeds at multiple placements within work zones and allowed the researchers to evaluate speed changes before, during, and after interventions. The second system, the Comprehensive Intersection Collision Avoidance system, used sensor networks and intersection representations to track vehicle position, speed, and lane of travel. Both systems were applied in field studies where data collection extended for several weeks, enabling statistical comparisons of mean speeds and the percentage of vehicles exceeding the speed limit (Lee et al., 2014). A summary table of the studies conducted by DOTs and the transportation research center on work zone safety is provided in

Table 1.

Table 1. Summary of solutions for enhancing work zone safety from transportation agencies

Organizations	Solutions	Examples	Literature Sources
Mississippi DOT	"Blue Light Law" was signed in Mississippi in 2019, which allows the presence of blue lights in work zones to ensure work zone safety. The effectiveness of blue light on safety was proposed to be evaluated in a project supported by MDOT (the first portion of this project is the work presented in this paper).		MDOT (2019)
Oregon DOT	Used three case studies for implementing blue lights in work zones, which resulted in speed reduction in all the cases.		Gambatese et al. (2019)
	NC-350 portable traffic sensors protected by elastic material were deployed every 0.2-0.3 miles to collect data on speed, length, gaps between vehicles, and distance from the preceding vehicle.		Gambatese et al. (2021)
Florida DOT	The presence of stationary police vehicles with blue lights reduced speed by 20%.		Gan et al. (2018)
Virginia DOT	Implemented temporary rumble strips for safety on one- and two-lane roads.		Chen and Cottrell (2005)
Missouri DOT	Used rumble strips for merging lanes, shifting lanes, and promoting speed reduction zones.		Brown et al. (2022)
	LiDAR sensors installed in work zones detected vehicle passing distance and updated the database simultaneously.		Brown et al. (2018)
California DOT	Used portable rumble strips for flagging operations, including signage, flagger installation, and channeling device placement.		Sanni (2019)
Indiana DOT	Used traffic cameras for gathering vehicle-related information (speed, density, lane) in three locations (before, in, and end of active work zones).		Chen and Tarko (2012)
University of Vermont Transportation Research Center	Two off-road sensors were implemented: • iCones measured vehicle speed in work zones, while their placement varied. • The Comprehensive Intersection Collision Avoidance system utilized sensors, computer processors, a communication network, and intersection representation to track vehicle position, speed, and lane of travel.		Brown et al. (2014)

Research outside of DOT programs also investigated innovative tools. Delineation devices were tested to guide motorists through alternative paths while maintaining separation between workers and vehicles. Grabber cones were emphasized in one study, and their effectiveness was evaluated through human factors experiment that used an instrumented vehicle equipped with eye tracking. The study measured driver glance frequency and duration, detection distances, missed turns, and perceptions of treatment visibility. The findings indicated that grabber cones enhanced drivers' attention to travel paths and reduced erratic maneuvers in urban work zones (Theiss et al., 2015). Another study used a driving simulator to test different crossover configurations in work zones. Vehicle speed profiles and lane selection behavior were recorded under each scenario. The results showed that drivers consistently exceeded temporary speed limits across all crossover configurations, but significant speed reductions occurred within bypass areas, highlighting the limitations of temporary speed control in simulated work zones (Domenichini et al., 2017). Overall, these studies illustrated how DOTs and transportation research centers applied innovative technologies and methods to improve work zone safety. The evaluations included both field studies and simulator-based experiments, with metrics ranging from crash frequency, vehicle speed, and headway to driver glance patterns and decision making. These applications demonstrated the growing role of real-time monitoring, sensor technology, and human factors analysis in advancing the understanding and management of safety risks in work zones.

2.3 Summary of the Literature Review

The reviewed studies showed that state DOTs and transportation research centers applied a variety of approaches to improve work zone safety. These approaches included the use of blue lights, traditional warning lights, rumble strips, sensors, and delineation devices. Research consistently measured driver behavior and traffic outcomes, including vehicle speed, lane choice, headway, detection distance, and driver attention. Findings demonstrated that blue lights influenced driver awareness and reduced speed under certain conditions, while other technologies contributed to improved traffic flow management and enhanced monitoring of real-time behavior. Independent studies also incorporated human factors methods and driving simulations to better understand how drivers responded to different work zone designs. **Table 2** presents a summary of the literature organized by category, focus, methodology, and findings.

Table 2. Literature review summary

Category	Focus	Methodology	Key Findings	Literature Sources
Implementation Practice	Blue lights in work zones (e.g., Mississippi's "Blue Light Law", police vehicle deployment, warning lights)	Policy actions and field applications	Improved vehicle behavior & safety presence; impact is dependent on the context of application of warning lights	MDOT 2019; Gan et al. 2018; Gambatese et al. 2019; Ullman & Lewis 1998
Analytical Study	Warning light effectiveness, crash causes, and risk modeling	Field studies, driving simulation, and machine learning	Identified factors affecting crash risk; confirmed behavioral impact of warning lights	Domenichini et al. 2017
Technology Development - DOTs	Use of rumble strips, sensors, and cameras in work zones	Deployment and monitoring by state agencies	Enhanced driver awareness and data collection on speed, spacing, and movement	Chen & Cottrell 2005; Brown et al. 2018; Ahmed et al. 2021; Chen & Tarko 2012
Technology Development - Independent Research	Design and testing of delineation & sensor-based systems	Lab and off-road evaluations	Improved navigation and understanding of driver behavior in various configurations	Theiss et al. 2015; Lee et al. 2014

Chapter 3. Methodology

This project employed a three-part methodology as illustrated in **Figure 1**. The first part is conducting a systematic literature review on studies related to work zone safety and warning lights configuration. This part is followed by a survey designed based on the results of the systematic literature review, survey pilot study, dissemination, and analysis. The third part is the field data collection by using radars in a work zone in Mississippi, with and without the presence of blue lights, and a set of statistical analyses of the data. The following sections in this report discuss the details of each part of the methodology.

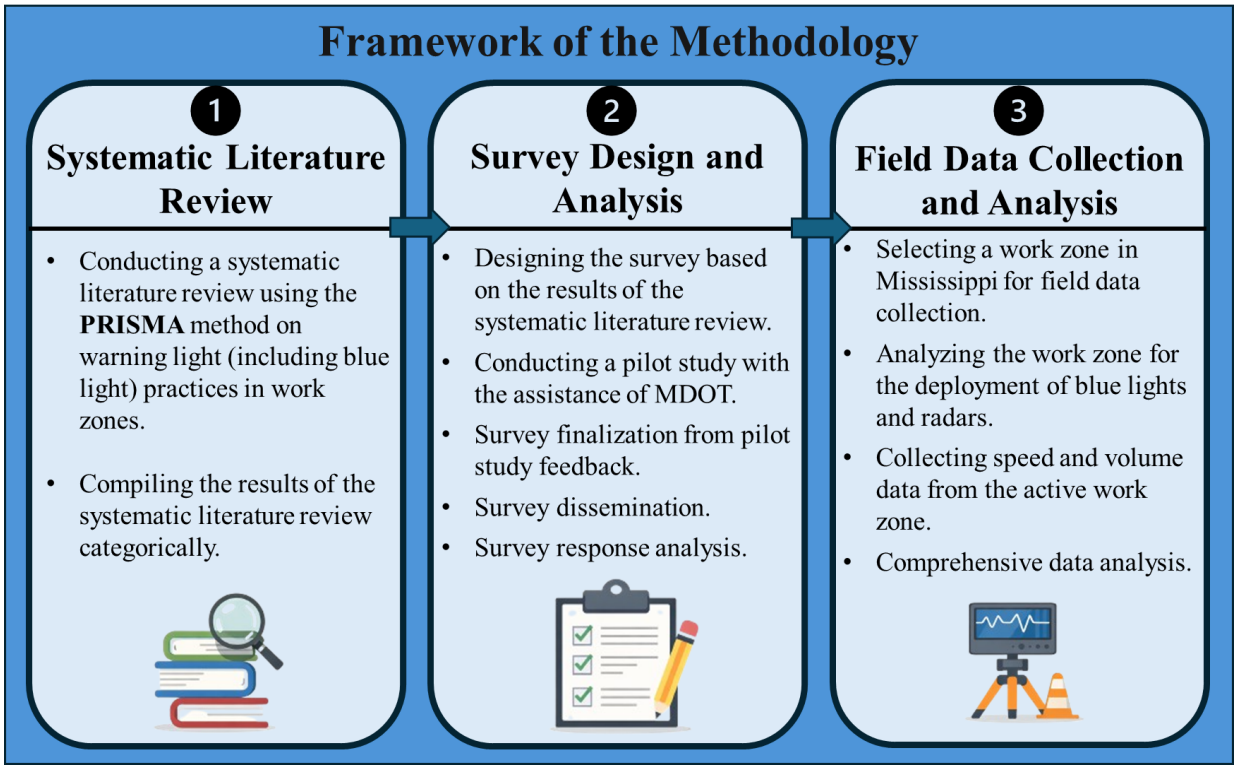


Figure 1. Framework of the methodology

3.1 Systematic Literature Review and Survey Design

The first part of the methodology is the systematic literature review, and the second part is survey design based on the results of the systematic literature review and survey analysis. **Figure 2** depicts the framework of the systematic literature review and survey design & analysis conducted for this project. For the systematic literature review, a **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-**based analysis was conducted, and the results were compiled into five categories (more details are presented in Chapter 4). Based on the results of the systematic literature review, the survey was designed with six categories. A pilot study was conducted with MDOT's assistance, and based on the pilot study's feedback, the survey questionnaire was finalized and disseminated (more details about the survey part are discussed in Chapter 5).

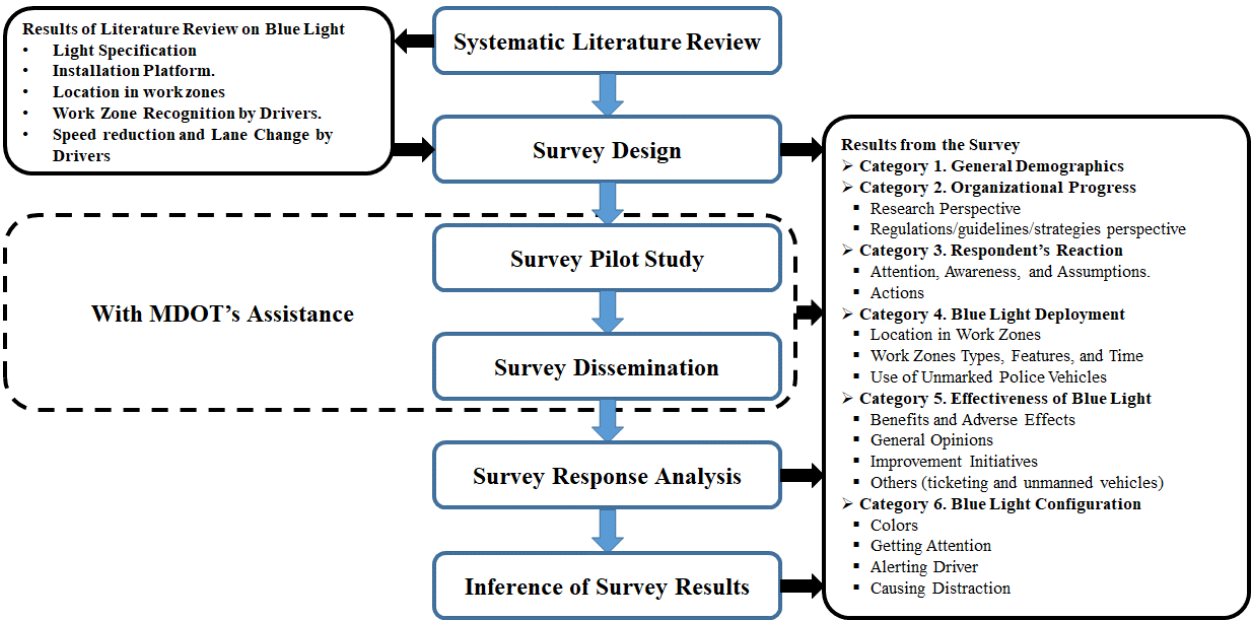


Figure 2. Framework of systematic literature review and survey design & analysis

3.2 Field Data Collection and Analysis

The third part of the methodology is the field data collection and analysis, as depicted in **Figure 3**. A work zone in Mississippi was selected with MDOT's assistance. Initially, several work zones were identified; however, due to limitations in schedule and availability of law enforcement personnel, only one work zone was selected for field data collection in this project. The details of the selected work zone were comprehensively studied, and the locations for blue light placement were confirmed with the help of local law enforcement officials and the work zone contractor. Radar deployment locations and the data collection procedures were also determined. The work zone schedule, the period of data collection, the metrics collected, and the conditions under which data were collected were established. Following completion of data collection, hypotheses were developed and tested using appropriate statistical analysis methods. More details about the field data collection and analysis are discussed in Chapter 6.

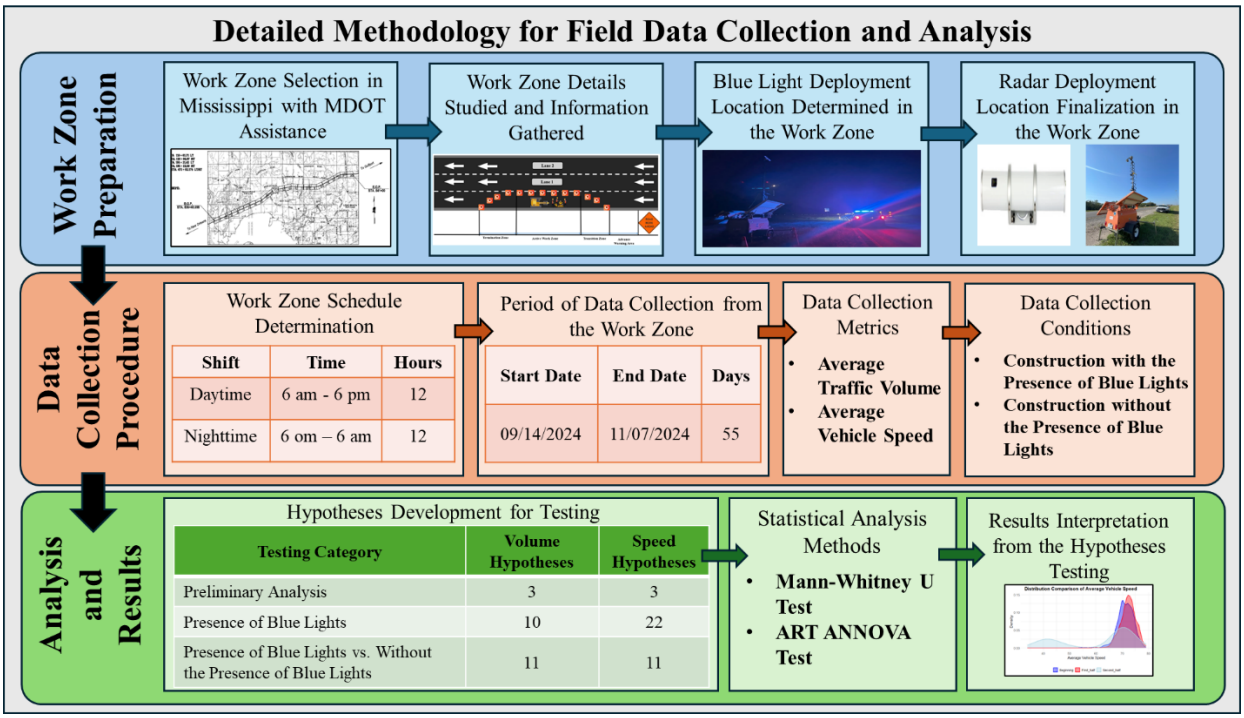


Figure 3. Methodology for field data collection and analysis

Chapter 4. Systematic Literature Review for Survey Design

This section includes the systematic literature review conducted for designing the survey. The studies related to work zone safety and warning light configuration, including blue lights, were reviewed. A PRISMA analysis was conducted to narrow down the relevant studies, and the results of the systematic literature review were discussed in five subcategories.

4.1 Analysis of Literature Reviewed

In this project, relevant literature on the implementation of warning lights for work zone safety was reviewed. Key search terms included work zone, safety, work zone safety, warning light, blue light, safety implementation, and safety practices. Databases including Elsevier, TRB, ASCE, IEEE, Scopus, Springer, Wiley Online Library, Web of Science, and Google Scholar were used. Additionally, project reports from state DOTs and equivalents were reviewed. Existing surveys (published online) related to warning lights for work zone safety were also considered. A total of 57 records were initially identified. After removing duplicates, 53 records remained and were screened. Of these, 45 were reviewed based on title and abstract, and 31 were assessed for full-text eligibility. The final selection of 31 studies was based on predefined inclusion criteria, which required studies to be published in English, focused on work zone safety, and specifically discussing the use, impact, or policy surrounding warning lights. Exclusion criteria included lack of full-text availability and studies unrelated to transportation, construction work zones, or traffic safety. The full literature screening and selection process is summarized in the PRISMA-style flow diagram (Page et al., 2021) shown in **Figure 4**.

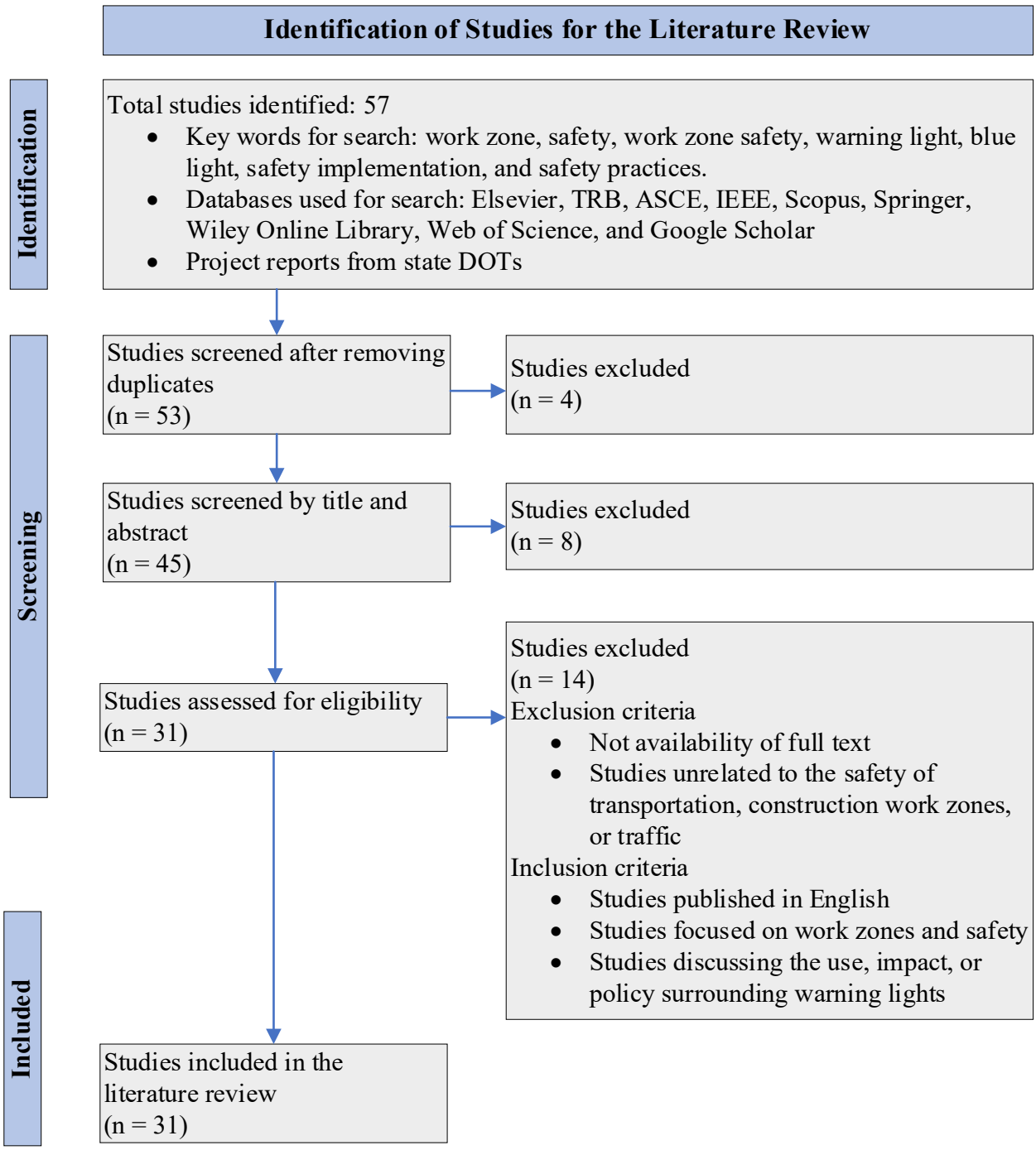


Figure 4. PRISMA flow diagram of the literature review

4.2 Results of Literature Review

The synthesized literature review findings are presented in this section. **Figure 5** presents a summary of the literature review analysis, summarized in five subcategories, including light specification, installation platform, light location, and driver behavior in response to light from two perspectives: (a) recognition of work zone and (b) speed reduction and lane change. More details about each subcategory are presented below, and further discussions and insights from the obtained results are presented in Chapter 7.

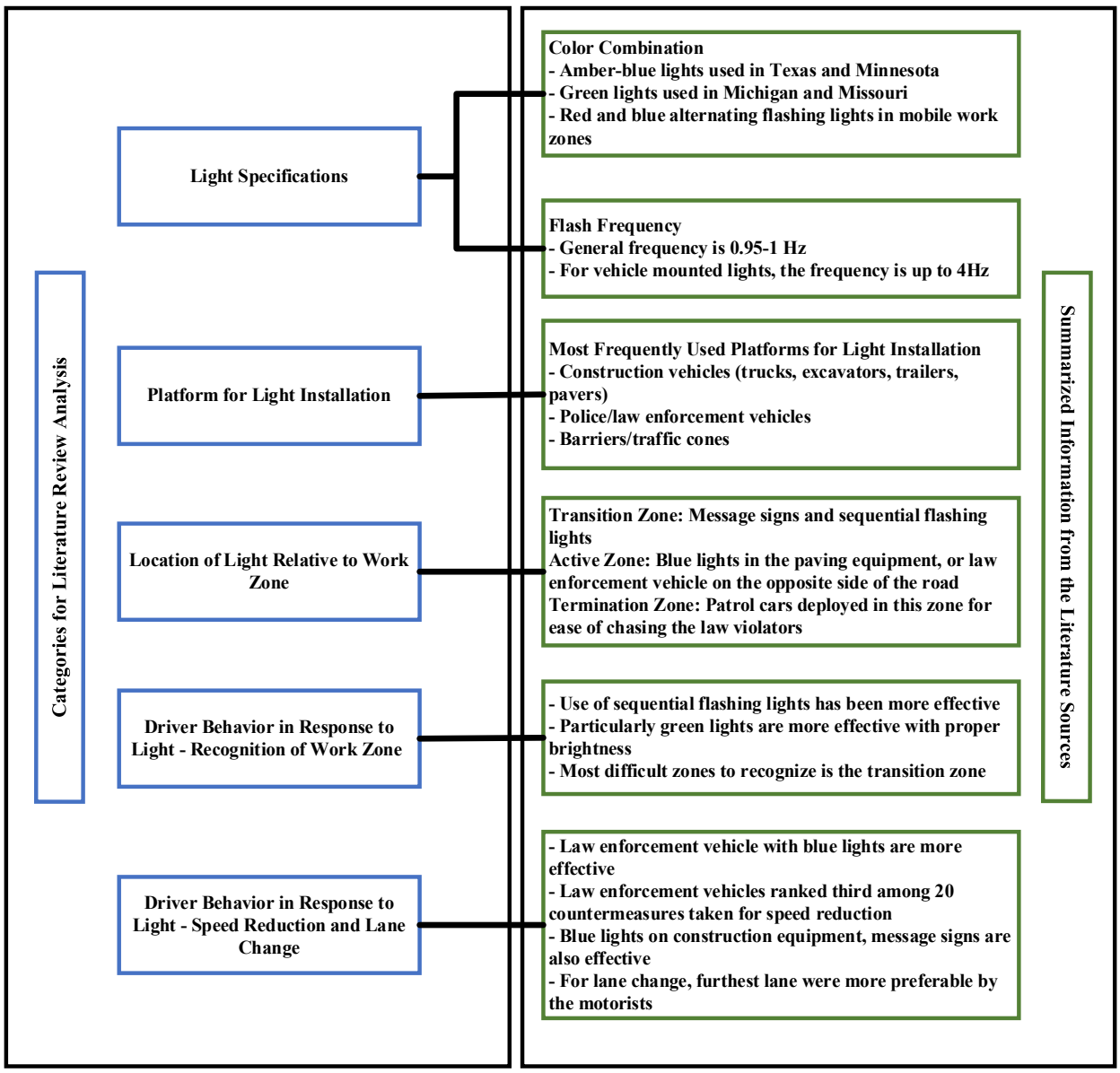


Figure 5. Summary of literature review analysis

4.2.1 Light Specification

Based on the literature review, the colors commonly used for warning lights were blue, green, amber/yellow, and white (Ullman et al., 1998). Different color combinations were also used in work zones, such as amber-blue, amber-white, and blue-white lights (Ullman, 2000). Among them, amber-blue lights were used in Texas (Ullman and Lewis, 1998), and green warning lights were used in Michigan and Missouri (Brown et al., 2018). The Minnesota DOT used amber and blue lights in work zones, which resulted in 99% of drivers merging over to the furthest lane from the work zone (MnDOT, 2013). Moreover, many studies used color combinations with alternate flashing lights to depict law enforcement vehicles, such as a red-blue combination with an alternate flashing sequence, and also green lights in mobile work zones (Fakhrmoosavi et al., 2021). The flash frequency of these warning lights ranged between 0.95-1 Hz, and for vehicle-mounted warning lights, it was extended up to 4 Hz (Rea et al., 2018). Due to the impaired capacity of

drivers to recognize work zones during nighttime operations, glare from these lights became highly dangerous, creating risky situations for both drivers and workers (Gambatese et al., 2019).

4.2.2 Platform for Light Installation

In active work zones, construction equipment vehicles and pavers were the main vehicles carrying warning lights in the work of Gambatese et al. (2019), and the light colors were mainly amber and white (WZB, 2022). In some cases, law enforcement vehicles in work zones were mainly equipped with blue and amber lights (Ravani et al., 2012). In California, warning lights could only be used in law enforcement vehicles placed in work zones instead of construction equipment as of a few years ago (Ravani et al., 2018). Overall, traffic officers not in uniforms or law enforcement vehicles used blue lights more in work zones (Gambatese et al., 2022). Apart from that, amber sequential flashing lights were also placed on the barriers or traffic cones along a work zone (Sommers and McAvoy, 2013). Green lights were normally mounted on the tops of all trucks involved in mobile work zones (Kersavage et al., 2019).

4.2.3 Location of Light Relative to Work Zone

Three lighting placement locations relative to a work zone were identified from the literature review. One option is the light placement in transition zones, where portable message signs were also widely used. Sequential flashing lights on the barriers were also practiced (Ravani et al., 2012; Zhang et al., 2014). Another option is the active work zones, where paving equipment was mostly used. Moreover, the vehicles of project officials also had blue lights in active work zones, and law enforcement vehicles with blue lights were placed on the opposite side of the road (Ahmed et al., 2021; Gambatese et al., 2019). Another option is to place lights in the termination zone. The only practice found from the literature sources that allowed for the placement of warning lights in the termination zone was one involving law enforcement vehicles. Patrol cars were then able to respond appropriately and chase after motorists who were speeding through the construction zone (Gambatese et al., 2022).

4.2.4 Driver Behavior in Response to Light - Recognition of Work Zone

Based on the literature, the use of warning lights in work zones has a contrasting effect on the behavior of drivers in terms of recognizing work zones. Traffic cones and barriers with sequential flashing lights worked well in both lab-simulated and in-field contexts to alert cars to a construction zone (Sommers and McAvoy, 2013). The addition of green lights is beneficial; however, it is important to take brightness into account (Kersavage et al., 2019). However, some studies have shown that drivers are not able to identify the work zone and open and closed lanes when approaching the transition zone with warning lights too bright (Huebschman et al., 2003).

4.2.5 Driver Behavior in Response to Light - Speed Reduction and Lane Change

The presence of law enforcement vehicles with flashing blue lights helped effectively reduce the speed of motorists (Gambatese et al., 2019; Kersavage et al., 2019; Cho et al., 2017). The presence of law enforcement vehicles in work zones has ranked third among 20 other countermeasures taken

to reduce the speed of drivers, along with the presence of workers and construction vehicles (Gambatese et al., 2022). Moreover, the blue light implementation practices were effective in speed reduction when lights were placed on construction equipment, message signs, or law enforcement vehicles (Ahmed et al., 2021; Chen and Tarko, 2012; Ullman et al., 1998). For lane change, it was found that drivers commonly switched to the available lane that was the furthest from the construction when there were closed lanes in the area. The use of blue lights and law enforcement was found to be quite effective at encouraging drivers to move over to the farthest lane away from the work zone in the tests that measured lane distribution (Ullman and Lewis, 1998).

4.2.6 Synthesis of Lighting Practices and Their Influence on Driver Behavior

The results from the systematic literature review suggested that the effectiveness of warning lights in work zones varied depending on color, placement, and mounting platform, each influencing driver behavior differently (Assafi et al., 2025). Blue lights, particularly when used by law enforcement or in combination with amber, were consistently linked with stronger safety outcomes, including reduced vehicle speeds and increased lane changes, compared to amber-only or green light setups (Ullman & Lewis, 1998; MnDOT, 2013; Kersavage et al., 2019). Amber-blue combinations demonstrated higher driver compliance, while green lights, though useful for visibility in mobile operations, showed limited behavioral impact due to their weaker association with enforcement (Brown et al., 2018; Fakhrmoosavi et al., 2021).

Platform and placement also influenced the effectiveness of warning lights. Law enforcement vehicles equipped with blue lights were more successful in reducing speeds and encouraging cautious driving than construction equipment with amber or white lights (Gambatese et al., 2019; Ravani et al., 2012; Gambatese et al., 2022). Lights placed in transition and termination zones, especially those mounted on patrol vehicles, supported early driver recognition and allowed for enforcement actions, such as intercepting speed violators (Gambatese et al., 2022; Ravani et al., 2012). In contrast, lights used solely for visibility or placed without enforcement cues had less measurable influence on driver behavior. The literature also suggested the importance of light intensity and flash frequency. While higher brightness and faster flashing rates (up to 4 Hz) improved visibility (Rea et al., 2018), overly bright lights, particularly in the transition zone, were reported to impair drivers' ability to recognize lane closures or work zone boundaries (Huebschman et al., 2003). These findings highlighted that safety outcomes depended on a thoughtful combination of light color, platform type, strategic placement, and calibrated intensity to effectively influence driver behavior in work zones.

Chapter 5 Survey Design, Analysis, and Results

In this section, the survey design, analysis, and results are discussed. The survey questionnaire was designed based on the results from the systematic literature review. A pilot study was conducted with the initial survey questionnaire, and after receiving feedback from the pilot study, the final questionnaire was prepared. The following sections discuss the design of the survey, the pilot study, the results from the pilot study, the improvements made to the survey, and the results of the final survey responses in six categories. Further discussions and insights from the obtained results are presented in Chapter 7.

5.1 Survey Design

Based on the literature review findings, a survey was designed and conducted. Questions were divided into six categories: general demographics, organizational progress of blue light implementation, respondents' reaction to blue light implementation, blue light deployment, blue light effectiveness, and blue light color configuration. The questionnaire consisted primarily of multiple-choice and perception-based questions, aimed at capturing a broad range of operational and policy viewpoints from transportation professionals. After the development of the questionnaire, a pilot study was conducted with the help of MDOT. Based on the feedback obtained from the pilot phase, some questions in the questionnaire were improved, but no changes were made to the categories. More details about the pilot study and survey dissemination are presented in Section 5.2. After the pilot study (i.e., after the improvements), the summarized contents of each category included in the final version of the survey questionnaire are described below. Sample questions used for the survey are presented in **Table 102** in Appendix A.

i. **General Demographics:** Three questions discuss survey participants' work organizations, job titles, and working states. This helped conceptualize the current usage of blue light by DOTs.

ii. **Current Progress at the Organizational Level:** Six questions are about the progress of blue light usage at the organizational level, covering two perspectives. One perspective is research-based, which considers projects using blue lights that (i) the organization has conducted or (ii) the organization considers proposing and developing. The other perspective is about regulations, guidelines, and strategies for blue light usage. This includes questions about whether blue lights are allowed in that state and the current progress of regulations/guidelines/strategies for implementing blue lights, e.g., whether the organization already has regulations, guidelines, and/or strategies in place or is currently in the process of proposing and developing, or consider proposing and developing in the future. Not sure and not available options are also provided.

iii. **Respondent's Reaction to Blue Lights:** Seven questions discuss the reaction of respondents in the presence of blue light in work zones, including two perspectives. The first perspective is about attention, awareness, and assumptions (4 questions), which includes information on how a respondent reacts to police vehicles in a work zone with blue lights flashing on or off. The other perspective discusses the particular actions that respondents take in the presence of blue light while they are driving and the actions that they observe the driver take while they

are traveling as a passenger. The actions taken in the presence of flashing blue lights in work zones while drivers are exceeding the speed limits are also covered in this category.

iv. **Blue Lights Deployment:** Five questions describe the details of blue light deployment in work zones. Specifically, the deployment strategies of blue lights in work zones consider the typical locations in a work zone, the types of work zones, work zone features (such as road volume and speed limit), and the most typical time to deploy. Moreover, the use of unmarked police vehicles with blue lights versus marked police vehicles with blue lights is also considered in this category.

v. **Blue Lights Effectiveness:** Eight questions discuss (i) the benefits and adverse effects of using blue lights, (ii) general opinions regarding their effectiveness, (iii) strategic initiatives for improvements, and (iv) others (ticket enforcement and unmanned vehicles that were recommended to be included by a state DOT). The strategic initiatives for improvement include questions about potential challenges that could be encountered if blue lights were to be implemented in work zones. The questions also look for additional strategic initiatives that could be implemented to further improve the effectiveness of blue lights.

vi. **Blue Lights Configuration:** Ten questions are about different configurations of blue/warning lights used in work zones and how they relate to work zone safety, including light colors and combinations with blue light (two questions), blue light styles and designs in getting attention (four questions), alerting drivers (two questions), and causing distractions (if any) for road users (two questions). For example, several blue light styles and designs (such as beacon style, blinking, rotating, oscillating, different numbers of flashing lights, flashing frequencies, or light off) are included to examine their effectiveness in getting attention and potentially changing driver behaviors.

5.2 Pilot Study and Dissemination

A pilot study was conducted with the assistance of MDOT officials to gather feedback on the initial questionnaire. This pilot phase yielded valuable input from a few state DOTs, including (i) more clear wording of the context about blue light implementations, i.e., existing implementations or when/if blue lights were to be implemented (if currently blue lights were not allowed or not implemented in work zones in that state), (ii) inclusion of questions addressing perspectives from passengers, the effect of blue lights on ticketing behavior, and scenarios involving unmanned law enforcement vehicles with flashing blue lights. Based on the feedback, the questionnaire was refined and updated accordingly and was thoroughly reviewed by transportation professionals from MDOT to ensure the clarity, relevance, and alignment of the questions with key themes identified in the literature before full dissemination. After finalizing the questionnaire (Appendix A), MDOT assisted in the dissemination of the survey to state DOTs, government agencies, including the American Association of State Highway and Transportation Officials Research Advisory Committee (AASHTO RAC), and the North American Association of Transportation Safety & Health Officials (NAATSHO) within the U.S. As this is an initial project aiming to gather insights into the implementation practices of blue lights for work zone safety, the target participants were confined to transportation professionals. Regarding the responses, the participants had the liberty of choosing one or multiple options according to their understanding.

There was also a separate option named "others," in which the participants could offer their valuable opinions in response to the questions.

5.3 Results of the Survey Responses

This section presents the results of the final survey, which was developed based on feedback from the pilot study. A total of 67 completed responses (i.e., N = 67) were collected and analyzed. The following sections present the survey findings, organized according to the six categories mentioned earlier. Both single- and multiple-choice responses, as well as open-ended suggestions from participants, are included to illustrate insights. The figures in the following sections have been developed by grouping or merging related questions for clearer presentation and easier understanding of the findings. Therefore, the question labels shown in figures may not always exactly match the original questionnaire wording as represented in **Table 102**, but they represent the same underlying items.

5.3.1 Category 1. General Demographics

This category included the state, organization, and job titles of the participants. **Figure 6** depicts the demographic distribution, showing that 57% of the 67 participants were from the southern U.S., with North Carolina having the highest representation at 22%. The Midwest accounted for 21%, the West for 13%, and the Northeast for 9%. Organizationally, 90% were affiliated with state DOTs, while the rest were from non-state DOTs and federal agencies. Regarding job sectors, 25% were construction safety professionals, 19% were from policy and regulation development, 22% were resident engineers, work zone coordinators, or construction managers, and 10% were project engineers, inspectors, researchers, OSHA directors, traffic operation professionals, or maintenance managers.

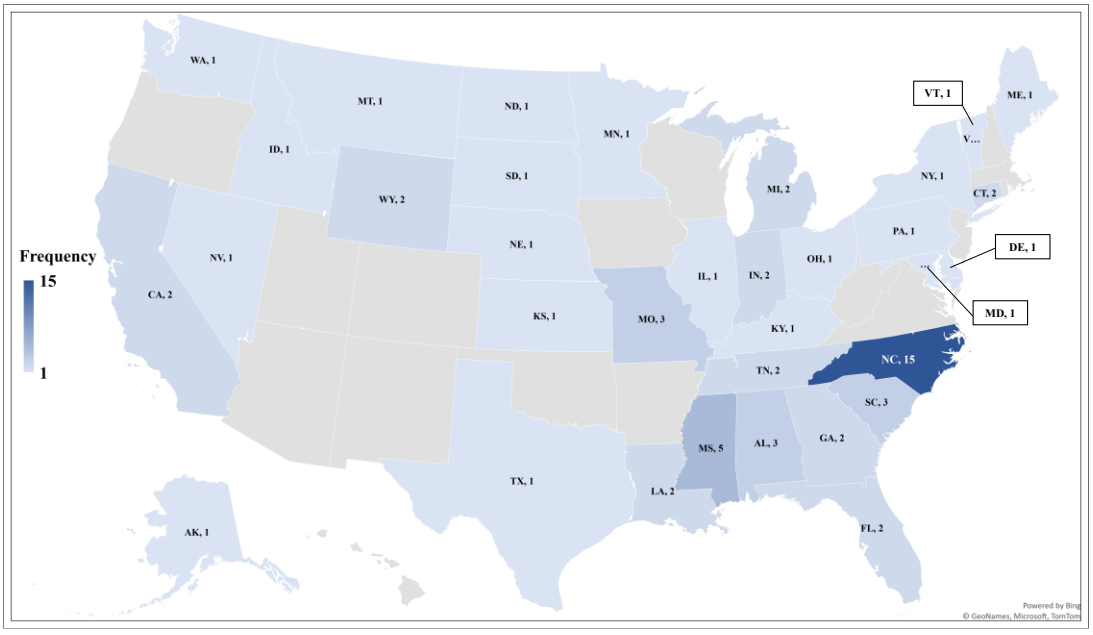


Figure 6. Distribution of survey respondents

5.3.2 Category 2. Current Progress at the Organizational Level

This section outlines the current progress of blue light usage at the organizational level, with a focus on research, regulations, guidelines, and strategies.

5.3.2.1 Research Perspective

This section discusses the perspectives of research progress in blue lights. The survey focused on two key research-related questions depicted in **Figure 7**. Regarding the research on blue light usage, 13% of respondents reported ongoing research projects, while 13% stated that projects were being considered but not yet implemented. A total of 57% and 47%, respectively, indicated no existing projects and no plans for proposing research in this area (**Figure 7**). The survey also gathered data about Yes/No/Not Sure regarding research projects in this regard only; no additional data on the progress of these research projects was obtained.

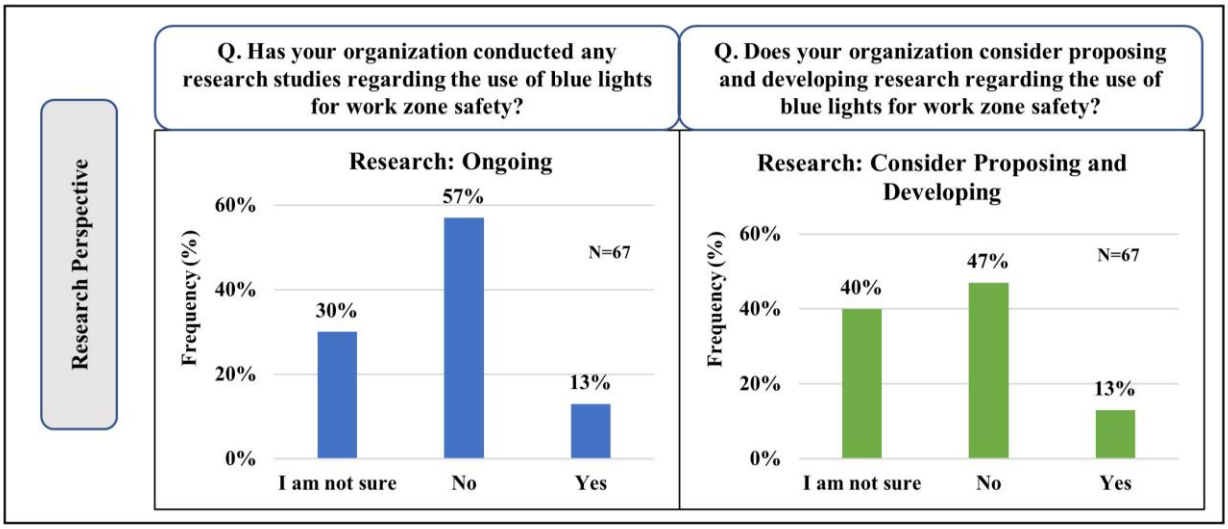


Figure 7. Current progress from the research perspective

5.3.2.2 Regulations/Guidelines/Strategies Perspective

This section states the responses from the perspective of the regulations/guidelines/strategies. Based on the responses, blue light has been more actively used for law enforcement purposes and in emergencies, which is about 48% (**Figure 8**). Blue light is also used for work zone notifications (34%) and for non-law enforcement vehicles using blue light specifically for warning signs (18%). Among the states involved in blue light usage, 48% were used for law enforcement and emergencies, 35% for work zones, and 17% for non-law enforcement vehicle warnings.

The survey also gathered information on the status of regulations/guidelines/strategies for using blue light, categorizing them as "existing," "under process," or "under consideration" (Figure 6). About 37% of the respondents agreed that there are existing policies in place, 7% agreed on policies under process, and 18% stated that there are policies under consideration and not decided yet. On the other hand, 49% agreed that there are no existing policies, 49% agreed that there are no policies under process, and 38% stated that there are no such policies under consideration.

Furthermore, some of the respondents opined that the policies related to blue light do not apply to their respective organizations.

The survey results in this section reveal inconsistencies in organizational blue light policies, with varying percentages across the categories of existing, in progress, and under consideration. Affirmative responses regarding blue light policies were fewer than negative ones, indicating a need for standardized regulations and clearer guidance.

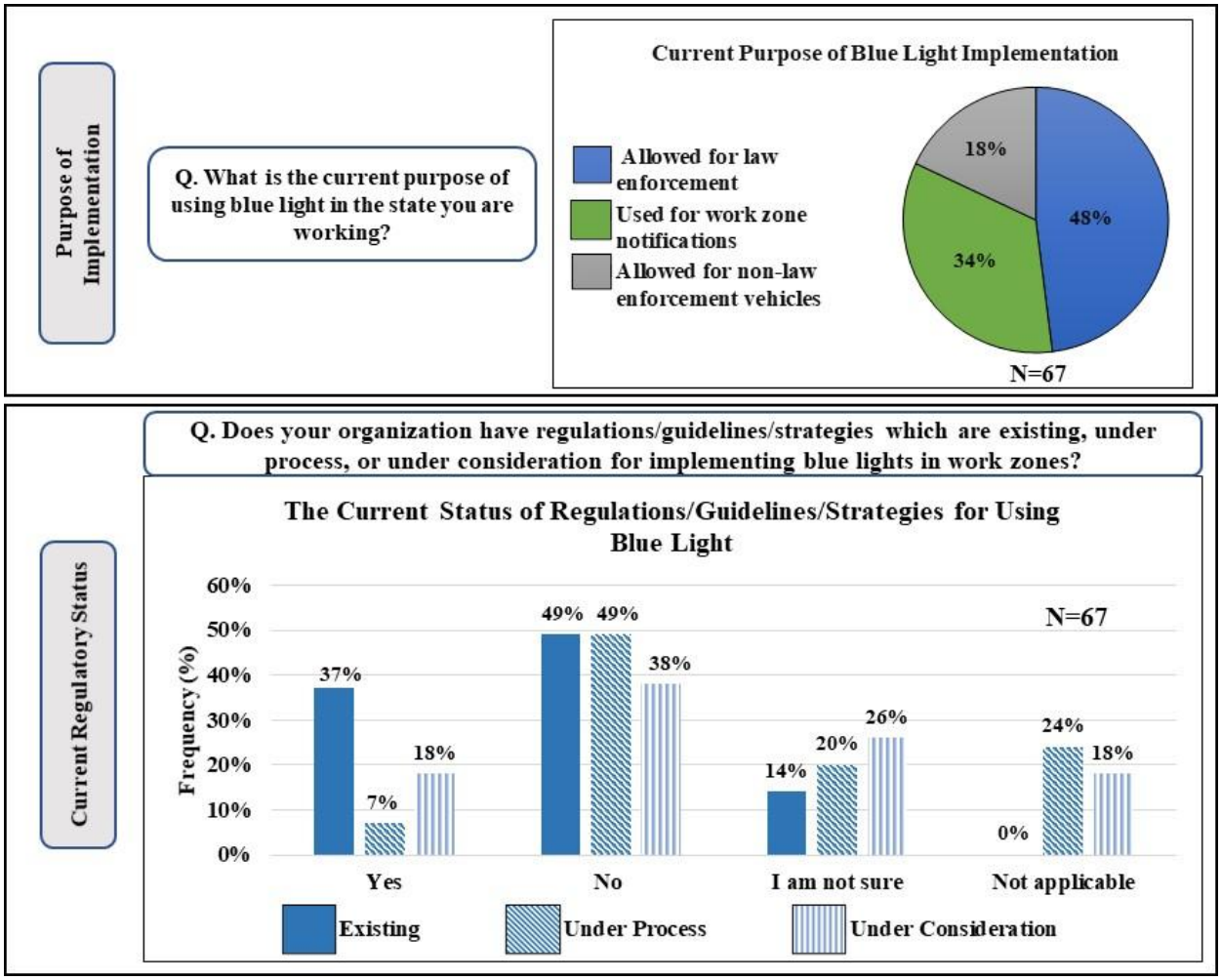


Figure 8. Current progress from the regulatory perspective

5.3.3 Category 3. Respondent's Reaction to Blue Lights

This category addresses respondents' reactions to the presence of blue lights, focusing on their attention, awareness, and assumptions in work zones. It also covers the actions they take while driving near blue lights.

5.3.3.1 Attention, Awareness, and Assumptions

Figure 9 shows the respondent's reactions to blue lights from perspectives of attention, awareness, and assumptions. Regarding the attention and awareness for both blue lights flashing on and off situations, approximately 87% remained alert and attentive when encountering police vehicles with flashing lights, maintaining this behavior until exiting the work zone. Around 10%

acknowledged heightened attention while passing these vehicles but returned to their normal driving behaviors afterward. Only 3% reported no change in their driving. In contrast, when passing work zones with blue lights off, 60% reported heightened alertness and attention, maintaining it until exiting the work zone.

In terms of assumptions about the presence of flashing blue lights, approximately 89% assumed that flashing blue lights, such as those on police vehicles, were for work zone safety (***Figure 9***). Regarding perceptions of hazardous severity, 14.5% of respondents considered flashing blue lights not hazardous, 32% viewed them as slightly hazardous, while the highest response rate, around 48%, considered them moderately hazardous (***Figure 9***). These results indicated that the level of attention and awareness among road users is primarily influenced by the presence of law enforcement entities, specifically police vehicles, in contrast to the state of blue lights (on or not).

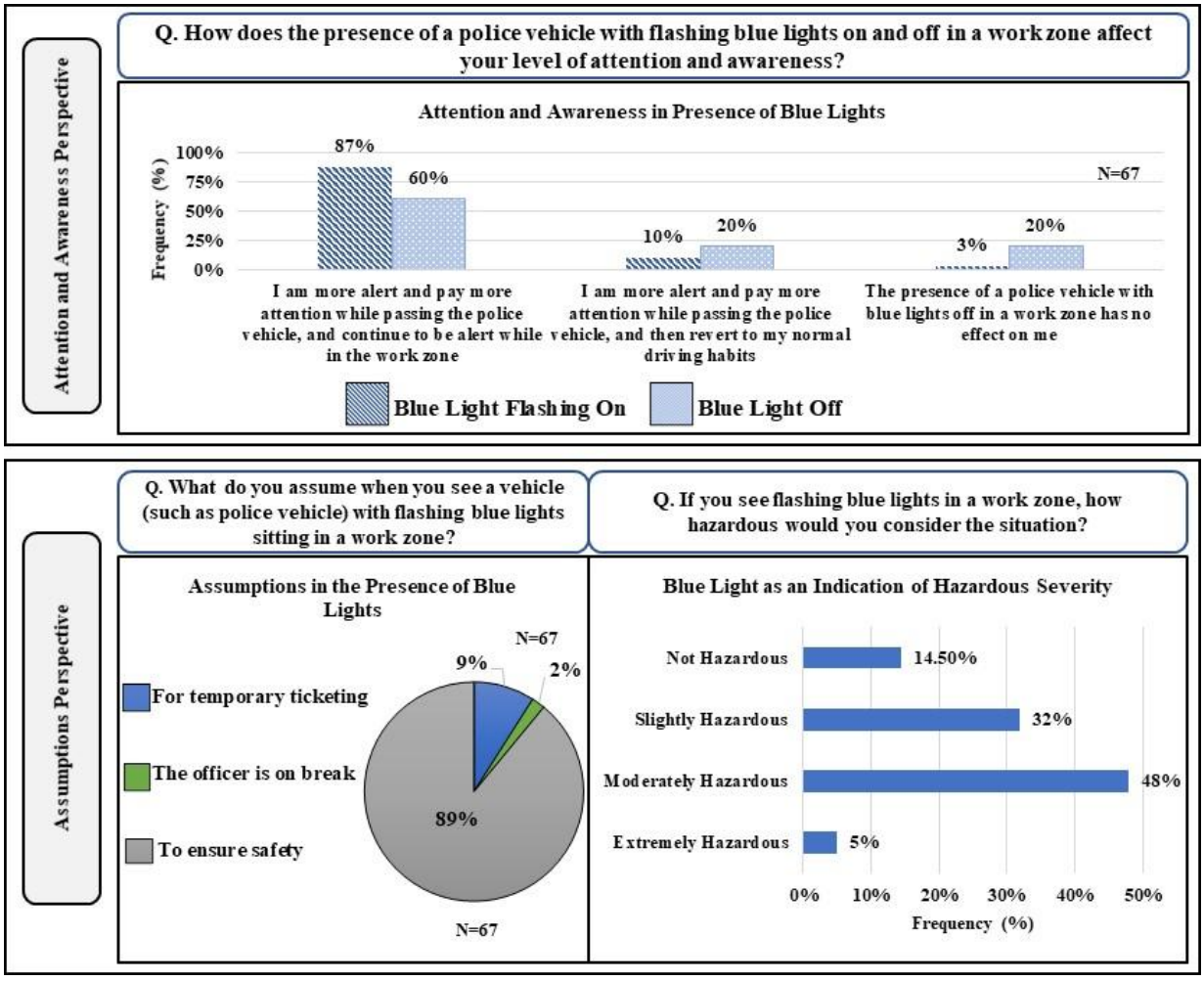


Figure 9. Respondents' reactions in terms of attention, awareness, and assumption

5.3.3.2 Actions

This section discusses the actions of road users in the presence of blue lights in work zones. In **Figure 10**, from the perspective of drivers and passengers, respectively, slowing down while crossing the work zone has been deemed as the first and primary action to take. Changing lanes

was also considered if road conditions allowed. Specifically, from the perspective of driving the vehicles when observing flashing blue lights, about 52% agreed to slow down instantly, and about 40% chose to change lanes if possible (**Figure 10**). When the respondents were not in the driving seat (i.e., as passengers observing the driver), about 72% stated to slow down in the presence of blue light, about 20% agreed that their vehicle changed lanes if possible, and 8% elected to proceed without changing the speed while crossing the work zone (**Figure 10**). Regarding the effect of flashing blue lights in work zones on road users exceeding the speed limit, 59% of road users with speeds exceeding the limit reduced their speed to match the posted limit when encountering flashing blue lights in work zones, 36% slowed down below the limit while passing, and 5% slowed down but remained above the limit.

Overall, the presence of flashing blue lights in work zones plays a meaningful role in influencing driver behavior, with a majority opting to slow down or match the posted speed limit. However, some road users might not fully comply with safety measures. Proper enforcement of blue light usage and public awareness are necessary for safer driving in work zones.

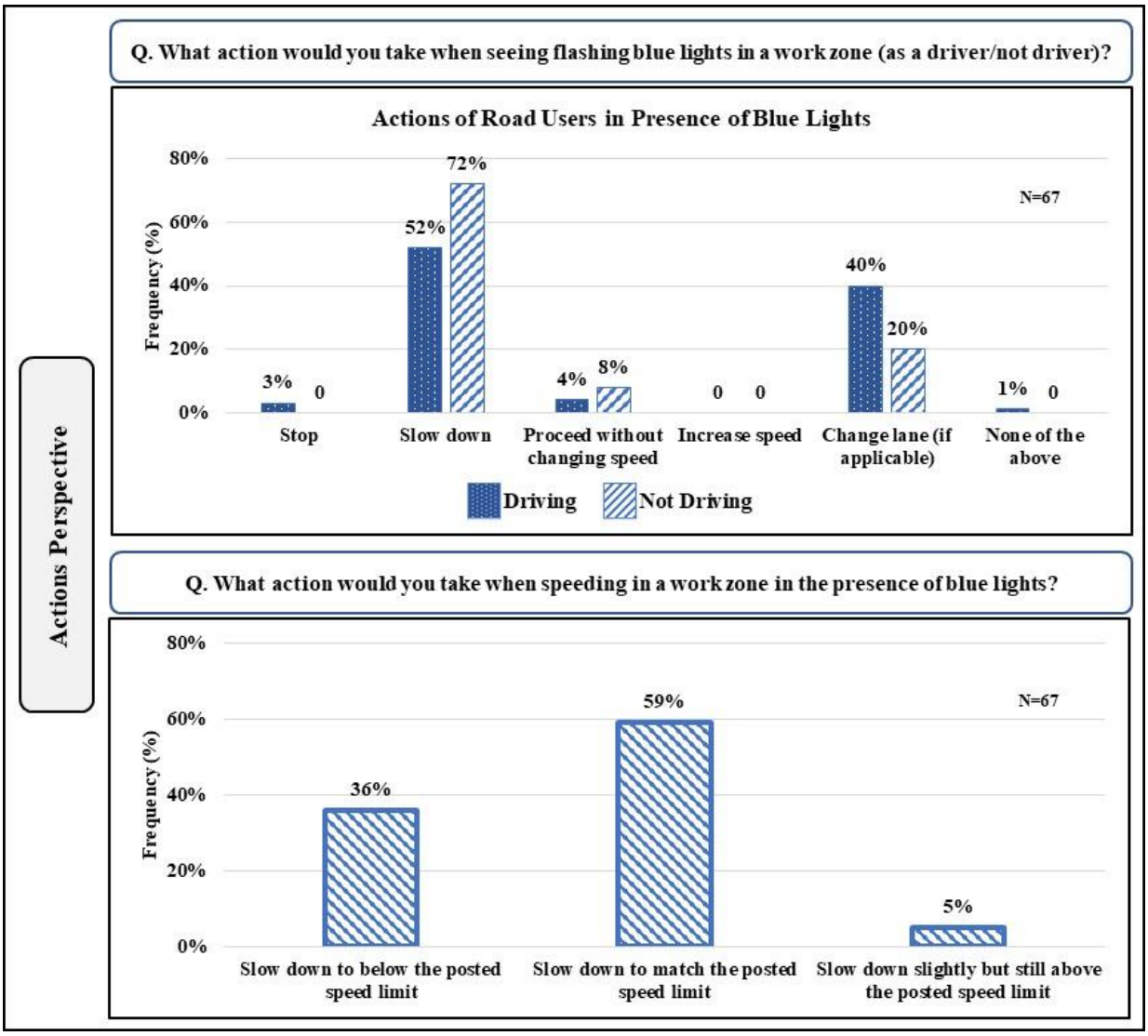


Figure 10. Actions pursued by respondents in the presence of blue lights in a work zone

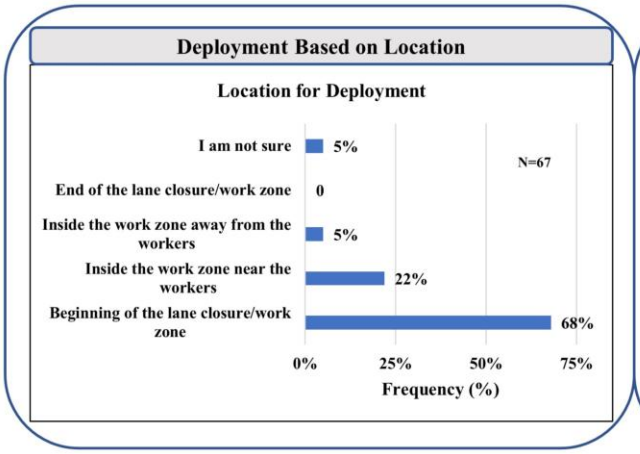
5.3.4 Category 4. Blue Light Deployment

This category details the deployment of blue lights in work zones. It covers deployment strategies, including typical locations, types of work zones, features like road volume and speed limit, and the most common deployment times.

5.3.4.1 Location Relative to Work Zone and Typical Time to Deploy

The deployment of blue lights in work zones based on the location and time of deployment is discussed in this section. According to **Figure 11**, for the location of deployment of blue lights, about 68% of the respondents agreed to deploy blue lights at the start of the lane closure/work zone, and about 22% agreed to deploy inside the work zone near the workers. About 5% suggested deploying blue lights inside the work zone but keeping them away from the workers, and 5% were unsure about the appropriate placement (**Figure 11**).

Regarding the typical time to deploy (**Figure 11**), about 24% agreed to deploy blue light throughout the entire project period. The rest of the respondents agreed to deploy blue light at specific times of the week (weekday versus weekend, frequently versus occasionally, day versus night, rush hours or not); specifically, 12% agreed to deploy blue light frequently on weekdays, including both daytime and nighttime; 7% suggested rush hours on weekdays. For weekends, 11% were in favor of frequent deployment during both daytime and nighttime (**Figure 11**).



Deployment Based on Time of Deployment

Time for Deployment	Frequency (%)
Weekday - day frequently	12%
Weekday - day occasionally	8%
Weekday - night frequently	12%
Weekday - night occasionally	4%
Weekday- rush hour frequently	7%
Weekday - rush hour occasionally	3%
Weekend - day frequently	5%
Weekend - day occasionally	11%
Weekend - night frequently	6%
Weekend - night occasionally	8%
All the time of a day	24%

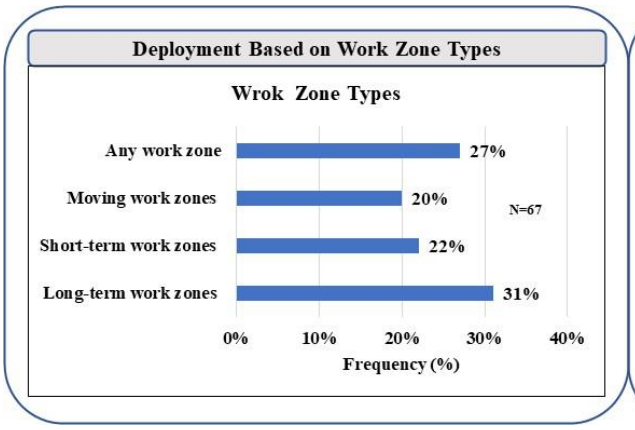
Figure 11. Blue light deployment based on location and time of deployment

5.3.4.2 Work Zone Types and Features

This section discusses the responses to blue light deployment based on work zone types and features (**Figure 12**). Regarding deployment by work zone type, 31% reported that blue lights are suitable for long-term work zones (lasting more than three days). About 22% supported their use mainly for short-term work zones (lasting 1 hour to 3 days), and 20% favored deploying blue lights in moving work zones (0 to 60 minutes of construction) due to their dynamic nature. Meanwhile, 27% suggested using blue lights in all types of work zones (**Figure 12**).

Ten features were identified and considered for the deployment of blue lights based on work zone features. Approximately 31% considered road volume as the primary factor necessitating blue lights, 27% relied on road classification, 20% agreed that congestion was a key feature, and approximately 9% favored blue lights in any work zone. Additionally, 5% considered speed, and 4% had the perspective that policies, past experience, records, or other were primary criteria (**Figure 12**).

Overall, the findings suggest that blue lights are perceived as versatile safety tools in work zones. Their suitability varies according to work zone types and the locations to deploy. Road volume, classification, and congestion are important factors that determine their deployment.



Deployment Based on Work Zone Features

Work Zone Feature	Frequency (%) (high to low)
Road volume	31%
Classification of the road	27%
Congestion	20%
Any work zone	9%
Speed	5%
Others: policy, past experience and records, crash prevention	4%
Project type	3%
No deployment of blue light	1%

Figure 12. Blue light deployment based on work zone types and features

5.3.5 Category 5. Blue Light Effectiveness

This category discusses the benefits and adverse effects of using blue lights, general opinions regarding their effectiveness, and strategic initiatives for improvements. This also includes the potential challenges in enforcing blue lights in work zones and suggests additional initiatives to enhance their effectiveness.

5.3.5.1 Benefits and Adverse Effects

This section presents the responses on the benefits and adverse effects of blue light effectiveness. According to **Figure 13**, 40% of respondents agreed that flashing blue lights in work zones improve safety conditions for workers and motorists. Additionally, 35% believed that blue lights help reduce high speeds, while 23% agreed that blue lights ensure proper adherence to work zone regulations. Regarding the probable adverse effects of blue light deployment (**Figure 13**), about 27% reported motorists rubbernecking as the prime adverse effect. About 23% stated the sudden reduction of speed due to blue lights as a source of increasing congestion on the road, and 19% agreed that suddenly slowing down below the posted speed limit can cause accidents for the vehicles in queue.

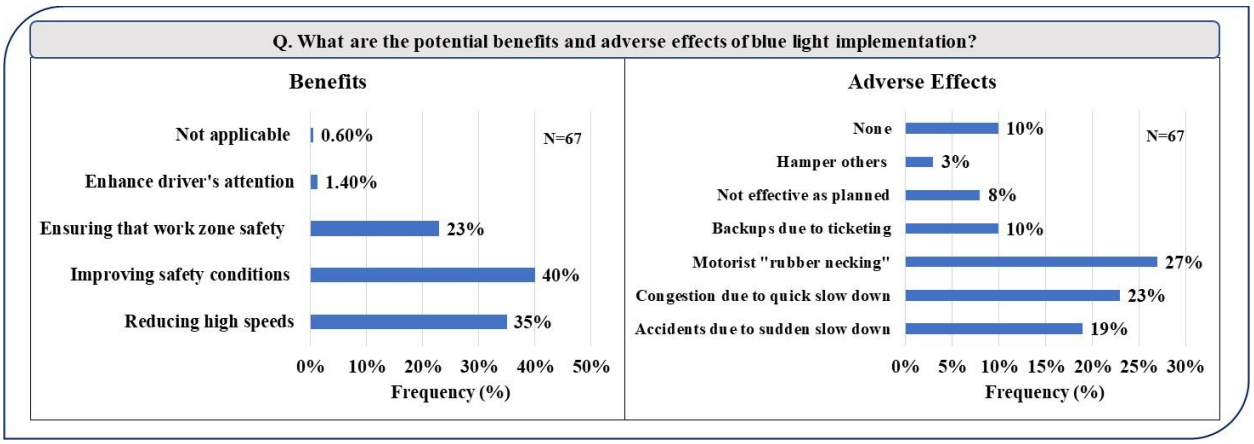


Figure 13. Benefits and adverse effects of blue light implementation

5.3.5.2 General Opinions on the Effectiveness of Blue Light

In general terms, opinions on the effectiveness of blue lights indicated approximately 83% supported blue lights for speed reduction, 78% agreed that they enhance safety conditions, and 48% affirmed their role in ensuring work zone regulations (**Figure 14**). Additionally, regarding the level of satisfaction with the effectiveness of police vehicles with flashing blue lights for work zone traffic control (compared with other temporary controls), about 37% found them excellent, 40% considered them good, with 14%, 6%, and 3% finding them average, fair and poor, respectively.

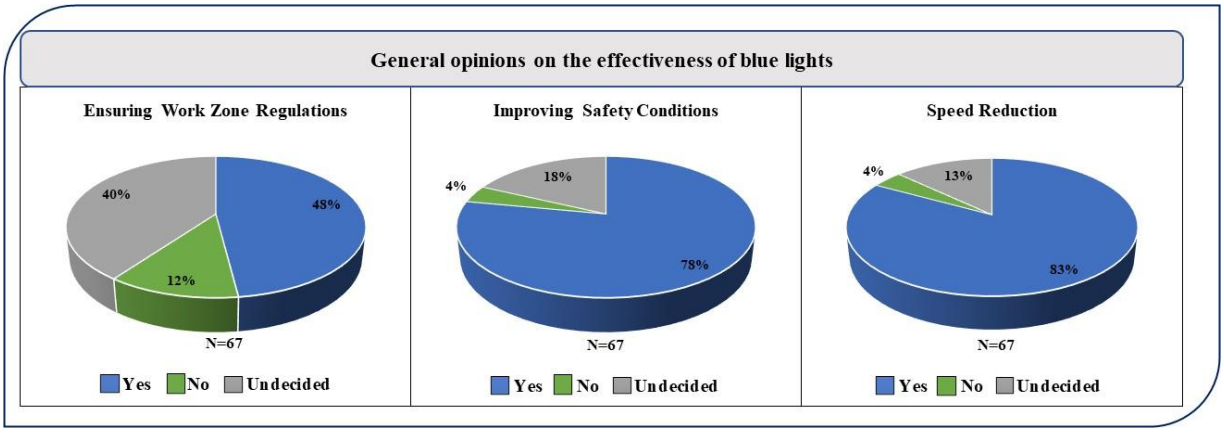


Figure 14. General opinions regarding the effectiveness of blue light

5.3.5.3 Strategic Initiatives for Improvement

The strategic initiatives section identifies the major issues encountered in blue light implementation and offers suggestions to mitigate these issues. According to **Figure 15**, the primary issues are (i) insufficient communication between enforcement and construction personnel (21%), (ii) an inappropriate number of police vehicles (20%), and (iii) the location of ticketing/officers in work zones (17%). To address these issues, the most popular recommendation

(32%) was to require work zone safety training for officers, followed by 28% suggesting improved communication between workers and law enforcement authorities (**Figure 15**).

Overall, the results from these sections show positive views on blue lights' effectiveness in work zones, especially for speed reduction. However, there is room for improvement, including optimizing police vehicle allocation and enhancing inter-team communication. Ticket enforcement strategies can be considered to maximize blue light effectiveness for safety enhancement.

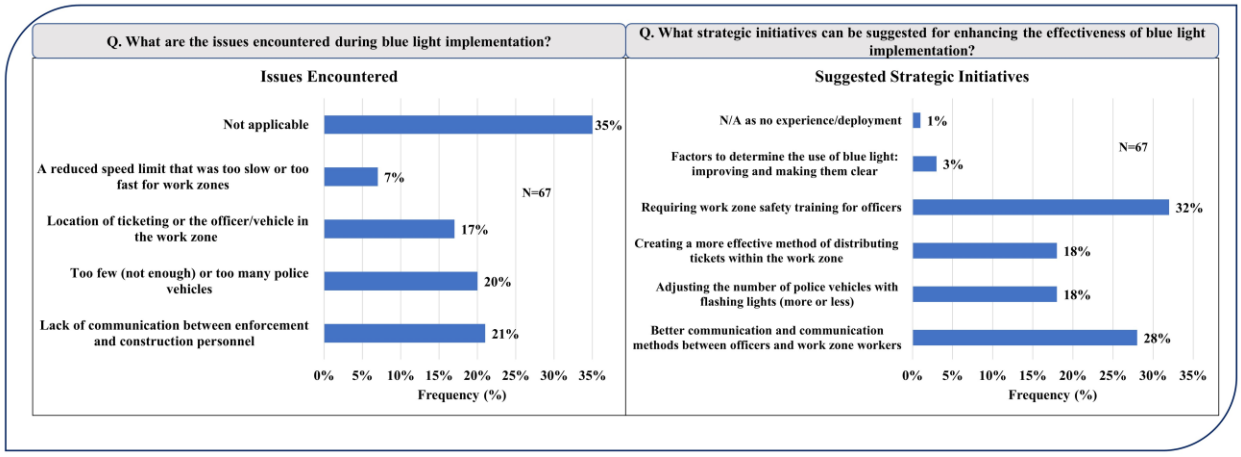


Figure 15. Issues and strategic improvements on blue light effectiveness

5.3.6 Category 6. Blue Light Configuration

This category is about different configurations of blue/warning lights used in work zones and how they relate to work zone safety, including light colors and combinations with blue light, blue light styles, and designs to get attention, alert drivers, and cause distractions (if any) for road users.

5.3.6.1 Colors

In examining the prevalent light colors utilized in work zones, the data collected indicated a diverse range of choices. **Figure 16** shows the results from the survey about the warning light colors encountered in the work zones and expected in the work zones.

Colors

Which of the warning light colors/ combinations have you encountered in active work zones?						
Warning light color/ Combination	Blue	Red	Green	Amber/Yellow	Blue & Red	White & Red
Frequency (%)	22%	11%	8%	30%	18%	11%

What color lights do you expect to see on a vehicle (such as police vehicle) in active work zones?					
Warning light color/ Combination	Blue	Red	Green	Amber/Yellow	Combination of some colors
Frequency (%)	51%	22%	0%	12%	15%

Figure 16. Existing and expected warning light color configuration

Among the warning light colors encountered in the work zones, amber or yellow lights constituted the highest percentage at 30%, followed by blue lights at a prevalence of 22%. A total of 18% of the instances involved a combination of blue and red lights. Furthermore, when asked about their expected warning light color in work zones, 51% suggested blue lights, 22% suggested red lights, 12% preferred amber lights, and 15% favored a combination of colors over a single color (**Figure 16**).

5.3.6.2 In Getting Attention

Two styles of blue light were surveyed to determine their effectiveness in capturing attention when approaching a work zone (**Figure 17**). A total of 87% preferred the visor light bar style as the most suitable. About 3% suggested the beacon light configuration, and 10% found no significant difference between the two styles. Regarding the type of emission (e.g., blinking, rotating, oscillating, no difference, not sure), most respondents indicated blinking and oscillating lights are equally effective in capturing attention, with approximately 31% supporting each. However, when exceeding the posted speed limit and observing the presence of police vehicles in the work zone, about 48% of the participants selected to reduce their speed regardless of whether the blue lights were on or off (**Figure 17**).

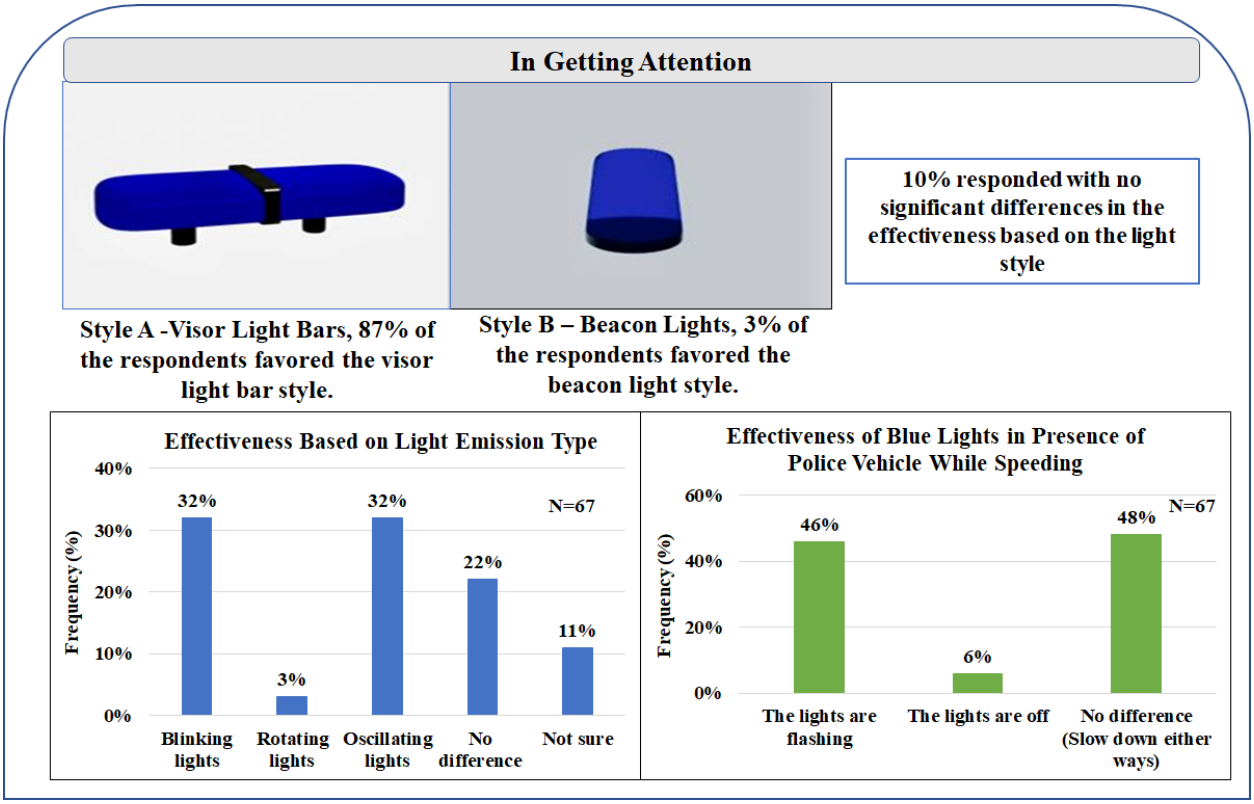


Figure 17. Blue light configuration for obtaining attention

5.3.6.3 In Alerting Drivers

This section discusses the effectiveness of different color patterns in terms of alerting drivers in work zones. According to **Figure 18**, for color patterns, 25% preferred single-color flashing warning lights (i.e., flashing blue lights), 36% favored alternating-color lights (i.e., a warning light flashing back and forth between red and blue), and 34% saw no notable difference for alertness. Regarding colors for alertness, 43% agreed blue lights are effective in alerting drivers, 12% for red lights, 7% for white lights, 4% agreed on green lights, and 32% agreed that a combination of blue and red lights is effective and useful.

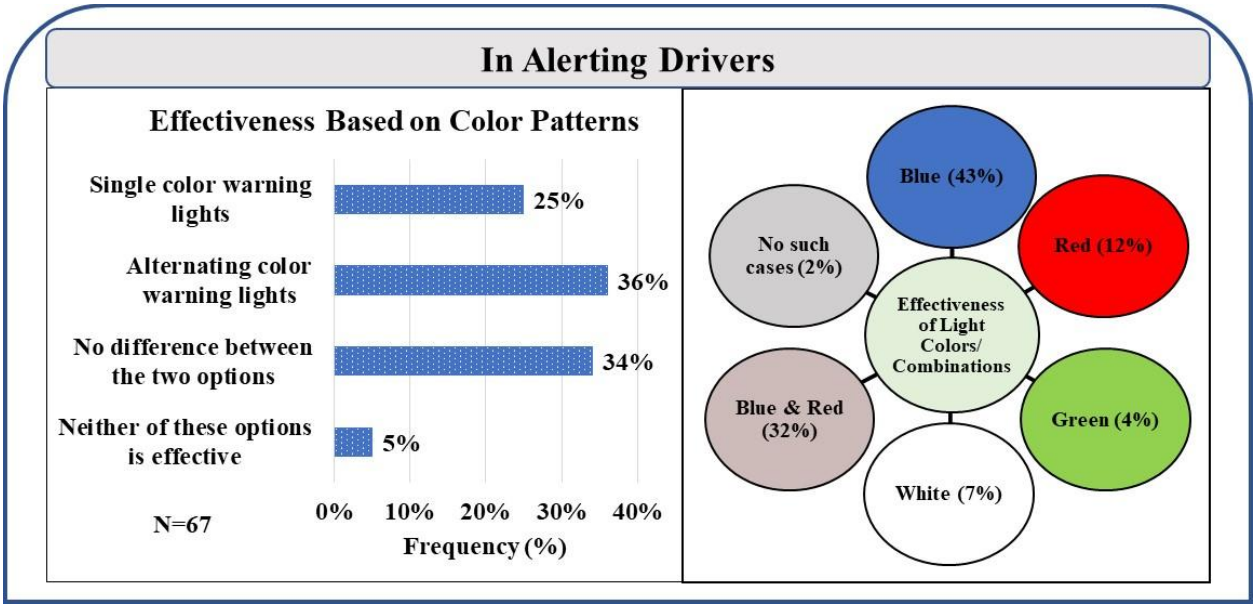


Figure 18. Effectiveness of color patterns in alerting drivers

5.3.6.4 In Causing Distraction

This section focuses on the responses based on blue lights causing distractions to road users passing work zones. Regarding potential distraction, 21% found them distracting, while 59% considered them non-distracting and effective (**Figure 19**). Specifically, 47% identified rapidly flashing blue lights as the most distracting when approaching or within a work zone, while 3% found slowly flashing blue lights to be distracting (**Figure 19**). Conversely, approximately 45% believed that none of the flashing configurations were distracting when using blue lights in work zones.

Overall, the results indicate amber/yellow and blue lights are most prevalent in work zones, with blue lights preferred for attention-capturing and warning signals. However, concerns exist about blue light distraction, especially rapid flashing. Understanding preferences and perceptions of drivers is crucial to optimizing blue light implementation strategies for greater effectiveness.

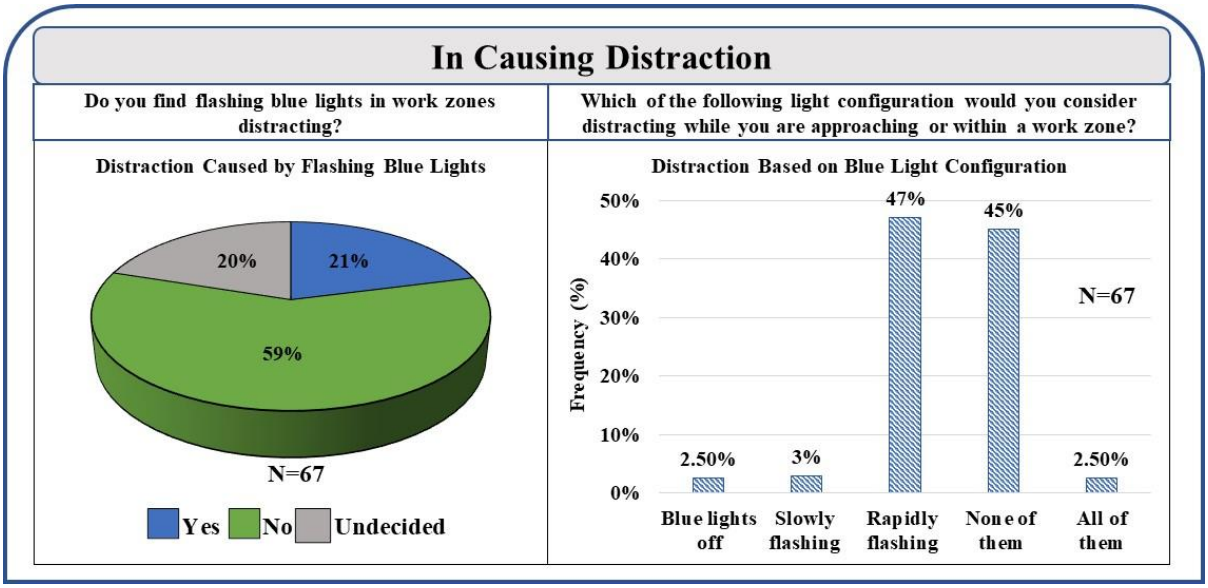


Figure 19. Blue light causes distractions for road users

Chapter 6. Field Data Collection, Analysis, and Results

After the survey responses analysis, a work zone was selected with the help of MDOT officials, where blue lights were deployed. Based on the work zone details, the traffic data collection procedure was set up, and the collected data were analyzed using statistical analysis methods. The following sections discuss field data collection, analysis, and results in detail.

6.1 Description of the Work Zone Site

A work zone site in Mississippi was selected for this project. The site was located in Hancock and Harrison counties of the Gulfport region. The primary task of this construction project was to widen the I-10 from Diamondhead to County Farm Road. The posted speed limit in the area was 70 mph. The project started on March 24, 2024, and is expected to continue for 1112 days with a completion date of March 30, 2027. The contractor assigned for this project was Huey P. Stockstill, LLC. A site map of the project is shown in **Figure 20**. The work zone was about 4 miles long, including the transition zone, active work zone, and termination zone. The beginning of the work zone, including the transition zone, was about 1 mile; the total active work zone was about 3 miles; and the termination zone was about 0.2 miles. The work zone included two active lanes adjacent to the main construction area (named Lane 1 and Lane 2 as shown in **Figure 21**). Lane 1 is the lane closer to the work zone, and Lane 2 is farther from the work zone. The lane configuration is depicted in **Figure 21**. The I-10 that ran along the work zone connected Alabama, Mississippi, and Louisiana. Specifically, the active work zone part of the work zone ran along Harrison and Hancock counties in Mississippi. These two counties played an important role in terms of blue light deployment.

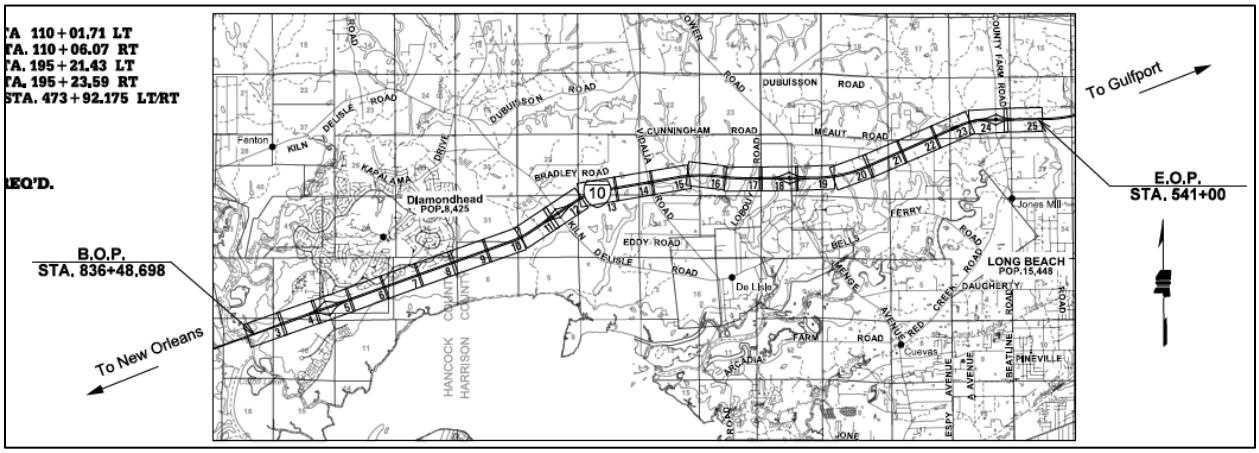


Figure 20. Site map of the work zone (Source: Provided by Huey P. Stockstill, LLC)

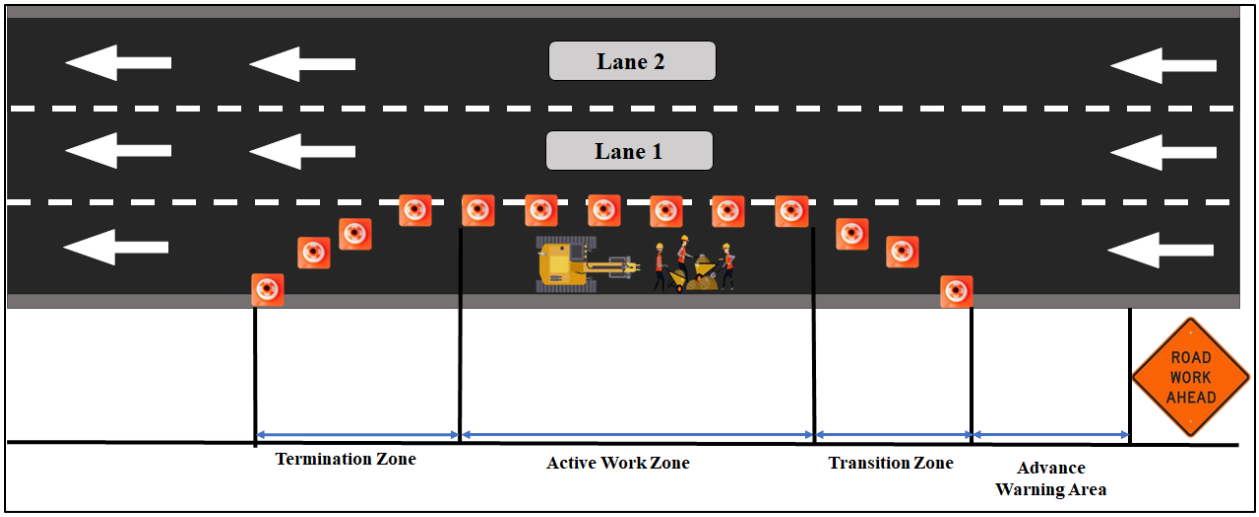


Figure 21. Lane configuration in the work zone

6.2 Locations of Blue Lights in the Work Zone

It is worth noting that the placement of police vehicles with blue lights in the work zone was determined by the contractor based on their requirements, instead of by the project team. No changes to the construction work zone layout or operational settings were requested or implemented to ensure that existing safety conditions were maintained. The project team only conducted measurements based on the configurations and conditions provided, without altering any construction activities or blue light locations.

Before commencing the data collection, an inspection of the work zone site was conducted by the project team, accompanied by the MDOT officials and site officials. This helped the project team assess the site and gather information on the locations of the blue lights. A Google map view of the work zone with the locations of blue lights and radars is shown in **Figure 22**. Two police vehicles with mounted blue lights were placed in the work zone. Blue light #1 belonged to the Harrison County Sheriff's Department, and blue light #2 belonged to the Hancock County Sheriff's Department. Neither of the police vehicles was allowed to cross the county line/border marked by the red line in **Figure 22**. In terms of their positions in the work zone during the construction tasks, the blue light #1 (**Figure 23a**) remained in the location between the beginning of the work zone and the portion of the active work zone that was on the right of the county line (i.e., always in Harrison County). It kept moving intermittently and stopped at different points instead of maintaining continuous motion or staying at the same location. Similarly, the movement of blue light #2 (**Figure 23b**) covered from the left of the county line towards the end of the active work zone (i.e., always in Hancock County). In this manner, the locations of blue lights varied in the work zone during the data collection period.

Figure 22. Details of the work zone with the locations of blue lights (Source: Google Earth)

(a) **(b)**

Figure 23. Blue light deployment: (a) at the beginning of the work zone (Harrison County), (b) at the active work zone (Hancock County)

6.3 Radar Deployment Corresponding to Blue Light Locations in the Work Zone

6.3.1 Description of the Radars

Three Speedlane Pro Radars from Houston Radar LLC (Houston Radar, n.d.) were used to collect data from the work zone. These radars were equipped to work under all weather conditions and collect data 24/7. The radars can collect data on volume and average speed from up to 16 lanes simultaneously. The collected data were stored in the Houston Radar Tetryon Server, which is a cloud server specifically designed to accompany these radars. **Figure 24** depicts the image of a Speedlane Pro radar used in this project for data collection.

Figure 24. Speedlane Pro radar used for data collection (Source: Houston Radar LLC)

6.3.2 Deployment of the Radars

The locations for deployment of the three radars were determined based on the work zone configuration and blue light deployment locations. Based on the blue light location, the work zone was divided into three parts (beginning of the work zone, first half of the active work zone, and second half of the active work zone) so that each radar represented a specific location for data collection. **Figure 25** represents the details of the work zone with the deployment locations of radars and blue lights.

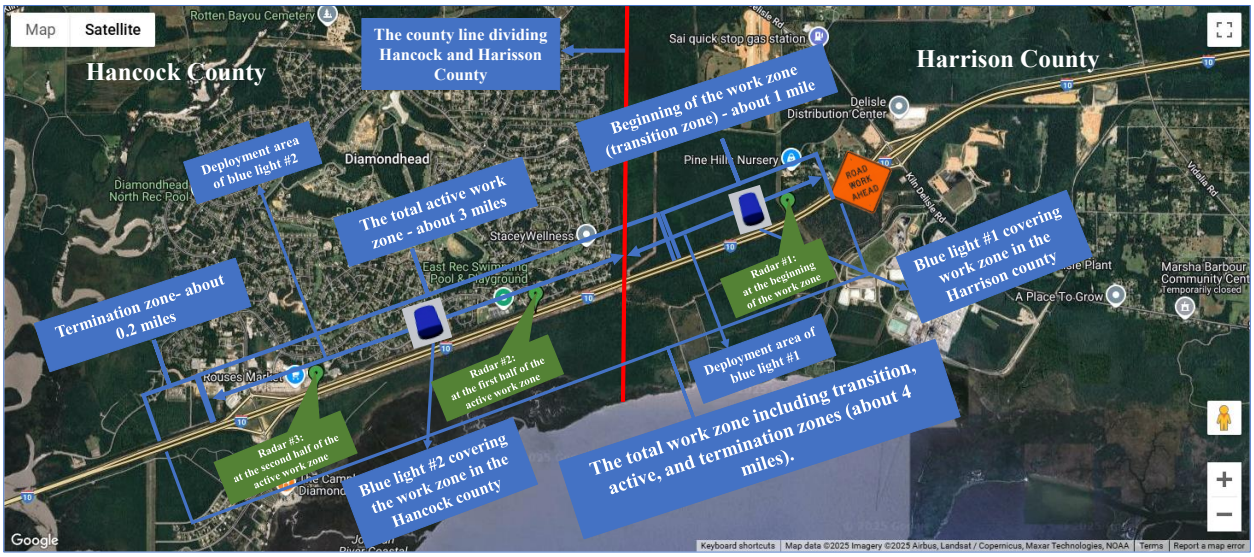


Figure 25. Details of the work zone with the locations of radars and blue lights (Source: Google Earth)

The first radar (Radar#1, **Figure 26a**) was deployed at the beginning of the work zone near the first blue light (**Figure 25**). Data collected from this radar represented the initial speed and volume of vehicles approaching the work zone. This location was important for understanding how drivers responded as they first encountered the work zone environment. The deployment of the second and third radars was stipulated based on the location of the second blue light. As the second blue light kept patrolling in the active work zone, for the radar deployment, the active work zone was divided into two parts. The second radar (Radar #2, **Figure 26b**) was deployed in the first half of the active work zone (**Figure 25**). Since the second blue light was patrolling within the active construction area, this radar was positioned to capture changes in traffic behavior after vehicles

had entered the work zone. The data provided insight into how speed and volume shifted once drivers moved beyond the entry point and encountered active construction activities. The third radar (Radar #3, **Figure 26c**) was placed in the second half of the active work zone (**Figure 25**). Data from this radar reflected vehicle speed and volume as motorists approached the termination zone while still in the active work zone area. This location allowed assessment of whether drivers increased, maintained, or reduced speed, and driving lane preference as they prepared to exit the work zone. The work zone had two active lanes all the time, and the radars collected data for both lanes simultaneously.

(a) **(b)** **(c)**

Figure 26. Setting of the radars deployed: (a) Radar #1 at the beginning of the work zone, (b) Radar #2 in the first half of the active work zone, (c) Radar #3 in the second half of the active work zone

6.4 Data Collection

The data collection for the project commenced after the deployment of the law enforcement vehicles with blue lights and radars. The data collection started from September 14th, 2024, to November 7th, 2024, which is a total of 55 days. During this period of data collection, all the radars were active for 24 hours, and the blue lights were deployed during most of the ongoing construction in the work zone.

The schedule of the construction work in the work zone was mainly determined by the contractor. The construction work in the work zone mostly occurred in 12-hour shifts for daytime and nighttime. The 6:00 am to 6:00 pm shifts were designated as daytime work shifts, and the 6:00 pm to 6:00 am shifts were designated as nighttime work shifts. The work shifts scheduled from Monday to Friday were designated as weekdays, and the work shifts scheduled from Saturday to Sunday were considered as weekends.

The work zone conditions were determined based on the presence and absence of construction in the work zone and the deployment of blue lights during the data collection process. The radars also collected data during the absence of ongoing construction work in the work zone, but that data was

excluded as it did not fall under the project scope. Accordingly, two work zone conditions were determined for this project:

I. **Construction with the Presence of Blue Lights:** This includes the data collected when there was the presence of law enforcement vehicles with blue lights during ongoing construction in the work zone for both the daytime and nighttime work shifts. The amount of data collected under this condition is about 372 hours, including both daytime and nighttime.
II. **Construction without the Presence of Blue Lights:** This includes the data collected when there was no presence of blue lights in the work zone during ongoing construction. This includes both the daytime and nighttime work shifts. The amount of data collected under this condition is about 104 hours, including both daytime and nighttime.

The amount of data collected under condition II was relatively low because the construction work conducted involved cleaning the sites, moving materials, and preparing the site for paving. In most cases, the contractor required blue light in the work zone during essential construction works; as a result, the amount of data for construction with the presence of blue lights (condition I) was more than the data collected in condition II. A summary of the collected data for both daytime and nighttime, including all the work zone conditions and locations, weekdays and weekends, is provided in **Error! Reference source not found.**. The data was collected using two metrics from the work zone, including volume and average speed (mph). For the volume, each radar collected data on the total number of vehicles at every five-minute interval. Each radar also collected the average vehicle speed of the vehicles during every five-minute interval. The distribution of data points for both metrics is summarized in **Table 4**.

Table 3. Summary of the collected data (Daytime: 6 am to 6 pm, Nighttime: 6 pm to 6 am)

Conditions	Construction with the Presence of Blue Lights						Construction without the Presence of Blue Lights					
Work Zone Location	The beginning of the work zone		The first half of the active zone		The second half of the active zone		The beginning of the work zone		The first half of the active zone		The second half of the active zone	
Radar	Radar #1		Radar #2		Radar #3		Radar #1		Radar #2		Radar #3	
Day/Time	Day (hours)	Night (hours)	Day (hours)	Night (hours)	Day (hours)	Night (hours)	Day (hours)	Night (hours)	Day (hours)	Night (hours)	Day (hours)	Night (hours)
Monday	12	72	12	72	12	72	10	0	10	0	10	0
Tuesday	12	72	12	72	12	72	0	0	0	0	0	0
Wednesday	0	66	0	66	0	66	30	6	30	6	30	6
Thursday	0	54	0	54	0	54	20	12	20	12	20	12
Friday	12	30	12	30	12	30	20	6	20	6	20	6
Saturday	0	6	0	6	0	6	0	0	0	0	0	0
Sunday	0	36	0	36	0	36	0	0	0	0	0	0
Total	36	336	36	336	36	336	80	24	80	24	80	24
	372		372		372		104		104		104	

Table 4. Distribution of data points (Daytime: 6 am to 6 pm, Nighttime: 6 pm to 6 am)

Conditions	Construction with the Presence of Blue Lights						Construction without the Presence of Blue Lights					
Work Zone Location	The beginning of the work zone		The first half of the active zone		The second half of the active zone		The beginning of the work zone		The first half of the active zone		The second half of the active zone	
Radar	Radar #1		Radar #2		Radar #3		Radar #1		Radar #2		Radar #3	
Days	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
Monday	288	1728	288	1728	288	1728	240	0	240	0	240	0
Tuesday	288	1728	288	1728	288	1728	0	0	0	0	0	0
Wednesday	0	1584	0	1584	0	1584	720	144	720	144	720	144
Thursday	0	1296	0	1296	0	1296	480	288	480	288	480	288
Friday	288	720	288	720	288	720	480	144	480	144	480	144
Saturday	0	144	0	144	0	144	0	0	0	0	0	0
Sunday	0	864	0	864	0	864	0	0	0	0	0	0
Total	864	8064	864	8064	864	8064	1920	576	1920	576	1920	576
	8928		8928		8928		2496		2496		2496	

6.5 Data Analysis Methods

6.5.1 Normality Testing of the Data

A normality test was conducted for both traffic volume and average speed under the two work zone conditions. The Kolmogorov-Smirnov test was used to evaluate whether the data followed a normal distribution, with the hypotheses set at a significance level of 0.05 (Hanusz & Tarasińska, 2015). The results indicated that the data did not meet the assumption of normality. All additional details of the normality test, including statistical values and visualizations, are presented in Appendix B.

6.5.2 Statistical Methods for Hypothesis Tests

According to the results of the normality test, the data collected for this project did not follow a normal distribution. This means the data were non-parametric, and thus non-parametric statistical tests were determined for the analysis of the data (Vrbin, 2022). For the hypothesis testing of the collected data, two statistical methods, i.e., the Mann-Whitney U test and the Aligned Rank Test ANOVA (ART ANOVA) test, were chosen based on the number of independent variables involved. The Mann-Whitney U test is a non-parametric statistical test that is used to compare the samples of two independent variables. It is used for hypothesis tests to determine whether there is any significant difference between the samples of the two independent variables (Nachar, 2008). ART ANOVA is a non-parametric statistical test that is used when dealing with multiple independent variables. For this project, to compare more than two independent variables, the ART ANOVA test was performed (Wobbrock et al., 2011).

Prior to conducting the hypothesis tests, power analysis was performed to ensure that the data met the minimum sample size requirements necessary for the selected statistical methods. For the Mann-Whitney U test, the power analysis was done using Cohen's r test (Okoye & Hosseini, 2024). The required assumptions for this analysis were set up beforehand. The effect size was set as 0.2, which means a minimum effect; the significance level, α, was set at 0.05, and the desired power was set at 0.8. For the ART ANOVA test, the power analysis was performed using Cohen's f test (Wobbrock et al., 2011). The analysis was based on the following assumptions: an effect size (f) of 0.25, which represents a medium effect according to Cohen's guidelines, a significance level (α) of 0.05, and a desired statistical power of 0.8. The power analysis results confirmed that the available data satisfied the minimum sample size requirements for the planned statistical tests.

6.6 Preliminary Data Analysis

Before conducting the hypothesis tests, the data were pre-processed and preliminarily analyzed. The data for traffic volume and average vehicle speed were separated. The preliminary analysis included conducting initial hypothesis tests, which helped organize the data for further in-depth analysis. This preliminary analysis focused on hypothesis testing for finding the difference between the data for daytime and nighttime, weekdays and weekends, under the work zone conditions: (i) construction with the presence of blue lights and (ii) construction without the presence of blue lights. The tests are listed below:

i. Differences in data between daytime and nighttime for construction with the presence of blue lights.
ii. Differences in data between weekdays and weekends for construction with the presence of blue lights.
iii. Difference in data between daytime and nighttime for construction without the presence of blue lights.

It is worth noting that the hypothesis testing for the data between the weekdays and weekends for construction without the presence of blue light has not been included, as there has not been any work scheduled during the weekends without the presence of blue lights (see **Error! Reference source not found.**). The above-listed hypothesis tests were conducted in terms of each metric (volume and average speed) as a preliminary analysis. The results of these tests helped organize the data for further hypothesis testing. The next section discusses the details of the statistical analysis performed for each metric.

6.7 Roadmap of Hypothesis Test

To maintain consistency in the presentation of results, each hypothesis is explained following a structured format depending on the type of statistical test applied. For the Mann-Whitney U tests (two-group comparisons), the structure is shown in

Table 5, and for the ART ANOVA tests (multi-group comparisons), the structure is shown in

Table 6. These roadmaps provide a clear guide for how the hypotheses are presented in the following sections (6.8-6.13).

Table 5. Structure of hypothesis explanations for the Mann Whitney U test

Step	Description
1. Hypothesis Statement	Presentation of the null (H_0) and alternative (H_1) hypotheses.
2. Data Collected	Description of the two independent groups, including the number of observations and a representative table.
3. Analysis Strategy	Indication that the Mann-Whitney U test was applied for two-group comparisons.
4. Analysis Results	Reporting statistical outcomes, including p-values and significance decisions. Descriptive statistics (e.g., median and interquartile range) are also included to support interpretation.
5. Discussion (when applicable)	In some cases, a discussion section is provided to interpret the results. Certain hypotheses also incorporate density plots to illustrate distributional differences, while others rely solely on statistical results and descriptive statistics.

Table 6. Structure of hypothesis explanations for the ART ANOVA test

Step	Description
1. Hypothesis Statement	Presentation of the null (H_0) and alternative (H_1) hypotheses.
2. Data Collected	Division of the dataset into three or more groups, with observation counts and a representative table.
3. Analysis Strategy	The specification that ART ANOVA was used to test for overall differences between groups.
4. Analysis Results	Presentation of the overall ART ANOVA results, including p-values and significance decisions. Descriptive statistics are also provided to highlight trends in the data.
5. Post Hoc Pairwise Comparisons	Where overall differences were significant, additional pairwise comparisons are reported to identify which specific groups differ.
6. Discussion (when applicable)	Interpretation of the results. In most cases, density plots are included to illustrate subtle shifts and distributional patterns between groups, reinforcing the statistical findings.

6.8 Preliminary Analysis for Volume

The preliminary analysis focused on exploring the collected traffic volume data. Three hypothesis tests were conducted to determine the most efficient manner for the collected data for further in-depth analysis to assess the effect of blue lights on traffic volume under different conditions. These tests included assessing the traffic volume differences between daytime and nighttime, as well as between weekdays and weekends, for two conditions: (i) construction with the presence of blue lights and (ii) construction without the presence of blue lights. A summary of the test results is provided in

Table 7, and more details about each hypothesis test are provided in the following sections, with a summary and insights at the end.

Table 7. Summarized results of the preliminary hypothesis tests for traffic volume

Number	Details	Results
Hypothesis 1	Daytime vs. Nighttime, for Construction with the Presence of Blue Lights	Significant difference
Hypothesis 2	Weekdays vs. Weekends, for Construction with the Presence of Blue Lights	No significant difference
Hypothesis 3	Daytime vs. Nighttime, for Construction without the Presence of Blue Lights	Significant difference

6.8.1 Hypothesis 1. Daytime vs. Nighttime, for Construction with the Presence of Blue Lights

H_0: *There is no significant difference in traffic volume between daytime and nighttime in the presence of blue lights during construction work.*

H_1: *There is a significant difference in traffic volume between daytime and nighttime in the presence of blue lights during construction work.*

Data Collected: For this analysis, the data collected were divided into two categories:

- Daytime construction with the presence of blue lights - 2592 observations
- Nighttime construction with the presence of blue lights - 24192 observations

An illustration of the dataset is depicted in **Table 8**.

Table 8. Data points for daytime vs. nighttime - construction with the presence of blue lights

Daytime Traffic Volume (per five minutes)	Nighttime Traffic Volume (per five minutes)
25	65
45	85
X	X
X	X
44	32
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Strategy: The Mann-Whitney U test was conducted for the hypothesis testing of comparing the data (two independent variables) shown in **Table 8**.

Analysis Results: The Mann-Whitney U test showed that the p-value is 2.2e-16, which is smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it can be concluded that there is a statistically significant difference in traffic volume between daytime and nighttime in the presence of blue lights during construction work.

As a result, for further analysis of the volume metric in terms of construction with the presence of blue lights, the data were organized by separating daytime and nighttime conditions in all cases.

6.8.2 Hypothesis 2. Weekdays vs. Weekends, for Construction with the Presence of Blue Lights

***H_0**: There is no significant difference in traffic volume between weekdays and weekends in the presence of blue lights during construction work.*

***H_1**: There is a significant difference in traffic volume between weekdays and weekends in the presence of blue lights during construction work.*

Data Collected: For this analysis, the data collected were divided into two categories:

- Weekday construction with the presence of blue lights - 23760 observations
- Weekend construction with the presence of blue lights - 3024 observations

An illustration of the dataset is depicted in **Table 9**.

Table 9. Data points for weekdays vs. weekends - construction with the presence of blue lights

Weekday Traffic Volume (per five minutes)	Weekend Traffic Volume (per five minutes)
30	47
50	25
X	X
X	X
28	58
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Strategy: The Mann-Whitney U test was conducted for the hypothesis testing of comparing the data (two independent variables) shown in **Table 9**.

Analysis Results: According to the results of the Mann-Whitney U test, the p-value is 0.7328, which is greater than the significance level ($\alpha = 0.05$). This provided insufficient evidence to reject the null hypothesis. Therefore, it can be concluded that there is no statistically significant difference in traffic volume between weekdays and weekends in the presence of blue lights during construction work.

As a result, for further analysis of the volume metric, the data for weekdays and weekends under the above-mentioned condition could be considered together.

6.8.3 Hypothesis 3. Daytime vs. Nighttime, for Construction without the Presence of Blue Lights

H_0: *There is no significant difference in traffic volume between daytime and nighttime when there is construction without the presence of blue lights.*

H_1: *There is a significant difference in traffic volume between daytime and nighttime when there is construction without the presence of blue lights.*

Data Collected: For this analysis, the data collected were divided into two categories:

- Daytime construction without the presence of blue lights - 5760 observations
- Nighttime construction without the presence of blue lights - 1728 observations

An illustration of the dataset is depicted in **Table 10**.

Table 10. Data points for daytime vs. nighttime - construction without the presence of blue lights

Daytime Traffic Volume (per five minutes)	Nighttime Traffic Volume (per five minutes)
55	20
85	35
X	X
X	X
45	28
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Strategy: The Mann-Whitney U test was conducted for the hypothesis testing of comparing the data (two independent variables) shown in **Table 10**.

Analysis Results: According to the results of the Mann-Whitney U test, the p-value is less than 2.2e-16, which is smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it can be concluded that there is a statistically significant difference in traffic volume between daytime and nighttime for construction without the presence of blue lights.

As a result, for further analysis of the volume metric in terms of construction without the presence of blue lights, the data was organized by separating daytime and nighttime conditions.

6.8.4 Summary of Preliminary Analysis for Traffic Volume

The results of the preliminary analysis (Hypothesis 1- Hypothesis 3) provide important insights into the data collected for traffic volume from the work zone. It provides an idea of how the daytime and nighttime, weekday and weekend conditions have an impact on the traffic volume. For the traffic volume between daytime and nighttime, significant differences were observed for all the work zone conditions, including construction with the presence of blue lights and construction without the presence of blue lights. In terms of traffic volume between weekdays and weekends, no significant differences were observed for the condition, construction with the presence of blue lights.

Based on these results, two categories of analysis strategies were determined. **Category One** focused on the analysis of traffic volume for individual work zone locations and lanes within the work zone condition, construction, with the presence of blue lights. **Category Two** compared the traffic volume for individual work zone locations and lanes between the conditions, construction with the presence of blue lights, and construction without the presence of blue lights.

6.9 Category One: Analysis of Traffic Volume for Construction with the Presence of Blue Lights in the Work Zone

This category focuses on analyzing the effect of construction with the presence of blue lights in the selected work zone on traffic volume. Based on the results from the preliminary analysis (Section 6.8), a total of ten hypothesis tests were proposed and conducted to assess the effect of construction with the presence of blue lights on traffic volume. This included comparing the traffic volume differences by considering several factors, including lanes, individual three work zone locations, and daytime and nighttime. **Table 11** summarizes the test results for the ten hypotheses under this category. More details about each hypothesis test, including the individual hypothesis statements, data pre-processing, results analysis, and discussion (following the roadmap explained in

Table 5 or

Table 6), are presented in the following sections. An overall summary and key insights are provided at the end of the section.

Table 11. Summarized results of the category 1 hypothesis tests for traffic volume

Number	Details	Results
Hypothesis 1	Daytime, Construction with the Presence of Blue Lights, Lane 1 vs. Lane 2	Significant difference
Hypothesis 2	Nighttime, Construction with the Presence of Blue Lights, Lane 1 vs. Lane 2	Significant difference
Hypothesis 3	Lane 1, Construction with the Presence of Blue Lights, Daytime vs. Nighttime	Significant difference
Hypothesis 4	Lane 2, Construction with the Presence of Blue Lights, Daytime vs. Nighttime	Significant difference
Hypothesis 5	Daytime, Lane 1, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	No significant difference
Hypothesis 6	Daytime, Lane 2, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 7	Nighttime, Lane 1, Construction with Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 8	Nighttime, Lane 2, Construction with Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 9	Daytime, Lane 1 vs. Lane 2, Construction with Blue Lights for Individual Work Zone Locations	Significant difference
Hypothesis 10	Nighttime, Lane 1 vs. Lane 2, Construction with Blue Lights for Individual Work Zone Locations	Significant difference

6.9.1 Hypothesis 1: Daytime, Construction with the Presence of Blue Lights, Lane 1 vs. Lane 2

This analysis examined whether traffic volume differed significantly between Lane 1 and Lane 2 during the daytime when construction work was ongoing in the presence of blue lights. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume between lane 1 and lane 2 during the daytime when blue lights are present during construction work.*

H_1: *There is a significant difference in traffic volume between lane 1 and lane 2 during the daytime when blue lights are present during construction work.*

Data Collected: For this analysis, the data collected were divided into two categories:

- Lane 1 daytime construction with the presence of blue lights - 1296 observations
- Lane 2 daytime construction with the presence of blue lights - 1296 observations

An illustration of the dataset is depicted in **Table 12**.

Table 12. Data points for traffic volume for lane 1 vs. lane 2 - daytime for construction with the presence of blue lights

Lane 1 Traffic Volume	Lane 2 Traffic Volume
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test.

Analysis Results: The Mann-Whitney U test showed that the p-value was 2.2e-16, which is smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it can be concluded that there was a statistically significant difference in traffic volume between Lane 1 and Lane 2 during daytime construction with the presence of blue lights. According to the descriptive statistics, the median volume for Lane 1 was 54, and for Lane 2 was 58, with an interquartile range (IQR) of 18 and 11, respectively. Although the median difference appeared small, the density plot in **Figure 27** helps illustrate the difference more clearly by visualizing the distribution of the traffic volume among the lanes. It shows that traffic volumes in Lane 2 were more consistently observed around slightly higher values, while Lane 1 had traffic counts that varied more. This visual pattern supports the statistical significance found in the test. This difference may have been attributed to drivers favoring Lane 2, which was the farthest from the work zone. This preference may have been influenced by the visual cue provided by the blue lights during daytime construction.

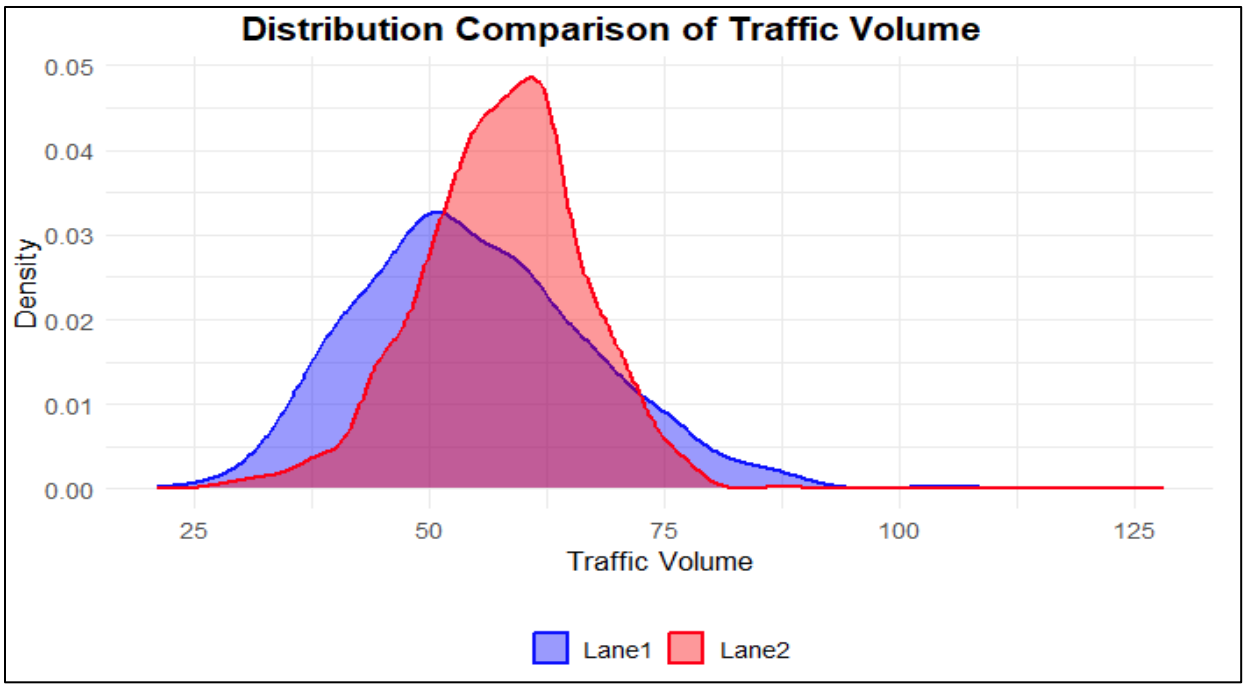


Figure 27. Traffic volume distribution in both lanes at daytime

6.9.2 Hypothesis 2: Nighttime, Construction with the Presence of Blue Lights, Lane 1 vs. Lane 2

This analysis examined whether traffic volume differed significantly between Lane 1 and Lane 2 during the nighttime when construction work is ongoing in the presence of blue lights. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume between lane 1 and lane 2 during the nighttime when blue lights are present during construction work.*

H_1: *There is a significant difference in traffic volume between lane 1 and lane 2 during the nighttime when blue lights are present during construction work.*

Data Collected: For this analysis, the data collected were divided into two categories:

- Lane 1 nighttime construction with the presence of blue lights - 1296 observations
- Lane 2 nighttime construction with the presence of blue lights - 1296 observations

An illustration of the dataset is depicted in

Table 13.

Table 13. Data points for traffic volume for lane 1 vs. lane 2 - nighttime for construction with the presence of blue lights

Lane 1 Traffic Volume	Lane 2 Traffic Volume
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test showed that the p-value is 2.2e-16, which is smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it can be concluded that there was a statistically significant difference in traffic volume between Lane 1 and Lane 2 during nighttime construction with the presence of blue lights. According to the descriptive statistics, the median volume for Lane 1 was 8, and for Lane 2 was 26, with an IQR of 22 and 24, respectively. Although both lanes displayed a wide range of traffic volumes, the density plot in **Figure 28** clearly illustrates the substantial difference between them. Lane 1 had most observations near zero, meaning fewer vehicles were using this lane during nighttime construction. In contrast, Lane 2 had higher traffic volumes more frequently. This visible difference supported the statistical result and confirmed that drivers preferred Lane 2. This lane preference may have been influenced by the visibility and positioning of the blue lights during nighttime construction. Moreover, nighttime traffic volumes were generally lower because fewer people traveled during these hours compared to daytime office hours. This overall reduction in traffic volume may also have contributed to the differences in traffic volume between the lanes.

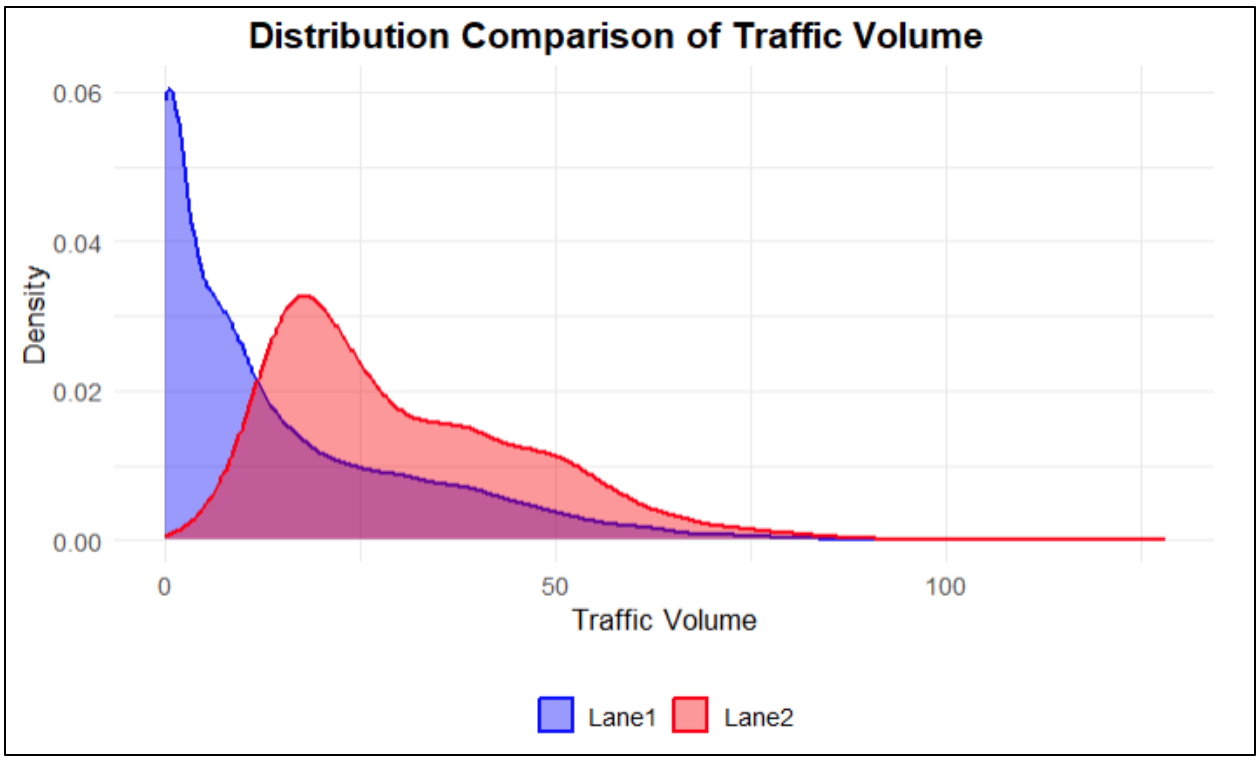


Figure 28. Traffic volume distribution in both lanes at nighttime

6.9.3 Hypothesis 3: Lane 1, Construction with the Presence of Blue Lights, Daytime vs. Nighttime

This analysis examined whether traffic volume in Lane 1 differed significantly between daytime and nighttime when construction work is ongoing in the presence of blue lights. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume during the daytime and nighttime for lane 1 when blue lights are present during construction work.*

H_1: *There is a significant difference in traffic volume during the daytime and nighttime for lane 1 when blue lights are present during construction work.*

Data Collected: For this analysis, the data collected were divided into two categories:

- Daytime lane 1 construction with the presence of blue lights - 1296 observations
- Nighttime lane 1 construction with the presence of blue lights - 12096 observations

An illustration of the dataset is depicted in

Table 14.

Table 14. Data points for traffic volume for daytime vs nighttime - lane 1 for construction with the presence of blue lights

Traffic Volume for Daytime	Traffic Volume for Nighttime
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test showed that the p-value was 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it can be concluded that there was a statistically significant difference in traffic volume in Lane 1 between daytime and nighttime during construction with the presence of blue lights.

According to the descriptive statistics, the median volume during the daytime was 54, while at nighttime it dropped to 8. Additionally, the IQR increased from 17 during the daytime to 22 at night, indicating greater variability in nighttime traffic volume despite the overall lower median. The difference in medians is substantial, and the density plot in **Figure 29** reinforces this finding. It shows that daytime traffic volume in Lane 1 was generally observed at higher values, while nighttime traffic volume was mostly recorded at very low values. This suggests that during the daytime, despite the presence of blue lights, drivers were more likely to use Lane 1 compared to nighttime. A possible reason is that blue lights are more visible at night, which may prompt drivers to avoid Lane 1 and shift to the farther lane for safety.

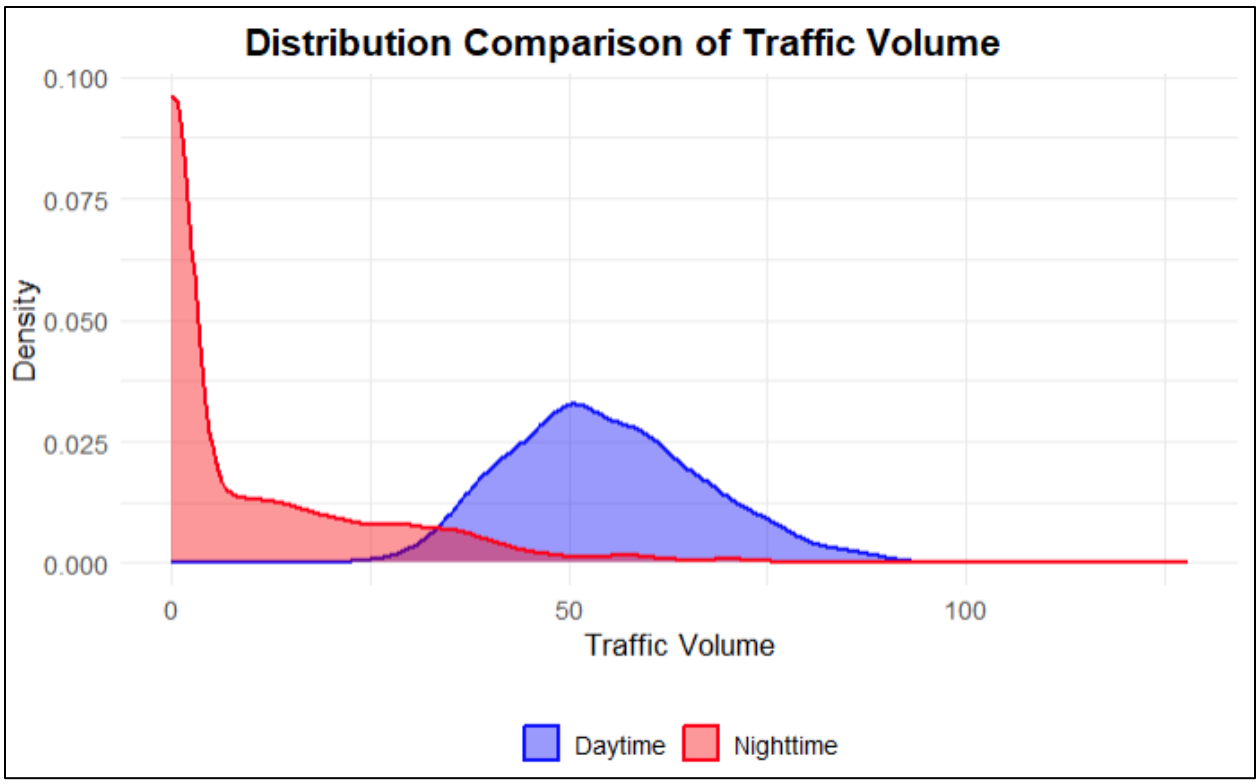


Figure 29. Traffic volume distribution in both daytime and nighttime

6.9.4 Hypothesis 4: Lane 2, Construction with the Presence of Blue Lights, Daytime vs. Nighttime

This analysis examined whether traffic volume in Lane 2 differed significantly between daytime and nighttime when construction work is ongoing in the presence of blue lights. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume during the daytime and nighttime for lane 2 when blue lights are present during construction work.*

H_1: *There is a significant difference in traffic volume during the daytime and nighttime for lane 2 when blue lights are present during construction work.*

Data Collected: For this analysis, the data collected were divided into two categories:

- Daytime lane 2 construction with the presence of blue lights - 1296 observations
- Nighttime lane 2 construction with the presence of blue lights - 12096 observations

An illustration of the dataset is depicted in the

Table 15.

Table 15. Data points for traffic volume for daytime vs nighttime - lane 2 for construction with the presence of blue lights

Traffic Volume for Daytime	Traffic Volume for Nighttime
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test showed that the p-value is 2.2e-16, which is smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it can be concluded that there was a statistically significant difference in traffic volume in Lane 2 between daytime and nighttime during construction with the presence of blue lights. According to the descriptive statistics, the median volume during the daytime was 58, while at nighttime it was 26. Additionally, the IQR increased from 11 during the daytime to 24 at night, indicating that traffic volume varied more during nighttime**.** To better illustrate this difference, the density plot in **Figure 30** compares the distribution of traffic volume between the two periods. shows that daytime traffic in Lane 2 was generally observed at higher volume levels, while nighttime traffic was recorded more frequently at lower values. This visual representation supports the statistical findings and highlights the drop in volume at night. This may be due to reduced traffic levels in general at night, as well as drivers being more cautious because the blue lights are more visible.

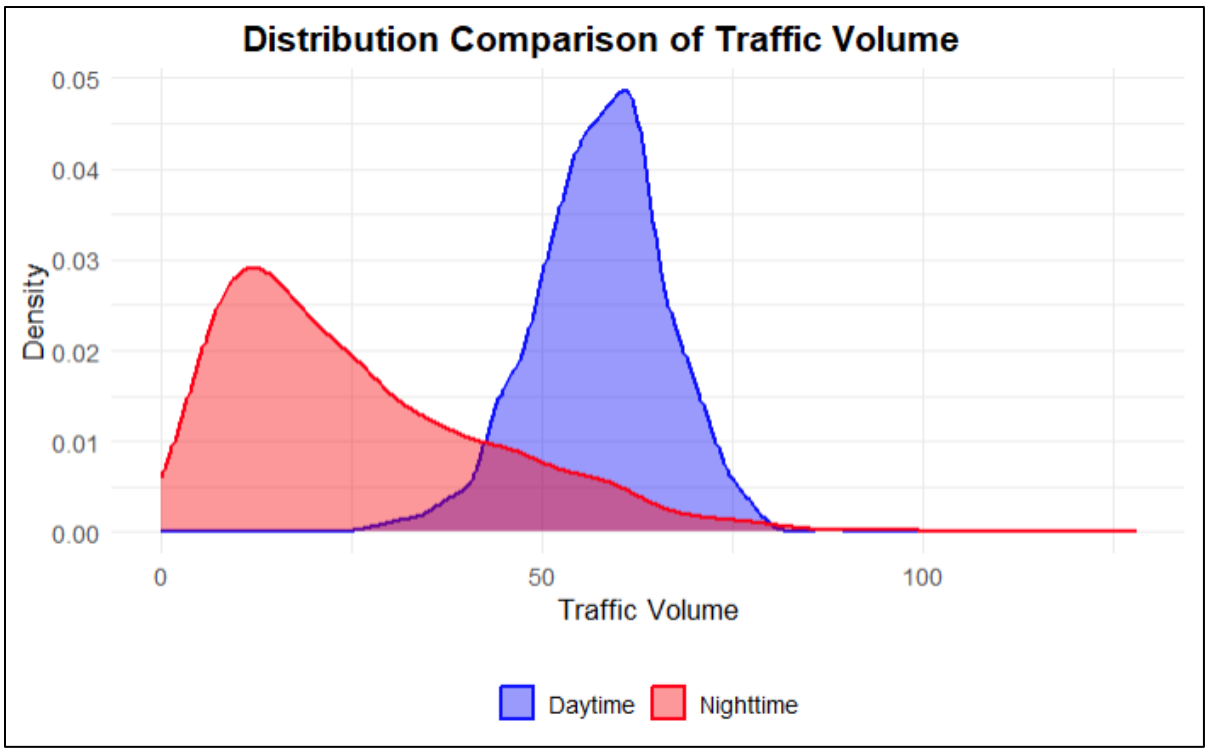


Figure 30. Traffic volume distribution in both daytime and nighttime

6.9.5 Hypothesis 5: Daytime, Lane 1, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis aimed to compare traffic volume for Lane 1 during daytime among three individual work zone locations - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone in the presence of blue lights during ongoing construction. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 1 during daytime when blue lights are present during construction work.*

H_1: *There is a significant difference in traffic volume between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 1 during daytime when blue lights are present during construction work.*

Data Collected: For hypothesis testing, the traffic volume for lane 1 during daytime in the presence of blue lights was divided into three categories:

- Daytime lane 1, beginning of the work zone: 432 observations
- Daytime lane 1, first half of the active work zone: 432 observations
- Daytime lane 1, second half of the active work zone: 432 observations

An illustration of the dataset is depicted in **Table 16**.

Table 16. Data points for daytime lane 1 traffic volume for individual work zone locations

Traffic Volume for the Beginning of the Work Zone	Traffic Volume for the First Half of the Active Work Zone	Traffic Volume for the Second Half of the Active Work Zone
56	40	35
45	37	48
X	X	X
X	X	X
X	X	X
22	44	21

Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 0.0965, which is greater than the significance level ($\alpha = 0.05$). Therefore, there was no sufficient evidence to reject the null hypothesis, and it can be concluded that there was no statistically significant difference in traffic volume for Lane 1 between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during daytime when construction work was ongoing with the presence of blue lights. The results from the post hoc pairwise comparisons are shown in **Table 17**.

Table 17. Post hoc pairwise comparison results

Comparison	p-value
Beginning - First Half	0.0918
Beginning - Second Half	0.8584
First Half - Second Half	0.818

Post Hoc Pairwise Comparisons:

Beginning of the work zone vs. First half of the active work zone: The comparison yielded a p-value of 0.0918, indicating no statistically significant difference. The median traffic volume was 53 vehicles at the beginning of the work zone and 55 vehicles in the first half of the active work zone.

Beginning of the work zone vs. Second half of the active work zone: The comparison yielded a p-value of 0.8584, indicating no statistically significant difference. The median traffic volume was 53 vehicles at the beginning of the work zone and 54 vehicles in the second half of the active work zone.

First half of the active work zone vs. Second half of the active work zone: The comparison yielded a p-value of 0.818, indicating no statistically significant difference. The median traffic volume was 55 vehicles in the first half of the active work zone and 54 vehicles in the second half of the active work zone.

6.9.6 Hypothesis 6: Daytime, Lane 2, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis aimed to compare traffic volume for Lane 2 during daytime among three individual work zone locations - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone in the presence of blue lights during ongoing construction. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 2 during daytime when blue lights are present during construction work.*

H_1: *There is a significant difference in traffic volume between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 2 during daytime when blue lights are present during construction work.*

Data Collected: For the hypothesis testing, the traffic volume for lane 2 during daytime in the presence of blue lights was divided into three categories:

- Daytime lane 2, beginning of the work zone: 432 observations
- Daytime lane 2, first half of the active work zone: 432 observations
- Daytime lane 2, second half of the active work zone: 432 observations

An illustration of the dataset is depicted in **Table 18**.

Table 18. Data points for lane 2 traffic volume for individual work zone locations

Traffic Volume for the Beginning of the Work Zone	Traffic Volume for the First Half of the Active Work Zone	Traffic Volume for the Second Half of the Active Work Zone
56	40	35
45	37	48
X	X	X
X	X	X
X	X	X
22	44	21
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.		

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 2.2493e-05, which is smaller than the significance level ($\alpha = 0.05$). Therefore, there was sufficient evidence to reject the null hypothesis, and it can be concluded that there was a statistically significant difference in traffic volume for Lane 2 between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during daytime when construction work was ongoing with the presence of blue lights. The results from the post hoc pairwise comparisons are shown in **Table 19**.

Table 19. Post hoc pairwise comparison results

Comparison	p-value
Beginning - First Half	<.0001
Beginning - Second Half	0.0018
First Half - Second Half	0.9616

Post Hoc Pairwise Comparisons:

Beginning of the work zone vs. First half of the active work zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median traffic volume was 60 vehicles at the beginning of the work zone and 57 vehicles in the first half of the active work zone.

Beginning of the work zone vs. Second half of the active work zone: The comparison yielded a p-value of 0.0018, suggesting a significant difference. The median traffic volume was 60 vehicles at the beginning of the work zone and 58 vehicles in the second half of the active work zone.

First half of the active work zone vs. Second half of the active work zone: The comparison yielded a p-value of 0.9616, indicating no statistically significant difference. The median traffic volume was 57 vehicles in the first half of the active work zone and 58 vehicles in the second half of the active work zone.

Discussion: The ART ANOVA results confirmed a statistically significant difference in traffic volume for Lane 2 among the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during daytime with the presence of blue lights. The descriptive statistics showed a slight reduction in median traffic volume from the beginning of the work zone (60 vehicles) to the first half (57 vehicles) and the second half (58 vehicles) of the active work zone.

The post hoc comparisons further supported this finding, revealing that the beginning of the work zone differed significantly from both the first and second halves of the active work zone, whereas no significant difference was observed between the two active work zone locations. To better understand this difference, the density plot in **Figure 31** visually compares the traffic volume distributions for the three segments. It shows that traffic volume at the beginning of the work zone was slightly higher compared to the first and second halves of the active work zone. As vehicles moved into the active work zone sections, the traffic volume appeared to decrease slightly. The differences are small, but the figure clearly shows these changes in traffic levels through the work

zone, supporting the statistical results. These findings suggest that the presence of blue lights, especially after entering the active work zone, may have contributed to a small reduction in traffic volume for Lane 2 during daytime conditions.

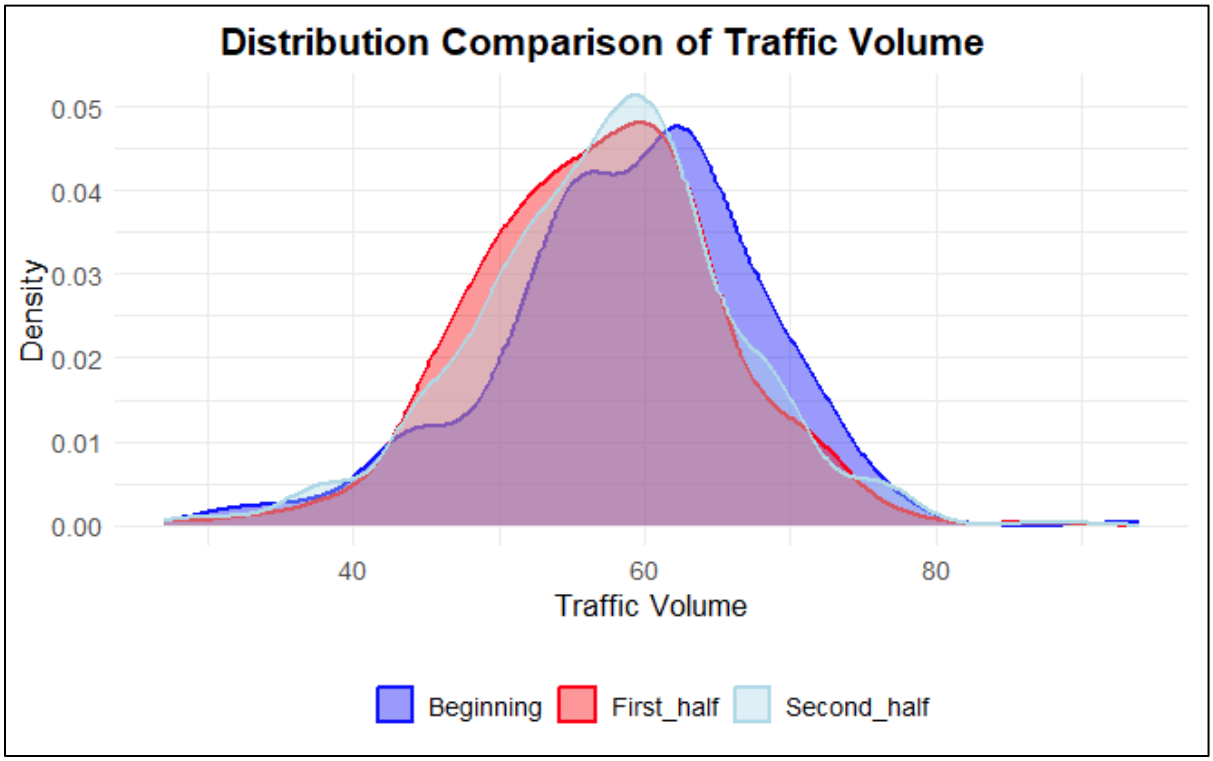


Figure 31. Traffic volume distribution for the individual work zone locations

6.9.7 Hypothesis 7: Nighttime, Lane 1, Construction with Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis aimed to compare traffic volume for lane 1 during nighttime between three individual work zone locations - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone in the presence of blue lights during ongoing construction. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 1 during nighttime when blue lights are present during construction work.*

H_1: *There is a significant difference in traffic volume between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 1 during nighttime when blue lights are present during construction work.*

Data Collected: For hypothesis testing, the traffic volume for lane 1 during nighttime in the presence of blue lights was divided into three categories:

- Nighttime lane 1, beginning of the work zone: 4032 observations

- Nighttime lane 1, first half of the active work zone: 4032 observations
- Nighttime lane 1, second half of the active work zone: 4032 observations

An illustration of the dataset is depicted in **Table 20**.

Table 20. Data points for nighttime lane 1 traffic volume for individual work zone locations

Traffic Volume for the Beginning of the Work Zone	Traffic Volume for the First Half of the Active Work Zone	Traffic Volume for the Second Half of the Active Work Zone
56	40	35
45	37	48
X	X	X
X	X	X
X	X	X
22	44	21
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.		

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 0.0007, which is smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it can be concluded that there was a statistically significant difference in traffic volume for Lane 1 among the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during nighttime when construction work was ongoing with the presence of blue lights. The results from the post hoc pairwise comparisons are shown in **Table 21**.

Table 21. Post hoc pairwise comparison results

Comparison	p value
Beginning - First Half	0.0046
Beginning - Second Half	1
First Half - Second Half	0.002

Post Hoc Pairwise Comparisons:

Beginning of the work zone vs. First half of the active work zone: The comparison yielded a p-value of 0.0046, suggesting a significant difference. The median traffic volume was 8 vehicles at both the beginning of the work zone and the first half of the active work zone.

Beginning of the work zone vs. Second half of the active work zone: The comparison yielded a p-value of 1, indicating no statistically significant difference. The median traffic volume was 8

vehicles at the beginning of the work zone and 7 vehicles in the second half of the active work zone.

First half of the active work zone vs. Second half of the active work zone: The comparison yielded a p-value of 0.002, suggesting a significant difference. The median traffic volume was 8 vehicles in the first half of the active work zone and 7 vehicles in the second half of the active work zone.

Discussion: The ART ANOVA results confirmed a statistically significant difference in traffic volume for Lane 1 for different locations of the work zone during nighttime under the presence of blue lights. Although the median traffic volumes appeared relatively close (7-8 vehicles), the post hoc comparisons revealed statistically significant differences between the beginning and the first half of the active work zone, as well as between the first and second halves. However, no significant difference was found between the beginning and the second half of the active work zone. To further support this interpretation, the density plot in **Figure 32** visualizes the volume distributions for all three segments. The plot showed that all three distributions had similar right-skewed shapes, but with subtle shifts in peak. The first half of the active work zone had a slightly sharper density around lower volumes, aligning with the reduced median. These subtle yet consistent shifts in the distribution supported the statistical findings. Overall, the results indicated that the presence of blue lights may influence drivers' lane selection behavior throughout the work zone. The shifts in volume suggested that while drivers made lane adjustments as they navigated the active work zone, they tended to return to their initial lane positions as they got near the exit of the construction area.

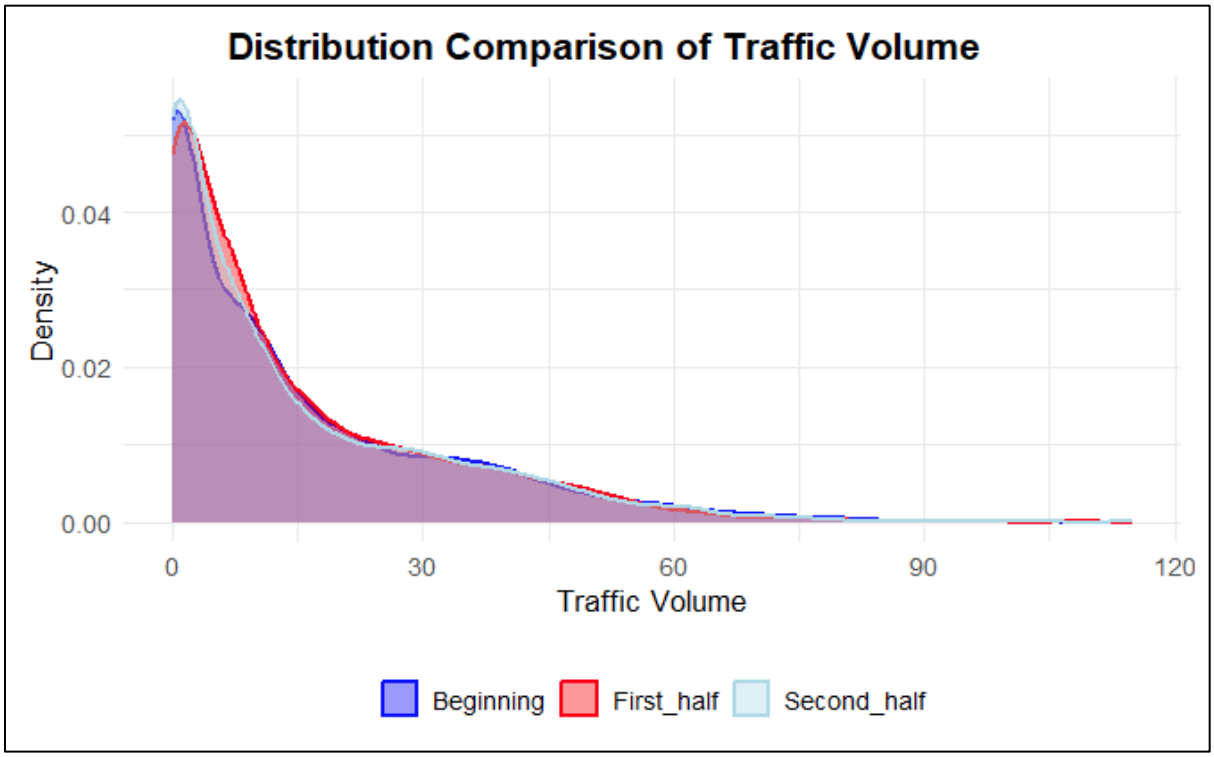


Figure 32. Traffic volume distribution for the individual work zone locations

6.9.8 Hypothesis 8: Nighttime, Lane 2, Construction with Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis aimed to compare traffic volume for lane 2 during nighttime between three individual work zone locations - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone in the presence of blue lights during ongoing construction. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 2 during nighttime when blue lights are present during construction work.*

H_1: *There is a significant difference in traffic volume between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 2 during nighttime when blue lights are present during construction work.*

Data Collected: For hypothesis testing, the traffic volume for lane 2 during nighttime in the presence of blue lights was divided into three categories:

- Nighttime lane 2, beginning of the work zone: 4032 observations
- Nighttime lane 2, first half of the active work zone: 4032 observations
- Nighttime lane 2, second half of the active work zone: 4032 observations

An illustration of the dataset is depicted in **Table 22**.

Table 22. Data points for nighttime lane 2 traffic volume for individual work zone locations

Traffic Volume for the Beginning of the Work Zone	Traffic Volume for the First Half of the Active Work Zone	Traffic Volume for the Second Half of the Active Work Zone
56	40	35
45	37	48
X	X	X
X	X	X
X	X	X
22	44	21
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.		

Analysis Strategy: Power analysis and ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 5.2692e-25, which is smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it can be concluded that there was a statistically significant difference in traffic volume for Lane 2 among the beginning of the work

zone, the first half of the active work zone, and the second half of the active work zone during nighttime when construction work was ongoing with the presence of blue lights. The results from the post hoc pairwise comparisons are shown in **Table 23**.

Table 23. Post hoc pairwise comparison results

Comparison	p-value
Beginning - First Half	<.0001
Beginning - Second Half	<.0001
First Half - Second Half	1.0000

Post Hoc Pairwise Comparisons:

Beginning of the work zone vs. First half of the active work zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median traffic volume was 24 vehicles at the beginning of the work zone and 27 vehicles in the first half of the active work zone.

Beginning of the work zone vs. Second half of the active work zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median traffic volume was 24 vehicles at the beginning of the work zone and 27 vehicles in the second half of the active work zone.

First half of the active work zone vs. Second half of the active work zone: The comparison yielded a p-value of 1.0000, indicating no statistically significant difference. The median traffic volume was 27 vehicles in both the first half and the second half of the active work zone.

Discussion: The ART ANOVA results confirmed a statistically significant difference in traffic volume for Lane 2 for individual locations of the work zone during nighttime under the presence of blue lights. The descriptive statistics showed an increase in median traffic volume from the beginning of the work zone (24 vehicles) to both the first half and second half of the active work zone (27 vehicles).

The post hoc comparisons supported this trend by revealing statistically significant differences between the beginning and both halves of the active work zone, while no significant difference was observed between the first and second halves. This indicated that drivers likely shifted into Lane 2 shortly after entering the active work zone and then maintained their lane position as they progressed through the remaining segments.

To illustrate these shifts, the density plot in **Figure 33** displays the distribution of traffic volume for all three segments. The beginning of the work zone showed a steeper and narrower peak concentrated around a lower volume range. In contrast, the first and second halves of the active work zone shared broader and more elevated distributions, reflecting higher and more consistent traffic volumes. Despite the relatively small differences in median values, these subtle yet consistent shifts in distribution further supported the statistical significance of the post hoc results.

Overall, the findings suggested that the presence of blue lights at night may have encouraged earlier lane changes into Lane 2, after which drivers continued in that lane through the active construction zone.

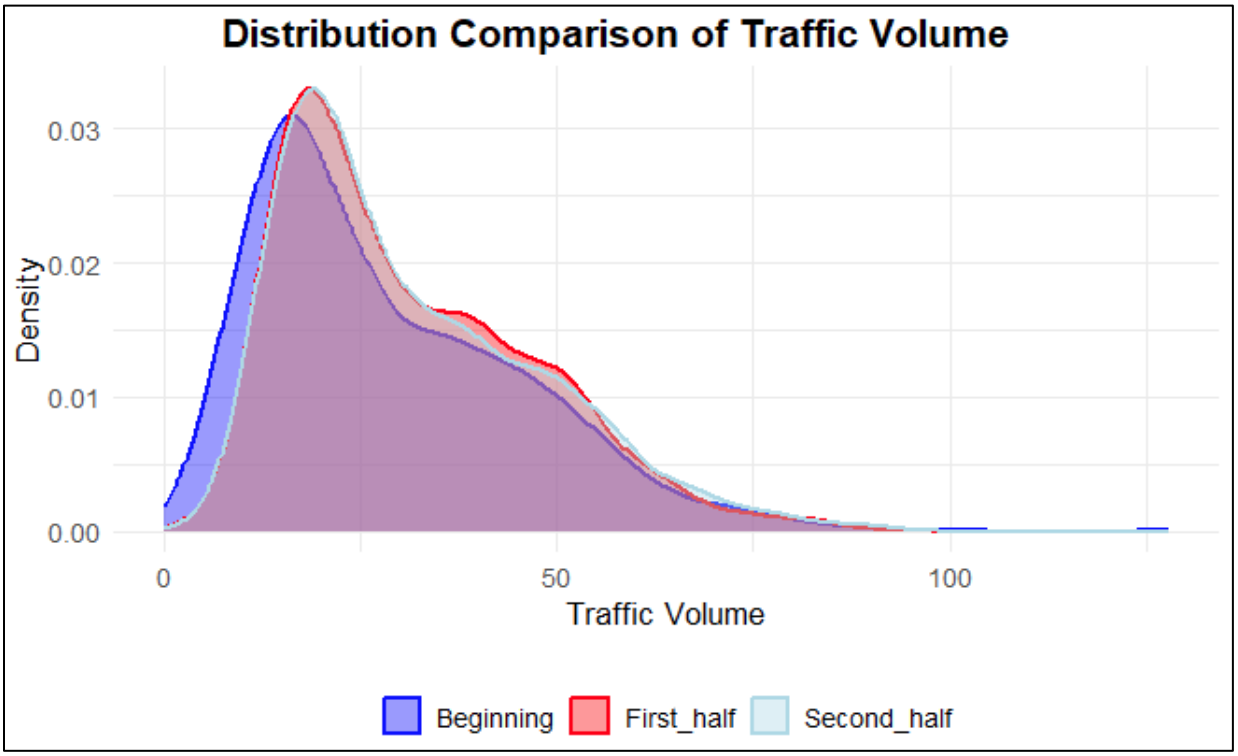


Figure 33. Traffic volume distribution for the individual work zone locations

6.9.9 Hypothesis 9: Daytime, Lane 1 vs. Lane 2, Construction with Blue Lights for Individual Work Zone Locations

***H₀**: There is no significant difference in the traffic volume between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during daytime, when blue lights are present for ongoing construction.*

***H₁**: There is a significant difference in the traffic volume between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during daytime, when blue lights are present for ongoing construction*

Data Collected: To test the hypothesis, the traffic volume data during daytime with blue lights while ongoing construction was categorized into six sections:

- Daytime lane 1, beginning of the work zone: 432 observations
- Daytime lane 2, beginning of the work zone: 432 observations
- Daytime lane 1, first half of the active work zone: 432 observations
- Daytime lane 2, first half of the active work zone: 432 observations
- Daytime lane 1, second half of the active work zone: 432 observations
- Daytime lane 2, second half of the active work zone: 432 observations

An illustration of the dataset is depicted in **Table 24.**

Table 24. Data points for daytime lane 1 vs. lane 2, for construction with the presence of blue lights for individual work zone locations

Traffic Volume Daytime Beginning of the Work Zone, Lane 1	Traffic Volume Daytime Beginning of the Work Zone, Lane 2	Traffic Volume Daytime First Half of the Active Work Zone, Lane 1	Traffic Volume Daytime First Half of the Active Work Zone, Lane 2	Traffic Volume Daytime Second Half of the Active Work Zone, Lane 1	Traffic Volume Daytime Second Half of the Active Work Zone, Lane 2
45	47	40	55	67	52
38	33	37	31	28	47
X	X	X	X	X	X
X	X	X	X	X	X
X	X	X	X	X	X
41	44	25	17	34	64

Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: Power analysis and ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value < 2.22e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it was concluded that there was a statistically significant difference in traffic volume between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during daytime when construction work was ongoing with the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 25.**

Table 25. Post hoc pairwise comparison results

Comparison	p-value
Beginning Lane 1 - Beginning Lane 2	8.277575e-15
First Half Lane 1 - First Half Lane 2	0.4192550
Second Half Lane 1 - Second Half Lane 2	4.380919e-04

Post Hoc Pairwise Comparisons:

Beginning of the work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the green columns in **Table 24** yielded a p-value of 8.277575e-15, suggesting a significant difference. The median volume was 53 for Lane 1 and 60 for Lane 2.

First half of the active work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the purple columns in **Table 24** yielded a p-value of 4.192550e-01, suggesting no statistically significant difference. The median speed was 55 for Lane 1 and 57 for Lane 2.

Second half of the active work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the blue columns in **Table 24** yielded a p-value of 4.380919e-04, confirming a significant difference. The median speed was 54 for Lane 1 and 58 for Lane 2.

Discussion

The ART ANOVA results confirmed that there was a statistically significant difference in traffic volume between Lane 1 and Lane 2 across different segments of the work zone during daytime construction with the presence of blue lights. Post hoc comparisons showed significant differences between the lanes at the beginning and the second half of the work zone, while no significant difference was found in the first half of the active work zone.

As illustrated in **Figure 34**, traffic volume at the beginning of the work zone was higher in Lane 2 compared to Lane 1. The distribution for Lane 2 was more peaked and concentrated, indicating that a larger number of vehicles occupied Lane 2 in this initial segment. This may suggest that drivers preferred to use the far lane (Lane 2), which is typically away from the active construction area, upon approaching the work zone. In the first half of the active work zone, as depicted in **Figure 35**, the density curves of both lanes became more aligned, and the difference in volume diminished. This alignment corresponds to the non-significant result from the post hoc test, indicating that vehicles were more evenly distributed across both lanes during this middle segment.

However, in the second half of the active work zone, as depicted in **Figure 36**, a notable shift was again observed. Lane 2 showed a more concentrated peak, and Lane 1 had a wider spread with lower density. This distribution pattern supported the significant difference found in the post hoc test and suggests that more drivers returned or remained in Lane 2 as they approached the end of the work zone.

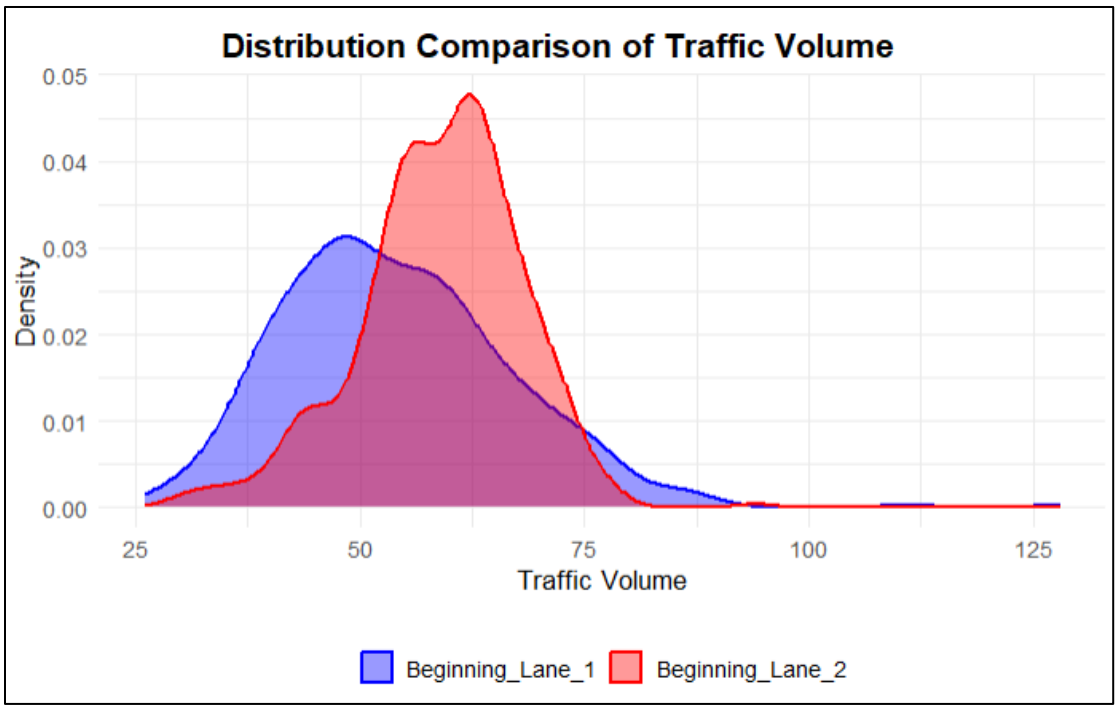


Figure 34. Traffic volume distribution between the lanes (beginning of the work zone)

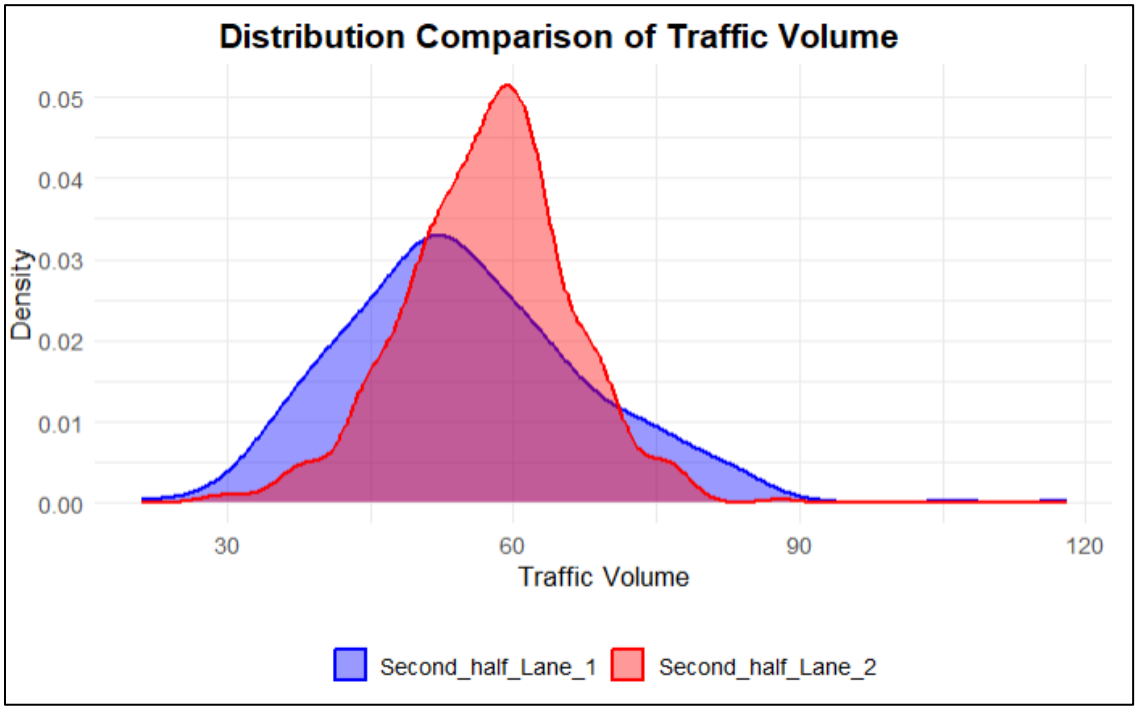


Figure 35. Traffic volume distribution between the lanes (first half of the active work zone)

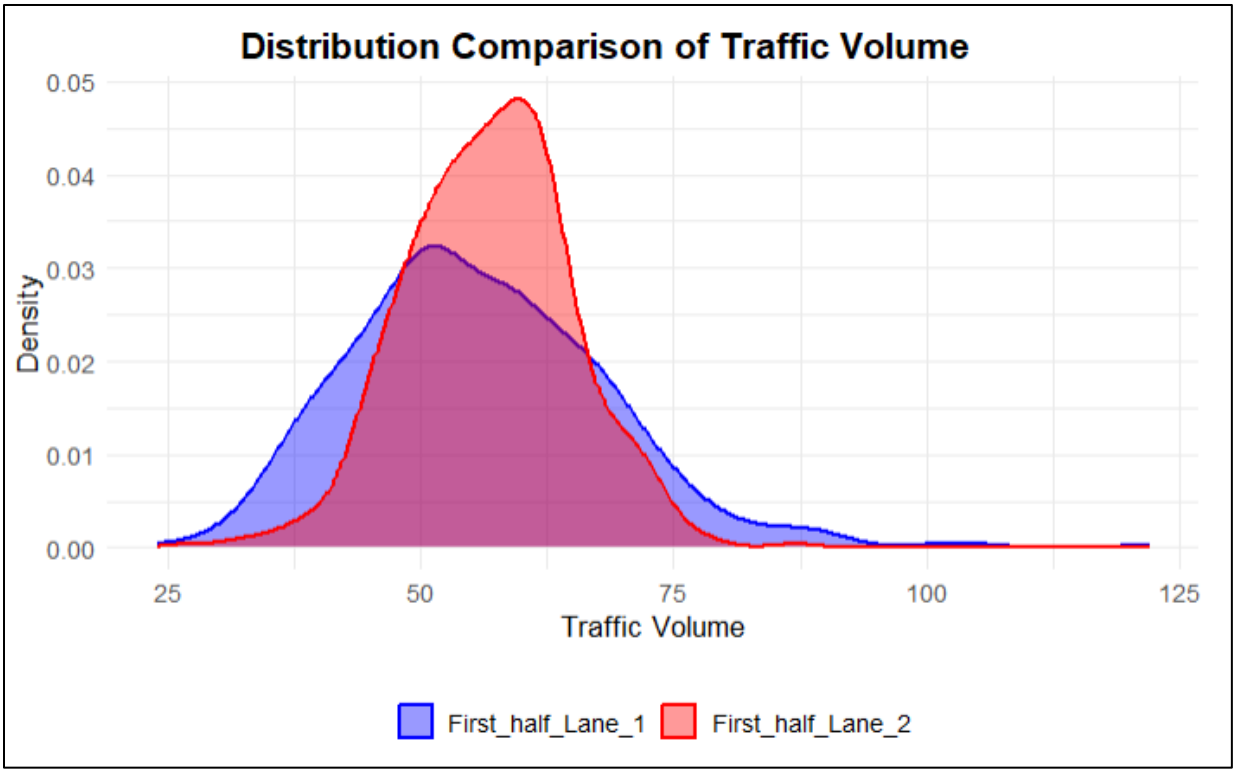


Figure 36. Traffic volume distribution between the lanes (second half of the active work zone)

6.9.10 Hypothesis 10: Nighttime, Lane 1 vs. Lane 2, Construction with Blue Lights for Individual Work Zone Locations

***H₀**: There is no significant difference in the traffic volume between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during nighttime, when blue lights are present for ongoing construction.*

***H₁**: There is a significant difference in the traffic volume between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during nighttime, when blue lights are present for ongoing construction*

Data Collected: To test the hypothesis, the traffic volume data during nighttime with blue lights while ongoing construction was categorized into six sections:

- Nighttime lane 1, beginning of the work zone: 4032 observations
- Nighttime lane 2, beginning of the work zone: 4032 observations
- Nighttime lane 1, first half of the active work zone: 4032 observations
- Nighttime lane 2, first half of the active work zone: 4032 observations
- Nighttime lane 1, second half of the active work zone: 4032 observations
- Nighttime lane 2, second half of the active work zone: 4032 observations

An illustration of the dataset is depicted in **Table 26.**

Table 26. Data points for nighttime lane 1 vs. lane 2, for construction with the presence of blue lights for individual work zone locations

Traffic Volume Nighttime Beginning of the Work Zone, Lane 1	Traffic Volume Nighttime Beginning of the Work Zone, Lane 2	Traffic Volume Nighttime First Half of the Active Work Zone, Lane 1	Traffic Volume Nighttime First Half of the Active Work Zone, Lane 2	Traffic Volume Nighttime Second Half of the Active Work Zone, Lane 1	Traffic Volume Nighttime Second Half of the Active Work Zone, Lane 2
45	47	40	55	67	52
38	33	37	31	28	47
X	X	X	X	X	X
X	X	X	X	X	X
X	X	X	X	X	X
41	44	25	17	34	64

Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: Power analysis and ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value < 2.22e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it was concluded that there was a statistically significant difference in traffic volume between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during nighttime when construction work was ongoing with the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 27.**

Table 27. Post hoc pairwise comparison results

Comparison	p-value
Beginning Lane 1 - Beginning Lane 2	< 2.2e-16
First Half Lane 1 - First Half Lane 2	< 2.2e-16
Second Half Lane 1 - Second Half Lane 2	< 2.2e-16

Post Hoc Pairwise Comparisons:

Beginning of the work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the green columns in **Table 26** yielded a p-value of < 2.2e-16, suggesting a significant difference. The median volume was 8 for Lane 1 and 24 for Lane 2.

First half of the active work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the purple columns in **Table 26** yielded a p-value of < 2.2e-16, suggesting a significant difference. The median speed was 8 for Lane 1 and 27 for Lane 2.

Second half of the active work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the blue columns in **Table 26** yielded a p-value of < 2.2e-16, suggesting a significant difference. The median speed was 7 for Lane 1 and 27 for Lane 2.

Discussion

The ART ANOVA results confirmed that there was a statistically significant difference in traffic volume between Lane 1 and Lane 2 for all three segments of the work zone during nighttime construction with the presence of blue lights. Post hoc comparisons indicated significant differences in each location, including the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone. **Figure 37,** illustrates that, at the beginning of the work zone, Lane 1 shows a sharp peak near the lower volume range, indicating a high frequency of lower traffic volumes. In contrast, Lane 2 has a broader distribution with higher volume levels. The volume pattern suggests that many vehicles shift into Lane 2 early in the work zone, likely influenced by the presence of blue lights drawing attention to the active work area. **Figure 38** (first half of the active work zone) shows a similar pattern. The blue peak for Lane 1 remains steep at the lower end, while Lane 2 distribution is concentrated around a higher volume range. This confirms that a larger portion of vehicles occupies Lane 2 in this segment. Finally, **Figure 39** (second half of the active work zone) shows that the trend remains consistent. Lane 1 has a higher density near the lower volume range, while Lane 2 distribution is more spread and shifted toward higher volumes, indicating a greater concentration of vehicles. These distribution trends supported the statistical findings and reinforced the interpretation that drivers consistently favored Lane 2 for the entire work zone when blue lights were present, likely as a way to maintain distance from the active construction activities in Lane 1.

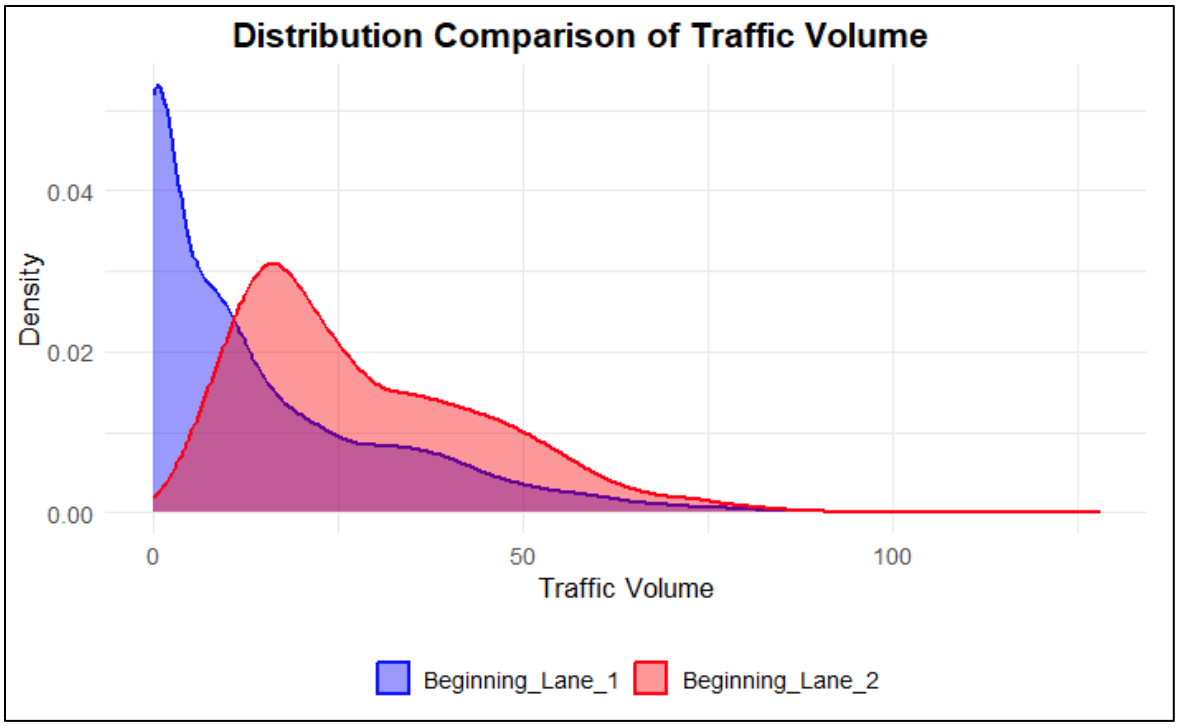


Figure 37. Traffic volume distribution between the lanes (beginning of the work zone)

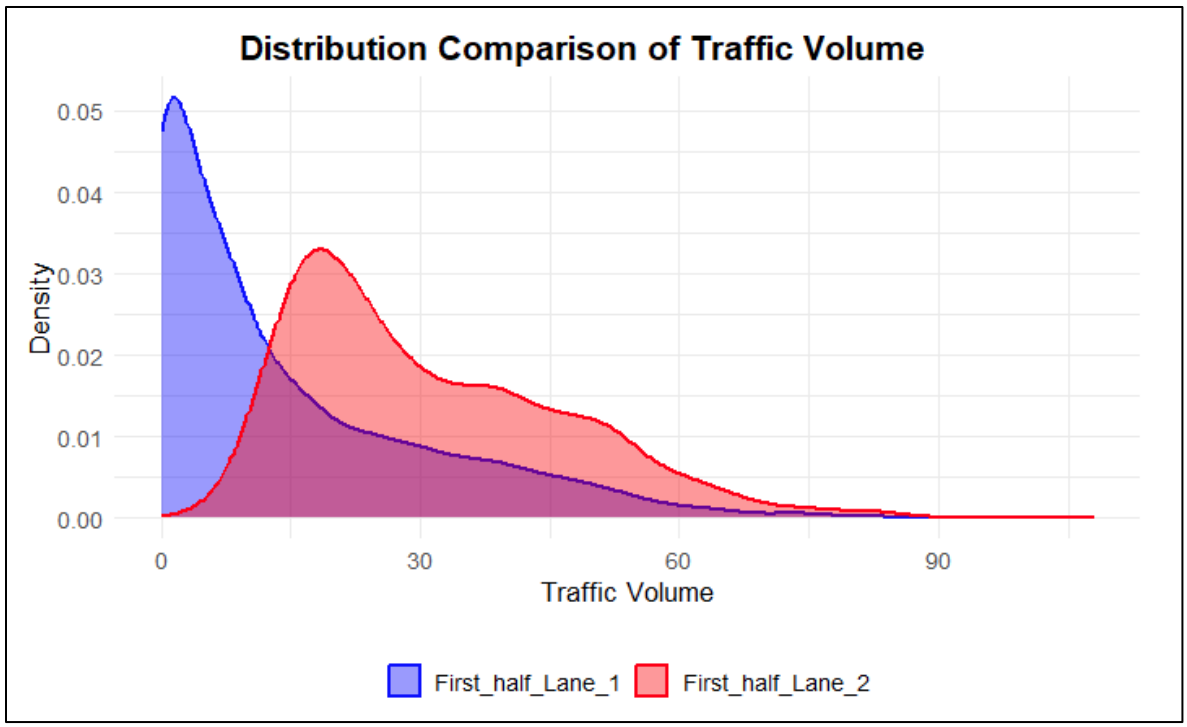


Figure 38. Traffic volume distribution between the lanes (first half of the active work zone)

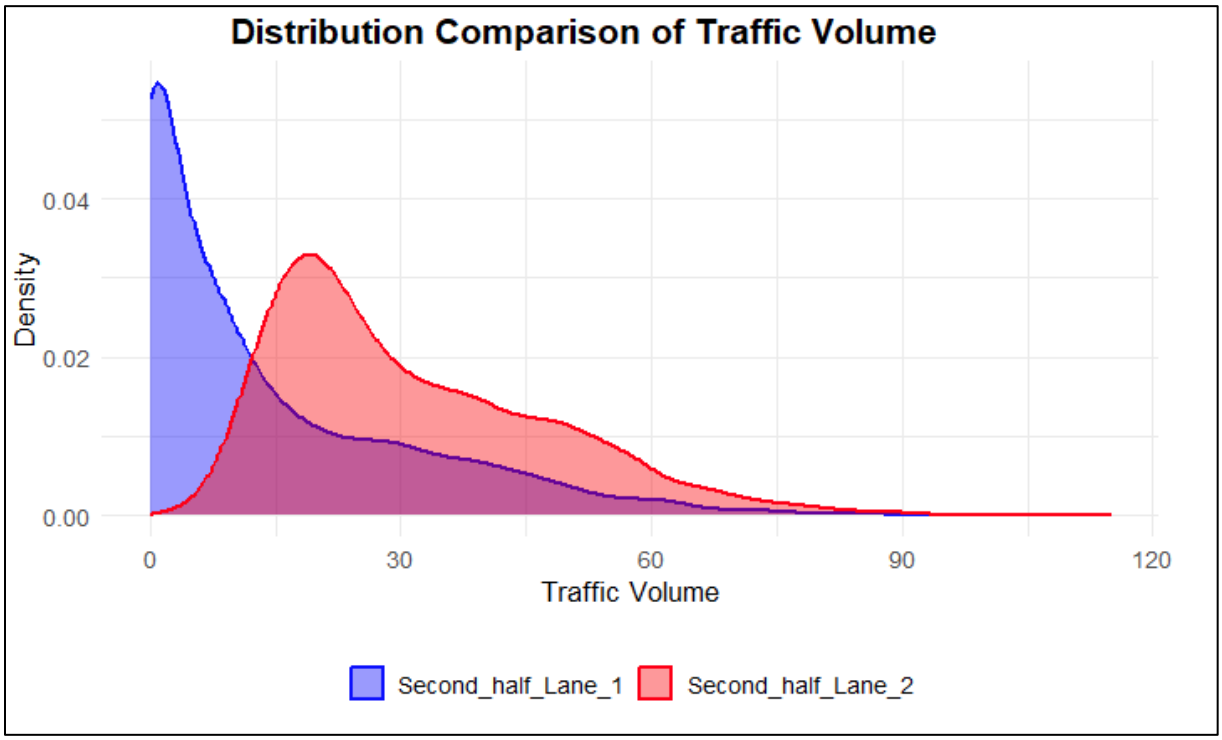


Figure 39. Traffic volume distribution between the lanes (second half of the active work zone)

6.9.11 Summary for Category One: Analysis of Traffic Volume for Construction with the Presence of Blue Lights in the Work Zone

This section provides a comprehensive summary based on the hypothesis tests conducted in this category and the insights gained from them.

6.9.11.1 Lane Preferences During Daytime and Nighttime with Blue Lights (Hypothesis 1- Hypothesis 2)

The hypothesis tests (Hypothesis 1-Hypothesis 2) on lane-level traffic volume during daytime and nighttime construction with blue lights indicated a consistent preference for Lane 2. During the daytime, Lane 2 showed more consistent traffic while Lane 1 exhibited greater variability, suggesting avoidance of the lane closer to the work zone. At nighttime, this preference intensified, with Lane 1 carrying very low volumes while Lane 2 sustained higher traffic. These findings established the presence of lane preference under blue light conditions and suggested that choosing the lane farthest from the active work zone became more prominent for the drivers during nighttime.

6.9.11.2 Daytime and Nighttime Traffic Patterns for Individual Lanes with Blue Lights (Hypothesis 3- Hypothesis 4)

The hypothesis tests (Hypothesis 3-Hypothesis 4) comparing daytime and nighttime traffic volumes for individual lanes showed that both lanes experienced nighttime volume reductions, with the decline being substantially greater for Lane 1. This pattern indicated increased driver awareness in the active work zone area during nighttime conditions. Although Lane 2 also showed reduced nighttime volumes, it consistently maintained higher usage than Lane 1, suggesting it was the preferred travel path under blue light presence.

6.9.11.3 Traffic Volume Shifts for Specific Work Zone Locations with Blue Lights (Hypothesis 5- Hypothesis 8)

The hypothesis tests (Hypothesis 5-Hypothesis 8) examining traffic volume at specific work zone locations revealed that lane use differed as drivers progressed through the site. During daytime construction, Lane 1 volumes remained relatively stable for all work zone locations, while Lane 2 volumes showed a slight reduction after vehicles entered the active work zone. At nighttime, Lane 1 volumes became slightly lower within the active work zone segments, while Lane 2 volumes increased after vehicles entered the active work zone and then remained relatively consistent through the remaining segments. These results indicated that location within the work zone influenced how drivers adjusted their lane use in the presence of blue lights, with clearer behavioral changes observed under nighttime conditions.

6.9.11.4 Lane-based Comparison for Work Zone Locations with Blue Lights (Hypothesis 9 - Hypothesis 10)

The hypothesis tests (Hypothesis 9 - Hypothesis 10) comparing lanes at different work zone locations showed that Lane 2 carried higher traffic volumes at the beginning and in the second half of the active work zone during daytime construction, while lane usage was more balanced within the first half of the active work zone. At nighttime, Lane 2 consistently carried more traffic for all locations, indicating a stronger and more uniform lane preference when blue lights were more

visually prominent. These findings suggested that lane usage varied by location and time of day within the work zone.

6.9.11.5 Insights from the Analysis

The findings from this category indicated that blue lights functioned as a persistent visual influence on drivers' lane selection instead of a temporary action. Drivers appeared to make lane decisions early and maintain those choices as they progressed through the work zone, particularly under nighttime conditions. This behavior suggested that once drivers observed the blue lights and perceived increased risk near construction activity, they preferred to remain in the lane farther from the work area for the remainder of the site.

The analysis also revealed that the effect of blue lights was not uniform throughout the work zone. Their influence appeared strongest near the beginning and within active work zones. This indicated that the placement and movement of blue lights played a role in complementing lane choices as drivers advanced through different sections of the work zone.

Overall, the category demonstrated that blue lights shaped traffic volume distribution by encouraging sustained avoidance of lanes adjacent to construction activity. This effect was more at night, when visual cues were clearer, and driver caution appeared higher. In addition, nighttime traffic volumes were generally lower because fewer people traveled during these hours compared to daytime office hours. This overall reduction in traffic demand may also have contributed to the observed differences in traffic volume between the lanes. These insights suggested that blue lights influenced not only immediate lane changes but also longer-duration lane commitment for the length of the work zone.

6.10 Category Two: Comparative Analysis of Traffic Volume Between Construction in the Presence of Blue Lights and Construction in the Absence of Blue Lights in the Work Zone

This category focuses on analyzing the comparative effect of construction with the presence of blue lights and construction without the presence of blue lights in the selected work zone on traffic volume. Based on the results from the preliminary analysis (Section 6.8), a total of eleven hypothesis tests were proposed and conducted to assess the differences in traffic volume under these two construction conditions. This included comparing traffic volume by considering several factors, including lanes, individual three work zone locations, and daytime and nighttime.

Table 28 summarizes the test results for the eleven hypotheses under this category. More details about each hypothesis test, including the individual hypothesis statements, data pre-processing, results analysis, and discussion (following the roadmap explained in

Table 5 or

Table 6), are presented in the following sections. An overall summary and key insights are provided at the end of the section.

Table 28. Summarized results of the category 2 hypothesis tests for traffic volume

Number	Details	Results
Hypothesis 1	Overall, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	Significant difference
Hypothesis 2	Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	Significant difference
Hypothesis 3	Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	Significant difference
Hypothesis 4	Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 5	Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 6	Lane 1, Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	Significant difference
Hypothesis 7	Lane 2, Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	Significant difference
Hypothesis 8	Lane 1, Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	No significant difference
Hypothesis 9	Lane 2, Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	Significant difference
Hypothesis 10	Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Lanes for Individual Work Zone Locations	Significant difference
Hypothesis 11	Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Lanes for Individual Work Zone Locations	Significant difference

6.10.1 Hypothesis 1: Overall, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

H_0: *There is no significant difference in traffic volume for the overall work zone between construction with the presence of blue lights and construction without the presence of blue lights.*

H_1: *There is a significant difference in traffic volume for the overall work zone between construction with the presence of blue lights and construction without the presence of blue lights.*

Data Collected: For the analysis, the data were divided into two categories:

- Construction with the presence of blue lights - 26784 observations
- Construction without the presence of blue lights - 7488 observations

An illustration of the dataset is depicted in **Table 29**.

Table 29. Data points for traffic volume for construction with the presence of blue lights vs. construction without the presence of blue lights

Volume for Construction with the Presence of Blue Lights	Volume for Construction without the Presence of Blue Lights
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test.

Analysis Results: The Mann-Whitney U test showed that the p-value was 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it was concluded that there was a statistically significant difference in traffic volume between construction with the presence of blue lights and construction without the presence of blue lights.

According to the descriptive statistics, the median traffic volume during construction with blue lights was 21, while it was 54 without blue lights. The IQR was 31 when blue lights were present and 27 when they were not, indicating slightly greater variability in traffic volume under the blue light condition. Although the medians showed a substantial reduction, the density plot in **Figure 40** illustrates this difference more clearly by showing a concentrated distribution for the construction without blue light conditions and a wider spread under construction with blue light conditions. This supported the statistical results and suggested that the presence of blue lights encouraged more cautious driving behavior, resulting in lower traffic volumes during construction.

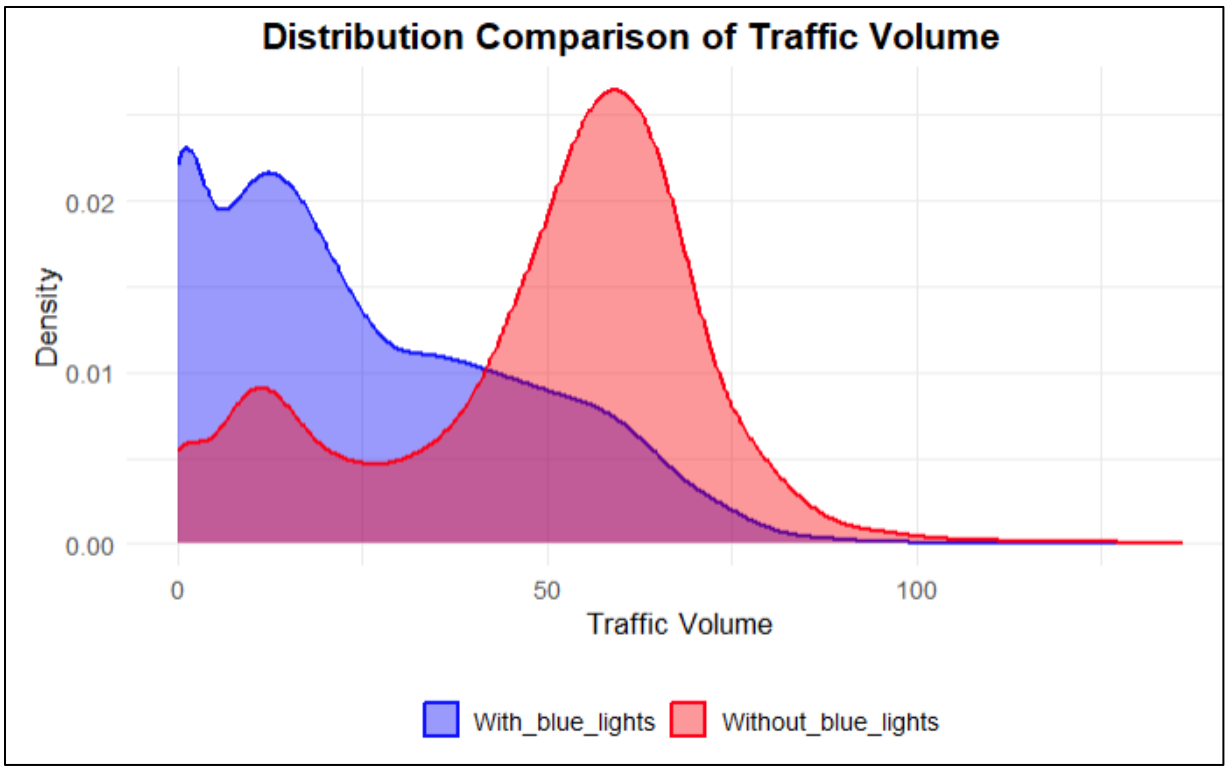


Figure 40. Traffic volume distribution with and without blue lights

6.10.2 Hypothesis 2: Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

H_0: *There is no significant difference in traffic volume between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

H_1: *There is a significant difference in traffic volume between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

Data Collected: For the analysis, the data were divided into two categories:

- Construction with the presence of blue lights - 2592 observations
- Construction without the presence of blue lights - 5760 observations

An illustration of the dataset is depicted in **Table 30**.

Table 30. Data points for traffic volume for construction with the presence of blue lights vs. construction without the presence of blue lights

Volume for Construction with the Presence of Blue Lights	Volume for Construction without the Presence of Blue Lights
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test.

Analysis Results: The Mann-Whitney U test showed that the p-value was 0.000773, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it was concluded that there was a statistically significant difference in traffic volume during the daytime between construction with the presence of blue lights and construction without the presence of blue lights.

According to the descriptive statistics, the median traffic volume was 56 for construction with the presence of blue lights and 58 for construction without the presence of blue lights. The IQR was 14 for construction with the presence of blue lights and 16 for construction without the presence of blue lights, showing slightly greater variability in the condition without blue lights. Although the medians were very close, the density plot in **Figure 41** illustrates a more concentrated distribution for construction without the presence of blue lights, while construction with the presence of blue lights showed a wider spread. This supported the statistical results and suggested that blue lights may have influenced driver behavior by reducing consistency in traffic flow during daytime construction.

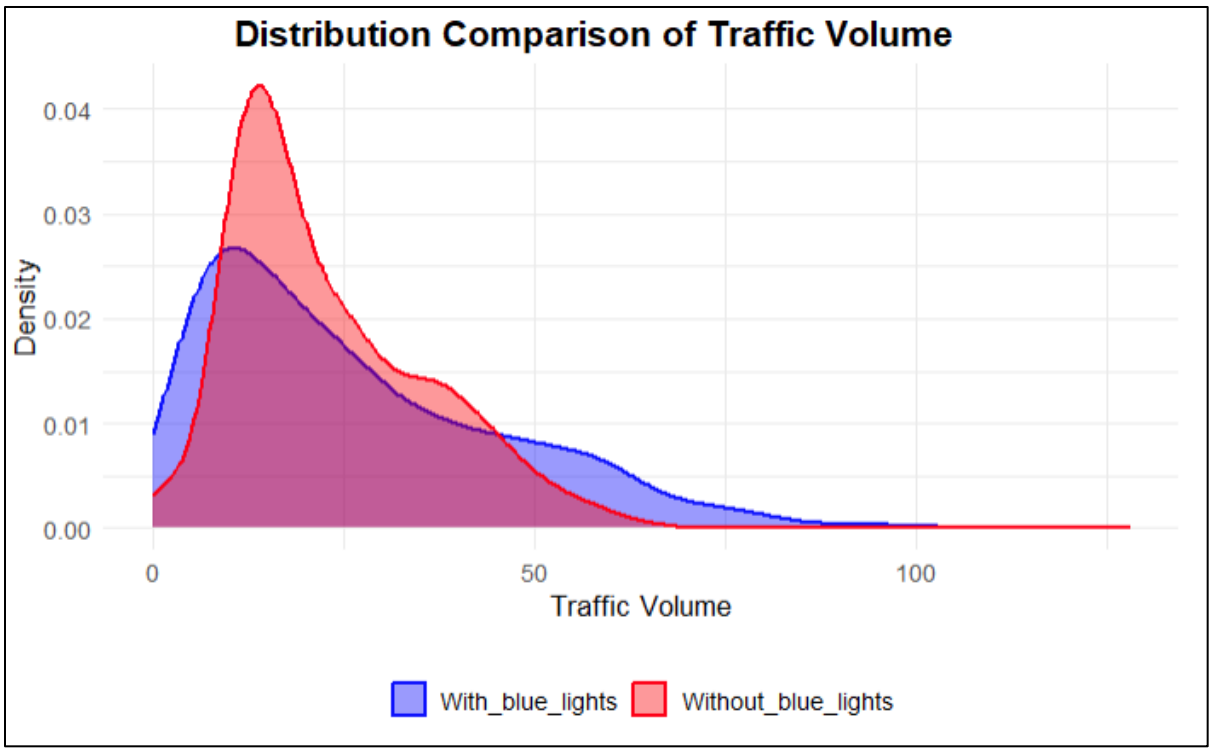


Figure 41. Traffic volume distribution with and without blue lights

6.10.3 Hypothesis 3: Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

H₀: *There is no significant difference in traffic volume between construction with the presence of blue lights and construction without the presence of blue lights during nighttime.*

H₁: *There is a significant difference in traffic volume between construction with the presence of blue lights and construction without the presence of blue lights during nighttime.*

Data Collected: For the analysis, the data were divided into two categories:

- Construction with the presence of blue lights - 24192 observations
- Construction without the presence of blue lights - 1728 observations

An illustration of the dataset is depicted in **Table 31**.

Table 31. Data points for traffic volume for construction with the presence of blue lights vs. construction without the presence of blue lights

Volume for Construction with the Presence of Blue Lights	Volume for Construction without the Presence of Blue Lights
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test.

Analysis Results: The Mann-Whitney U test yielded a p-value of less than 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it was concluded that there was a statistically significant difference in traffic volume during the nighttime between construction with the presence of blue lights and construction without the presence of blue lights.

According to the descriptive statistics, the median traffic volume was 19 for construction with the presence of blue lights and 17 for construction without the presence of blue lights. The IQR was 27 for construction with the presence of blue lights and 20 for construction without the presence of blue lights, showing greater variability under the blue light condition. Although the medians were close, the density plot in **Figure 42** illustrates that construction without the presence of blue lights had a wider spread, while construction with the presence of blue lights was more concentrated at lower volumes. This supported the statistical results and suggested that the presence of blue lights influenced driver behavior by creating a more stable traffic pattern during nighttime construction.

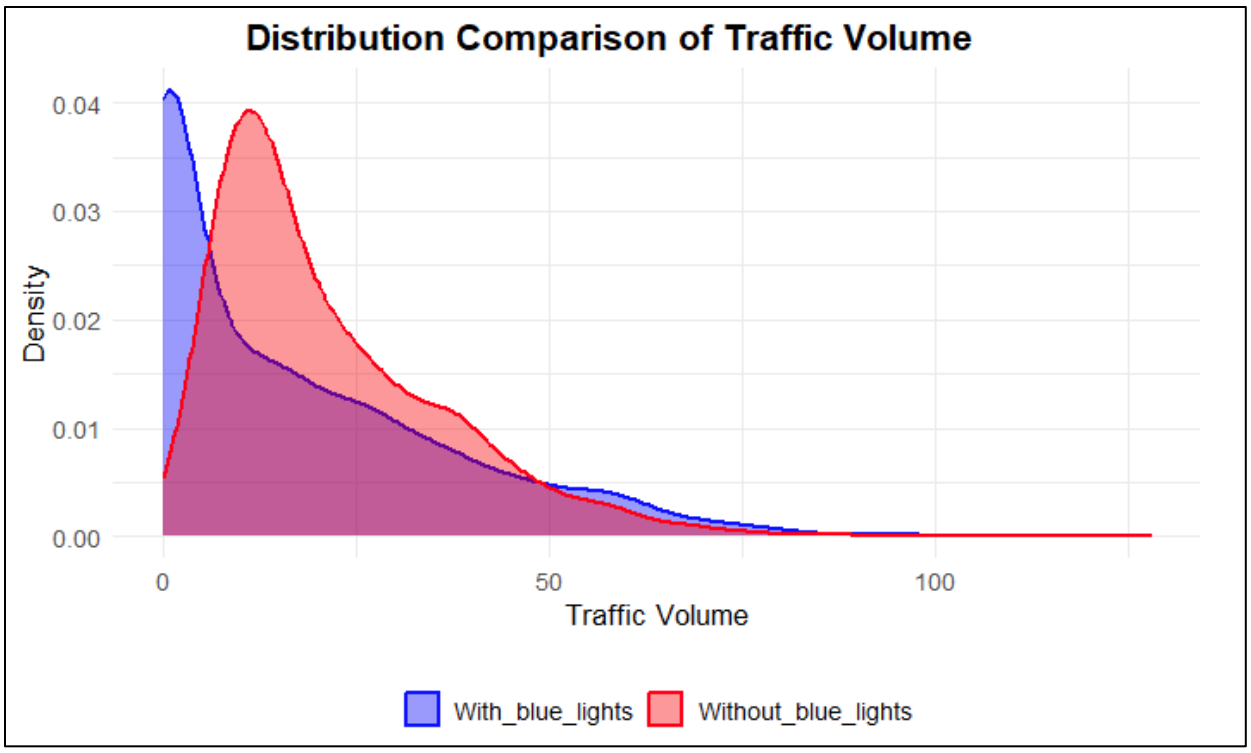


Figure 42. Traffic volume distribution with and without blue lights

6.10.4 Hypothesis 4: Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis aimed to compare traffic volume during daytime in the presence and absence of blue lights for three individual work zone locations - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume during the daytime in the presence of blue lights during construction work* for *the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work* for *the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

H_1: *There is a significant difference in traffic volume during the daytime in the presence of blue lights during construction work* for *the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work* for *the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

Data Collected: For hypothesis testing, the traffic volume data during daytime was categorized into six conditions:

- **With Blue Light Beginning (WB_Beg)** - Construction with the presence of blue lights at the beginning of the work zone, 864 observations
- **Without Blue Light Beginning (WOB_Beg)** - Construction without the presence of blue lights at the beginning of the work zone, 1920 observations
- **With Blue Light First Half (WB_1stH)** - Construction with the presence of blue lights in the first half of the active work zone, 864 observations
- **Without Blue Light First Half (WOB_1stH)** - Construction without the presence of blue lights in the first half of the active work zone, 1920 observations
- **With Blue Light Second Half (WB_2ndH)** - Construction with the presence of blue lights in the second half of the active work zone, 864 observations
- **Without Blue Light Second Half (WOB_2ndH)** - Construction without the presence of blue lights in the second half of the active work zone, 1920 observations

An illustration of the dataset is depicted in **Table 32**.

Table 32. Data points for daytime traffic volume differences between construction with the presence of blue lights and construction without the presence of blue lights for individual work zone locations

WB_Beg	WOB_Beg	WB_1stH	WOB_1stH	WB_2ndH	WOB_2ndH
45	47	40	55	67	52
38	33	37	31	28	47
X	X	X	X	X	X
X	X	X	X	X	X
X	X	X	X	X	X
41	44	25	17	34	64

Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Methods: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 5.8679e-17, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in traffic volume between construction with the presence of blue lights and construction without the presence of blue lights for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during daytime. The results from the post hoc pairwise comparisons are shown in **Table 33.**

Table 33. Post hoc pairwise comparison results

Comparison	p-value
WB_Beg - WOB_Beg	1
WB_1stH - WOB_1stH	<.0001
WB_2ndH - WOB_2ndH	<.0001

Post Hoc Pairwise Comparisons:

Beginning of the work zone: The comparison between construction with and without blue lights, which included the data from the green columns in **Table 32** yielded a p-value of 1, indicating no statistically significant difference. The median traffic volume was 57 vehicles with blue lights and 58 vehicles without blue lights.

First half of the active work zone: The comparison between construction with and without blue, which included the data from the purple columns in **Table 32** lights yielded a p-value of <0.0001, suggesting a significant difference. The median traffic volume was 56 vehicles with blue lights and 59 vehicles without blue lights.

Second half of the active work zone: The comparison between construction with and without blue lights, which included the data from the orange columns in **Table 32** yielded a p-value of <0.0001, suggesting a significant difference. The median traffic volume was 56 vehicles with blue lights and 58 vehicles without blue lights.

Discussion: The ART ANOVA results confirmed a statistically significant difference in traffic volume between construction with and without the presence of blue lights for the active work zone during daytime. While the median volumes appeared close, the post hoc comparisons revealed significant differences for both the first and second halves of the active work zone, whereas no difference was observed at the beginning.

The density plot in **Figure 43** showed that with blue lights, the distribution shifted slightly toward lower volumes, resulting in a sharper concentration compared to the condition without blue lights. This suggested that drivers responded to the visual cue earlier in the work zone, reducing flow through this segment. In **Figure 44**, a similar pattern was observed, with the blue light condition again producing a leftward shift and a more compact distribution at lower volumes. This reflected a similar driver behavior as they continued through the active work zone.

Overall, the results indicate that blue lights influenced traffic flow primarily within the active work zone locations. The shifts in the distributions suggested that drivers became more cautious and altered their movement patterns as they advanced through the work zone, highlighting the effectiveness of blue lights in the active work zone locations.

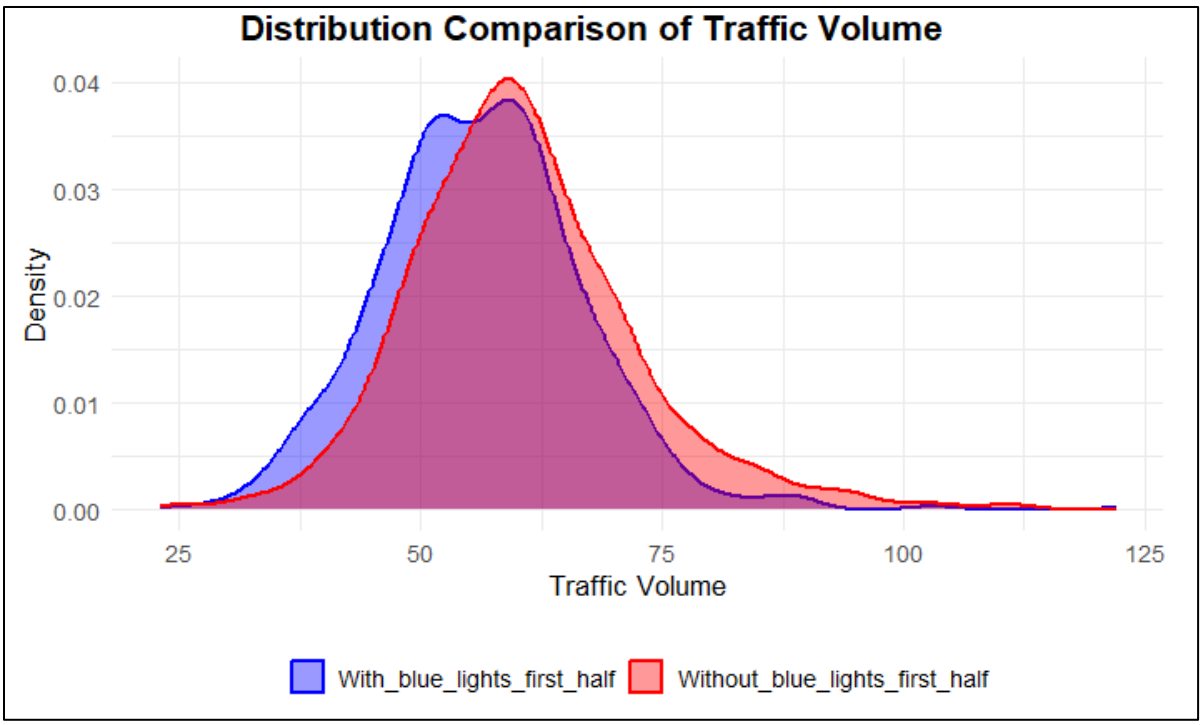


Figure 43. Traffic volume distribution for the first half of the active work zone

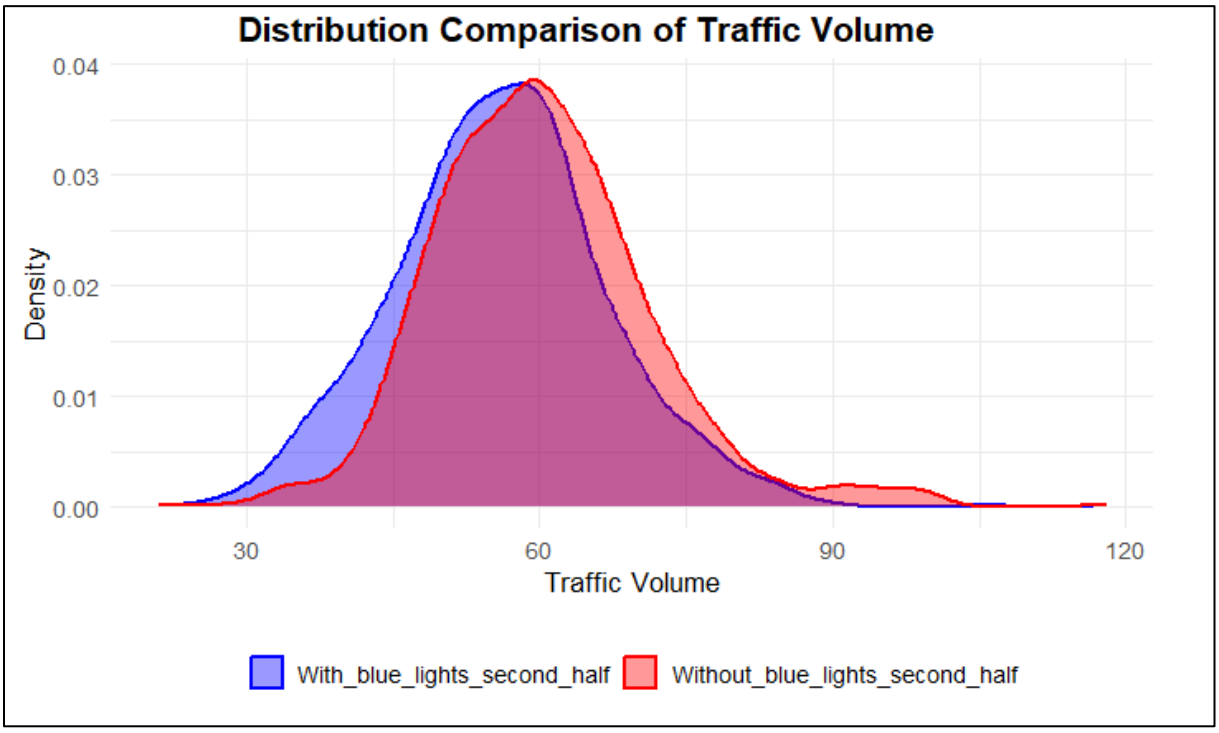


Figure 44. Traffic volume distribution for the second half of the active work zone

6.10.5 Hypothesis 5: Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis aimed to compare traffic volume during nighttime in the presence and absence of blue lights for three individual work zone locations - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume during the nighttime in the presence of blue lights during construction work* for *the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work* for *the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

H_1: *There is a significant difference in traffic volume during the nighttime in the presence of blue lights during construction work* for *the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work* for *the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

Data Collected: For hypothesis testing, the traffic volume data during nighttime were categorized into six conditions:

- **With Blue Light Beginning (WB_Beg)** - Construction with the presence of blue lights at the beginning of the work zone, 8064 observations
- **Without Blue Light Beginning (WOB_Beg)** - Construction without the presence of blue lights at the beginning of the work zone, 576 observations
- **With Blue Light First Half (WB_1stH)** - Construction with the presence of blue lights in the first half of the active work zone, 8064 observations
- **Without Blue Light First Half (WB_1stH)** - Construction without the presence of blue lights in the first half of the active work zone, 576 observations
- **With Blue Light Second Half (WB_2ndH)** - Construction with the presence of blue lights in the second half of the active work zone, 8064 observations
- **Without Blue Light Second Half (WB_2ndH)** - Construction without the presence of blue lights in the second half of the active work zone, 576 observations

An illustration of the dataset is depicted in

Table 34.

Table 34. Data points for nighttime traffic volume differences between construction with the presence of blue lights and construction without the presence of blue lights for individual work zone locations

WB_Beg	WOB_Beg	WB_1stH	WOB_1stH	WB_2ndH	WOB_2ndH
45	47	40	55	67	52
38	33	37	31	28	47
X	X	X	X	X	X
X	X	X	X	X	X
X	X	X	X	X	X
41	44	25	17	34	64

Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Methods: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 4.9887e-10, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in traffic volume between construction with the presence of blue lights and construction without the presence of blue lights for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during nighttime. The results from the post hoc pairwise comparisons are shown in **Table 35**.

Table 35. Post hoc pairwise comparison results

Comparison	p-value
WB_Beg - WOB_Beg	0.0041
WB_1stH - WOB_1stH	0.1004
WB_2ndH - WOB_2ndH	1

Post Hoc Pairwise Comparisons:

Beginning of the work zone: The comparison between construction with and without blue lights, which included the data from the green columns in

Table 34 yielded a p-value of 0.0041, suggesting a significant difference. The median traffic volume was 17 vehicles with blue lights and 19 vehicles without blue lights.

First half of the active work zone: The comparison between construction with and without blue lights, which included the data from the purple columns in

Table 34 yielded a p-value of 0.1004, indicating no statistically significant difference. The median traffic volume was 19 vehicles with blue lights and 15 vehicles without blue lights.

Second half of the active work zone: The comparison between construction with and without blue lights, which included the data from the orange columns in

Table 34 yielded a p-value of 1, indicating no statistically significant difference. The median traffic volume was 19 vehicles with blue lights and 18 vehicles without blue lights.

Discussion: The ART ANOVA results confirmed a statistically significant difference in traffic volume between construction with the presence of blue lights and construction without the presence of blue lights for the beginning of the work zone during nighttime. However, no significant differences were found for the first or second halves of the active work zone.

The density plot in **Figure 45** illustrates that in the beginning of the work zone with blue lights, the distribution shifted slightly leftward and displayed a broader spread, while the condition without blue lights showed a sharper concentration at higher volumes. This difference highlights that drivers were more responsive to blue lights when first approaching the work zone, leading to a reduction in flow.

Overall, the results suggest that the impact of construction with the presence of blue lights was strongest at the entry point of the work zone, where drivers first adjusted their behavior. Once drivers moved into the active parts of the work zone, the influence of construction with the presence of blue lights became weaker, and traffic volumes looked more similar to construction without the presence of blue lights.

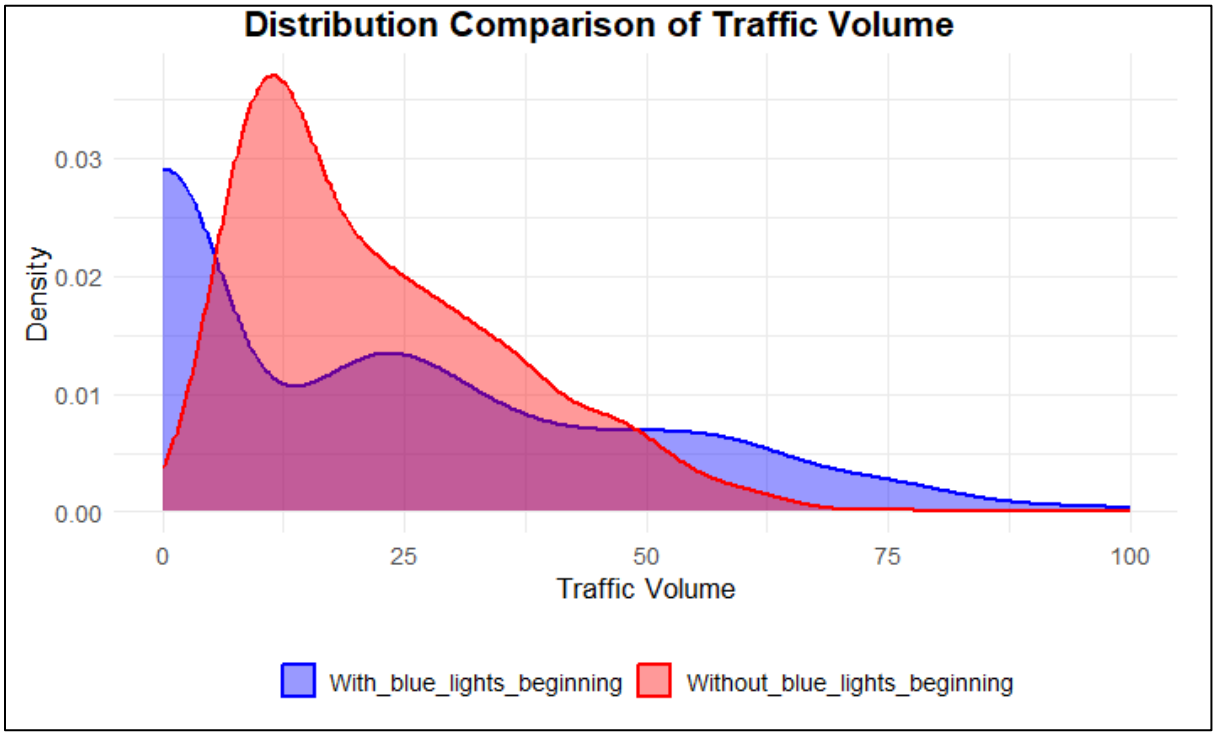


Figure 45. Traffic volume distribution for the beginning of the work zone

6.10.6 Hypothesis 6: Lane 1, Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

This analysis examined whether traffic volume in Lane 1 differed significantly between construction with blue lights in the work zone and construction without blue lights in the work zone during the daytime. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume within lane 1 between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

H_1: *There is a significant difference in traffic volume within lane 1 between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

Data Collected: For the analysis, the data were divided into two categories:

- Daytime lane 1 construction with the presence of blue lights - 1296 observations
- Daytime lane 1 construction without the presence of blue lights - 2880 observations

An illustration of the dataset is depicted in **Table 36** below:

Table 36. Data points for traffic volume for construction with the presence of blue lights vs. construction without the presence of blue lights - daytime, lane 1

Volume for Construction with the Presence of Blue Lights	Volume for Construction without the Presence of Blue Lights
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test.

Analysis Results: The Mann-Whitney U test yielded a p-value of 2.054e-09, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it was concluded that there was a statistically significant difference in traffic volume within Lane 1 between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.

According to the descriptive statistics, the median traffic volume during construction with the presence of blue lights was 54, while it was 55 for construction without the presence of blue lights. The IQR was 17 for construction with the presence of blue lights and 21 for construction without the presence of blue lights, showing slightly more variability in the condition without blue lights. Although the difference in median values was small, the density plot in **Figure 46** illustrates that

the distribution was more concentrated when blue lights were present, while traffic volume showed wider variability without the presence of blue lights. This supported the statistical results and suggested that the presence of blue lights helped maintain a stable traffic flow in Lane 1 by improving driver awareness during daytime construction.

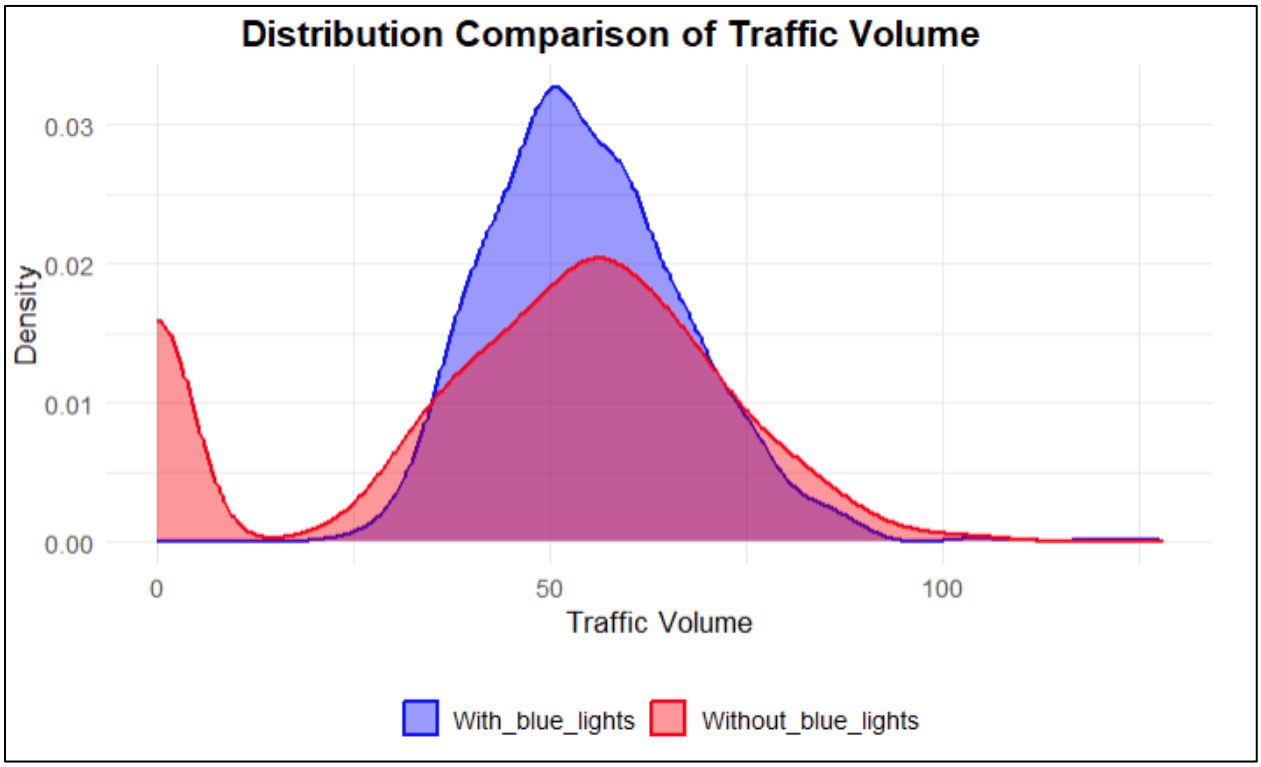


Figure 46. Traffic volume distribution with and without blue lights

6.10.7 Hypothesis 7: Lane 2, Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

This analysis examined whether traffic volume in Lane 2 differed significantly between construction with blue lights in the work zone and construction without blue lights in the work zone during the daytime. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume within lane 2 between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

H_1: *There is a significant difference in traffic volume within lane 2 between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

Data Collected: For the analysis, the data were divided into two categories:

- Daytime lane 2 construction with the presence of blue lights - 1296 observations
- Daytime lane 2 construction without the presence of blue lights - 2880 observations

An illustration of the dataset is depicted in **Table 37** below:

Table 37. Data points for traffic volume for construction with the presence of blue lights vs. construction without the presence of blue lights - daytime, lane 2

Volume for Construction with the Presence of Blue Lights	Volume for Construction without the Presence of Blue Lights
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test.

Analysis Results: The Mann-Whitney U test yielded a p-value of less than 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it was concluded that there was a statistically significant difference in traffic volume within Lane 2 between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.

According to the descriptive statistics, the median traffic volume during construction with the presence of blue lights was 58, while it was 60 for construction without the presence of blue lights. The IQR was 11 for construction with the presence of blue lights and 12 for construction without the presence of blue lights, indicating slightly greater variability in the condition without blue lights. Although the difference in medians was small, the density plot in **Figure 47** showed that traffic volumes were more consistent when blue lights were present, as reflected by the narrower distribution. This supported the statistical results and suggested that the presence of blue lights helped promote stable traffic flow in Lane 2 during daytime construction.

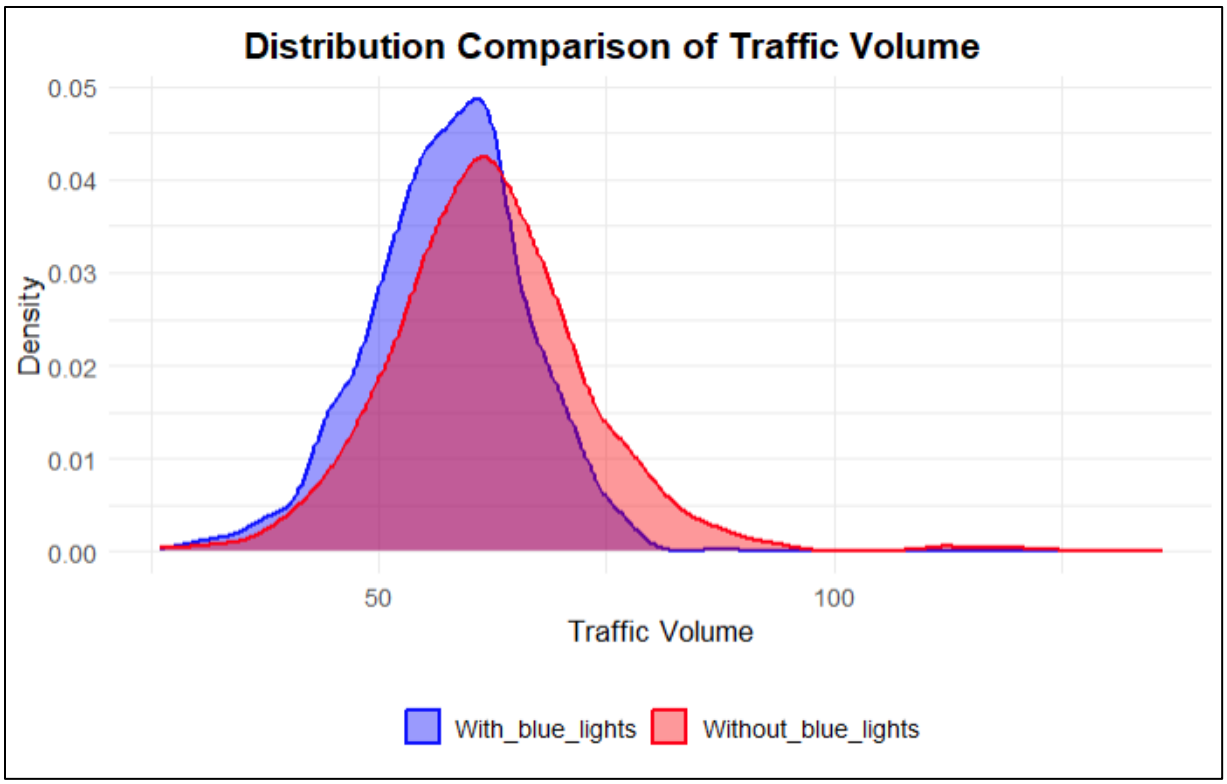


Figure 47. Traffic volume distribution with and without blue lights

6.10.8 Hypothesis 8: Lane 1, Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

This analysis examined whether traffic volume in Lane 1 differed significantly between construction with blue lights in the work zone and construction without blue lights in the work zone during nighttime. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume within lane 1 between construction with the presence of blue lights and construction without the presence of blue lights during nighttime.*

H_1: *There is a significant difference in traffic volume within lane 1 between construction with the presence of blue lights and construction without the presence of blue lights during nighttime.*

Data Collected: For the analysis, the data were divided into two categories:

- Nighttime lane 1 construction with the presence of blue lights - 12096 observations
- Nighttime lane 1 construction without the presence of blue lights - 864 observations

An illustration of the dataset is depicted in **Table 38** below:

Table 38. Data points for traffic volume for construction with the presence of blue lights vs. construction without the presence of blue lights - nighttime, lane 1

Volume for Construction with the Presence of Blue Lights	Volume for Construction without the Presence of Blue Lights
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test.

Analysis Results: The Mann-Whitney U test showed that the p-value was 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it was concluded that there was a statistically significant difference in traffic volume within Lane 1 between construction with the presence of blue lights and construction without the presence of blue lights during nighttime.

According to the descriptive statistics, the median traffic volume during construction with the presence of blue lights was 8, while it was 14 for construction without the presence of blue lights. The IQR was 22 for construction with the presence of blue lights and 20 for construction without the presence of blue lights, showing a slightly wider spread in the blue light condition. The density plot in **Figure 48** illustrates that traffic volumes were concentrated at very low levels when blue lights were present, whereas the distribution shifted rightward when blue lights were absent. This supported the statistical results and suggested that drivers were less likely to use Lane 1 when blue lights were present, likely due to greater visibility of the work zone during nighttime construction.

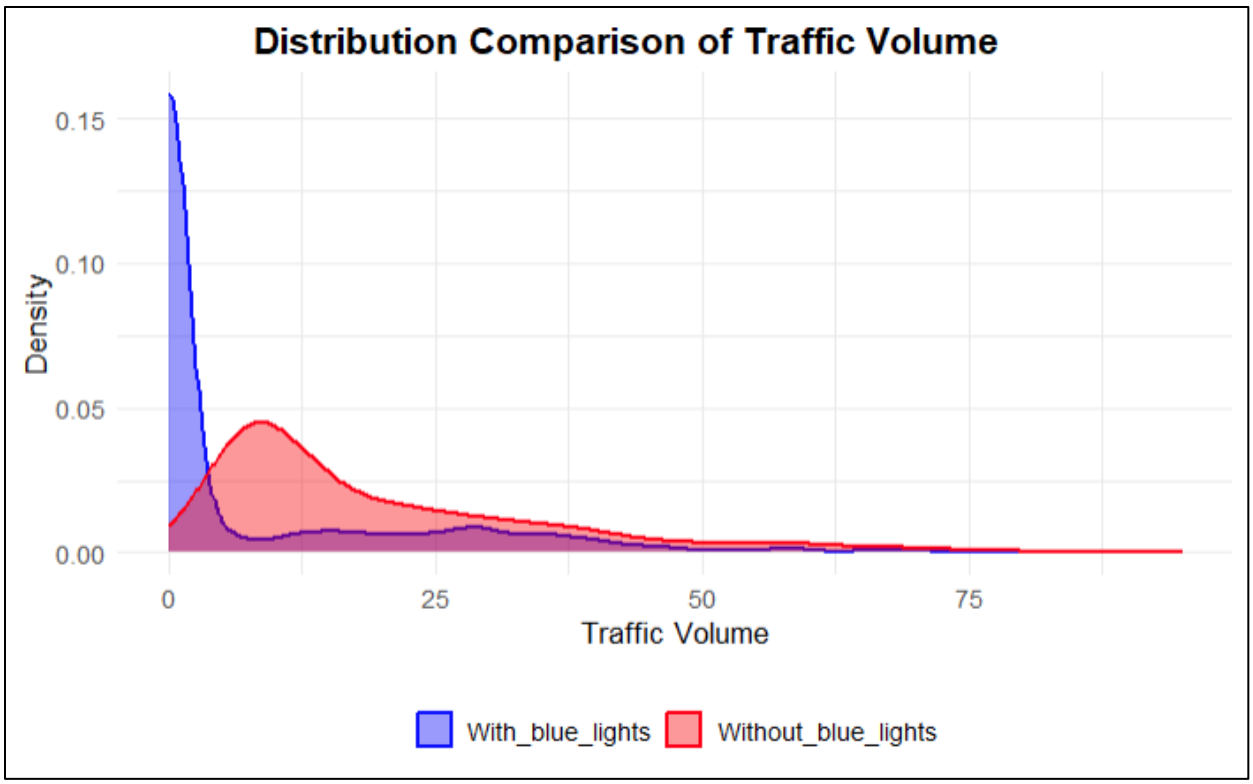


Figure 48. Traffic volume distribution with and without blue lights

6.10.9 Hypothesis 9: Lane 2, Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

This analysis examined whether traffic volume in Lane 2 differed significantly between construction with blue lights in the work zone and construction without blue lights in the work zone during nighttime. The null and alternative hypotheses formulated for this test are as follows:

H_0: *There is no significant difference in traffic volume within lane 2 between construction with the presence of blue lights and construction without the presence of blue lights during nighttime.*

H_1: *There is a significant difference in traffic volume within lane 2 between construction with the presence of blue lights and construction without the presence of blue lights during nighttime.*

Data Pre-processing: For the analysis, the data were divided into two categories:

- Nighttime lane 2 construction with the presence of blue lights - 12096 observations
- Nighttime lane 2 construction without the presence of blue lights - 864 observations

An illustration of the dataset is depicted in **Table 39** below:

Table 39. Data points for traffic volume for construction with the presence of blue lights vs. construction without the presence of blue lights - nighttime, lane 2

Volume for Construction with the Presence of Blue Lights	Volume for Construction without the Presence of Blue Lights
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test.

Analysis Results: The Mann-Whitney U test yielded a p-value of 0.3794, which was greater than the significance level of 0.05. Therefore, there was insufficient evidence to reject the null hypothesis. This indicated that there was no statistically significant difference in traffic volume within Lane 2 between construction with and without the presence of blue lights during nighttime. According to the descriptive statistics, the median traffic volume was 26 for construction with the presence of blue lights and 19 for construction without the presence of blue lights. The IQR was 25 for construction with the presence of blue lights and 21 for construction without the presence of blue lights, suggesting slightly greater variability under the blue light condition.

6.10.10 Hypothesis 10: Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Lanes for Individual Work Zone Locations

This analysis compared traffic volume during the daytime between construction with blue lights and construction without blue lights for individual lanes at individual work zone locations. The analysis spanned three work zone locations-the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone-and two lanes (lane 1 and lane 2). The null and alternative hypotheses are as follows:

H_0: *There is no significant difference in traffic volume during the daytime for individual lanes in the presence of blue lights during construction work* for *the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work* for *the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

H_1: *There is a significant difference in traffic volume during the daytime for individual lanes in the presence of blue lights during construction work* for *the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work* for *the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

Data Collected: For hypothesis testing, the traffic volume data during the daytime were categorized into the following conditions:

- **Lane 1 With Blue Lights Beginning (L1_WB_Beg)** - Lane 1, construction with the presence of blue lights at the beginning of the work zone, 432 observations
- **Lane 1 Without Blue Lights Beginning (L1_WOB_Beg)** - Lane 1, construction without the presence of blue lights at the beginning of the work zone, 960 observations
- **Lane 1 With Blue Light First Half (L1_WB_1stH)** - Lane 1, construction with the presence of blue lights at the first half of the active work zone, 432 observations
- **Lane 1 Without Blue Light First Half (L1_WOB_1stH)** - Lane 1, construction without the presence of blue lights at the first half of the active work zone, 960 observations
- **Lane 1 With Blue Light Second Half (L1_WB_2ndH)** - Lane 1, construction with the presence of blue lights at the second half of the active work zone, 432 observations
- **Lane 1 Without Blue Light Second Half (L1_WOB_2ndH)** - Lane 1, construction without the presence of blue lights at the second half of the active work zone, 960 observations
- **Lane 2 With Blue Lights Beginning (L2_WB_Beg)** - Lane 2, construction with the presence of blue lights at the beginning of the work zone, 432 observations
- **Lane 2 With Blue Lights Beginning (L2_WOB_Beg)** - Lane 2, construction without the presence of blue lights at the beginning of the work zone, 960 observations
- **Lane 2 With Blue Light First Half (L2_WB_1stH)** - Lane 2, construction with the presence of blue lights at the first half of the active work zone, 432 observations
- **Lane 2 With Blue Light First Half (L2_WOB_1stH)** - Lane 2, construction without the presence of blue lights at the first half of the active work zone, 960 observations
- **Lane 2 With Blue Light Second Half (L2_WB_2ndH)** - Lane 2, construction with the presence of blue lights at the second half of the active work zone, 432 observations
- **Lane 2 Without Blue Light Second Half (L2_WOB_2ndH)** - Lane 2, construction without the presence of blue lights at the second half of the active work zone, 960 observations

An illustration of the dataset is depicted in **Table 40**.

Table 40. Data points for daytime traffic volume differences between construction with the presence of blue lights and construction without the presence of blue lights for individual lanes for individual work zone locations

L1_WB_ Beg	L1_ WOB_Beg	L1_WB_1 stH	L1_ WOB_ 1stH	L1_WB_2 ndH	L1_ WOB_ 2ndH	L2_WB_ Beg	L2_ WOB_Beg	L2_WB_1 stH	L2_ WOB_ 1stH	L2_WB_2 ndH	L2_ WOB_ 2ndH
22	25	65	87	41	12	23	29	30	35	12	27
42	12	55	62	41	78	32	65	20	11	9	47
X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X
41	53	49	67	23	25	64	11	20	27	30	48

Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Methods: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of < 2.22e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in traffic volume during the daytime for individual lanes between construction with the presence of blue lights and construction without the presence of blue lights for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone. The results from the post hoc pairwise test are shown in **Table 41**.

Table 41. Post hoc pairwise comparison results

Comparison	p-value
L1_WB_Beg - L1_WOB_Beg	<.0001
L1_WB_1stH - L1_WOB_1stH	0.0045
L1_WB_2ndH - L1_WOB_2ndH	<.0001
L2_WB_Beg - L2_WOB_Beg	0.3815
L2_WB_1stH - L2_WOB_1stH	<.0001
L2_WB_2ndH - L2_WOB_2ndH	<.0001

Post Hoc Pairwise Comparisons:

Lane 1 - Beginning of the work zone: The comparison between construction with and without blue lights, which included the data from the green columns in **Table 40** yielded a p-value of <0.0001, suggesting a significant difference. The median traffic volume was 53 vehicles with blue lights and 59 vehicles without blue lights.

Lane 1 - First half of the active work zone: The comparison between construction with and without blue lights, which included the data from the purple columns in **Table 40** yielded a p-value of 0.0045, suggesting a significant difference. The median traffic volume was 55 vehicles with blue lights and 62 vehicles without blue lights.

Lane 1 - Second half of the active work zone: The comparison between construction with and without blue lights, which included the data from the light blue columns in **Table 40** yielded a p-value of <0.0001, suggesting a significant difference. The median traffic volume was 54 vehicles with blue lights and 60 vehicles without blue lights.

Lane 2 - Beginning of the work zone: The comparison between construction with and without blue lights, which included the data from the orange columns in **Table 40** yielded a p-value of 0.3815, indicating no statistically significant difference. The median traffic volume was 60 vehicles with blue lights and 62 vehicles without blue lights.

Lane 2 - First half of the active work zone: The comparison between construction with and without blue lights, which included the data from the deep blue columns in **Table 40** yielded a p-

value of <0.0001, suggesting a significant difference. The median traffic volume was 57 vehicles with blue lights and 58 vehicles without blue lights.

Lane 2 - Second half of the active work zone: The comparison between construction with and without blue lights, which included the data from the light red columns in **Table 40** yielded a p-value of <0.0001, suggesting a significant difference. The median traffic volume was 58 vehicles with blue lights and 59 vehicles without blue lights.

Discussion: The ART ANOVA results confirmed that traffic volumes were significantly different between construction with the presence of blue lights and construction without the presence of blue lights for lane and location comparisons during daytime. The post hoc comparisons also provided lane-wise insights, showing bigger differences in Lane 1 for all locations, while Lane 2 showed shifts only in the active work zones.

In **Figure 49**, the density plot shows a clear separation between the two conditions. Construction without the presence of blue lights produced a sharp peak at higher volumes, while construction with the presence of blue lights displayed a wider spread at lower levels. This indicated that drivers reduced flow into Lane 1 when blue lights were present. In **Figure 50**, the same trend continues. Construction with the presence of blue lights produced flatter distributions and lower volumes, compared to the concentrated peak under construction without the presence of blue lights. This suggests that drivers maintained the same lane further into the work zone. In **Figure 51**, the difference depicts the strongest. Construction with the presence of blue lights produced a pronounced shift toward lower volumes, while construction without the presence of blue lights remained clustered at higher levels. This highlights stronger avoidance of Lane 1 under blue light conditions. In **Figure 52**, the difference appears smaller but still significant. Construction with the presence of blue lights shifted slightly toward lower volumes, while construction without the presence of blue lights was concentrated at higher levels. This indicated some redistribution of traffic between lanes. In **Figure 53**, the difference becomes clearer again. Construction with the presence of blue lights produced a broader, flatter distribution, while construction without the presence of blue lights showed a narrow peak at higher values. This suggested that the influence of blue lights persisted as drivers moved toward the exit of the work zone.

Overall, the results suggested that construction with the presence of blue lights had the strongest impact on Lane 1, where drivers consistently reduced volume, while Lane 2 showed smaller but consistent shifts. These findings indicated that blue lights encouraged drivers to favor the lane farther from the work area, improving safety conditions near active construction zones.

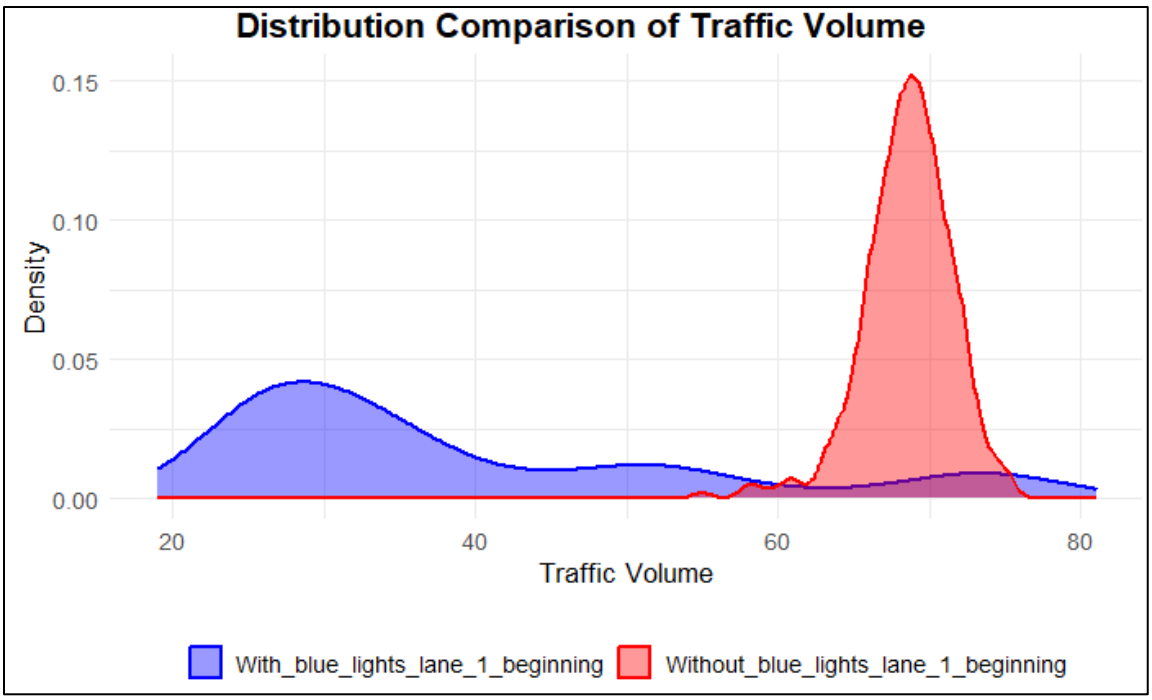


Figure 49. Lane 1 - Beginning of the work zone

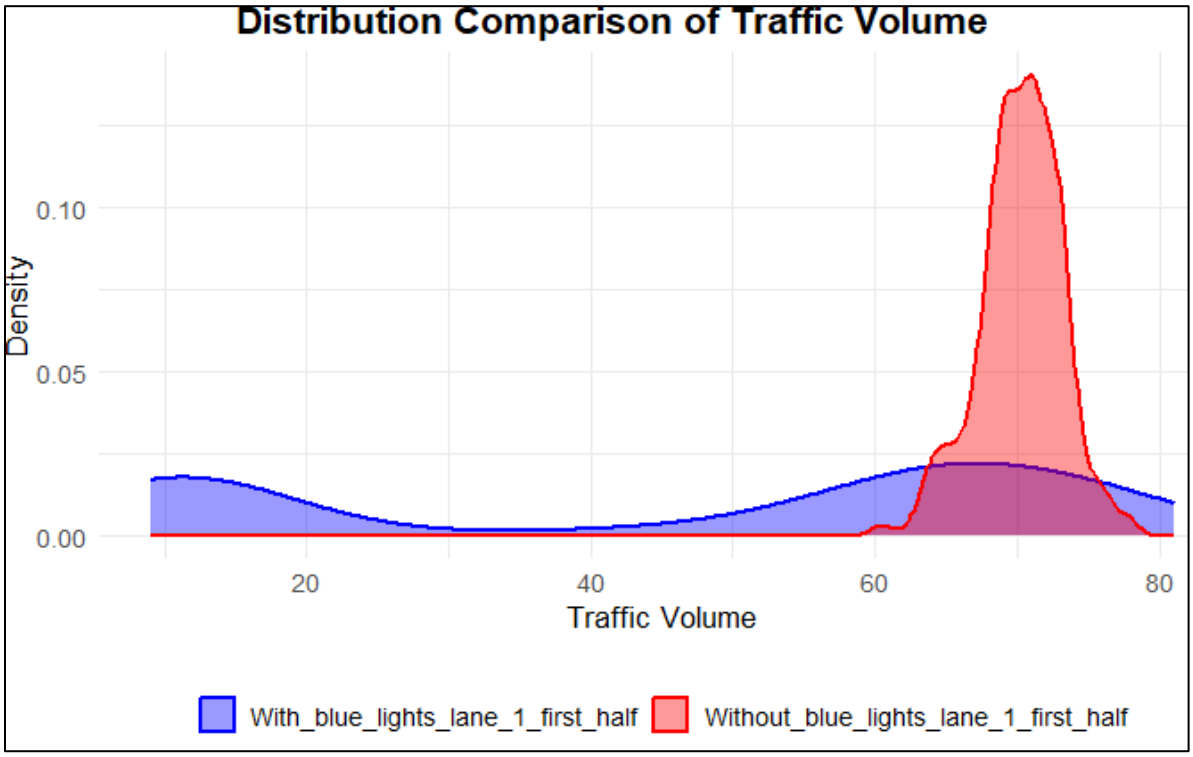


Figure 50. Lane 1 - First half of the active work zone

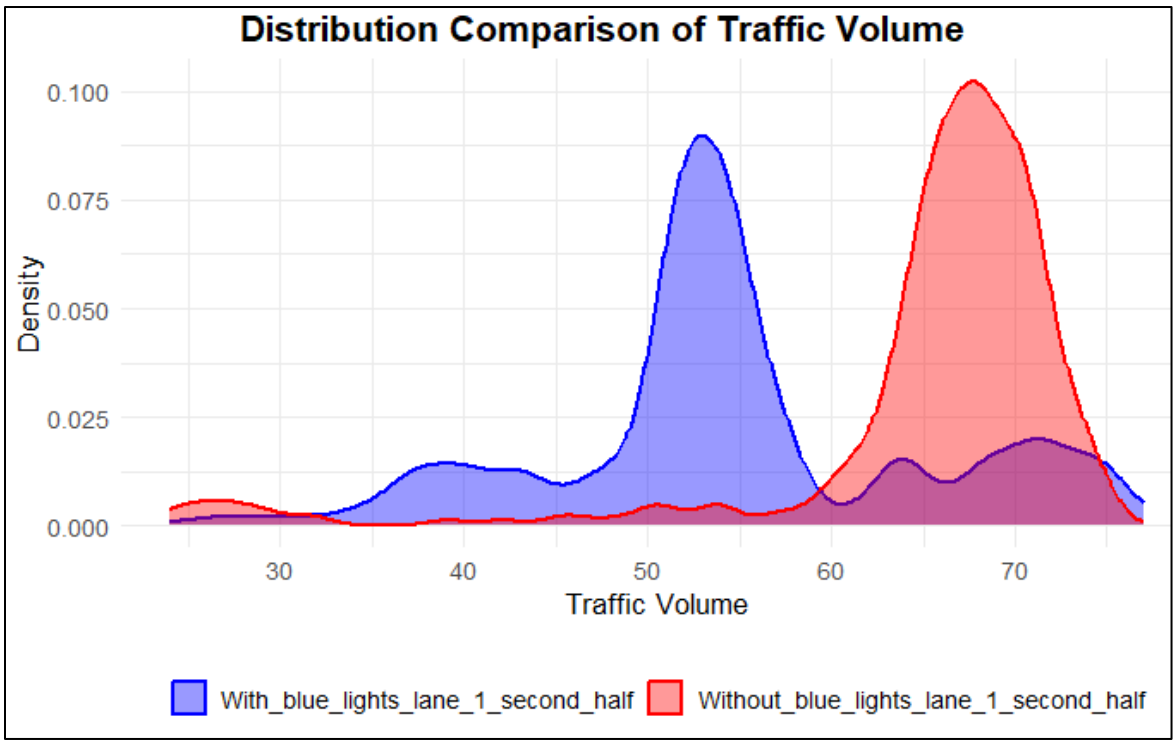


Figure 51. Lane 1 - Second half of the active work zone

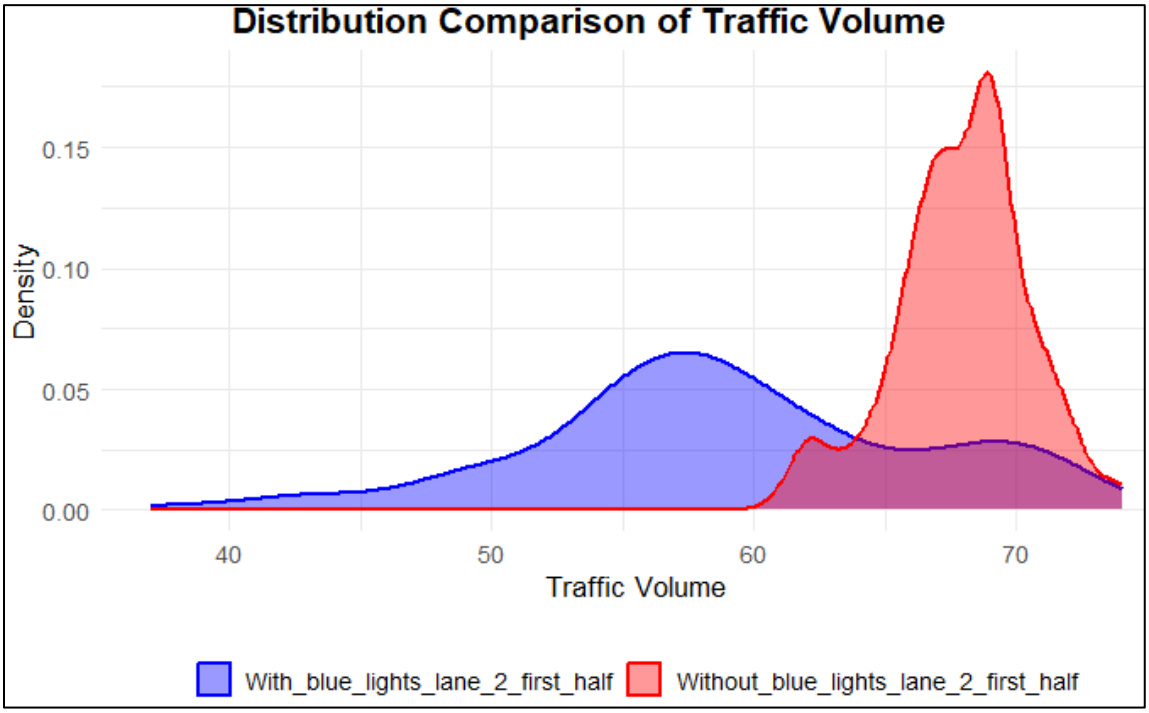


Figure 52. Lane 2 - First half of the active work zone

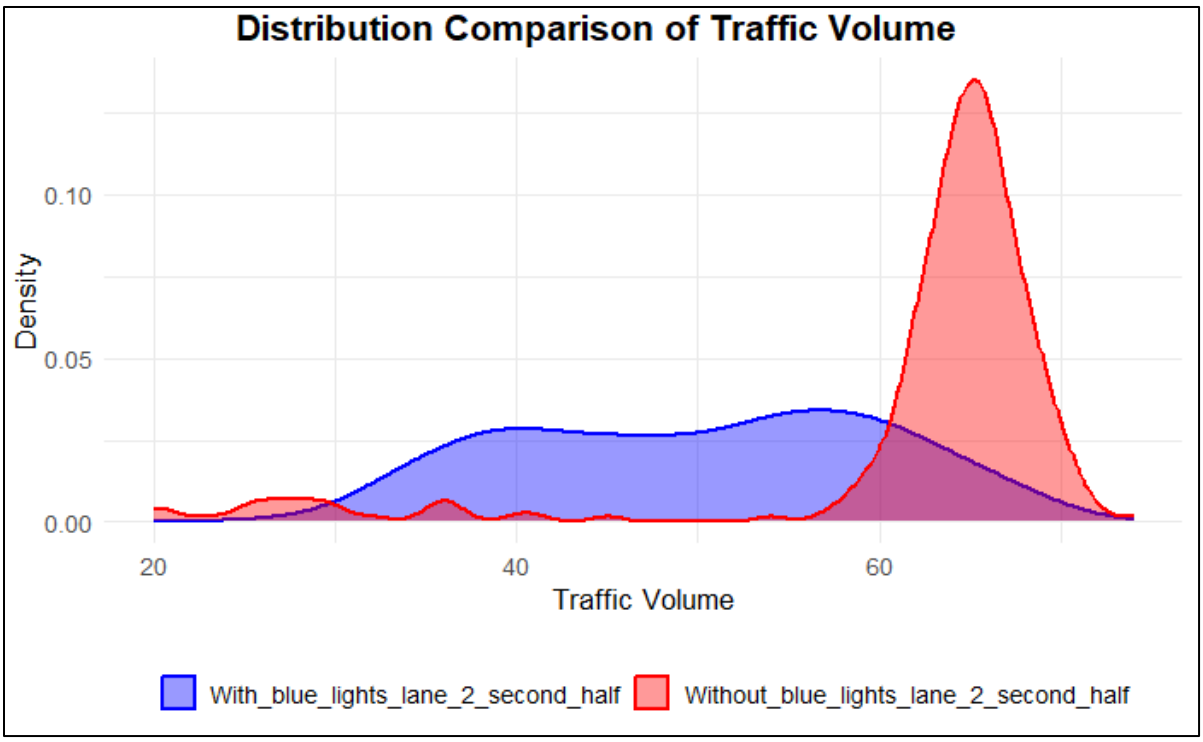


Figure 53. Lane 2 - Second half of the active work zone

6.10.11 Hypothesis 11: Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Lanes for Individual Work Zone Locations

This analysis examined traffic volume differences during nighttime between construction with blue lights and construction without blue lights for individual lanes and work zone locations. The null and alternative hypotheses are as follows:

***H_0**: There is no significant difference in traffic volume during the nighttime for individual lanes in the presence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

***H_1**: There is no significant difference in traffic volume during the nighttime for individual lanes in the presence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

Data Collected: For hypothesis testing, the traffic volume data during the nighttime were categorized into the following conditions:

- **Lane 1 With Blue Lights Beginning (L1_WB_Beg)** - Lane 1, construction with the presence of blue lights at the beginning of the work zone, 4032 observations

- **Lane 1 Without Blue Lights Beginning (L1_WOB_Beg)** - Lane 1, construction without the presence of blue lights at the beginning of the work zone, 288 observations
- **Lane 1 With Blue Light First Half (L1_WB_1stH)** - Lane 1, construction with the presence of blue lights at the first half of the active work zone, 4032 observations
- **Lane 1 Without Blue Light First Half (L1_WOB_1stH)** - Lane 1, construction without the presence of blue lights at the first half of the active work zone, 288 observations
- **Lane 1 With Blue Light Second Half (L1_WB_2ndH)** - Lane 1, construction with the presence of blue lights at the second half of the active work zone, 4032 observations
- **Lane 1 Without Blue Light Second Half (L1_WOB_2ndH)** - Lane 1, construction without the presence of blue lights at the second half of the active work zone, 288 observations
- **Lane 2 With Blue Lights Beginning (L2_WB_Beg)** - Lane 2, construction with the presence of blue lights at the beginning of the work zone, 4032 observations
- **Lane 2 With Blue Lights Beginning (L2_WOB_Beg)** - Lane 2, construction without the presence of blue lights at the beginning of the work zone, 288 observations
- **Lane 2 With Blue Light First Half (L2_WB_1stH)** - Lane 2, construction with the presence of blue lights at the first half of the active work zone, 4032 observations
- **Lane 2 With Blue Light First Half (L2_WOB_1stH)** - Lane 2, construction without the presence of blue lights at the first half of the active work zone, 288 observations
- **Lane 2 With Blue Light Second Half (L2_WB_2ndH)** - Lane 2, construction with the presence of blue lights at the second half of the active work zone, 4032 observations
- **Lane 2 Without Blue Light Second Half (L2_WOB_2ndH)** - Lane 2, construction without the presence of blue lights at the second half of the active work zone, 288 observations

An illustration of the dataset is depicted in **Table 42**

Table 42. Data points for nighttime traffic volume differences between construction with the presence of blue lights and construction without the presence of blue lights for individual lanes for individual work zone locations

L1_WB_Beg	L1_WOB_Beg	L1_WB_1stH	L1_WOB_1stH	L1_WB_2ndH	L1_WOB_2ndH	L2_WB_Beg	L2_WOB_Beg	L2_WB_1stH	L2_WOB_1stH	L2_WB_2ndH	L2_WOB_2ndH
22	25	65	87	41	12	23	29	30	35	12	27
42	12	55	62	41	78	32	65	20	11	9	47
X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X
41	53	49	67	23	25	64	11	20	27	30	48

Note: The 'X' marks in the table represent similar data points of the same type (traffic volume). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of <2.22e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in traffic volume during the nighttime for individual lanes between construction with the presence of blue lights and construction without the presence of blue lights for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone. The results from the post hoc pairwise comparison are shown in **Table 43**.

Table 43. Post hoc pairwise comparison results

Comparison	p-value
L1_WB_Beg - L1_WOB_Beg	<.0001
L1_WB_1stH - L1_WOB_1stH	0.0045
L1_WB_2ndH - L1_WOB_2ndH	<.0001
L2_WB_Beg - L2_WOB_Beg	0.3815
L2_WB_1stH - L2_WOB_1stH	<.0001
L2_WB_2ndH - L2_WOB_2ndH	<.0001

Post Hoc Pairwise Comparisons:

Lane 1 - Beginning of the work zone: The comparison between construction with and without blue lights, which included the data from the green columns in **Table 42** yielded a p-value of <0.0001, suggesting a significant difference. The median traffic volume was 8 vehicles with blue lights and 15 vehicles without blue lights.

Lane 1 - First half of the active work zone: The comparison between construction with and without blue lights, which included the data from the purple columns in **Table 42** yielded a p-value of 0.0045, suggesting a significant difference. The median traffic volume was 8 vehicles with blue lights and 11 vehicles without blue lights.

Lane 1 - Second half of the active work zone: The comparison between construction with and without blue lights, which included the data from the light blue columns in **Table 42** yielded a p-value of <0.0001, suggesting a significant difference. The median traffic volume was 7 vehicles with blue lights and 15 vehicles without blue lights.

Lane 2 - Beginning of the work zone: The comparison between construction with and without blue lights, which included the data from the orange columns in **Table 42** yielded a p-value of 0.3815, indicating no statistically significant difference. The median traffic volume was 24 vehicles with blue lights and 22 vehicles without blue lights.

Lane 2 - First half of the active work zone: The comparison between construction with and without blue lights, which included the data from the deep blue columns in **Table 42** yielded a p-value of <0.0001, suggesting a significant difference. The median traffic volume was 27 vehicles with blue lights and 18 vehicles without blue lights.

Lane 2 - Second half of the active work zone: The comparison between construction with and without blue lights, which included the data from the light red columns in **Table 42** yielded a p-value of <0.0001, suggesting a significant difference. The median traffic volume was 27 vehicles with blue lights and 19 vehicles without blue lights.

Discussion: The ART ANOVA results confirmed that traffic volumes were significantly different between construction with the presence of blue lights and construction without the presence of blue lights for lane and location comparisons during nighttime. The post hoc comparisons also provided lane-wise insights, showing consistent reductions in Lane 1 for all locations, while Lane 2 showed increases in the active work zones. In **Figure 54**, the density plot shows that construction with the presence of blue lights produced a sharp peak at very low volumes, while construction without the presence of blue lights displayed a broader distribution with higher values. This indicated that drivers adjusted quickly when blue lights were present, reducing flow into Lane 1 right at the entry. **Figure 55**, depicts a similar pattern. Construction with the presence of blue lights kept the density concentrated at lower volumes, while construction without the presence of blue lights spread toward higher volumes. This suggested that the influence of blue lights continued as drivers moved further into the active area. In **Figure 56**, the difference is again clear. Construction with the presence of blue lights showed peak concentrations at lower volumes, while construction without the presence of blue lights was more heavily centered at higher volumes. This showed that the blue lights sustained their effect through the end of Lane 1. In **Figure 57**, the distributions shifts oppositely compared to Lane 1. Construction with the presence of blue lights pushed the density toward higher volumes, while construction without the presence of blue lights stayed concentrated at lower levels. This suggested that drivers favored Lane 2 once they noticed the blue lights, moving away from the active construction lane. In **Figure 58**, the difference becomes more visible. Construction with the presence of blue lights produced a broader distribution with higher volumes, while construction without the presence of blue lights remained concentrated at lower levels. This indicated that the preference for Lane 2 was reinforced as drivers approached the exit.

Overall**,** the results suggested that construction with the presence of blue lights reduced volumes in Lane 1 and increased them in Lane 2. These shifts showed that blue lights guided drivers to favor the lane farther from the work zone, which may enhance safety for both drivers and workers.

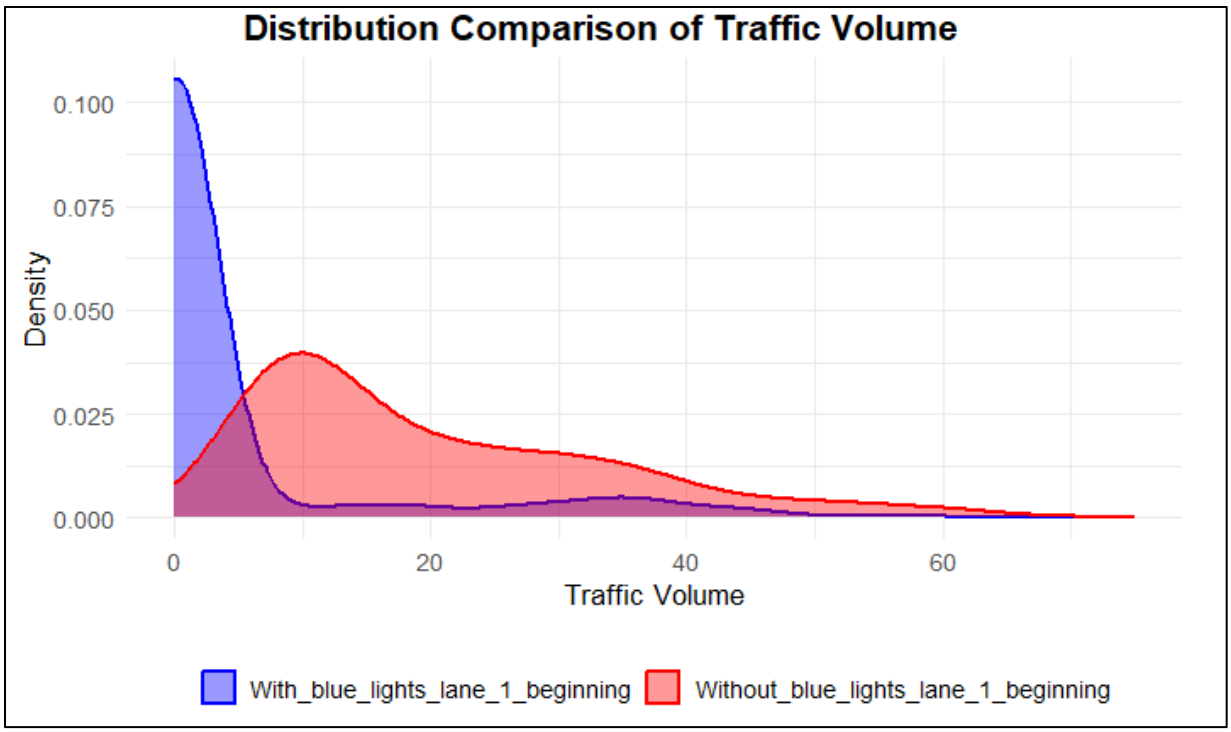


Figure 54. Lane 1 - Beginning of the work zone

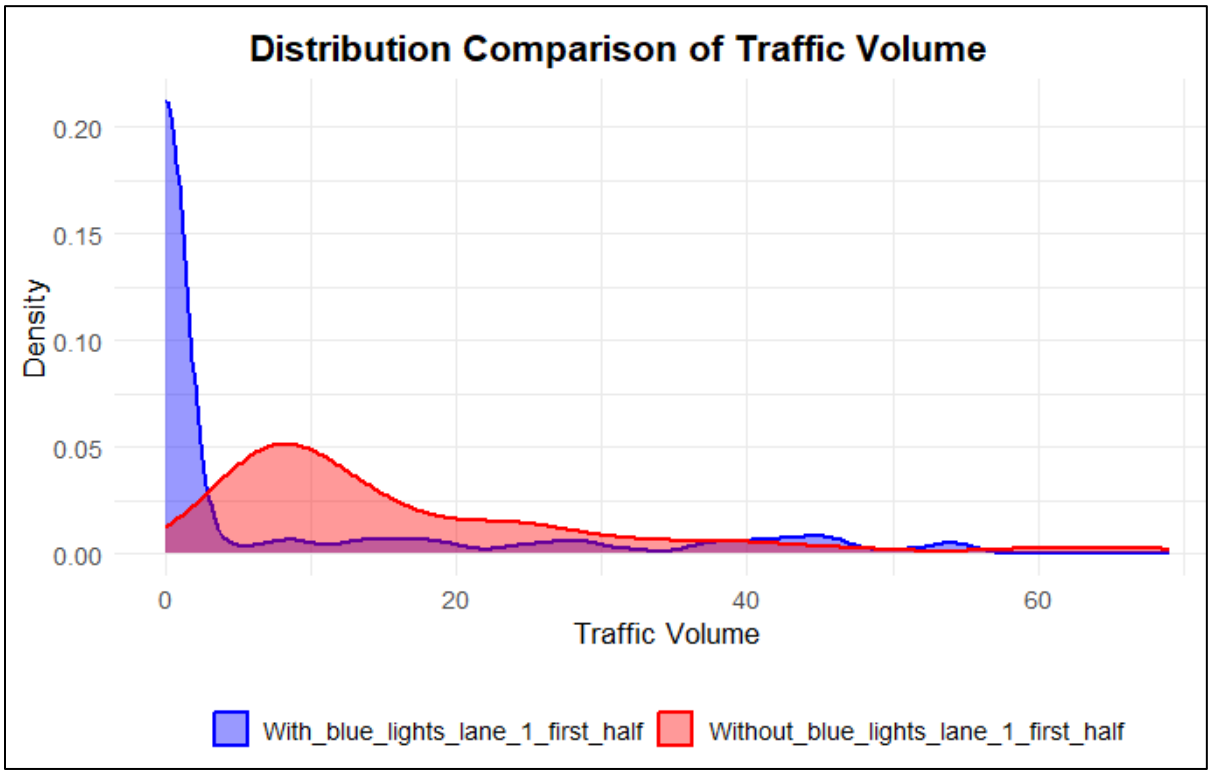


Figure 55. Lane 1 - First half of the active work zone

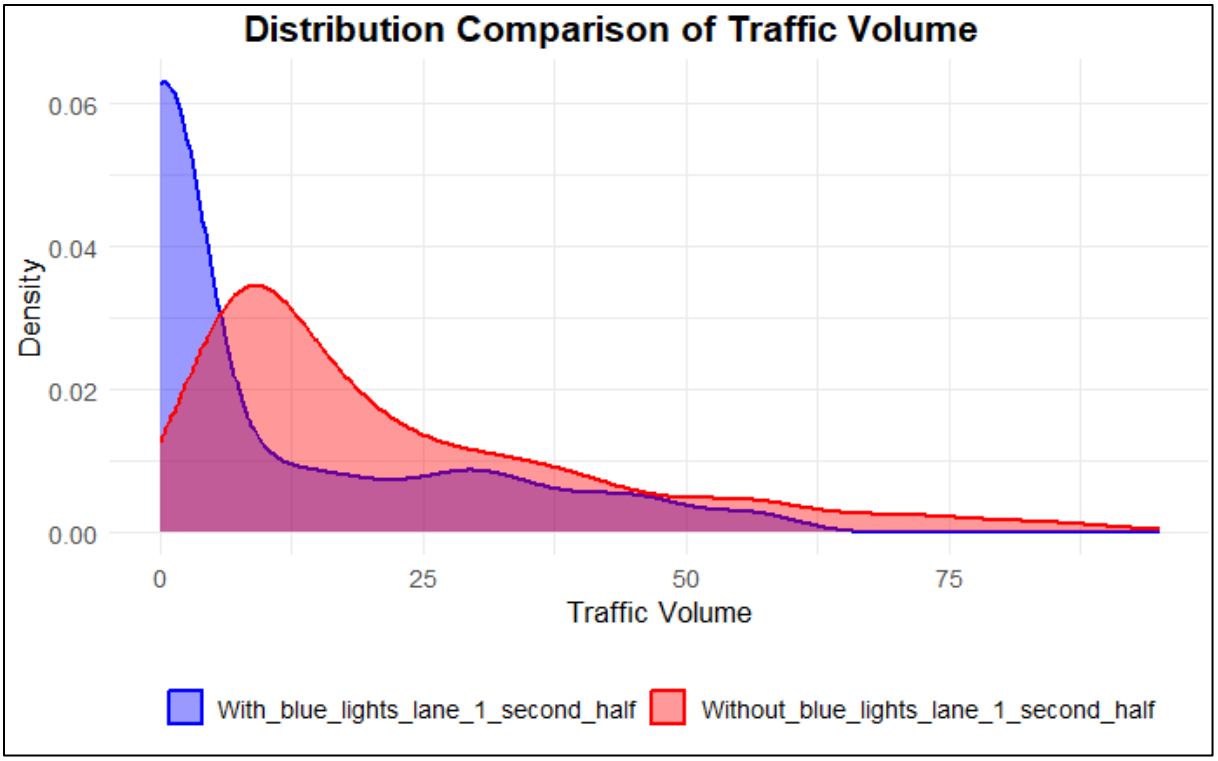


Figure 56. Lane 1 - Second half of the active work zone

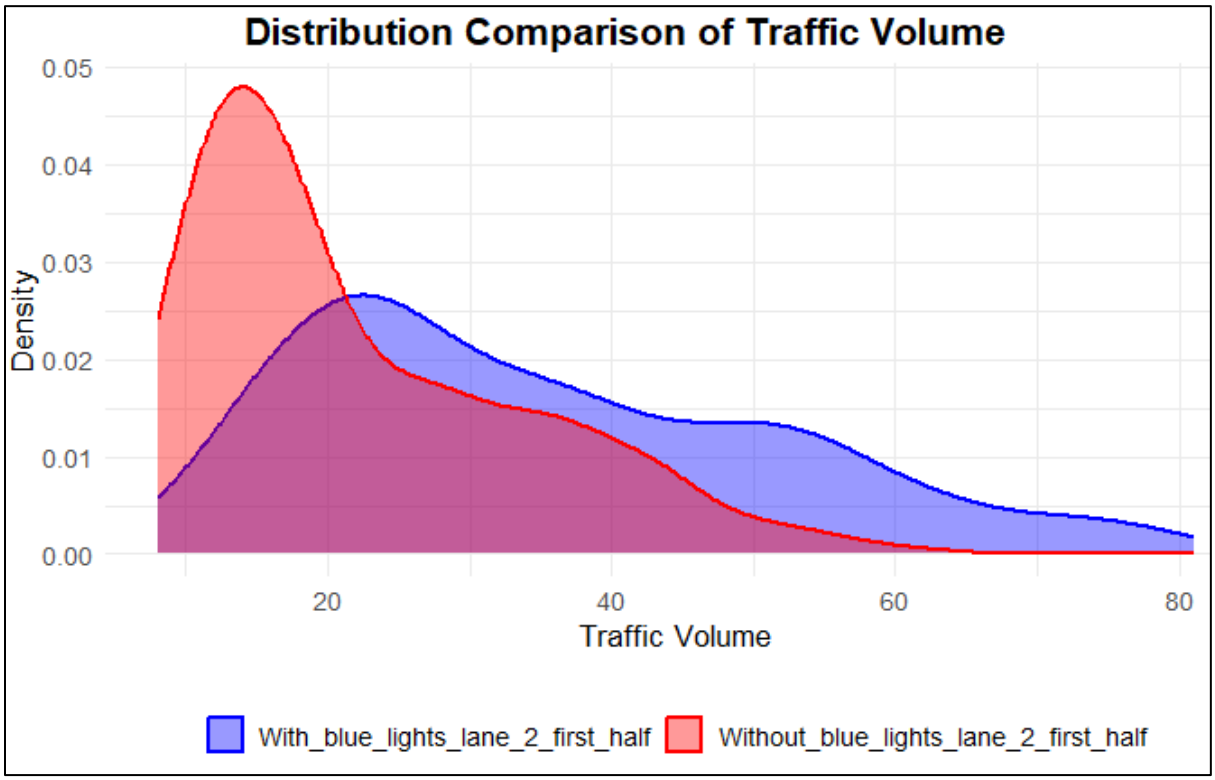


Figure 57. Lane 2 - First half of the active work zone

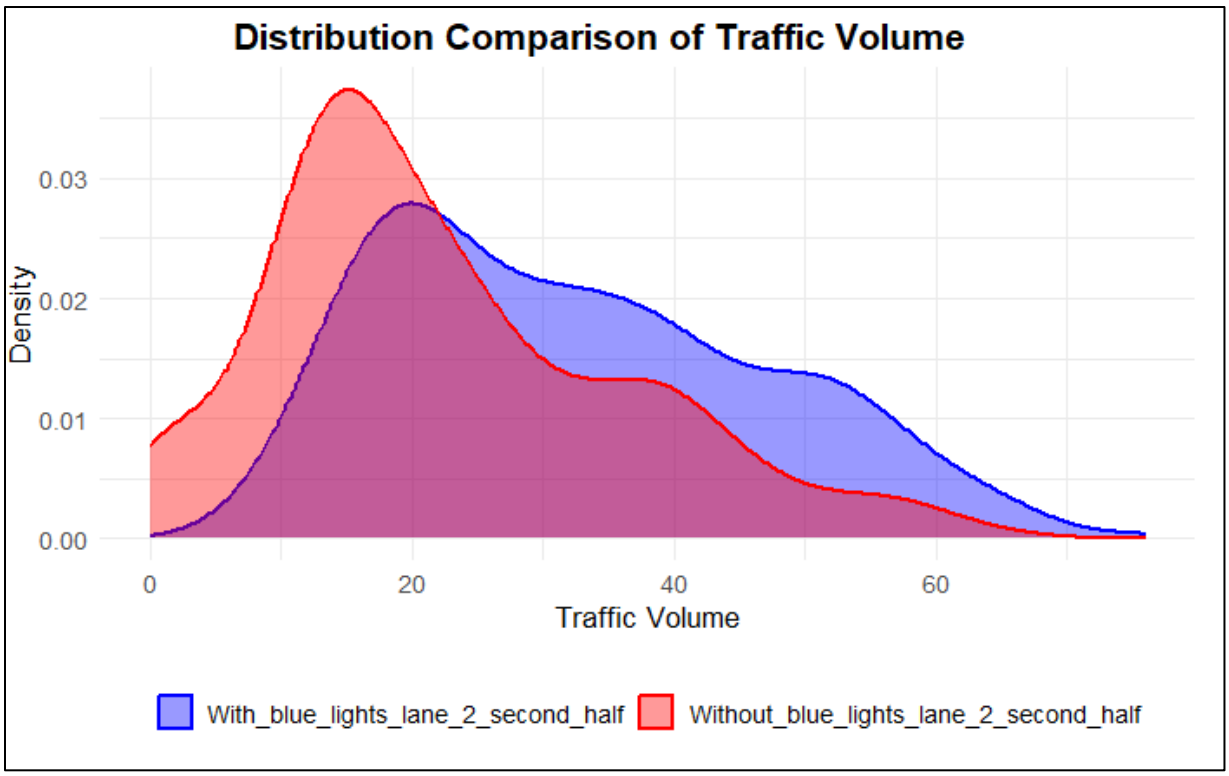


Figure 58. Lane 2 - Second half of the active work zone

6.10.12 Summary for Category Two: Comparative Analysis of Traffic Volume Between Construction with the Presence of Blue Lights and Construction without the Presence of Blue Lights in the Work Zone

This section provides a comprehensive summary based on the hypothesis tests conducted in this category and the insights gained from them.

6.10.12.1 Traffic Volume Differences with and without the Presence of Blue Lights (Hypothesis 1-Hypothesis 3)

The hypothesis tests (Hypothesis 1-Hypothesis 3) comparing overall traffic volume indicated that construction with the presence of blue lights was associated with slightly lower and more consistent traffic volumes compared to construction without the presence of blue lights. During daytime conditions, the difference was limited. This suggested a weaker overall influence of blue lights. During nighttime conditions, traffic volumes in the presence of blue lights became lower compared to construction without the presence of blue lights. During nighttime, these low traffic volumes were also more consistent, indicating a stronger response when the lights were more visually prominent.

6.10.12.2 Traffic Volume for Work Zone Locations with and without Blue Lights (Hypothesis 4-Hypothesis 5)

The hypothesis tests (Hypothesis 4-Hypothesis 5) examining work zone locations showed that the influence of blue lights varied by work zone location and time of day. During daytime construction, volume reductions under blue light conditions were concentrated within the active work zone, while the beginning of the work zone showed minimal change. During nighttime construction, the

most significant differences occurred at the beginning of the work zone. This indicated that drivers adjusted their behavior earlier when approaching the work zone.

6.10.12.3 Lane-Based Traffic Volume with and without Blue Lights (Hypothesis 6-Hypothesis 9)

The hypothesis tests (Hypothesis 6-Hypothesis 9) on lane-level traffic volume showed, during daytime conditions, traffic volumes under blue light conditions were slightly lower and showed less variation for both lanes compared to conditions without blue lights. At nighttime, the influence of blue lights was more evident for Lane 1, where traffic volumes decreased and remained more consistent. Lane 2 showed no significant difference between conditions. This suggested that the effect of blue lights at night was more noticeable in Lane 1.

6.10.12.4 Lane-Based Volumes for Work Zone Locations with and without the Presence of Blue Lights (Hypothesis 10-Hypothesis 11)

The hypothesis tests (Hypothesis 10-Hypothesis 11), combining lane and location effects, showed that blue lights had the strongest influence on Lane 1 for both daytime and nighttime conditions. During daytime construction, Lane 1 volumes were consistently lower under blue light conditions for all work zone locations, while Lane 2 showed smaller changes primarily within active work zones. During nighttime construction, Lane 1 volumes remained lower for all locations, while Lane 2 volumes increased within the active work zone, indicating consistent lane selection under blue light presence.

6.10.12.5 Insights from the Analysis

The findings from this category indicated that blue lights influenced traffic volume by moderating overall flow and shifting vehicles away from lanes adjacent to construction activity. The effect was conditional on visibility, with stronger responses observed during nighttime conditions when visual cues might be clearer, and driver caution appeared higher.

The analysis also showed that the influence of blue lights was dependent on work zone location. During daytime construction, their impact emerged primarily within active work zone segments, while during nighttime construction, the greatest change occurred at the entry to the work zone. This pattern might suggest that blue lights affected driver behavior differently at different work zone locations.

Lane-level results indicated that traffic volume reductions were driven mainly by changes in Lane 1 usage. Drivers consistently shifted away from the lane nearest to construction when blue lights were present. The reduced volume in Lane 1 appeared to be redistributed to Lane 2, particularly within active work zone segments. These findings suggested that blue lights might function as a visual signal that influenced both early decision-making and consistent lane selection as drivers progressed through the work zone.

Overall, the results indicated that blue lights influenced traffic volume by encouraging drivers to shift away from lanes adjacent to construction and maintain that choice as they progressed through the work zone. This influence varied by time of day and location, with stronger and earlier adjustments observed under nighttime conditions.

6.11 Preliminary Analysis for Average Vehicle Speed

The preliminary analysis focused on exploring the collected average vehicle speed data. Three hypothesis tests were conducted to determine the most efficient manner for further in-depth analysis to assess the effect of blue lights on average vehicle speed under the work zone conditions. These tests included assessing the average vehicle speed differences between daytime and nighttime, as well as between weekdays and weekends, for two conditions: (i) construction with the presence of blue lights and (ii) construction without the presence of blue lights. A summary of the test results is provided in **Table 44**, and more details about each hypothesis test are provided in the following sections, with a summary and insights at the end.

Table 44. Summarized results of the preliminary hypothesis tests for average vehicle speed

Number	Details	Results
Hypothesis 1	Daytime vs. Nighttime, for Construction with the Presence of Blue Lights	Significant difference
Hypothesis 2	Weekdays vs. Weekends, for Construction with the Presence of Blue Lights	Significant difference
Hypothesis 3	Daytime vs. Nighttime, for Construction without the Presence of Blue Lights	Significant difference

6.11.1 Hypothesis 1: Daytime vs. Nighttime, for Construction with the Presence of Blue Lights

***H_0**: There is no significant difference in the average traffic speed between daytime and nighttime in the presence of blue lights during construction work.*

***H_1**: There is a significant difference in the average traffic speed between daytime and nighttime in the presence of blue lights during construction work.*

Data Pre-processing: For this analysis, the data collected were divided into two categories:

- Daytime construction with the presence of blue lights - 2592 observations
- Nighttime construction with the presence of blue lights - 24192 observations

An illustration of the dataset is depicted in **Table 45**.

Table 45. Data points for daytime vs nighttime - construction with the presence of blue lights

Daytime Average Vehicle Speed (mph)	Nighttime Average Vehicle Speed (mph)
65	70
72	55
X	X
X	X
68	60
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Strategy: The Mann-Whitney U test was conducted for the hypothesis testing of comparing the data (two independent variables) shown in **Table 45**.

Analysis Results: The Mann-Whitney U test showed that the p-value was 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed between daytime and nighttime in the presence of blue lights during construction.

Based on the result, for further analysis of the average vehicle speed metric in terms of construction with the presence of blue lights, the data were organized by separating daytime and nighttime conditions in all cases.

6.11.2 Hypothesis 2: Weekdays vs. Weekends, for Construction with the Presence of Blue Lights

***H_0**: There is no significant difference in average vehicle speed between weekdays and weekends in the presence of blue lights during construction work.*

***H_1**: There is a significant difference in average vehicle speed between weekdays and weekends in the presence of blue lights during construction work.*

Data Collected: For this analysis, the data collected were divided into two categories:

- Weekday construction with the presence of blue lights - 23760 observations
- Weekend construction with the presence of blue lights - 3024 observations

An illustration of the dataset is depicted in the **Table 46**.

Table 46. Data points for weekdays vs. weekends - construction with the presence of blue lights

Weekday Average Vehicle Speed (mph)	Weekend Average Vehicle Speed (mph)
65	70
72	55
X	X
X	X
68	60
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Strategy: The Mann-Whitney U test was conducted for the hypothesis testing of comparing the data (two independent variables) shown in ***Table 46***.

Analysis Results: According to the results of the Mann-Whitney U test, the p-value was 1.331e-08, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it was concluded that

there was a statistically significant difference in average vehicle speed between weekdays and weekends in the presence of blue lights during construction.

Based on the result, for further analysis of the average vehicle speed metric in terms of construction with the presence of blue lights, the data were organized by separating weekdays and weekends in all cases.

6.11.3 Hypothesis 3: Daytime vs. Nighttime, for Construction without the Presence of Blue Lights

H_0: *There is no significant difference in average vehicle speed between daytime and nighttime when there is construction without the presence of blue lights.*

H_1: *There is a significant difference in average vehicle speed between daytime and nighttime when there is construction without the presence of blue lights.*

Data Collected: For this analysis, the data collected were divided into two categories:

- Daytime construction without the presence of blue lights - 5760 observations
- Nighttime construction without the presence of blue lights - 1728 observations

An illustration of the dataset is depicted in the **Table 47**.

Table 47. Data points for daytime vs. nighttime - construction without blue lights

Daytime Average Vehicle Speed (mph)	Nighttime Average Vehicle Speed (mph)
65	70
72	55
X	X
X	X
68	60
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Strategy: The Mann-Whitney U test was conducted for the hypothesis testing of comparing the data (two independent variables) shown in **Table 47**.

Analysis Results: According to the results of the Mann-Whitney U test, the p-value was 1.884e-09, which was much smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed between daytime and nighttime in the absence of blue lights during construction.

Based on the results, further analysis of the average vehicle speed metric in terms of construction without the presence of blue lights, the data was organized by separating daytime and nighttime in all cases.

6.11.4 Summary of Preliminary Analysis for Average Vehicle Speed

The results of the preliminary analysis provide important insights into the data collected for the average vehicle speed from the work zone. They offer an understanding of how factors, including daytime/nighttime and weekdays/weekends, impact average vehicle speed. For the average vehicle speed between daytime and nighttime, significant differences were observed for both work zone conditions: construction with the presence of blue lights and construction without the presence of blue lights. In terms of average vehicle speed between weekdays and weekends, significant differences were observed for construction with the presence of blue lights.

Based on these results, the two categories of analysis strategies were determined. **Category one** focused on the analysis of average vehicle speed for individual work zone locations and lanes for the work zone condition, construction with the presence of blue lights. **Category two** compared the average vehicle speed for individual work zone locations and lanes between the conditions, construction with the presence of blue lights, and construction without the presence of blue lights.

6.12 Category One: Analysis of Average Vehicle Speed for Construction with the Presence of Blue Lights in the Work Zone

This category focuses on analyzing the effect of construction with the presence of blue lights in the selected work zone on average vehicle speed. Based on the results from the preliminary analysis (Section 6.11), significant differences were observed between daytime and nighttime

construction with the presence of blue lights for average vehicle speed. Significant differences were also found between weekdays and weekends for average vehicle speed under construction with blue lights. Accordingly, a total of twenty-two hypothesis tests were proposed and conducted to assess the effect of construction with the presence of blue lights on average vehicle speed. This included comparing speed differences by considering several factors, including daytime and nighttime, weekday and weekend, lanes, and individual three work zone locations. It is important to note that for construction with the presence of blue lights, there was no scheduled construction activity during weekend daytime periods, as confirmed by project officials at the site. Therefore, weekend daytime cases were not included in the analysis under this category.

Table 48 summarizes the test results for the twenty-two hypotheses under this category. More details about each hypothesis test, including the individual hypothesis statements, data pre-processing, results analysis, and discussion (following the roadmap explained in

Table 5 or

Table 6), are presented in the following sections. An overall summary and key insights are provided at the end of the section.

Table 48. Summarized results of the category one hypothesis tests for average vehicle speed

Number	Details	Results
Hypothesis 1	Weekday Daytime, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 2	Weekday Nighttime, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 3	Weekend Nighttime, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 4	Weekday, Daytime, Lane 1, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 5	Weekday Daytime, Lane 2, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 6	Weekday, Nighttime, Lane 1, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 7	Weekday, Nighttime, Lane 2, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 8	Weekend, Nighttime, Lane 1, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 9	Weekend, Nighttime, Lane 2, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 10	Weekday Daytime, Construction with the Presence of Blue Lights, Lane 1 vs. Lane 2	Significant difference
Hypothesis 11	Weekday Nighttime, Construction with the Presence of Blue Lights, Lane 1 vs. Lane 2	Significant difference
Hypothesis 12	Weekend Nighttime, Construction with the Presence of Blue Lights, Lane 1 vs. Lane 2	Significant difference

Hypothesis 13	Weekday Daytime, Lane 1 vs. Lane 2, Construction with Blue Lights for Individual Work Zone Locations	Significant difference
Hypothesis 14	Weekday Nighttime, Lane 1 vs. Lane 2, Construction with Blue Lights for Individual Work Zone Locations	Significant difference
Hypothesis 15	Weekend Nighttime, Lane 1 vs. Lane 2, Construction with Blue Lights for Individual Work Zone Locations	Significant difference
Hypothesis 16	Weekday, Beginning of the Work Zone, Construction with the Presence of Blue Lights, Daytime vs. Nighttime	Significant difference
Hypothesis 17	Weekday, First Half of the Active Work Zone, Construction in the Presence of Blue Lights, Daytime vs. Nighttime	Significant difference
Hypothesis 18	Weekday, Second Half of the Active Work Zone, Construction with the Presence of Blue Lights, Daytime vs. Nighttime	Significant difference
Hypothesis 19	Weekday, Lane 1, Construction with the Presence of Blue Lights, Daytime vs. Nighttime	Significant difference
Hypothesis 20	Weekday, Lane 2, Construction with the Presence of Blue Lights, Daytime vs. Nighttime	Significant difference
Hypothesis 21	Weekday Daytime vs. Weekday Nighttime, Construction with the Presence of Blue Lights for Individual Work Zone Locations for Lane 1	Significant difference
Hypothesis 22	Weekday Daytime vs. Weekday Nighttime, Construction with Blue Lights for Individual Work Zone Locations for Lane 2	Significant difference

6.12.1 Hypothesis 1: Weekday Daytime, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis aimed to compare vehicle speeds during weekday daytime between three individual work zone locations - beginning of the work zone, first half of the active work zone, and second half of the active work zone in the presence of blue lights during construction. The null and alternative hypotheses developed for this test are as follows:

***H_0**: There is no significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday daytime when construction work is ongoing in the presence of blue lights.*

***H_1**: There is a significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday daytime when construction work is ongoing in the presence of blue lights.*

Data Collected: For hypothesis testing, the vehicle speed data during weekday daytime with blue lights present was divided into three categories:

- Weekday daytime, beginning of the work zone: 864 observations
- Weekday daytime, first half of the active work zone: 864 observations
- Weekday daytime, second half of the active work zone: 864 observations

An illustration of the dataset is depicted in

Table 49.

Table 49. Data points for weekday daytime average vehicle speed differences for construction with the presence of blue lights for individual work zone locations

Average Vehicle Speed for the Beginning of the Work Zone (mph)	Average Vehicle Speed for the First Half of the Active Work Zone (mph)	Average Vehicle Speed for the Second Half of the Active Work Zone (mph)
56	40	35
45	37	48
X	X	X
X	X	X
X	X	X
22	44	21
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.		

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 2.657939e-114, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday daytime when construction work was ongoing in the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 50**.

Table 50. Post hoc pairwise comparison results

Comparison	p-value
Beginning - First Half	<0.0001
Beginning - Second Half	<0.0001
First Half - Second Half	<0.0001

Post Hoc Pairwise Comparisons:

Beginning vs. First Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 68 mph in the beginning and 70 mph in the first half.

Beginning vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 68 mph in the beginning and 65 mph in the second half.

First Half vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 70 mph in the first half and 65 mph in the second half.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday daytime under construction with the presence of blue lights. The post hoc comparisons also provided insights into location-specific differences, showing that each pair of locations had statistically significant differences in speed behavior. In **Figure 59**, the density plot illustrates clear shifts among the three segments of the work zone. At the beginning of the work zone, speeds clustered around higher values, while in the first half of the active work zone, the distribution shifted slightly higher, indicating faster driving in this section. In contrast, the second half of the active work zone showed a pronounced spread toward lower speeds, suggesting that drivers slowed down more noticeably as they approached the end of the work zone. Overall, the results suggested that construction with the presence of blue lights influenced driver speed behavior differently depending on location. Drivers tended to increase speed slightly in the first half of the active work zone but slowed down significantly in the second half, reflecting a stronger awareness of the ongoing construction as they moved deeper into the zone.

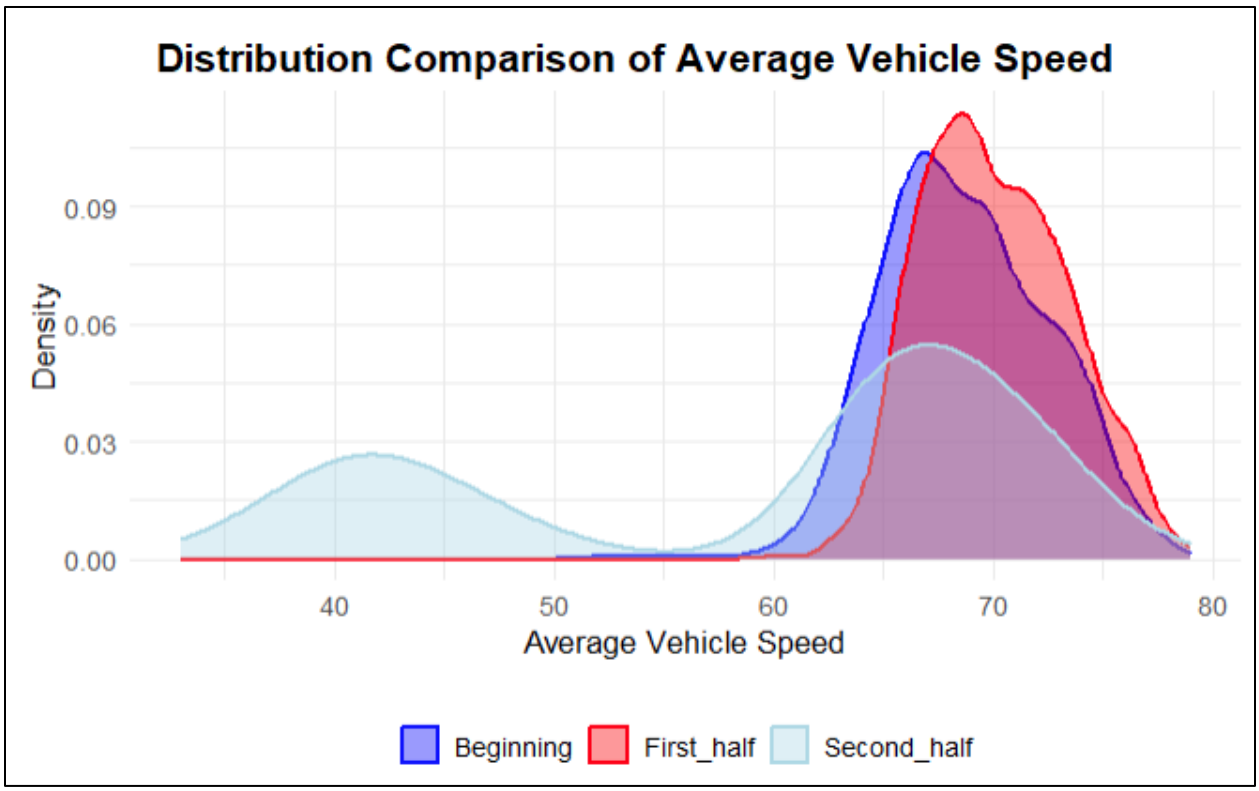


Figure 59. Average vehicle speed distribution for the work zone locations

6.12.2 Hypothesis 2: Weekday Nighttime, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis aimed to compare vehicle speeds during weekday nighttime between three individual work zone locations - beginning of the work zone, first half of the active work zone, and second half of the active work zone in the presence of blue lights during construction. The null and alternative hypotheses developed for this test are as follows:

***H_0**: There is no significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday nighttime when construction work is ongoing in the presence of blue lights.*

***H_1**: There is a significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday nighttime when construction work is ongoing in the presence of blue lights.*

Data Collected: For hypothesis testing, the average vehicle speed data during weekday daytime with blue lights present was divided into three categories:

- Weekday nighttime, beginning of the work zone: 7056 observations
- Weekday nighttime, first half of the active work zone: 7056 observations
- Weekday nighttime, second half of the active work zone: 7056 observations

An illustration of the dataset is depicted in **Table 51**.

Table 51. Data points for weekday nighttime average vehicle speed differences for construction with the presence of blue lights for individual work zone locations

Average Vehicle Speed for the Beginning of the Work Zone (mph)	Average Vehicle Speed for the First Half of the Active Work Zone (mph)	Average Vehicle Speed for the Second Half of the Active Work Zone (mph)
56	40	35
X	X	X
X	X	X
22	44	21
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.		

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 2.026128e-174, which provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday nighttime when construction work was ongoing in the presence of blue lights. The results from the post hoc comparisons are presented in **Table 52**.

Table 52. Post hoc pairwise comparison results

Comparison	p-value
Beginning - First Half	<0.0001
Beginning - Second Half	<0.0001
First Half - Second Half	<0.0001

Post Hoc Pairwise Comparisons:

Beginning vs. First Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 66 mph at the beginning and 66 mph in the first half.

Beginning vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 66 mph at the beginning and 63 mph in the second half.

First Half vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 66 mph in the first half and 63 mph in the second half.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday nighttime under construction with the presence of blue lights. The post hoc comparisons also showed significant differences for all location pairs, even though the median speeds were the same or very close. This highlighted that the differences were more strongly reflected in the shape and spread of the speed distributions. In **Figure 60**, the density plot provides a clearer picture of these differences. At the beginning of the work zone and in the first half of the active work zone, the peaks were concentrated at similar higher speeds, showing that drivers generally maintained consistent speeds in these segments. However, for the second half of the active work zone, the distribution shifted leftward, spreading more toward lower speeds. This pattern indicated that while the median values appeared stable, drivers increasingly slowed down toward the end of the work zone.

Overall, the results suggested that blue lights encouraged drivers to reduce their speeds more gradually, with the most noticeable effect emerging in the second half of the active work zone. This reinforces the importance of looking beyond median speed values to distributional patterns when evaluating driver responses.

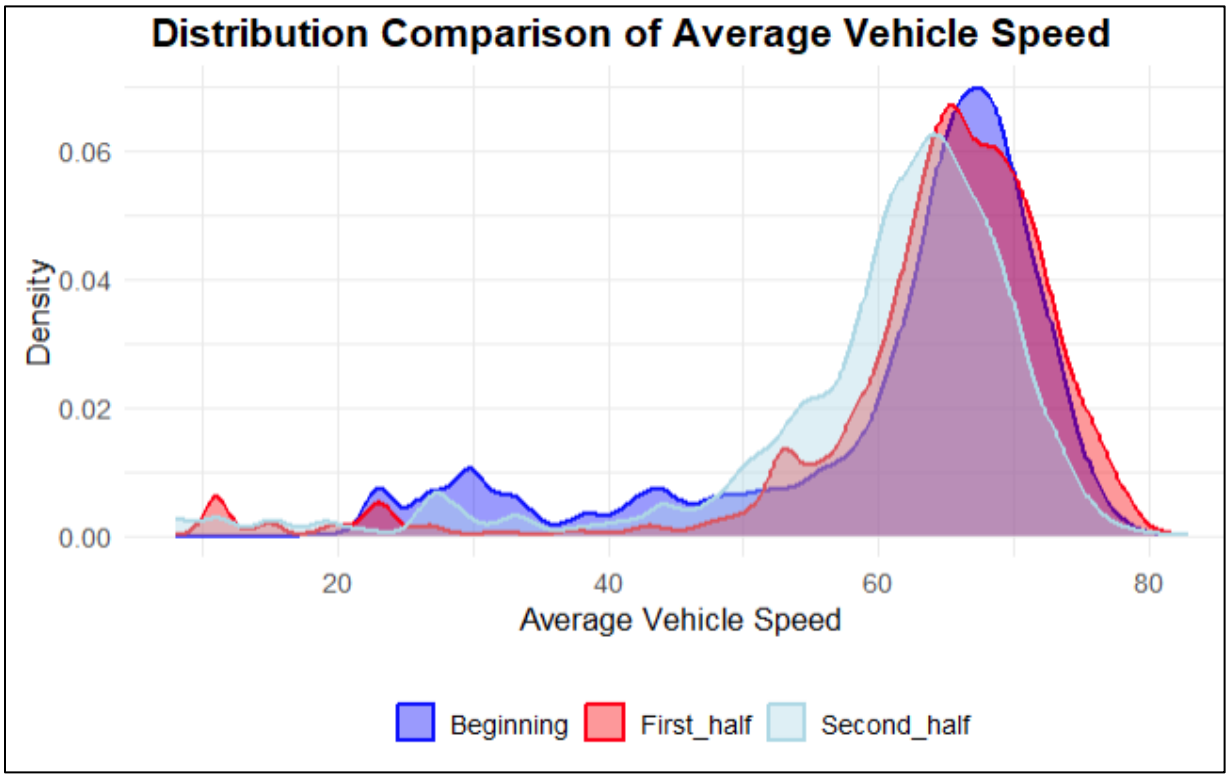


Figure 60. Average vehicle speed distribution for the work zone locations

6.12.3 Hypothesis 3: Weekend Nighttime, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis aimed to compare vehicle speeds during weekend nighttime between three individual work zone locations - beginning of the work zone, first half of the active work zone, and second half of the active work zone in the presence of blue lights during construction. The null and alternative hypotheses developed for this test are as follows:

***H_0**: There is no significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekend nighttime when construction work is ongoing in the presence of blue lights.*

***H_1**: There is a significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekend nighttime when construction work is ongoing in the presence of blue lights.*

Data Collected: For hypothesis testing, the average vehicle speed data during weekday daytime with blue lights present was divided into three categories:

- Weekend nighttime, beginning of the work zone: 1008 observations
- Weekend nighttime, first half of the active work zone: 1008 observations
- Weekend nighttime, second half of the active work zone: 1008 observations

An illustration of the dataset is depicted in **Table 53**.

Table 53. Data points for weekend nighttime average vehicle speed differences for construction with the presence of blue lights for individual work zone locations

Average Vehicle Speed for the Beginning of the Work Zone (mph)	Average Vehicle Speed for the First Half of the Active Work Zone (mph)	Average Vehicle Speed for the Second Half of the Active Work Zone (mph)
56	40	35
45	37	48
X	X	X
X	X	X
X	X	X
22	44	21

Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 1.502547e-57, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null

hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekend nighttime when construction work was ongoing in the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 54**.

Table 54. Post hoc pairwise comparison results

Comparison	p-value
Beginning - First Half	<0.0001
Beginning - Second Half	<0.0001
First Half - Second Half	<0.0001

Post Hoc Pairwise Comparisons:

Beginning vs. First Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 67 mph at the beginning and 67 mph in the first half.

Beginning vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 67 mph at the beginning and 62 mph in the second half.

First Half vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 67 mph in the first half and 62 mph in the second half.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekend nighttime under construction with the presence of blue lights. The post hoc comparisons also showed significant differences for all location pairs, even though the median speeds were the same or close. This indicated that the distribution patterns, rather than the central values, revealed the most meaningful changes in driver behavior. In **Figure 61**, the density plot highlights these location-based differences. At the beginning of the work zone and in the first half of the active work zone, the peaks overlapped closely, showing that drivers generally maintained similar speeds in both segments despite the statistical difference. However, for the second half of the active work zone, the distribution shifted leftward, with a broader spread toward lower speeds. This indicates that drivers slowed down more noticeably as they approached the end of the work zone.

Overall, these findings suggested that construction with the presence of blue lights influenced speed patterns more strongly toward the exit of the work zone. While median speeds stayed similar for segments, the density plots captured gradual adjustments in driver behavior that would not have been visible from summary values alone.

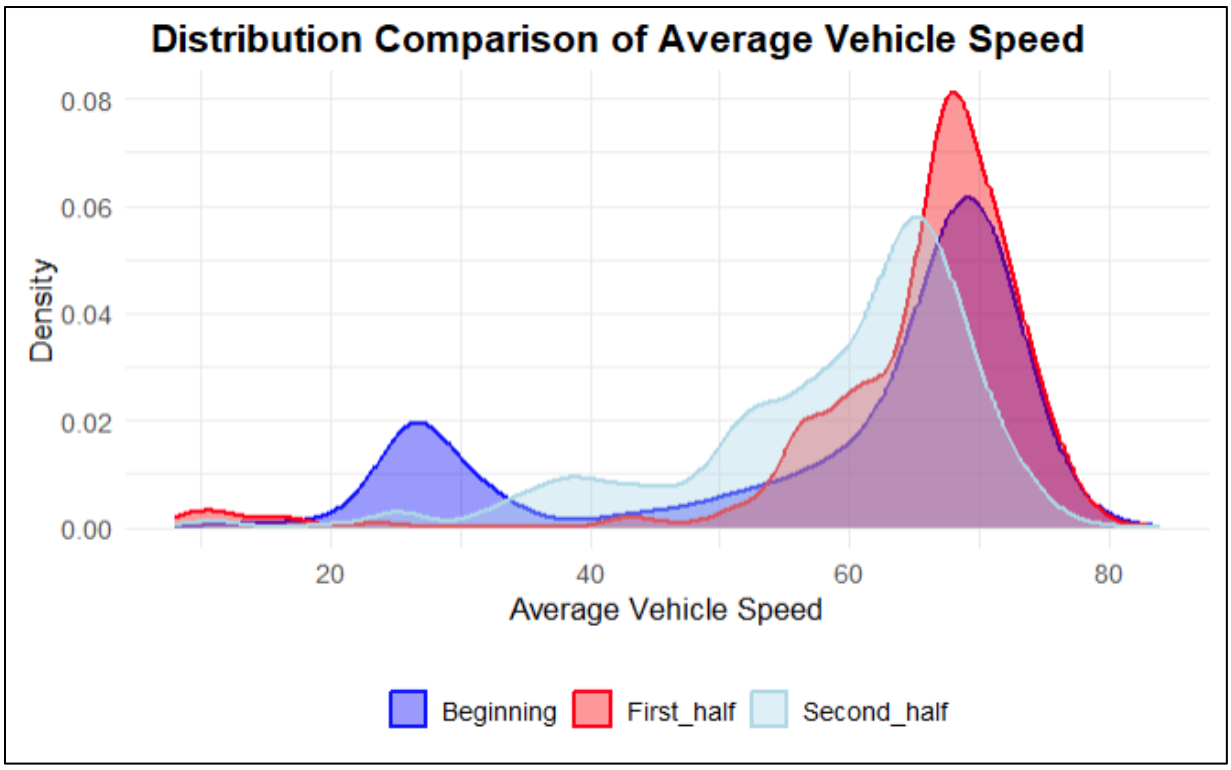


Figure 61. Average vehicle speed distribution for the work zone locations

6.12.4 Hypothesis 4: Weekday, Daytime, Lane 1, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis examined whether vehicle speeds differed for three distinct locations within the work zone - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone - during weekday daytime construction with blue lights. The null and alternative hypotheses formulated for this test are as follows:

***H_0**: There is no significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 1 during weekday daytime when blue lights are present during construction work.*

***H_1**: There is a significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 1 during weekday daytime when blue lights are present during construction work.*

Data Collected: To test the hypothesis, vehicle speed data during weekday daytime with blue lights while ongoing construction was categorized into three sections:

- Weekday daytime lane 1, beginning of the work zone: 432 observations
- Weekday daytime lane 1, first half of the active work zone: 432 observations
- Weekday daytime lane 1, second half of the active work zone: 432 observations

An illustration of the dataset is depicted in **Table 55**.

Table 55. Data points for weekday, daytime, lane 1 average vehicle speed for individual work zone locations

Average Vehicle Speed for the Beginning of the Work Zone (mph)	Average Vehicle Speed for the First Half of the Active Work Zone (mph)	Average Vehicle Speed for the Second Half of the Active Work Zone (mph)
56	40	35
45	37	48
X	X	X
X	X	X
X	X	X
22	44	21

Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 1.495924e-58, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 1 during weekday daytime when construction work was ongoing in the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 56**.

Table 56. Post hoc pairwise comparison results

Comparison	p-value
Beginning - First Half	<0.0001
Beginning - Second Half	<0.0001
First Half - Second Half	<0.0001

Post Hoc Pairwise Comparisons:

Beginning vs. First Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 71 mph at the beginning and 72 mph in the first half.

Beginning vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 71 mph at the beginning and 68 mph in the second half.

First Half vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 72 mph in the first half and 68 mph in the second half.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 1 during weekday daytime under construction with the presence of blue lights. The post hoc comparisons also showed significant differences for all location pairs, even though the median speeds were very close, especially between the beginning and the first half of the active work zone. This indicated that the shape of the speed distributions provided the clearest explanation of these differences. In **Figure 62**, the density plot highlights how speed behavior shifted within Lane 1. At the beginning and the first half of the active work zone, the peaks were close, but the first half showed a sharper concentration at slightly higher speeds, while the beginning was more broadly spread. The second half of the active work zone shifted leftward, with a wider distribution at lower speeds compared to the other two segments. This explained why, despite similar median values, the statistical tests detected significant differences.

Overall, these findings suggested that drivers tended to maintain higher speeds through the early parts of the lane but gradually reduced their speeds as they moved into the second half of the active work zone.

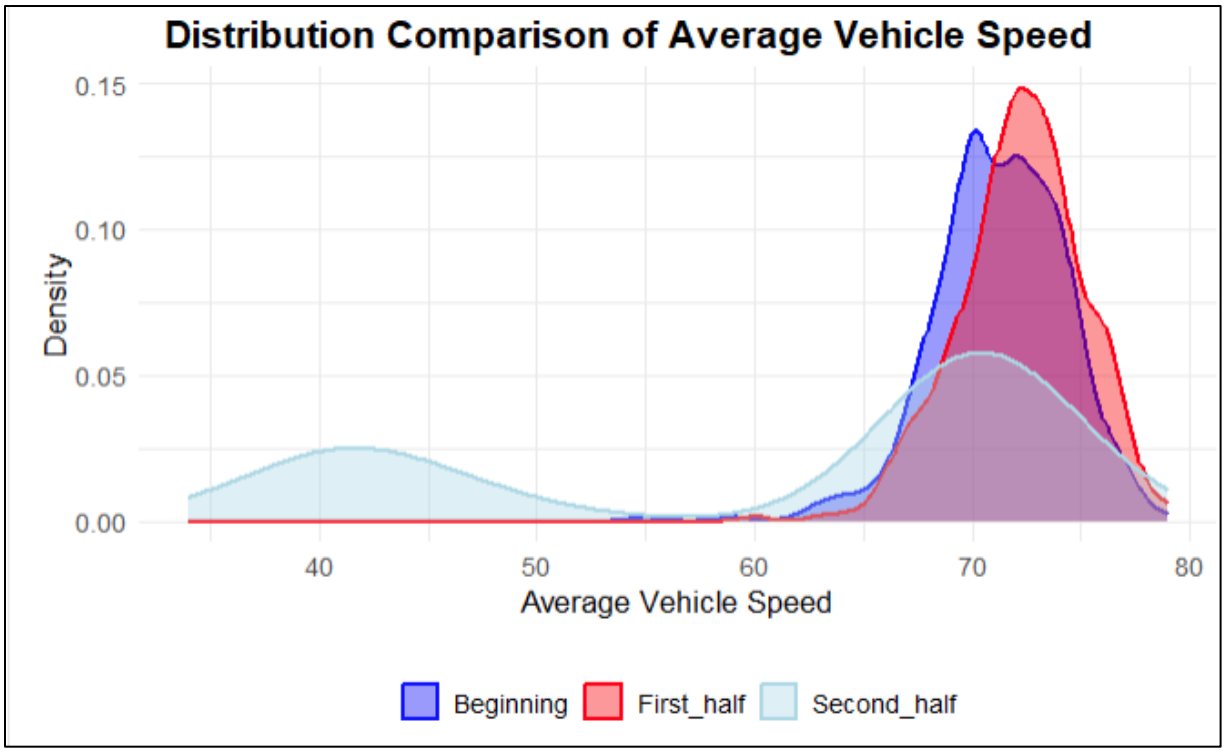


Figure 62. Average vehicle speed distribution for lane 1

6.12.5 Hypothesis 5: Weekday Daytime, Lane 2, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis examined whether vehicle speeds differed for three distinct locations within the work zone - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone - during weekday daytime construction with blue lights for lane 2. The null and alternative hypotheses formulated for this test are as follows:

***H_0**: There is no significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 2 during weekday daytime when blue lights are present during construction work.*

***H_1**: There is a significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 2 during weekday daytime when blue lights are present during construction work.*

Data Collected: To test the hypothesis, vehicle speed data during weekday daytime with blue lights while ongoing construction was categorized into three sections:

- Weekday daytime lane 2, beginning of the work zone: 432 observations
- Weekday daytime lane 2, first half of the active work zone: 432 observations
- Weekday daytime lane 2, second half of the active work zone: 432 observations

An illustration of the dataset is depicted in **Table 57**.

Table 57. Data points for weekday, daytime, lane 2 average vehicle speed for **individual work zone locations**

Average Vehicle Speed for the Beginning of the Work Zone (mph)	Average Vehicle Speed for the First Half of the Active Work Zone (mph)	Average Vehicle Speed for the Second Half of the Active Work Zone (mph)
56	40	35
45	37	48
X	X	X
X	X	X
X	X	X
22	44	21
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.		

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 1.173209e-121, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null

hypothesis. Therefore, it can be concluded that there was a statistically significant difference in average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 2 during weekday daytime when construction work is ongoing in the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 58**.

Table 58. Post hoc pairwise comparison results

Comparison	p-value
Beginning - First Half	<0.0001
Beginning - Second Half	<0.0001
First Half - Second Half	<0.0001

Post Hoc Pairwise Comparisons:

Beginning vs. First Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 66 mph at the beginning and 68 mph in the first half.

Beginning vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 66 mph at the beginning and 64 mph in the second half.

First Half vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 68 mph in the first half and 64 mph in the second half.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 2 during weekday daytime when construction work was ongoing in the presence of blue lights. The post hoc comparisons showed significant differences for all location pairs, even though the median values remained fairly close. This indicated that the main differences were explained by the shape and spread of the distributions rather than large changes among the values. In **Figure 63**, the density plot illustrates how speed behavior shifted within Lane 2. At the beginning, the speeds were tightly clustered at higher values, while in the first half of the active work zone, the peak shifted slightly rightward, showing a sharper concentration at higher speeds. The second half of the active work zone showed a clear shift toward lower speeds, with a wider distribution extending into slower ranges.

Overall, these results suggested that drivers in Lane 2 generally maintained higher speeds at the entry and during the first half of the active work zone but reduced their speeds more noticeably in the second half. The density plot highlights how even subtle differences in distribution contributed to the statistical significance, showing that blue lights influenced drivers to slow down as they progressed deeper into the active work zone.

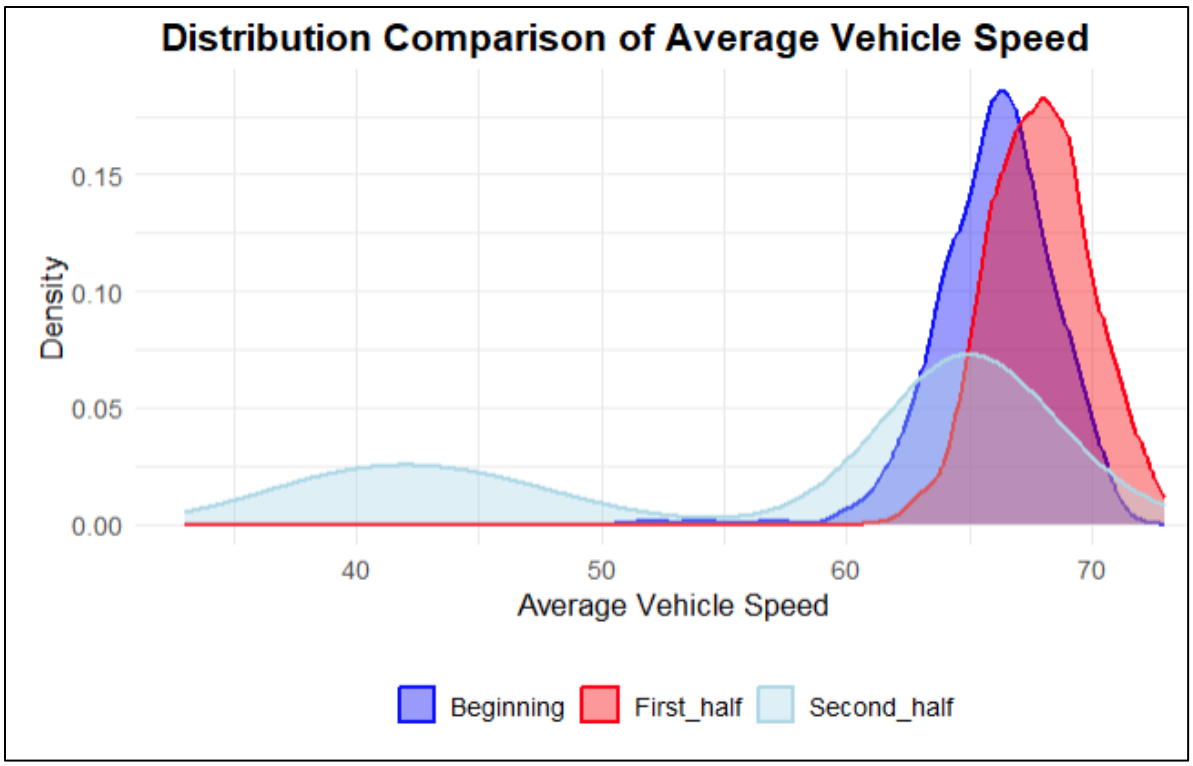


Figure 63. Average vehicle speed distribution for lane 2

6.12.6 Hypothesis 6: Weekday, Nighttime, Lane 1, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis examined whether vehicle speeds differed for three distinct locations within the work zone - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone - during weekday nighttime construction with blue lights for lane 1. The null and alternative hypotheses formulated for this test are as follows:

***H_0**: There is no significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 1 during weekday nighttime when blue lights are present during construction work.*

***H_1**: There is a significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 1 during weekday nighttime when blue lights are present during construction work.*

Data Collected: To test the hypothesis, vehicle speed data during weekday nighttime with blue lights while ongoing construction was categorized into three sections:

- Weekday nighttime lane 1, beginning of the work zone: 3528 observations
- Weekday nighttime lane 1, first half of the active work zone: 3528 observations
- Weekday nighttime lane 1, second half of the active work zone: 3528 observations

An illustration of the dataset is depicted in **Table 59**.

Table 59. Data points for weekday, nighttime, lane 1 average vehicle speed for individual work zone locations

Average Vehicle Speed for the Beginning of the Work Zone (mph)	Average Vehicle Speed for the First Half of the Active Work Zone (mph)	Average Vehicle Speed for the Second Half of the Active Work Zone (mph)
56	40	35
45	37	48
X	X	X
X	X	X
X	X	X
22	44	21

Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 2.643876e-93, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it can be concluded that there was a statistically significant difference in average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 1 during weekday nighttime when construction work is ongoing in the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 60**.

Table 60. Post hoc pairwise comparison results

Comparison	p-value
Beginning - First Half	<0.0001
Beginning - Second Half	<0.0001
First Half - Second Half	<0.0001

Post Hoc Pairwise Comparisons:

Beginning vs. First Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 66 mph at the beginning and 68 mph in the first half.

Beginning vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 66 mph at the beginning and 64 mph in the second half.

First Half vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 68 mph in the first half and 64 mph in the second half.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 1 during weekday nighttime when construction work was ongoing in the presence of blue lights. The post hoc comparisons revealed significant differences for all location pairs, even though the median values were relatively close. This means that the main differences came from the distributional patterns shown in the density plot rather than large changes in central tendency. In **Figure 64**, the density plot shows that speeds in the first half of the active work zone were more concentrated at higher values. At the beginning of the work zone, speeds were more spread out, with noticeable observations at lower speeds. In the second half of the active work zone, the distribution shifted slightly toward lower speeds and showed a broader spread. The distribution suggested that speeds remained relatively high at the beginning and first half, with a slight shift toward lower speeds in the second half.

Overall, the results suggested that construction with the presence of blue lights may have influenced Lane 1 drivers to maintain relatively higher speeds at the entry and first half of the active work zone, but reduced speeds more clearly by the second half of the active work zone. This gradual adjustment highlights how blue lights shaped driver behavior throughout the progression of the work zone.

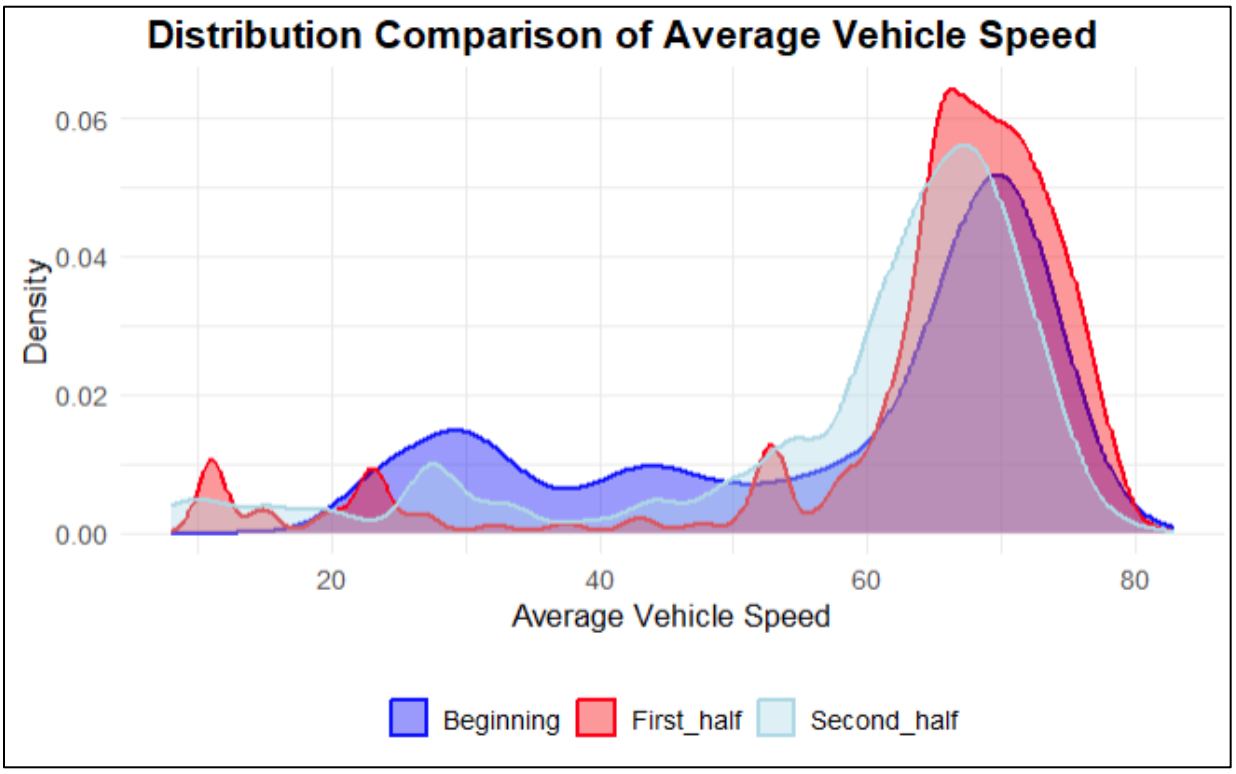


Figure 64. Average vehicle speed distribution for lane 1

6.12.7 Hypothesis 7: Weekday, Nighttime, Lane 2, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis examined whether vehicle speeds differed for three distinct locations within the work zone - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone - during weekday nighttime construction with blue lights for lane 2. The null and alternative hypotheses formulated for this test are as follows:

***H_0**: There is no significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 2 during weekday nighttime when blue lights are present during construction work.*

***H_1**: There is a significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 2 during weekday nighttime when blue lights are present during construction work.*

Data Collected: To test the hypothesis, vehicle speed data during weekday nighttime with blue lights while ongoing construction was categorized into three sections:

- Weekday nighttime lane 2, beginning of the work zone: 3528 observations
- Weekday nighttime lane 2, first half of the active work zone: 3528 observations
- Weekday nighttime lane 2, second half of the active work zone: 3528 observations

An illustration of the dataset is depicted in **Table 61**.

Table 61. Data points for weekday, nighttime, lane 2 average vehicle speed for **individual work zone locations**

Average Vehicle Speed for the Beginning of the Work Zone (mph)	Average Vehicle Speed for the First Half of the Active Work Zone (mph)	Average Vehicle Speed for the Second Half of the Active Work Zone (mph)
56	40	35
45	37	48
X	X	X
X	X	X
X	X	X
22	44	21
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.		

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 1.247306e-177, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null

hypothesis. Therefore, it can be concluded that there was a statistically significant difference in average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 2 during weekday nighttime when construction work is ongoing in the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 62**.

Table 62. Post hoc pairwise comparison results

Comparison	p-value
Beginning - First Half	<0.0001
Beginning - Second Half	<0.0001
First Half - Second Half	<0.0001

Post Hoc Pairwise Comparisons:

Beginning vs. First Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 65 mph at the beginning and 64 mph in the first half.

Beginning vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 65 mph at the beginning and 62 mph in the second half.

First Half vs. Second Half of the Active Work Zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 64 mph in the first half and 62 mph in the second half.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 2 during weekday nighttime when construction work was ongoing in the presence of blue lights. Although the median speeds appeared close for all three segments, the post hoc comparisons revealed significant differences, showing that speed adjustments were location dependent. In **Figure 65**, the density plot shows that at the beginning of the work zone, speeds were concentrated at lower values. As drivers moved into the first half of the active work zone, speeds increased noticeably, with a strong peak at higher values. In the second half of the active work zone, the distribution shifted slightly toward lower speeds compared to the first half, indicating some reduction.

Overall, these results suggested that drivers entered the work zone at lower speeds, increased their speed in the first half, and then reduced speed again in the second half. This pattern indicated that speed adjustments occurred throughout the work zone, with a slight reduction observed into the active construction area.

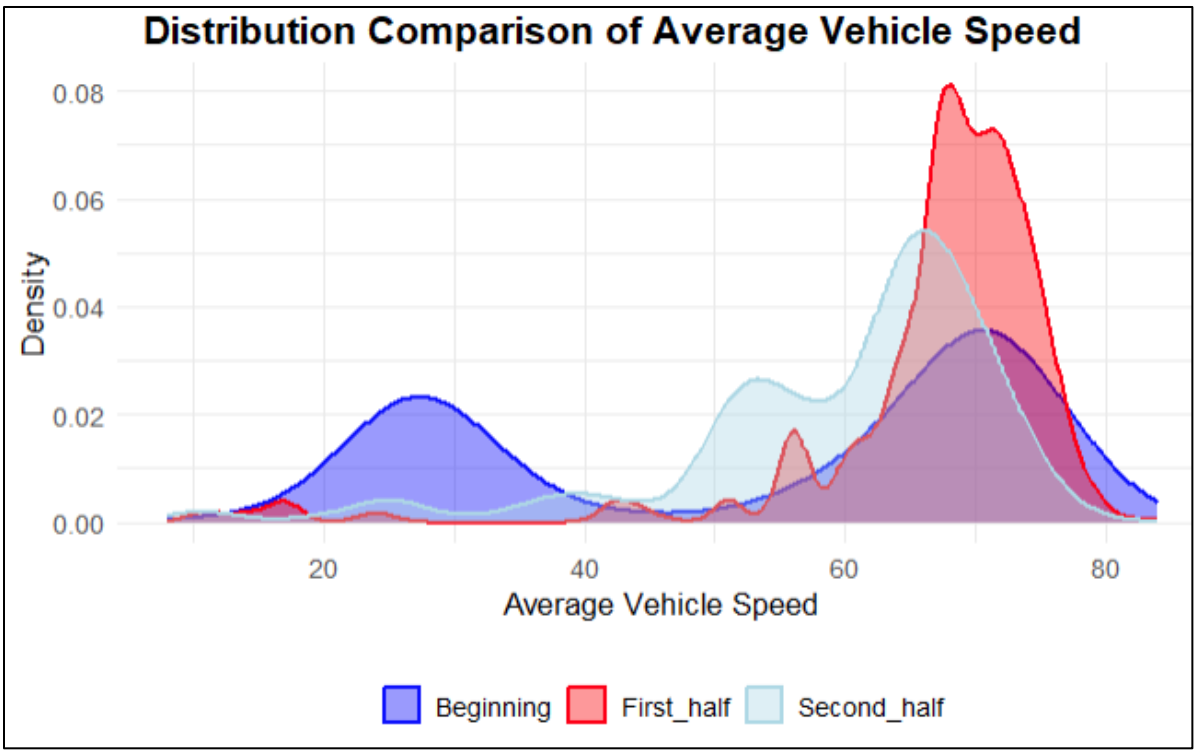


Figure 65. Average vehicle speed distribution for lane 2

6.12.8 Hypothesis 8: Weekend, Nighttime, Lane 1, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis examined whether vehicle speeds differed for three distinct locations within the work zone - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone - during weekend nighttime construction with blue lights for lane 1. The null and alternative hypotheses formulated for this test are as follows:

***H_0**: There is no significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 1 during weekend nighttime when blue lights are present during construction work.*

***H_1**: There is a significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 1 during weekend nighttime when blue lights are present during construction work.*

Data Collected: To test the hypothesis, vehicle speed data during weekend nighttime with blue lights while ongoing construction was categorized into three sections:

- Weekend nighttime lane 1, beginning of the work zone: 504 observations
- Weekend nighttime lane 1, first half of the active work zone: 504 observations
- Weekend nighttime lane 1, second half of the active work zone: 504 observations

An illustration of the dataset is depicted in **Table 63**.

Table 63. Data points for weekend, nighttime, lane 1 average vehicle speed for individual work zone locations

Average Vehicle Speed for the Beginning of the Work Zone (mph)	Average Vehicle Speed for the First Half of the Active Work Zone (mph)	Average Vehicle Speed for the Second Half of the Active Work Zone (mph)
56	40	35
45	37	48
X	X	X
X	X	X
X	X	X
22	44	21

Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 2.497158e-33, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it can be concluded that there was a statistically significant difference in average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 1 during weekend nighttime when construction work is ongoing in the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 64**.

Table 64. Post hoc pairwise comparison results

Comparison	p-value
Beginning - First Half	<0.0001
Beginning - Second Half	0.0642
First Half - Second Half	<0.0001

Post Hoc Pairwise Comparisons:

Beginning of the work zone vs. First half of the active work zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 66 mph at the beginning of the work zone and 69 mph in the first half of the active work zone.

Beginning of the work zone vs. Second half of the active work zone: The comparison yielded a p-value of 0.0642, indicating no statistically significant difference. The median speed was 66 mph at the beginning of the work zone and 64 mph in the second half of the active work zone.

First half of the active work zone vs. Second half of the active work zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 69 mph in the first half of the active work zone and 64 mph in the second half of the active work zone.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 1 during weekend nighttime when construction work was ongoing in the presence of blue lights. While the median speeds appeared close for the beginning and the second half of the active work zone, the post hoc results revealed that the significant differences were location dependent, with the largest variation occurring between the first and second halves. In **Figure 66**, the density plot shows clear differences between locations. At the beginning of the work zone, speeds were concentrated around higher values, creating a sharp peak. In the first half of the active work zone, the peak shifted slightly upward, indicating a higher concentration of faster speeds. However, in the second half of the active work zone, the distribution shifted downward with a wider spread toward lower speeds. This pattern explained why the difference between the beginning and the second half was not statistically significant, yet the contrast between the first half and the second half was more pronounced.

Overall, these results suggested that while blue lights encouraged relatively stable speeds at the beginning and end of Lane 1, drivers adjusted their behavior more noticeably within the active construction area, particularly in the transition from the first to the second half of the active work zone.

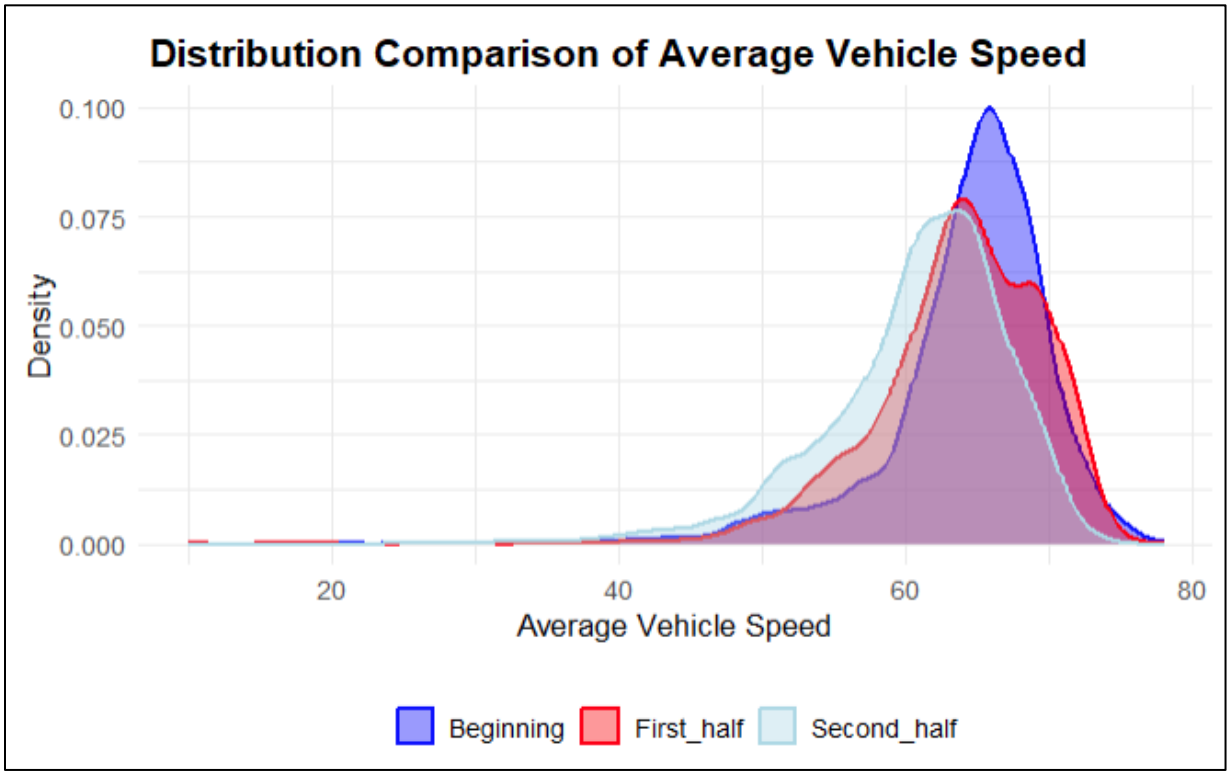


Figure 66. Average vehicle speed distribution for lane 1

6.12.9 Hypothesis 9: Weekend, Nighttime, Lane 2, Construction with the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis examined whether vehicle speeds differed for three distinct locations within the work zone - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone - during weekend nighttime construction with blue lights for lane 2. The null and alternative hypotheses formulated for this test are as follows:

***H_0**: There is no significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 2 during weekend nighttime when blue lights are present during construction work.*

***H_1**: There is a significant difference in the average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for lane 2 during weekend nighttime when blue lights are present during construction work.*

Data Collected: To test the hypothesis, vehicle speed data during weekend nighttime with blue lights while ongoing construction was categorized into three sections:

- Weekend nighttime lane 2, beginning of the work zone: 504 observations
- Weekend nighttime lane 2, first half of the active work zone: 504 observations
- Weekend nighttime lane 2, second half of the active work zone: 504 observations

An illustration of the dataset is depicted in **Table 65**.

Table 65. Data points for weekend, nighttime, lane 2 average vehicle speed for **individual work zone locations**

Average Vehicle Speed for the Beginning of the Work Zone (mph)	Average Vehicle Speed for the First Half of the Active Work Zone (mph)	Average Vehicle Speed for the Second Half of the Active Work Zone (mph)
56	40	35
45	37	48
X	X	X
X	X	X
X	X	X
22	44	21
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.		

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 4.959544e-49, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null

hypothesis. Therefore, it can be concluded that there was a statistically significant difference in average vehicle speed between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 2 during weekend nighttime when construction work is ongoing in the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 66**.

Table 66. Post hoc pairwise comparison results

Comparison	p-value
Beginning - First Half	0.1098
Beginning - Second Half	<0.0001
First Half - Second Half	<0.0001

Post Hoc Pairwise Comparisons:

Beginning of the work zone vs. First half of the active work zone: The comparison yielded a p-value of 0.1098, indicating no statistically significant difference. The median speed was 67 mph at the beginning of the work zone and 66 mph in the first half of the active work zone.

Beginning of the work zone vs. Second half of the active work zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 67 mph at the beginning of the work zone and 61 mph in the second half of the active work zone.

First half of the active work zone vs. Second half of the active work zone: The comparison yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 66 mph in the first half of the active work zone and 61 mph in the second half of the active work zone.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different between the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone for Lane 2 during weekend nighttime when construction work was ongoing in the presence of blue lights. Although the median speeds appeared similar between the beginning and the first half, the post hoc comparisons revealed that meaningful differences became evident when comparing the second half of the active work zone with both earlier segments. In **Figure 67,** the density plot shows that speeds at the beginning and the first half of the active work zone were closely aligned, with peaks concentrated at higher values. However, in the second half of the active work zone, the distribution shifted leftward, producing a broader spread at lower speeds. This indicated that the most noticeable reductions occurred later in the work zone.

Overall, these results suggested that speed adjustments under blue light conditions were minimal at the entry and in the first half of the active work zone but became stronger by the second half of the active work zone. This pattern indicated that drivers gradually reduced their speeds as they progressed, with the largest reductions emerging near the second half of the active work zone.

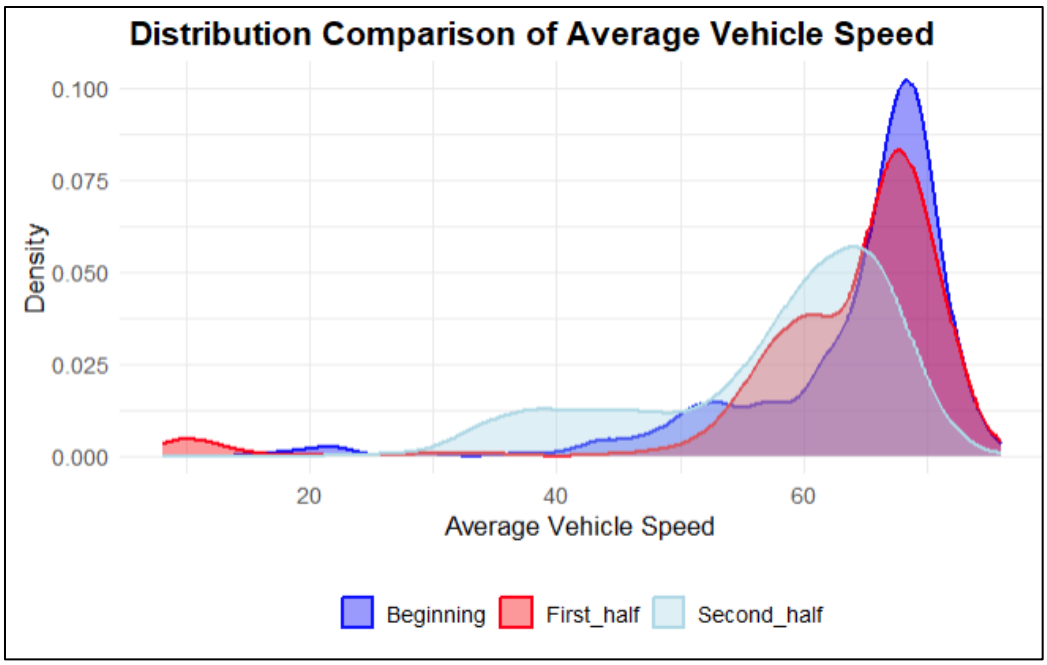


Figure 67. Average vehicle speed distribution for lane 2

6.12.10 Hypothesis 10: Weekday Daytime, Construction with the Presence of Blue Lights, Lane 1 vs. Lane 2

***H₀**: There is no significant difference in the average vehicle speed between lane 1 and lane 2 during the weekday daytime when blue lights are present during construction work.*

***H₁**: There is a significant difference in the average vehicle speed between lane 1 and lane 2 during the weekday daytime when blue lights are present during construction work.*

Data Collected: For the analysis, the data were divided into two categories:

- Lane 1 weekday daytime construction with the presence of blue lights - 1296 observations
- Lane 2 weekday daytime construction with the presence of blue lights - 1296 observations

An illustration of the dataset is depicted in **Table 67**.

Table 67. Data points for average vehicle speed for lane 1 vs. lane 2 - weekday daytime for construction with the presence of blue lights

Average Vehicle Speed Lane 1 (mph)	Average Vehicle Speed Lane 2 (mph)
65	70
72	55
X	X
X	X
68	60
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test yielded a p-value of less than 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it can be concluded that there was a statistically significant difference in average vehicle speed between Lane 1 and Lane 2 during weekday daytime when blue lights are present during construction work. According to the descriptive statistics, the median average vehicle speed was 71 mph for Lane 1 and 66 mph for Lane 2. The IQR was 5 for Lane 1 and 4 for Lane 2, suggesting slightly more consistent speeds in Lane 2. Although the medians were not far apart, the density plot in **Figure 68** illustrates a sharper and more concentrated distribution for Lane 2, while Lane 1 showed a wider spread at higher speeds. This supported the statistical results and suggested that drivers tended to maintain higher speeds in Lane 1, which was closer to the work zone, possibly due to traffic flow and merging behaviors, while Lane 2 reflected greater caution in the presence of blue lights.

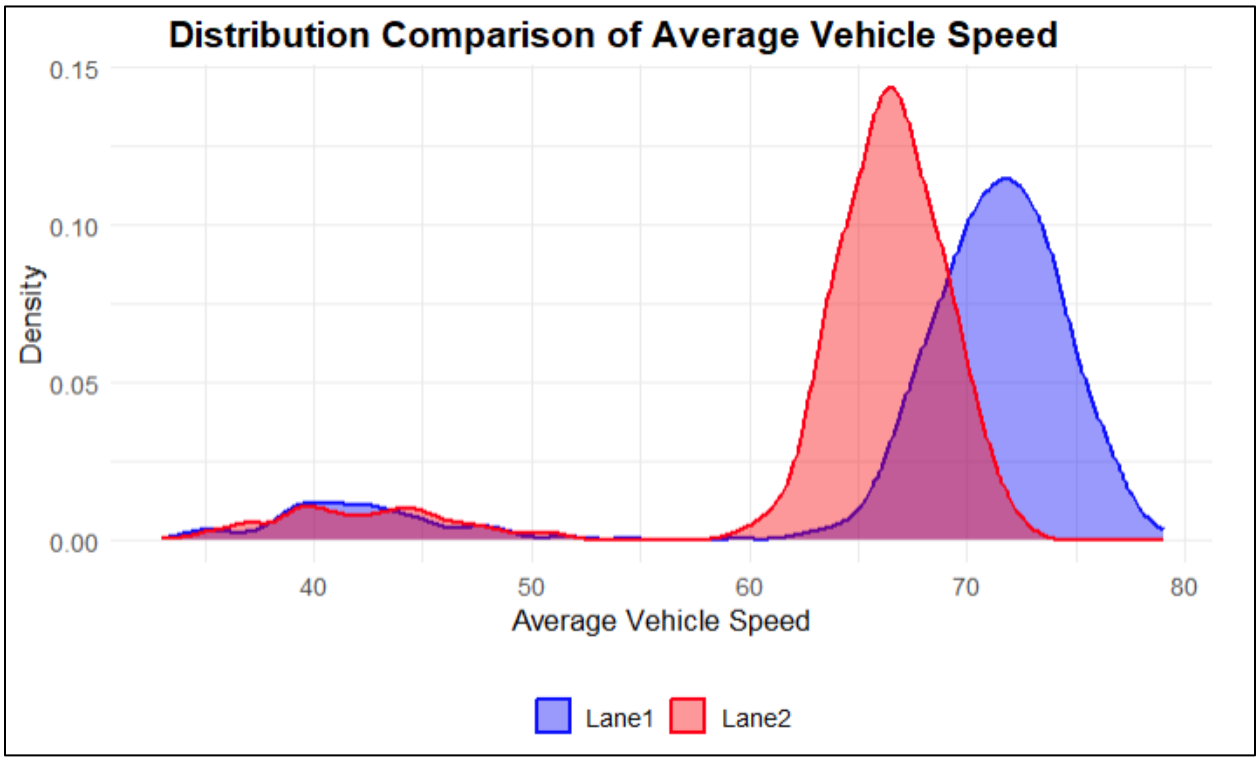


Figure 68. Average vehicle speed distribution for both lanes

6.12.11 Hypothesis 11: Weekday Nighttime, Construction with the Presence of Blue Lights, Lane 1 vs. Lane 2

***H₀**: There is no significant difference in the average vehicle speed between lane 1 and lane 2 during the weekday nighttime when blue lights are present during construction work.*

***H₁**: There is a significant difference in the average vehicle speed between lane 1 and lane 2 during the weekday nighttime when blue lights are present during construction work.*

Data Collected: For the analysis, the data were divided into two categories:

- Lane 1 weekday nighttime construction with the presence of blue lights - 10584 observations
- Lane 2 weekday nighttime construction with the presence of blue lights - 10584 observations

An illustration of the dataset is depicted in **Table 68**.

Table 68. Data points for average vehicle speed for lane 1 vs. lane 2 - weekday nighttime for construction with the presence of blue lights

Average Vehicle Speed Lane 1 (mph)	Average Vehicle Speed Lane 2 (mph)
65	70
72	55
X	X
X	X
68	60
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test yielded a p-value of less than 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it can be concluded that there was a statistically significant difference in average vehicle speed between Lane 1 and Lane 2 during weekday nighttime construction with the presence of blue lights. According to the descriptive statistics, the median average vehicle speed in Lane 1 was 66 mph, while in Lane 2 it was 64 mph. The IQR was 13 for Lane 1 and 7 for Lane 2. Although the median values were relatively close for both lanes, the density plot in **Figure 69** highlights the differences in the overall distribution. Lane 2 showed a sharp, narrow peak, reflecting a more consistent pattern of reduced speeds, while Lane 1 had a wider spread with some vehicles traveling at higher speeds. This suggested that drivers in Lane 1 maintained slightly higher speeds compared to Lane 2. The lower and more consistent speeds in Lane 2 may indicate a stronger influence of blue lights in that lane.

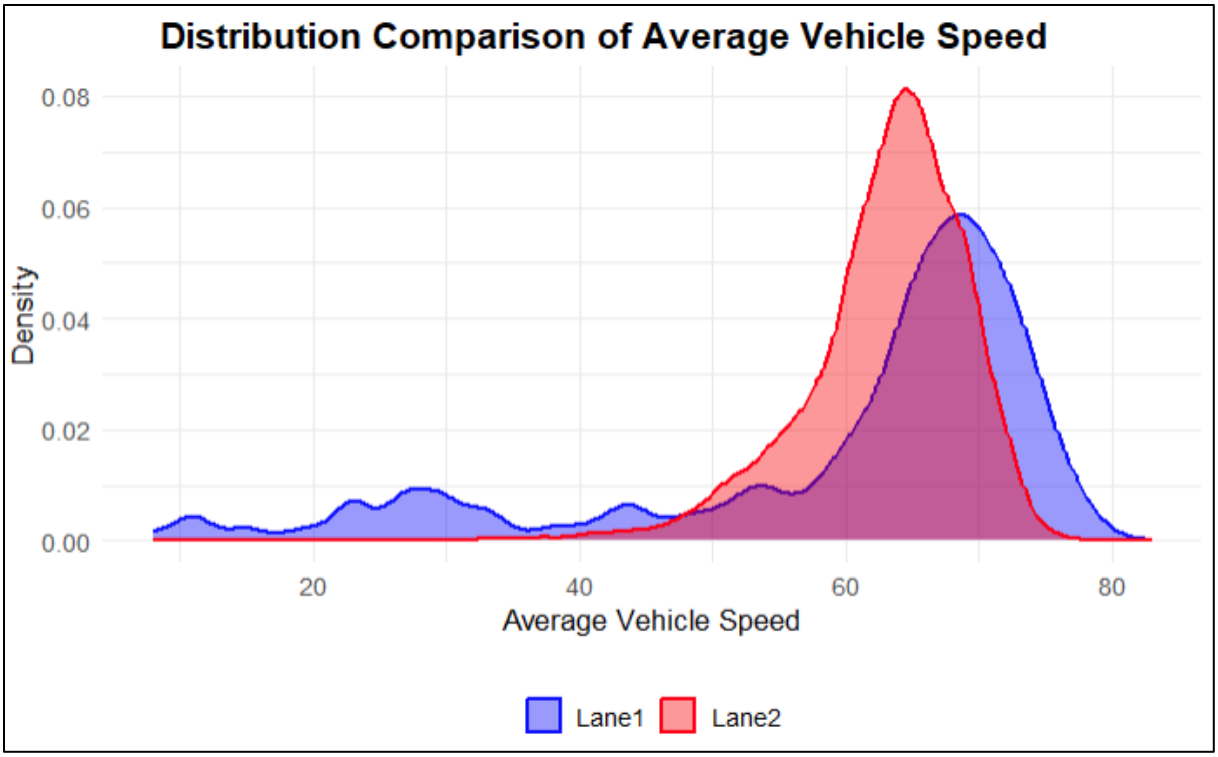


Figure 69. Average vehicle speed distribution for both lanes

6.12.12 Hypothesis 12: Weekend Nighttime, Construction with the Presence of Blue Lights, Lane 1 vs. Lane 2

***H₀**: There is no significant difference in the average vehicle speed between lane 1 and lane 2 during the weekend nighttime when blue lights are present during construction work.*

***H₁**: There is a significant difference in the average vehicle speed between lane 1 and lane 2 during the weekend nighttime when blue lights are present during construction work.*

Data Collected: For the analysis, the data were divided into two categories:

- Lane 1 weekend nighttime construction with the presence of blue lights - 1512 observations
- Lane 2 weekend nighttime construction with the presence of blue lights - 1512 observations

An illustration of the dataset is depicted in

Table 69.

Table 69. Data points for average vehicle speed for lane 1 vs. lane 2 - weekend nighttime for construction with the presence of blue lights

Average Vehicle Speed Lane 1 (mph)	Average Vehicle Speed Lane 2 (mph)
65	70
72	55
X	X
X	X
68	60
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test yielded a p-value of 4.723e-09, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed between Lane 1 and Lane 2 during weekend nighttime in construction with the presence of blue lights. According to the descriptive statistics, the median average vehicle speed was 67 mph for Lane 1 and 65 mph for Lane 2. The IQR was 15 for Lane 1 and 10 for Lane 2, suggesting that speeds in Lane 2 were slightly more consistent. Although the medians were close, the density plot in **Figure 70** illustrates a sharper and narrower distribution for Lane 2, while Lane 1 shows a broader spread that extends toward both higher and lower speeds. This supported the statistical results and suggested that during weekend nighttime construction, drivers traveled at more consistent speeds in Lane 2. In contrast, Lane 1 reflects greater variability, which may be influenced by merging activity and its closer proximity to the active work zone.

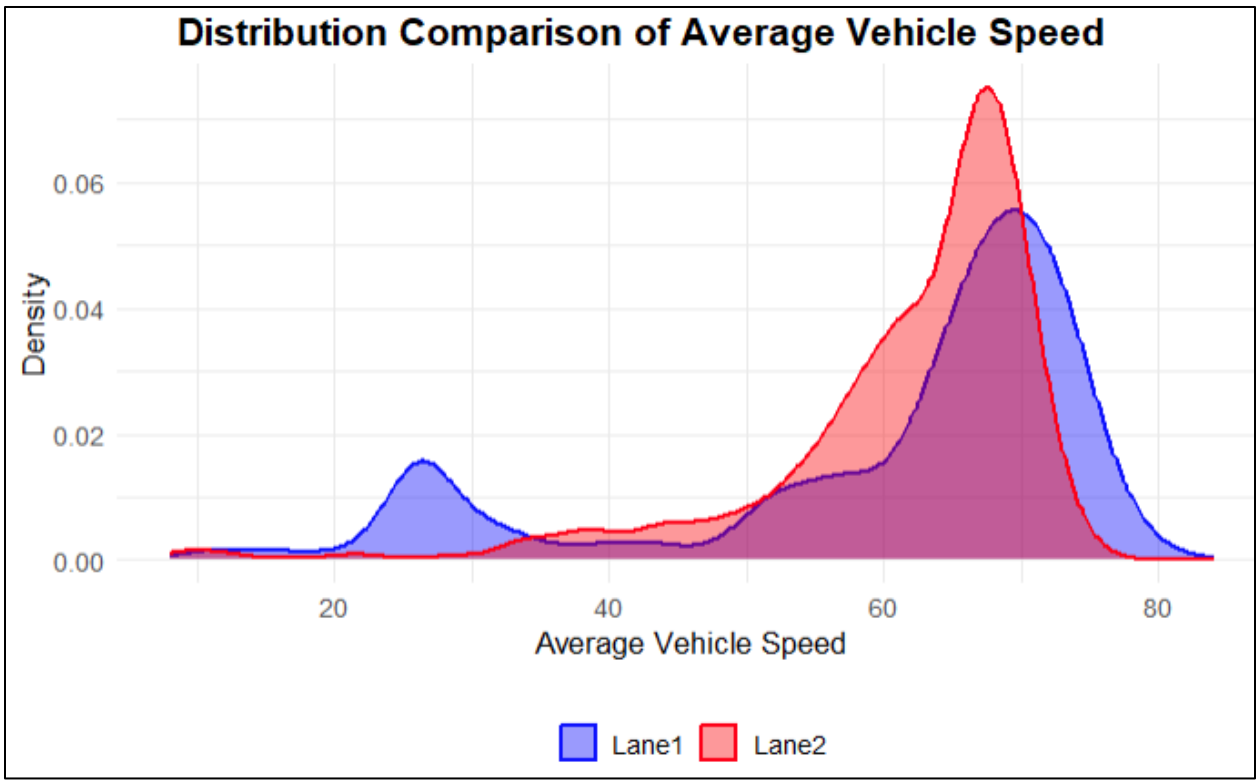


Figure 70. Average vehicle speed distribution for both lanes

6.12.13 Hypothesis 13: Weekday Daytime, Lane 1 vs. Lane 2, Construction with Blue Lights for Individual Work Zone Locations

***H₀**: There is no significant difference in the average vehicle speed between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday daytime, when blue lights are present for ongoing construction.*

***H₁**: There is a significant difference in the average vehicle speed between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday daytime, when blue lights are present for ongoing construction.*

Data Collected: To test the hypothesis, the average vehicle speed data during weekday daytime with blue lights while ongoing construction was categorized into six sections:

- Weekday daytime lane 1, beginning of the work zone: 432 observations
- Weekday daytime lane 2, beginning of the work zone: 432 observations
- Weekday daytime lane 1, first half of the active work zone: 432 observations
- Weekday daytime lane 2, first half of the active work zone: 432 observations
- Weekday daytime lane 1, second half of the active work zone: 432 observations
- Weekday daytime lane 2, second half of the active work zone: 432 observations

An illustration of the dataset is depicted in **Table 70**.

Table 70. Data points for weekday daytime lane 1 vs. lane 2, for construction with the presence of blue lights for individual work zone locations

Average Vehicle Speed Weekday Daytime Beginning of the Work Zone, Lane 1 (mph)	Average Vehicle Speed Weekday Daytime Beginning of the Work Zone, Lane 2 (mph)	Average Vehicle Speed Weekday Daytime First Half of the Active Work Zone, Lane 1 (mph)	Average Vehicle Speed Weekday Daytime First Half of the Active Work Zone, Lane 2 (mph)	Average Vehicle Speed Weekday Daytime Second Half of the Active Work Zone, Lane 1 (mph)	Average Vehicle Speed Weekday Daytime Second Half of the Active Work Zone, Lane 2 (mph)
45	47	40	55	67	52
38	33	37	31	28	47
X	X	X	X	X	X
X	X	X	X	X	X
X	X	X	X	X	X
41	44	25	17	34	64

Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of < 2.22e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it can be concluded that there was a statistically significant difference in average vehicle speed between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday daytime when construction work is ongoing with the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 71**.

Table 71. Post hoc pairwise comparison results

Comparison	p-value
Beginning Lane 1 - Beginning Lane 2	2.123279e-142
First Half Lane 1 - First Half Lane 2	4.172859e-95
Second Half Lane 1 - Second Half Lane 2	1.121550e-72

Post Hoc Pairwise Comparisons:

Beginning of the work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the green columns in **Table 70**, yielded a p-value of 2.123279e-142, suggesting a significant difference. The median speed was 71 mph for Lane 1 and 66 mph for Lane 2.

First half of the active work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the purple columns in **Table 70**, yielded a p-value of 4.172859e-95, indicating a significant difference. The median speed was 72 mph for Lane 1 and 68 mph for Lane 2.

Second half of the active work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the orange columns in **Table 70** yielded a p-value of 1.121550e-72, confirming a significant difference. The median speed was 68 mph for Lane 1 and 64 mph for Lane 2.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different between Lane 1 and Lane 2 at the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday daytime when construction work was ongoing with the presence of blue lights. The post hoc comparisons showed that Lane 1 consistently had higher speeds than Lane 2, indicating that lane choice played a role in how drivers adjusted their speeds in response to blue lights. In **Figure 71**, for the beginning of the work zone, Lane 1 displayed a distribution shifted to the right, with speeds clustered at higher values. Lane 2 showed a sharp peak concentrated at lower speeds. This suggested that drivers entering the work zone in Lane 2 reduced their speeds earlier, possibly due to its closer proximity to construction activity. In **Figure 72**, for the first half of the active work zone, the separation between the two lanes becomes more visible. Lane 1 maintained a distribution centered at higher speeds, while Lane 2 shifted further leftward, reinforcing the tendency for drivers in Lane 2 to sustain lower speeds. This indicates that speed adjustments became stronger as drivers proceeded into the active work area. In **Figure 73**, for the second half of the active work zone, both lanes showed broader distributions, but Lane 2 remained concentrated at lower speeds compared to Lane 1. The difference here illustrated that drivers maintained their lower speeds in Lane 2 through the end of the work zone, while Lane 1 drivers continued to travel faster.

Overall, these findings indicate that blue lights influenced speed patterns differently for the two lanes. Drivers in Lane 2 consistently reduced speeds more than those in Lane 1, suggesting that lane proximity to the work activity and visibility of blue lights might have played an important role in shaping driver behavior throughout the work zone.

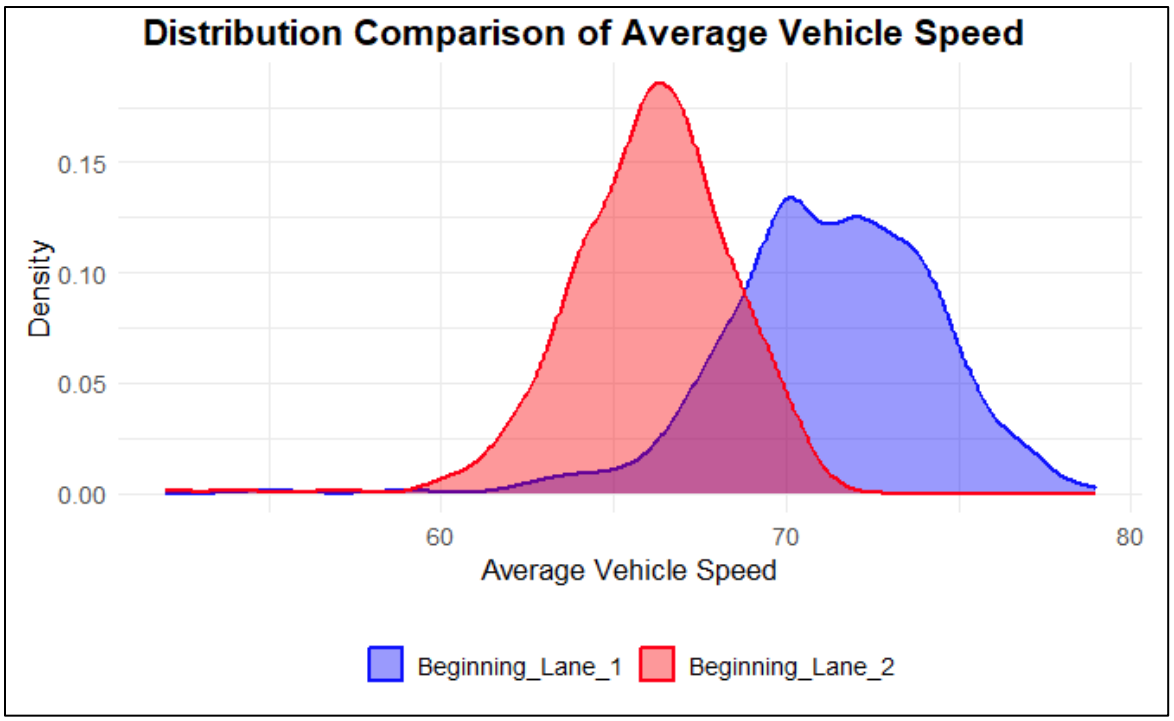


Figure 71. Average vehicle speed distribution for the beginning of the work zone

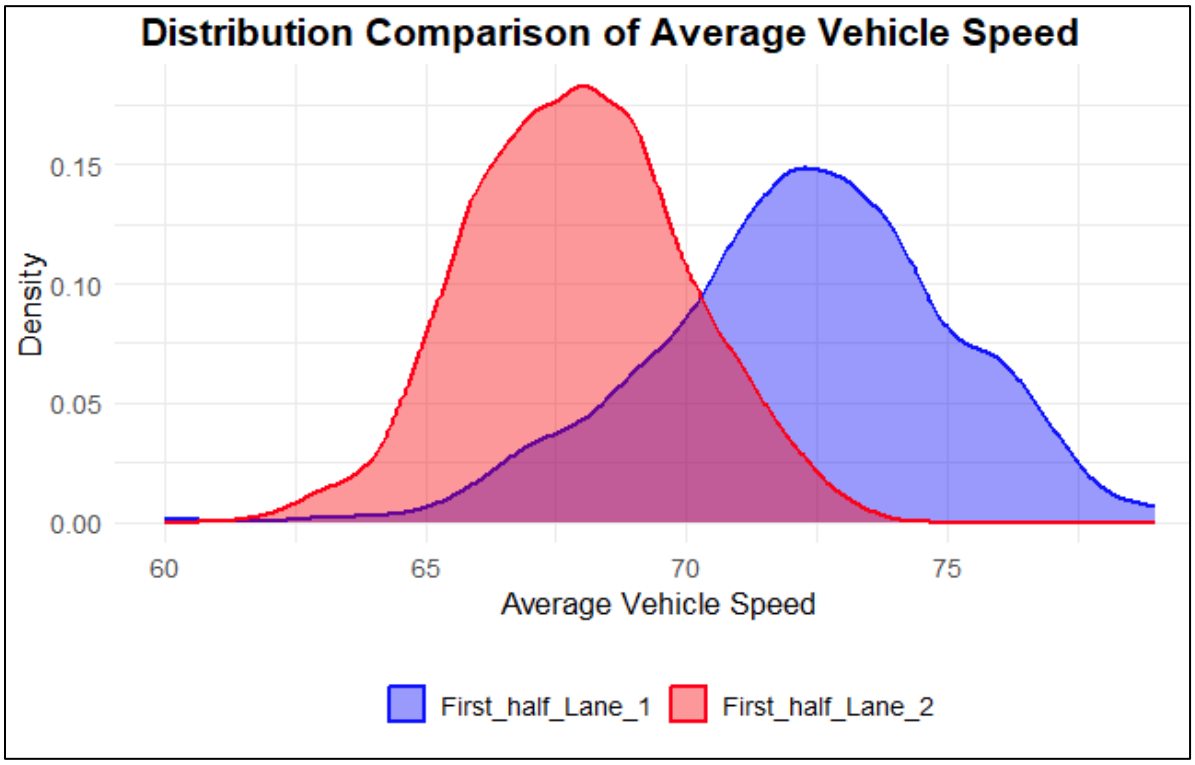


Figure 72. Average vehicle speed distribution for the first half of the active work zone

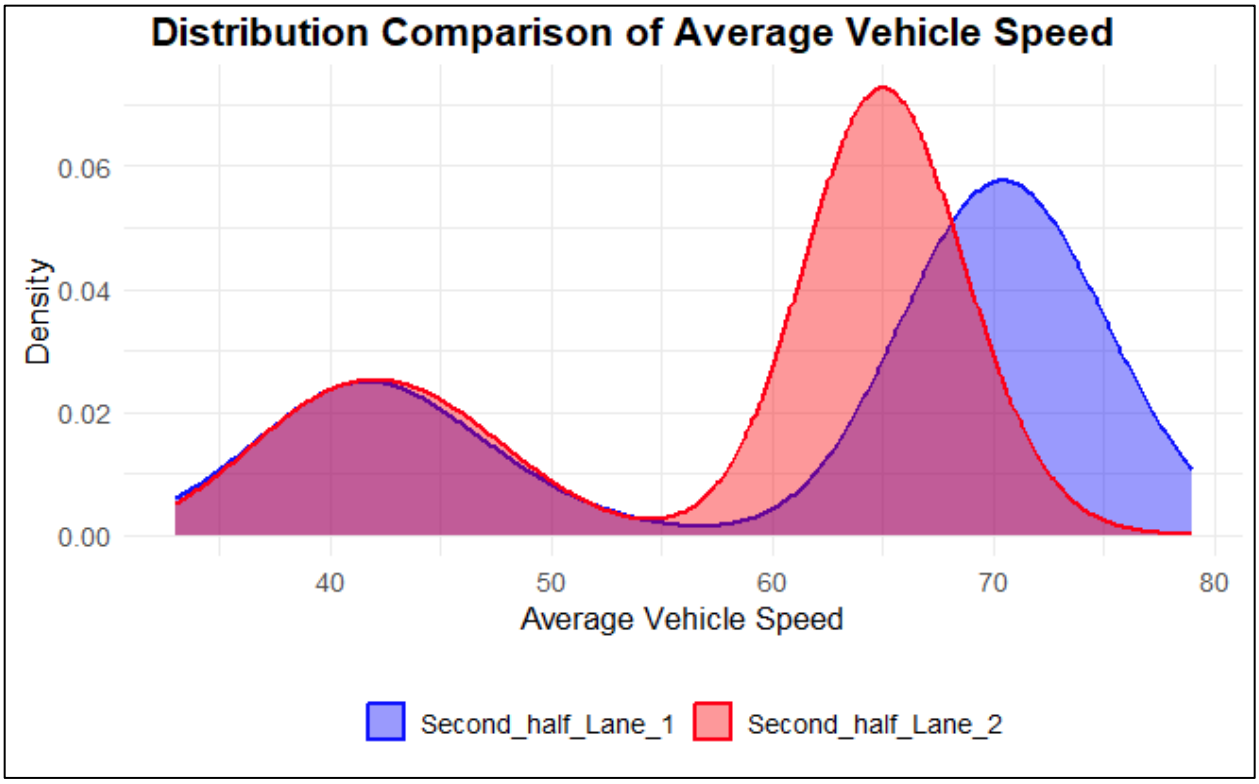


Figure 73. Average vehicle speed distribution for the second half of the active work zone

6.12.14 Hypothesis 14: Weekday Nighttime, Lane 1 vs. Lane 2, Construction with Blue Lights for Individual Work Zone Locations

***H₀**: There is no significant difference in the average vehicle speed between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday nighttime, when blue lights are present for ongoing construction.*

***H₁**: There is a significant difference in the average vehicle speed between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday nighttime, when blue lights are present for ongoing construction.*

Data Collected: To test the hypothesis, the average vehicle speed data during weekday nighttime with blue lights while ongoing construction was categorized into six sections:

- Weekday nighttime lane 1, beginning of the work zone: 3528 observations
- Weekday nighttime lane 2, beginning of the work zone: 3528 observations
- Weekday nighttime lane 1, first half of the active work zone: 3528 observations
- Weekday nighttime lane 2, first half of the active work zone: 3528 observations
- Weekday nighttime lane 1, second half of the active work zone: 3528 observations
- Weekday nighttime lane 2, second half of the active work zone: 3528 observations

An illustration of the dataset is depicted in the **Table 72**.

Table 72. Data points for weekday nighttime lane 1 vs. lane 2, for construction with the presence of blue lights for **individual work zone locations**

Average Vehicle Speed Weekday Nighttime Beginning of the Work Zone, Lane 1 (mph)	Average Vehicle Speed Weekday Nighttime Beginning of the Work Zone, Lane 2 (mph)	Average Vehicle Speed Weekday Nighttime First Half of the Active Work Zone, Lane 1 (mph)	Average Vehicle Speed Weekday Nighttime First Half of the Active Work Zone, Lane 2 (mph)	Average Vehicle Speed Weekday Nighttime Second Half of the Active Work Zone, Lane 1 (mph)	Average Vehicle Speed Weekday Nighttime Second Half of the Active Work Zone, Lane 2 (mph)
45	47	40	55	67	52
38	33	37	31	28	47
X	X	X	X	X	X
X	X	X	X	X	X
X	X	X	X	X	X
41	44	25	17	34	64

Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 7.708147e-298, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it can be concluded that there is a statistically significant difference in average vehicle speed between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday nighttime when construction work is ongoing with the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 73**.

Table 73. Post hoc pairwise comparison results

Comparison	p-value
Beginning Lane 1 - Beginning Lane 2	2.220333e-03
First Half Lane 1 - First Half Lane 2	5.832615e-83
Second Half Lane 1 - Second Half Lane 2	4.683770e-44

Post Hoc Pairwise Comparisons:

Beginning of the work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the green columns in **Table 72** yielded a p-value of 2.220333e-03, suggesting a significant difference. The median speed was 68 mph for Lane 1 and 65 mph for Lane 2.

First half of the active work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the blue columns in **Table 72** yielded a p-value of 5.832615e-83, indicating a significant difference. The median speed was 65 mph for Lane 1 and 60.5 mph for Lane 2.

Second half of the active work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the orange columns in **Table 72** yielded a p-value of 4.683770e-44, confirming a significant difference. The median speed was 59 mph for Lane 1 and 58 mph for Lane 2.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekday nighttime when construction work was ongoing in the presence of blue lights. The post hoc comparisons indicated that while differences were consistent, the magnitude of variation shifted depending on the segment of the work zone. In **Figure 74**, for the beginning of the work zone, speeds for Lane 2 were concentrated at lower values with a narrower distribution, while speeds for Lane 1 extended further right, showing higher overall values. This demonstrated that drivers in Lane 2 were more cautious upon entering the work zone, likely influenced by their proximity to the construction area. In **Figure 75**, for the first half of the active work zone, Lane 2 continued to show a concentration of vehicles at slightly lower speeds compared to Lane 1. The separation between the peaks of the distributions was more evident in this segment, indicating that lane choice strongly influenced driving behavior as drivers encountered ongoing activity. In **Figure 76**, for the second half of the active work zone, both lanes displayed broader spreads, but Lane 2 shifted toward lower values compared to Lane 1. This suggested that the influence of blue lights and construction activity sustained drivers' preference to reduce speeds more noticeably in Lane 2.

Overall, the results highlight that speed differences between the two lanes were present throughout the work zone, with Lane 2 consistently showing lower speeds than Lane 1. This pattern suggests that drivers in Lane 2 were more responsive to blue lights and construction activity, particularly in the beginning and first half of the active work zone, while Lane 1 maintained comparatively higher speeds.

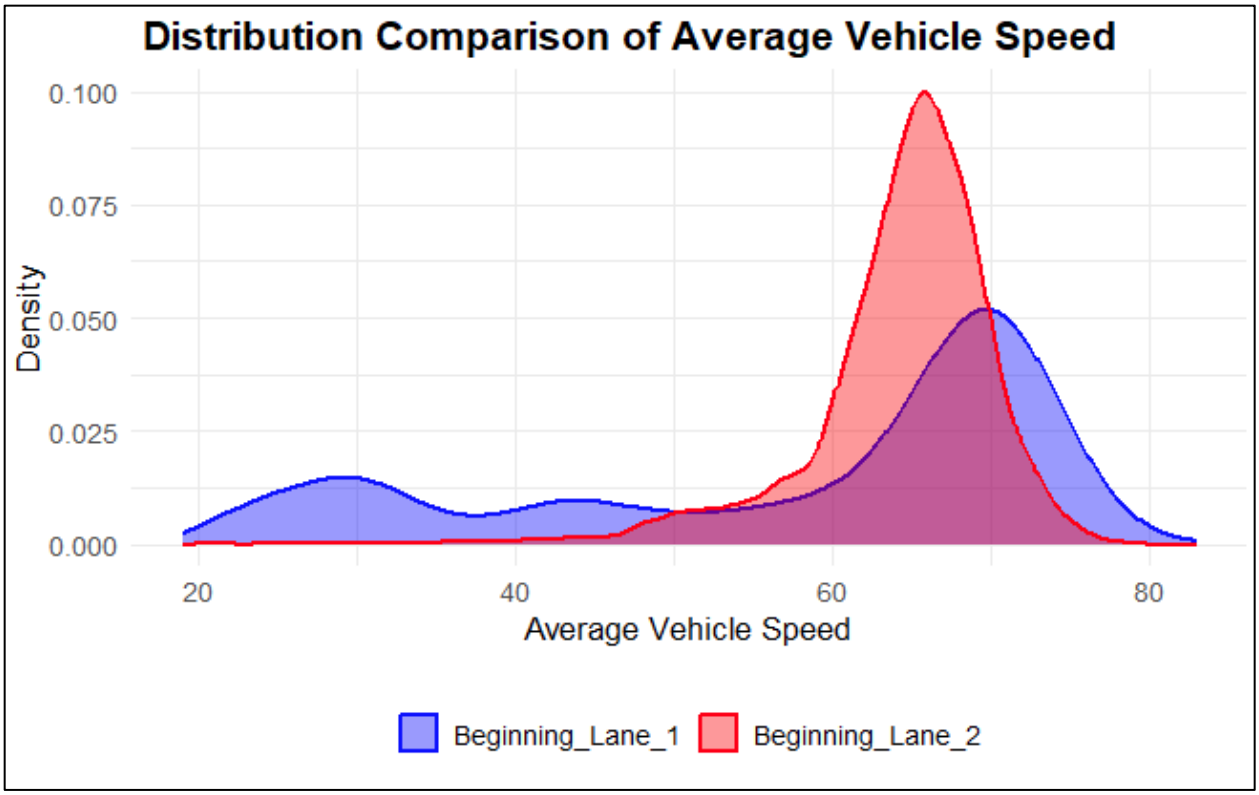


Figure 74. Average vehicle speed distribution at the beginning of the work zone

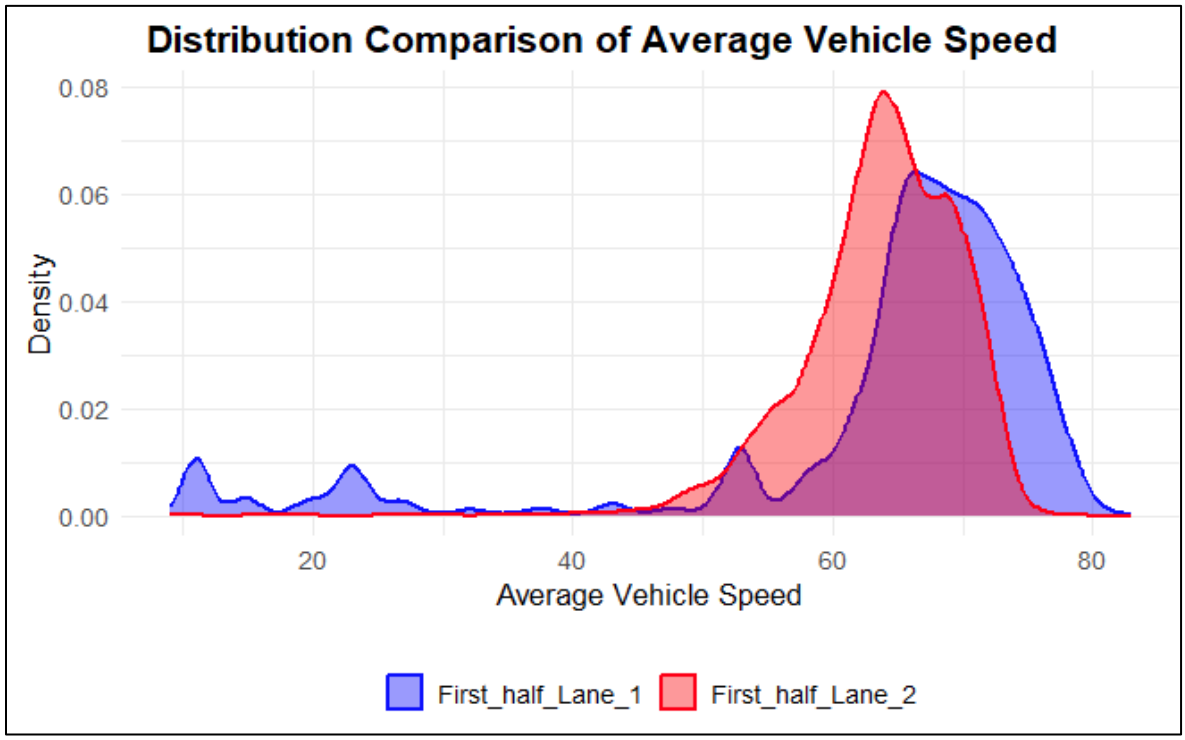


Figure 75. Average vehicle speed distribution for the first half of the active work zone

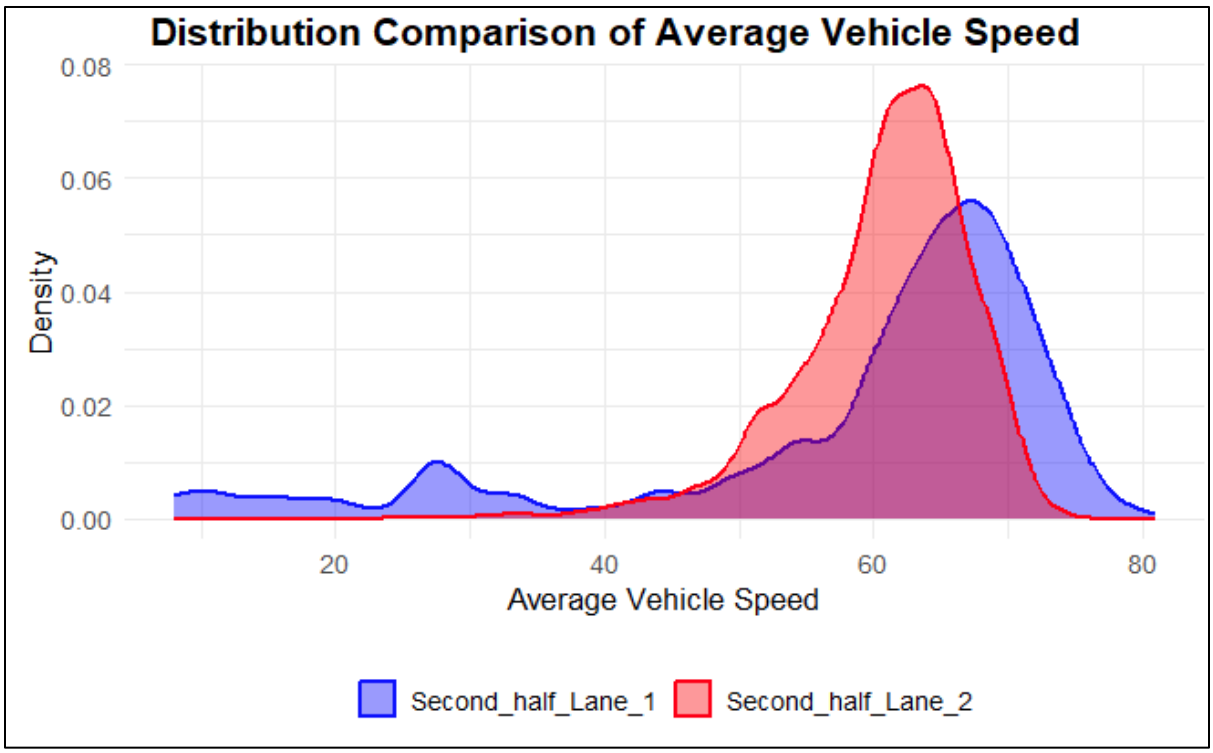


Figure 76. Average vehicle speed distribution for the second half of the active work zone

6.12.15 Hypothesis 15: Weekend Nighttime, Lane 1 vs. Lane 2, Construction with Blue Lights for Individual Work Zone Locations

***H₀**: There is no significant difference in the average vehicle speed between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekend nighttime, when blue lights are present for ongoing construction.*

***H₁**: There is a significant difference in the average vehicle speed between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekend nighttime, when blue lights are present for ongoing construction.*

Data Collected: To test the hypothesis, the average vehicle speed data during weekend nighttime with blue lights while ongoing construction was categorized into six sections:

- Weekend nighttime lane 1, beginning of the work zone: 504 observations
- Weekend nighttime lane 2, beginning of the work zone: 504 observations
- Weekend nighttime lane 1, first half of the active work zone: 504 observations
- Weekend nighttime lane 2, first half of the active work zone: 504 observations
- Weekend nighttime lane 1, second half of the active work zone: 504 observations
- Weekend nighttime lane 2, second half of the active work zone: 504 observations

An illustration of the dataset is depicted in **Table 74**.

Table 74. Data points for weekday nighttime lane 1 vs. lane 2, for construction with the presence of blue lights for individual work zone locations

Average Vehicle Speed Weekend Nighttime Beginning of the Work Zone, Lane 1 (mph)	Average Vehicle Speed Weekend Nighttime Beginning of the Work Zone, Lane 2 (mph)	Average Vehicle Speed Weekend Nighttime First Half of the Active Work Zone, Lane 1 (mph)	Average Vehicle Speed Weekend Nighttime First Half of the Active Work Zone, Lane 2 (mph)	Average Vehicle Speed Weekend Nighttime Second Half of the Active Work Zone, Lane 1 (mph)	Average Vehicle Speed Weekend Nighttime Second Half of the Active Work Zone, Lane 2 (mph)
45	47	40	55	67	52
38	33	37	31	28	47
X	X	X	X	X	X
X	X	X	X	X	X
X	X	X	X	X	X
41	44	25	17	34	64

Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 8.06478e-82, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it can be concluded that there was a statistically significant difference in average vehicle speed between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekend nighttime when construction work is ongoing with the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 75**.

Table 75. Post hoc pairwise comparison results

Comparison	p-value
Beginning Lane 1 - Beginning Lane 2	1.427635e-03
First Half Lane 1 - First Half Lane 2	1.927906e-18
Second Half Lane 1 - Second Half Lane 2	3.647636e-07

Post Hoc Pairwise Comparisons:

Beginning of the work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the green columns in **Table 74** yielded a p-value of 1.427635e-03, indicating a significant difference. The median speed was 68 mph for both lanes.

First half of the active work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the blue columns in **Table 74** yielded a p-value of 1.927906e-18, confirming a highly significant difference. The median speed was 69 mph for Lane 1 and 66 mph for Lane 2.

Second half of the active work zone (Lane 1 vs. Lane 2): The comparison, which included the data from the orange columns in **Table 74** yielded a p-value of 3.647636e-07, also indicating a significant difference. The median speed was 65 mph for Lane 1 and 62 mph for Lane 2.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different between Lane 1 and Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during weekend nighttime when construction work was ongoing with the presence of blue lights. Although the median speeds appeared close in some cases, the density plots reveal meaningful differences in the speed distributions, highlighting how drivers' choices varied between lanes. In **Figure 77**, for the beginning of the work zone, both lanes showed similar medians, yet the distributions differed. Lane 2 displayed a sharp, narrow peak at higher speeds, while Lane 1 showed a wider spread extending toward both lower and higher values. This pattern indicated that some drivers in Lane 1 adjusted speeds more variably, while Lane 2 traffic remained more tightly grouped. In **Figure 78**, for the first half of the active work zone, Lane 1 clustered around slightly higher speeds, while Lane 2 concentrated at slightly lower values. This suggested that speed patterns varied by lane within the active work zone. In **Figure 79**, for the second half of the active work zone, both lanes again showed significant differences. Lane 1 maintained higher speeds with a distribution peak shifted rightward, while Lane 2 shifted further left, emphasizing slower speeds. This suggested that drivers in Lane 2 continued to travel at lower speeds deeper into the work zone.

Overall, the results suggested that while both lanes were influenced by the presence of blue lights, Lane 2 consistently showed lower speeds, particularly in the active work zone segments. Lane 1, in contrast, exhibited slightly higher speeds and greater variability across segments. This pattern indicated that driver speed behavior differed between lanes during weekend nighttime construction under blue light conditions.

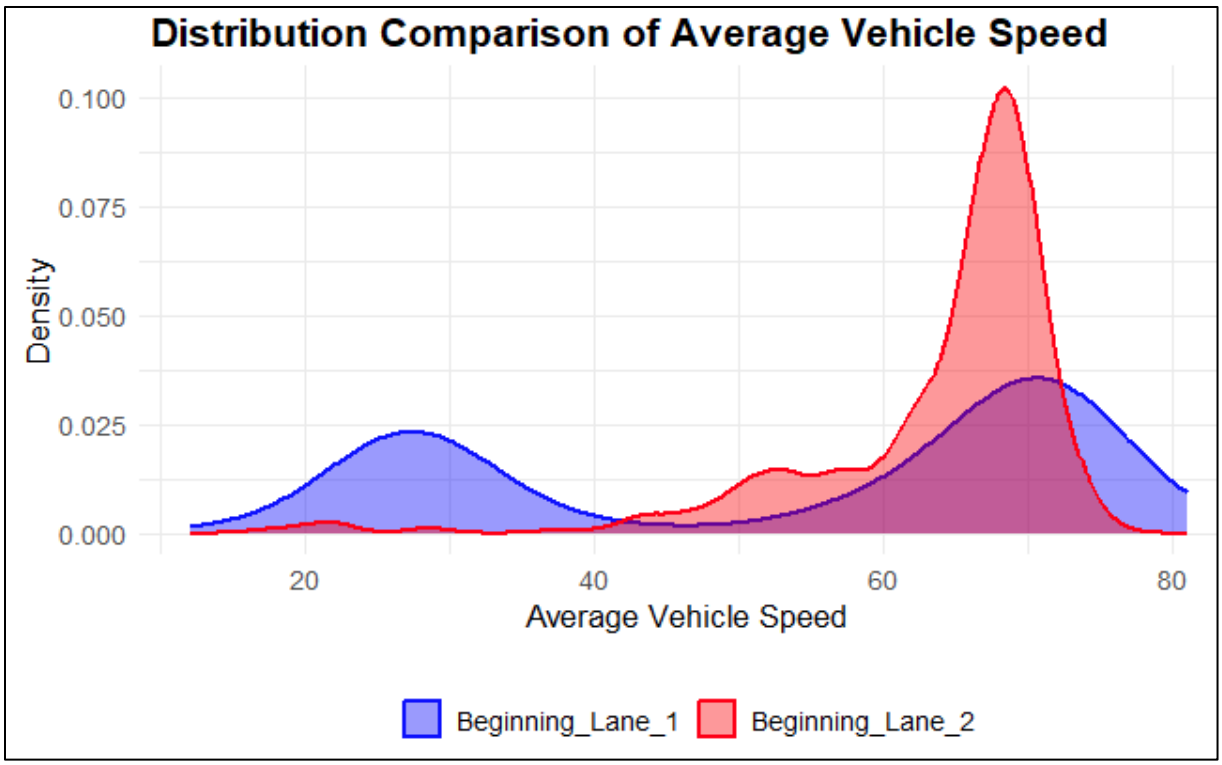


Figure 77. Average vehicle speed distribution for the beginning of the work zone

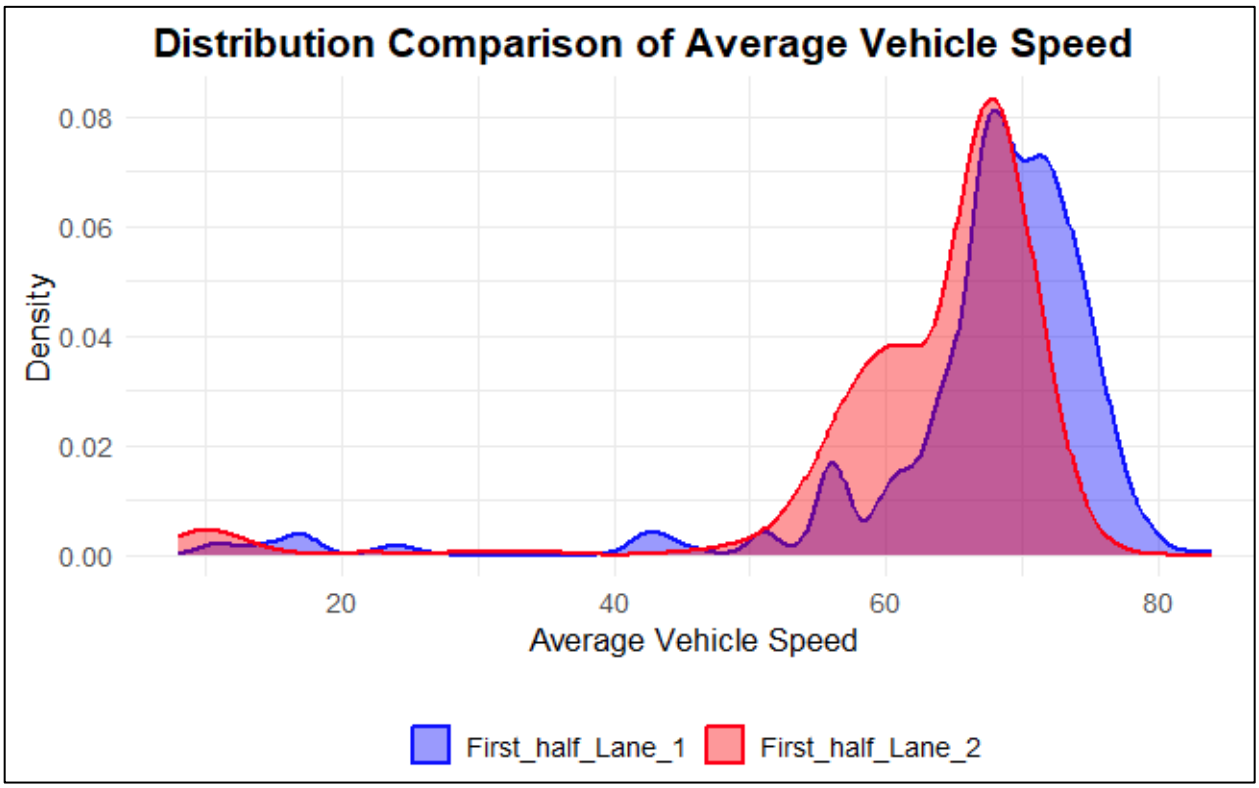


Figure 78. Average vehicle speed distribution for the first half of the active work zone

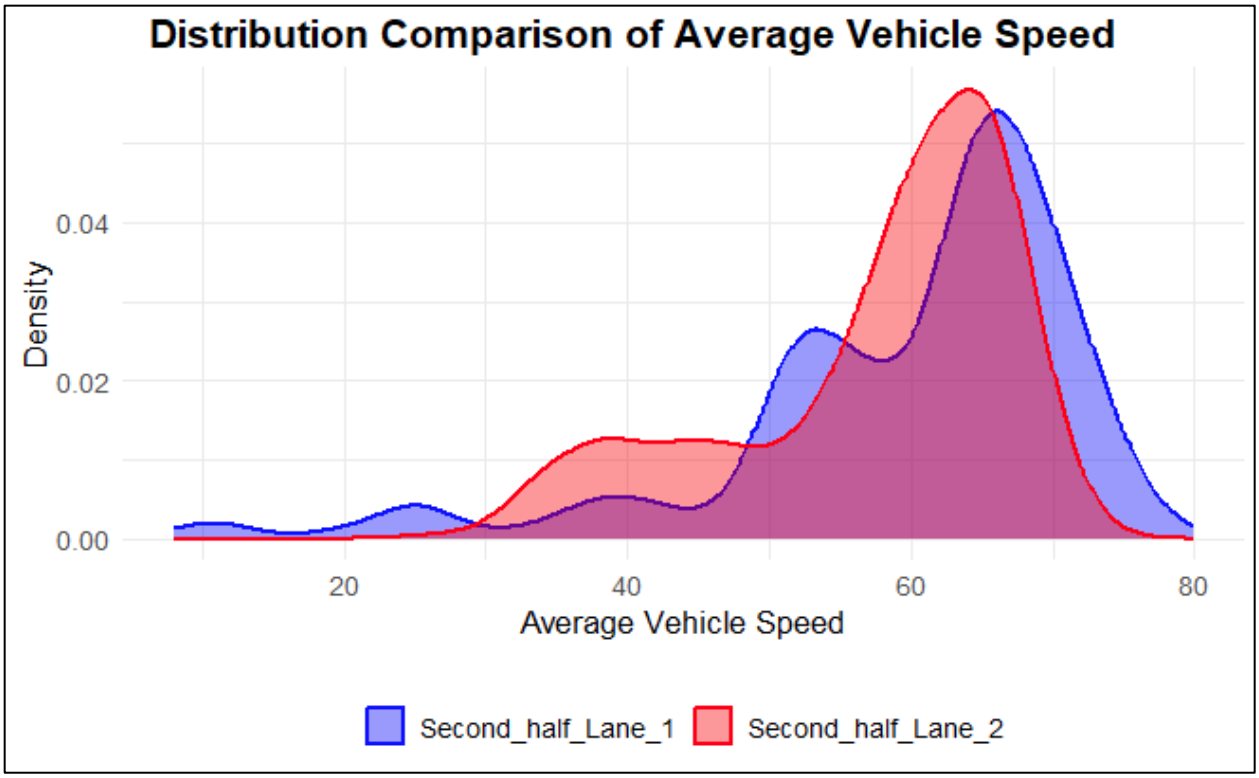


Figure 79. Average vehicle speed distribution for the second half of the active work zone

6.12.16 Hypothesis 16: Weekday, Beginning of the Work Zone, Construction with the Presence of Blue Lights, Daytime vs. Nighttime

***H₀**: There is no significant difference in average vehicle speed at the beginning of the work zone between weekday daytime and weekday nighttime when construction work is ongoing in the presence of blue lights.*

***H₁**: There is a significant difference in average vehicle speed at the beginning of the work zone between weekday daytime and weekday nighttime when construction work is ongoing in the presence of blue lights.*

Data Collected: For the analysis, the data were divided into two categories:

- Weekday daytime construction with the presence of blue lights - 864 observations
- Weekday nighttime construction with the presence of blue lights - 8064 observations

An illustration of the dataset is depicted in **Table 76**.

Table 76. Data points for average vehicle speed for weekday daytime vs. weekday nighttime - beginning of work zone for construction with the presence of blue lights

Average Traffic Speed Daytime (mph)	Average Traffic Speed Nighttime (mph)
65	70
72	55
X	X
X	X
68	60
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test showed that the p-value is 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it can be concluded that there was a statistically significant difference in average vehicle speed between weekday daytime and weekday nighttime at the beginning of the work zone during construction with the presence of blue lights. According to the descriptive statistics, the median average vehicle speed was 68 mph during weekday daytime and 66 mph during weekday nighttime. The IQR was 5 for weekday daytime and 9 for weekday nighttime, suggesting that speeds were more consistent during the daytime and more variable during nighttime. Although the medians were close, the density plot in **Figure 80** illustrates that weekday daytime had a sharp, concentrated peak around higher speeds, while weekday nighttime displayed a broader and more dispersed distribution. This supported the statistical results and indicated that the presence of blue lights contributed to greater reductions and variability in speeds during nighttime conditions at the beginning of the work zone.

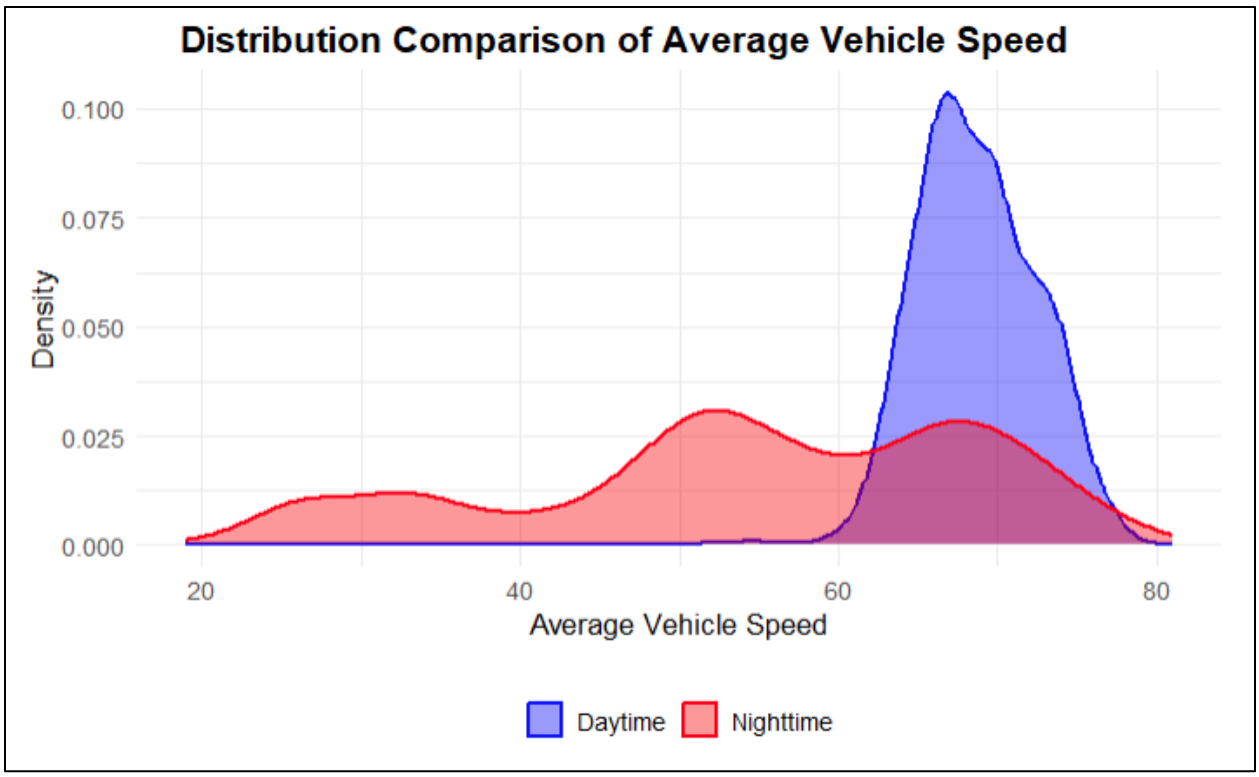


Figure 80. Average vehicle speed distribution for both daytime and nighttime

6.12.17 Hypothesis 17: Weekday, First Half of the Active Work Zone, Construction in the Presence of Blue Lights, Daytime vs. Nighttime

***H₀**: There is no significant difference in the average vehicle speed in the first half of the active work zone between weekday daytime and weekday nighttime when construction work is ongoing in the presence of blue lights.*

***H₁**: There is a significant difference in the average vehicle speed in the first half of the active work zone between weekday daytime and weekday nighttime when construction work is ongoing in the presence of blue lights.*

Data Collected: For the analysis, the data were divided into two categories:

Weekday daytime construction with the presence of blue lights - 864 observations

Weekday nighttime construction with the presence of blue lights - 8064 observations

An illustration of the dataset is depicted in **Table 77**.

Table 77. Data points for average vehicle speed for weekday daytime vs. weekday nighttime - first half of the active work zone for construction with the presence of blue lights

Average Traffic Speed Daytime (mph)	Average Traffic Speed Nighttime (mph)
65	70
72	55
X	X
X	X
68	60
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test showed that the p-value is 2.2e-16, which is smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it can be concluded that there is a statistically significant difference in average vehicle speed between weekday daytime and weekday nighttime in the first half of the active work zone during construction with the presence of blue lights. According to the descriptive statistics, the median average vehicle speed was 70 mph during weekday daytime and 66 mph during weekday nighttime. The IQR was 4 for weekday daytime and 8 for weekday nighttime, indicating more consistent speeds during the daytime and greater variability during the nighttime. Although the medians were close, the density plot in **Figure 81** illustrated a sharp, narrow peak for weekday daytime, while weekday nighttime showed a broader spread and heavier lower tail. This supported the statistical results and suggested that the presence of blue lights had a stronger moderating effect on vehicle speeds during nighttime in the first half of the active work zone.

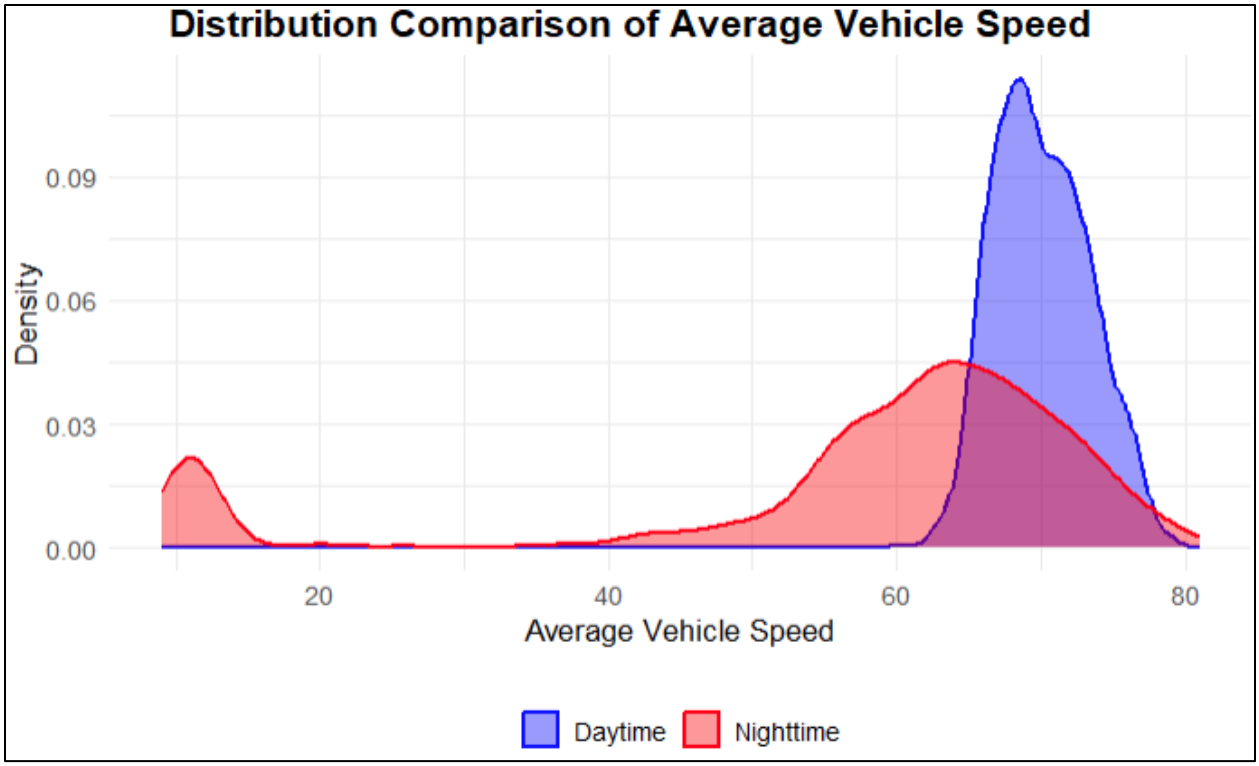


Figure 81. Average vehicle speed distribution for both daytime and nighttime

6.12.18 Hypothesis 18: Weekday, Second Half of the Active Work Zone, Construction with the Presence of Blue Lights, Daytime vs. Nighttime

***H₀**: There is no significant difference in the average vehicle speed in the second half of the active work zone between weekday daytime and weekday nighttime when construction work is ongoing in the presence of blue lights.*

***H₁**: There is a significant difference in the average vehicle speed in the second half of the active work zone between weekday daytime and weekday nighttime when construction work is ongoing in the presence of blue lights.*

Data Collected: For the analysis, the data were divided into two categories:

- Weekday daytime construction with the presence of blue lights - 864 observations
- Weekday nighttime construction with the presence of blue lights - 8064 observations

An illustration of the dataset is depicted in **Table 78**.

Table 78. Data points for average vehicle speed for weekday daytime vs. weekday nighttime - second half of the active work zone for construction with the presence of blue lights

Average Traffic Speed Daytime (mph)	Average Traffic Speed Nighttime (mph)
65	70
72	55
X	X
X	X
68	60
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test showed that the p-value is 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it can be concluded that there was a statistically significant difference in average vehicle speed between weekday daytime and weekday nighttime in the second half of the active work zone during construction with the presence of blue lights. According to the descriptive statistics, the median average vehicle speed was 65 mph during weekday daytime and 63 mph during weekday nighttime. The IQR was 24 for weekday daytime and 10 for weekday nighttime, suggesting greater variability in daytime speeds. Although the medians were close, the density plot in **Figure 82** illustrates sharper peaks and narrower spread during nighttime, while daytime speeds were more dispersed. This supported the statistical results and suggested that the presence of blue lights was associated with steadier nighttime speeds in the second half of the active work zone, while daytime speeds varied more widely.

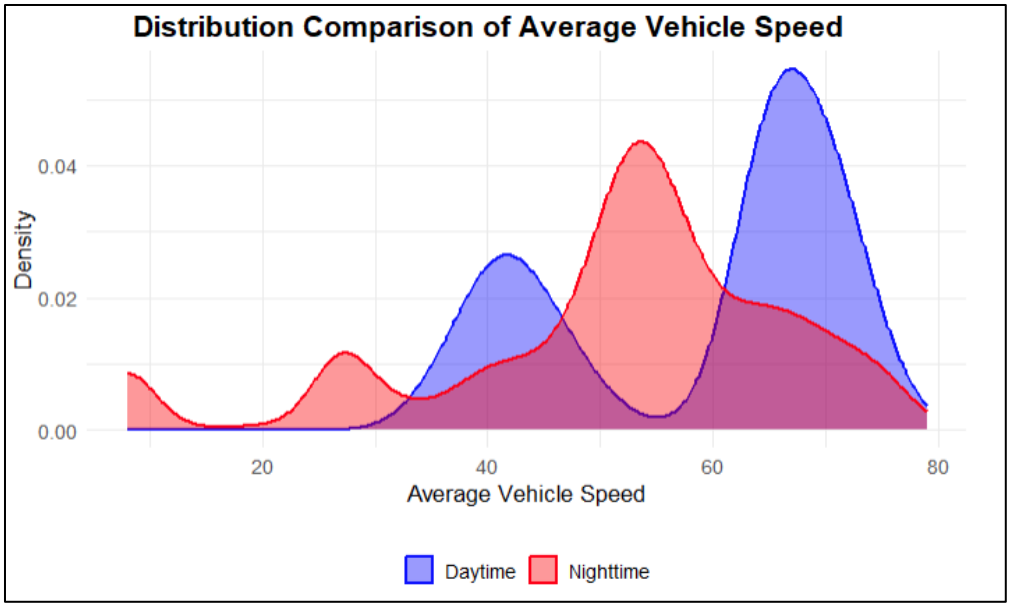


Figure 82. Average vehicle speed distribution for both daytime and nighttime

6.12.19 Hypothesis 19: Weekday, Lane 1, Construction with the Presence of Blue Lights, Daytime vs. Nighttime

***H_0**: There is no significant difference in the average vehicle speed between the weekday daytime and weekday nighttime for lane 1 when blue lights are present during construction work.*

***H_1**: There is a significant difference in the average vehicle speed between the weekday daytime and weekday nighttime for lane 1 when blue lights are present during construction work.*

Data Collected: For the analysis, the data were divided into two categories:

- Lane 1 weekday daytime construction with the presence of blue lights - 1296 observations
- Lane 1 weekday nighttime construction with the presence of blue lights - 10584 observations

An illustration of the dataset is depicted in **Table 79**.

Table 79. Data points for average vehicle speed for daytime vs nighttime - lane 1 for construction with the presence of blue lights

Average Vehicle Speed Daytime (mph)	Average Vehicle Speed Nighttime (mph)
65	70
72	55
X	X
X	X
68	60
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test yielded a p-value of less than 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed between weekday daytime and weekday nighttime for Lane 1 during construction with the presence of blue lights. According to the descriptive statistics, the median average vehicle speed was 71 mph during weekday daytime and 61 mph during weekday nighttime. The IQR was 5 for weekday daytime and 47 for weekday nighttime, indicating much greater variability in nighttime speeds. The density plot in **Figure 83** illustrates a sharp, narrow peak for daytime, while nighttime speeds were widely dispersed with heavier concentrations at lower ranges. This supported the statistical results and suggested that blue lights might have a stronger influence on reducing and dispersing speeds during nighttime in Lane 1 compared to daytime.

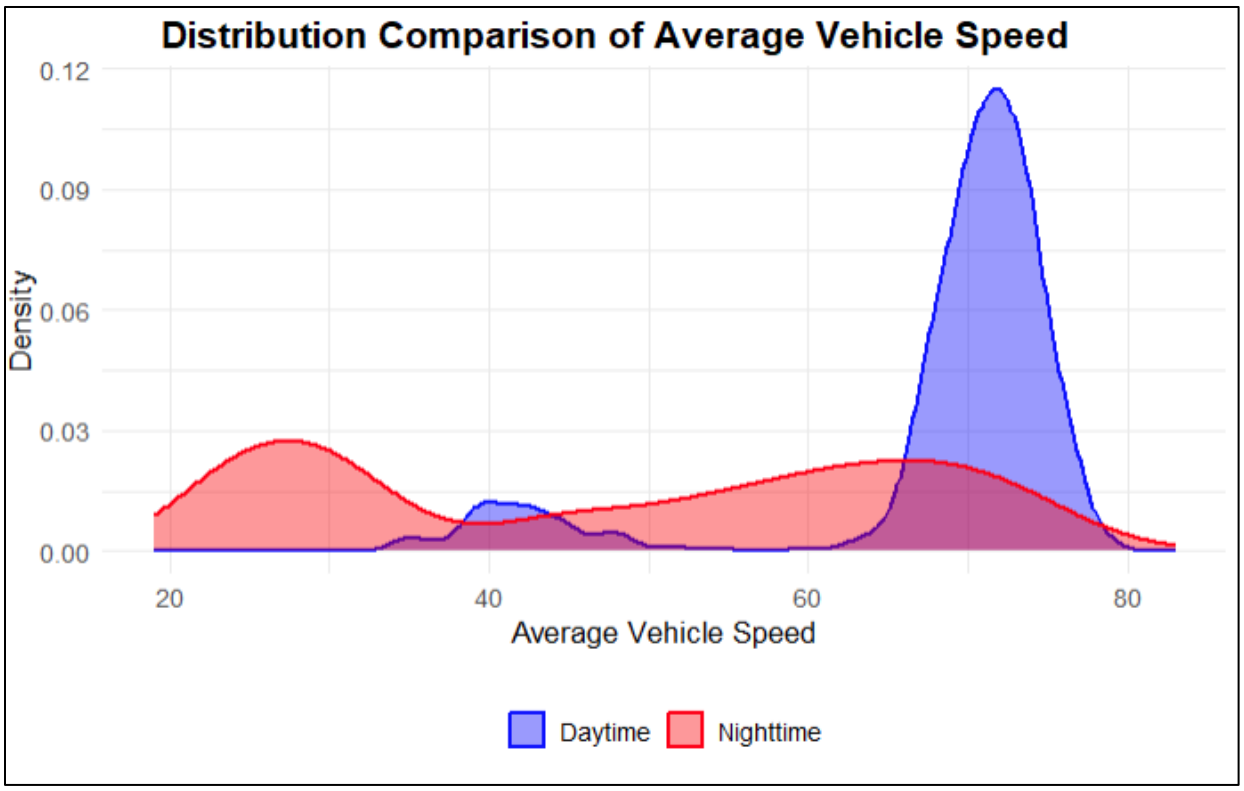


Figure 83. Average vehicle speed distribution for both daytime and nighttime

6.12.20 Hypothesis 20: Weekday, Lane 2, Construction with the Presence of Blue Lights, Daytime vs. Nighttime

***H₀**: There is no significant difference in the average vehicle speed during the weekday daytime and weekday nighttime for lane 1 when blue lights are present during construction work.*

***H₁**: There is a significant difference in the average vehicle speed during the weekday daytime and weekday nighttime for lane 1 when blue lights are present during construction work.*

Data Collected: For the analysis, the data were divided into two categories:

- Lane 2 weekday daytime construction with the presence of blue lights - 1296 observations
- Lane 2 weekday nighttime construction with the presence of blue lights - 10584 observations

An illustration of the dataset is depicted in **Table 80**.

Table 80. Data points for average vehicle speed for daytime vs nighttime - lane 2 for construction with the presence of blue lights

Average Vehicle Speed Daytime (mph)	Average Vehicle Speed Nighttime (mph)
65	70
72	55
X	X
X	X
68	60
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test yielded a p-value of 3.401e-09, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed between weekday daytime and weekday nighttime for Lane 2 during construction with the presence of blue lights. According to the descriptive statistics, the median average vehicle speed was 66 mph during weekday daytime and 64 mph during weekday nighttime. The IQR was 4 for weekday daytime and 7 for weekday nighttime, suggesting that speeds were slightly more variable during nighttime. Although the medians were close, the density plot in **Figure 84** illustrates a sharp and narrow distribution for daytime, while nighttime displayed a wider spread extending toward lower speeds. This supported the statistical results and suggested that blue lights might have contributed to greater reductions and variability in speeds during nighttime compared to daytime in Lane 2.

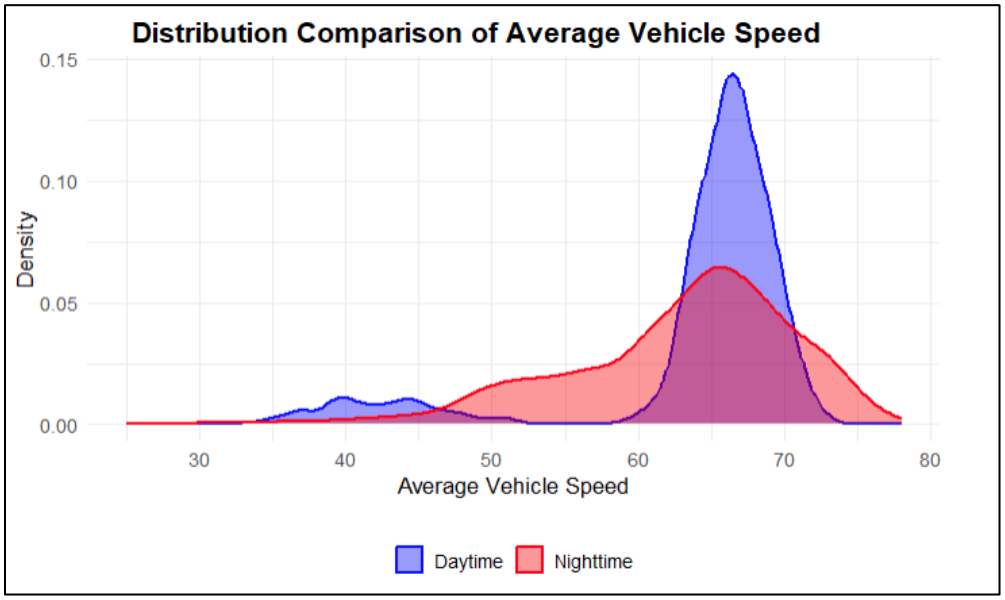


Figure 84. Average vehicle speed distribution for both daytime and nighttime

6.12.21 Hypothesis 21: Weekday Daytime vs. Weekday Nighttime, Construction with the Presence of Blue Lights for Individual Work Zone Locations for Lane 1

This analysis examines whether vehicle speeds differ for three distinct locations within the work zone - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone - during weekday daytime compared to weekday nighttime construction with blue lights for lane 1. The null and alternative hypotheses formulated for this test are as follows:

***H_0**: There is no significant difference in the average vehicle speed for Lane 1 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during the weekday daytime compared to the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during the weekday nighttime, when blue lights are present for ongoing construction.*

***H_1**: There is a significant difference in the average vehicle speed for Lane 1 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during the weekday daytime compared to the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during the weekday nighttime, when blue lights are present for ongoing construction.*

Data Collected: To test the hypothesis, vehicle speed data from weekday daytime and weekday nighttime with blue lights during ongoing construction were categorized into six sections:

- Weekday daytime lane 1, beginning of the work zone: 432 observations.
- Weekday daytime lane 1, first half of the active work zone: 432 observations.
- Weekday daytime lane 1, second half of the active work zone: 432 observations.
- Weekday nighttime lane 1, beginning of the work zone: 3528 observations.
- Weekday nighttime lane 1, first half of the active work zone: 3528 observations.
- Weekday nighttime lane 1, second half of the active work zone: 3528 observations.

An illustration of the dataset is depicted in **Table 81**.

Table 81. Data points for weekday daytime vs. weekday nighttime, for construction with the presence of blue lights for individual work zone locations for lane 1

Average Vehicle Speed Daytime Beginning of the Work Zone (mph)	Average Vehicle Speed Nighttime Beginning of the Work Zone (mph)	Average Vehicle Speed Daytime First Half of the Active Work Zone (mph)	Average Vehicle Speed Nighttime First Half of the Active Work Zone (mph)	Average Vehicle Speed Daytime Second Half of the Active Work Zone (mph)	Average Vehicle Speed Nighttime Second Half of the Active Work Zone (mph)
45	47	40	55	67	52
38	33	37	31	28	47
X	X	X	X	X	X
X	X	X	X	X	X
X	X	X	X	X	X
41	44	25	17	34	64

Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 2.485591e-289, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it can be concluded that there is a statistically significant difference in average vehicle speed for Lane 1 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone between weekday daytime and weekday nighttime when construction work is ongoing with the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 82**.

Table 82. Post hoc pairwise comparison results

Comparison	p-value
Daytime_Beginning - Nighttime_Beginning	<0.0001
Daytime _First_Half - Nighttime _First_Half	<0.0001
Daytime _Second_Half - Nighttime _Second_Half	<0.0001

Post Hoc Pairwise Comparisons:

Beginning of the work zone (Daytime) vs. Beginning of the work zone (Nighttime): The comparison, which included the data from the green columns in **Table 81**, yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 71 mph during daytime and 66 mph during nighttime.

First half of the active work zone (Daytime) vs. First half of the active work zone (Nighttime): The comparison, which included the data from the blue columns in **Table 81**, yielded a p-value of

<0.0001, suggesting a significant difference. The median speed was 72 mph during daytime and 68 mph during nighttime.

Second half of the active work zone (Daytime) vs. Second half of the active work zone (Nighttime): The comparison, which included the data from the orange columns in **Table 81**, yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 68 mph during daytime and 64 mph during nighttime.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different for Lane 1 between weekday daytime and weekday nighttime at the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone when construction work was ongoing in the presence of blue lights. The post hoc comparisons provided additional insights, showing that daytime speeds were consistently higher than nighttime speeds for all segments of the work zone. In **Figure 85**, for the beginning of the work zone, the density plot showed that during daytime, speeds were concentrated at higher values, producing a sharp peak. At nighttime, the distribution flattened and shifted leftward, with more vehicles traveling at lower speeds. This indicates that drivers slowed down earlier in the work zone during nighttime conditions. In **Figure 86**, for the first half of the active work zone, a similar pattern appeared. Daytime speeds were concentrated at higher levels, while nighttime speeds spread out more widely with a visible shift toward lower values. This suggests that blue lights contributed to reinforcing speed reductions as drivers moved into the active portion of the work zone at night.

In **Figure 87**, for the second half of the active work zone, the difference between daytime and nighttime speeds became most apparent. Daytime distributions stayed clustered at higher speeds, while nighttime distributions shifted clearly leftward, showing a broader spread at lower speeds. This highlights that the influence of nighttime conditions with blue lights was strongest near the exit of the work zone.

Overall, these results suggest that while drivers consistently reduced speeds at night, the magnitude of reduction varied by location. The most significant speed reductions occurred in the second half of the active work zone, indicating that drivers became more cautious as they progressed further into the work area under blue light conditions.

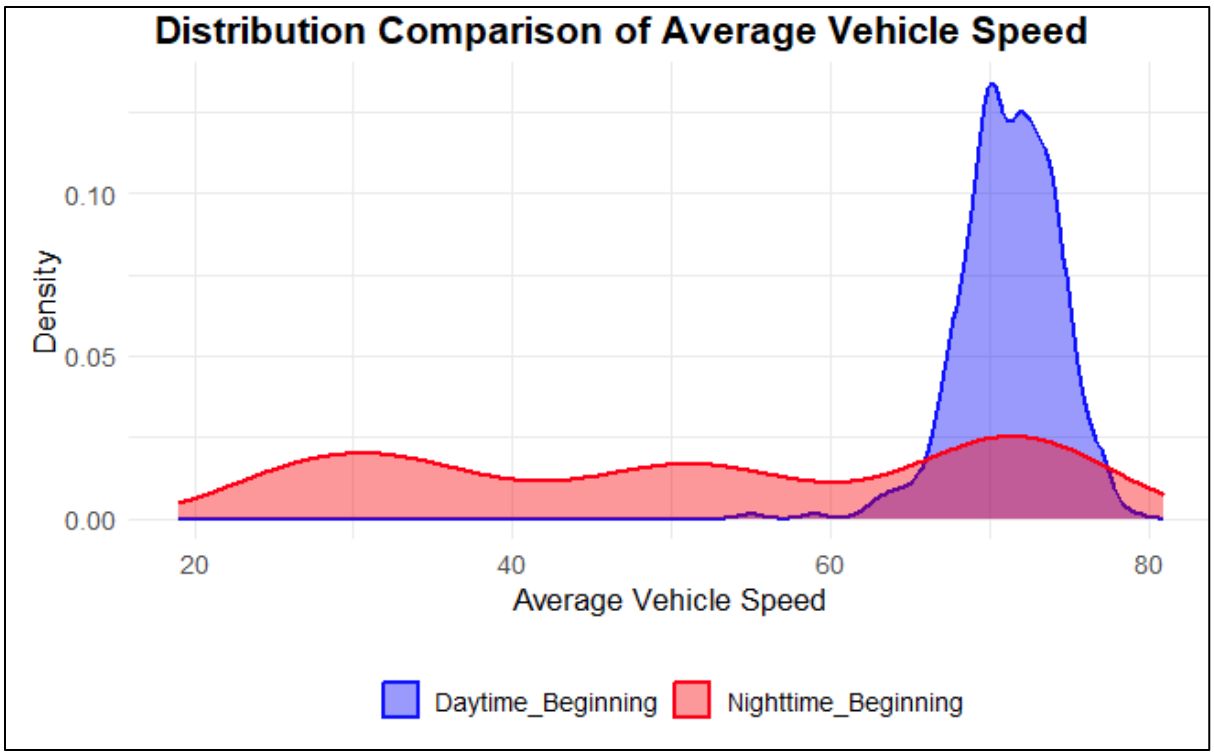


Figure 85. Average vehicle speed distribution for the beginning of the work zone (lane 1)

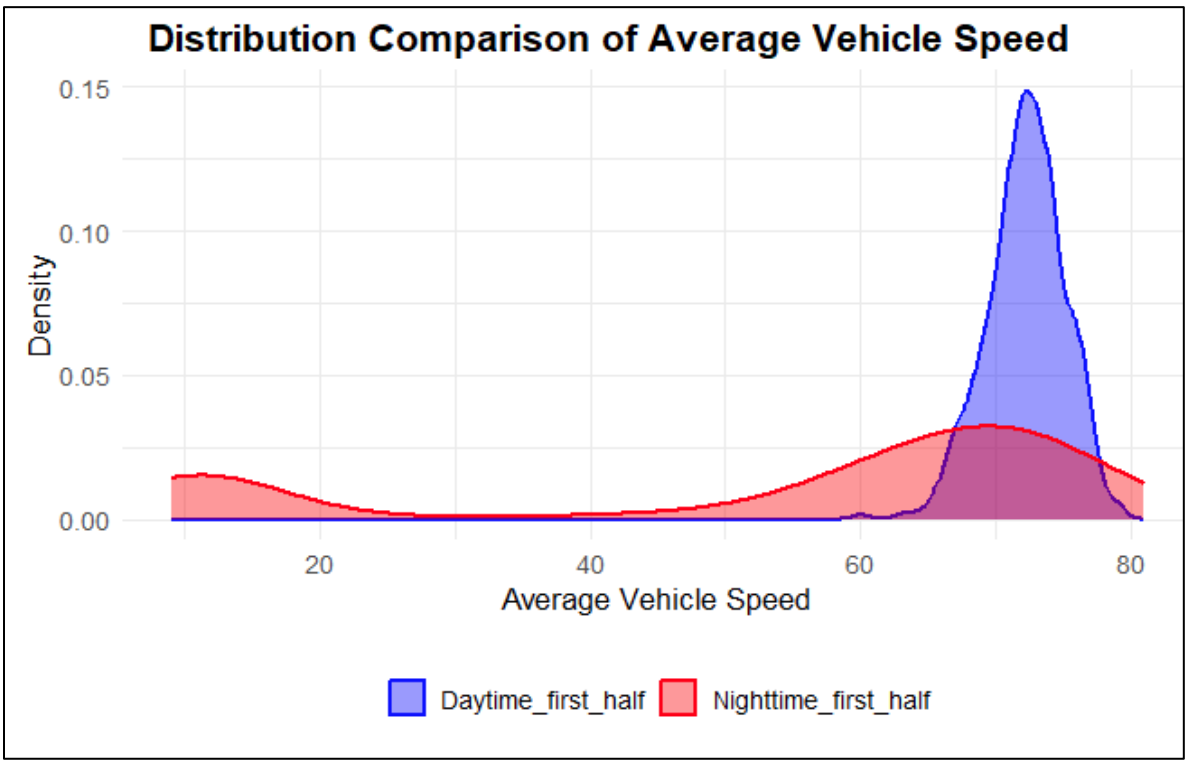


Figure 86. Average vehicle speed distribution for the first half of the active work zone (lane 1)

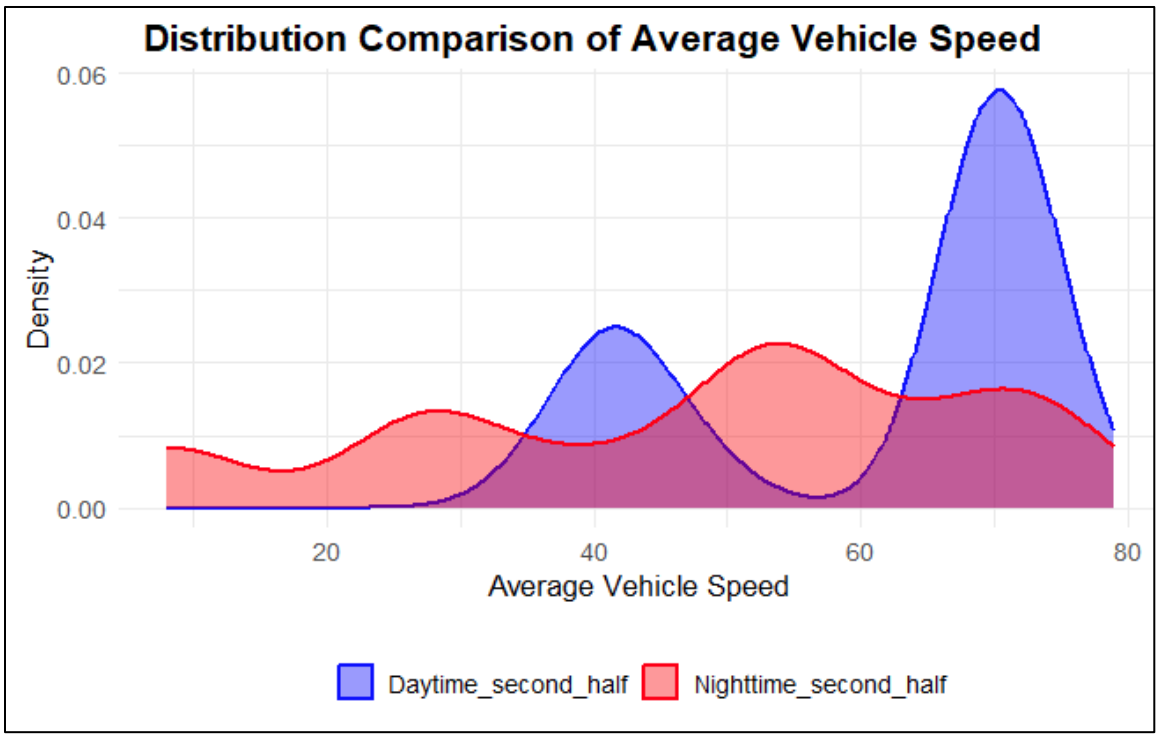


Figure 87. Average vehicle speed distribution for the second half of the active work zone (lane 1)

6.12.22 Hypothesis 22: Weekday Daytime vs. Weekday Nighttime, Construction with Blue Lights for Individual Work Zone Locations for Lane 2

This analysis examines whether vehicle speeds differ for three distinct locations within the work zone - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone - between weekday daytime and weekday nighttime construction with blue lights for lane 2. The null and alternative hypotheses formulated for this test are as follows:

***H_0**: There is no significant difference in the average vehicle speed for Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during the weekday daytime compared to the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during the weekday nighttime, when blue lights are present for ongoing construction.*

***H_1**: There is a significant difference in the average vehicle speed for Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during the weekday daytime compared to the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during the weekday nighttime, when blue lights are present for ongoing construction.*

Data Collected: To test the hypothesis, vehicle speed data during weekday daytime and weekday nighttime with blue lights while ongoing construction was categorized into six sections:

- Weekday daytime lane 2, beginning of the work zone: 432 observations.

- Weekday daytime lane 2, first half of the active work zone: 432 observations.
- Weekday daytime lane 2, second half of the active work zone: 432 observations.
- Weekday nighttime lane 2, beginning of the work zone: 3528 observations.
- Weekday nighttime lane 2, first half of the active work zone: 3528 observations.
- Weekday nighttime lane 2, second half of the active work zone: 3528 observations.

An illustration of the dataset is depicted in **Table 83**.

Table 83. Data points for weekday daytime vs. weekday nighttime, for construction with the presence of blue lights for individual work zone locations for lane 2

Average Vehicle Speed Daytime Beginning of the Work Zone (mph)	Average Vehicle Speed Nighttime Beginning of the Work Zone (mph)	Average Vehicle Speed Daytime First Half of the Active Work Zone (mph)	Average Vehicle Speed Nighttime First Half of the Active Work Zone (mph)	Average Vehicle Speed Daytime Second Half of the Active Work Zone (mph)	Average Vehicle Speed Nighttime Second Half of the Active Work Zone (mph)
45	47	40	55	67	52
38	33	37	31	28	47
X	X	X	X	X	X
X	X	X	X	X	X
X	X	X	X	X	X
41	44	25	17	34	64

Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 5.825069e-311, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed for Lane 2 for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone between weekday daytime and weekday nighttime when construction work was ongoing with the presence of blue lights. The results from the post hoc pairwise comparisons are presented in **Table 84**.

Table 84. Post hoc pairwise comparison results

Comparison	p-value
Daytime Beginning - Nighttime Beginning	<0.0001
Daytime First Half - Nighttime First Half	<0.0001
Daytime Second Half - Nighttime Second Half	1

Post Hoc Pairwise Comparisons:

Beginning of the work zone (Daytime) vs. Beginning of the work zone (Nighttime): The comparison, which included the data from the green columns in **Table 83**, yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 66 mph during the daytime and 65 mph during nighttime.

First half of the active work zone (Daytime) vs. First half of the active work zone (Nighttime): The comparison, which included the data from the blue columns in **Table 83** yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 68 mph during the daytime and 64 mph during nighttime.

Second half of the active work zone (Daytime) vs. Second half of the active work zone (Nighttime): The comparison, which included the data from the orange columns in **Table 83** yielded a p-value of 1, indicating no statistically significant difference. The median speed was 64 mph during the daytime and 62 mph during nighttime.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different for Lane 2 between daytime and nighttime conditions at the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone when construction work was ongoing with the presence of blue lights. The post hoc comparisons showed that differences were significant for the beginning and the first half of the active work zone, but not for the second half. In **Figure 88**, for the beginning of the work zone, daytime speeds were concentrated at higher values, forming a sharp and narrow peak. At nighttime, the distribution flattened and shifted leftward, showing more vehicles traveling at lower speeds. This suggested that blue lights encouraged stronger speed reductions during nighttime as drivers entered the work zone. In **Figure 89**, for the second half of the active work zone, both daytime and nighttime distributions overlapped more closely, with no statistically significant difference in speeds. This shows that drivers had already adapted their speeds earlier in the work zone, resulting in similar patterns by the time they reached the exit area.

Overall, the results suggest that blue lights had the strongest influence at the entry and first half of the active work zone during nighttime, where drivers made clear speed adjustments. By the second half of the active work zone, speeds had stabilized, and the difference between daytime and nighttime diminished.

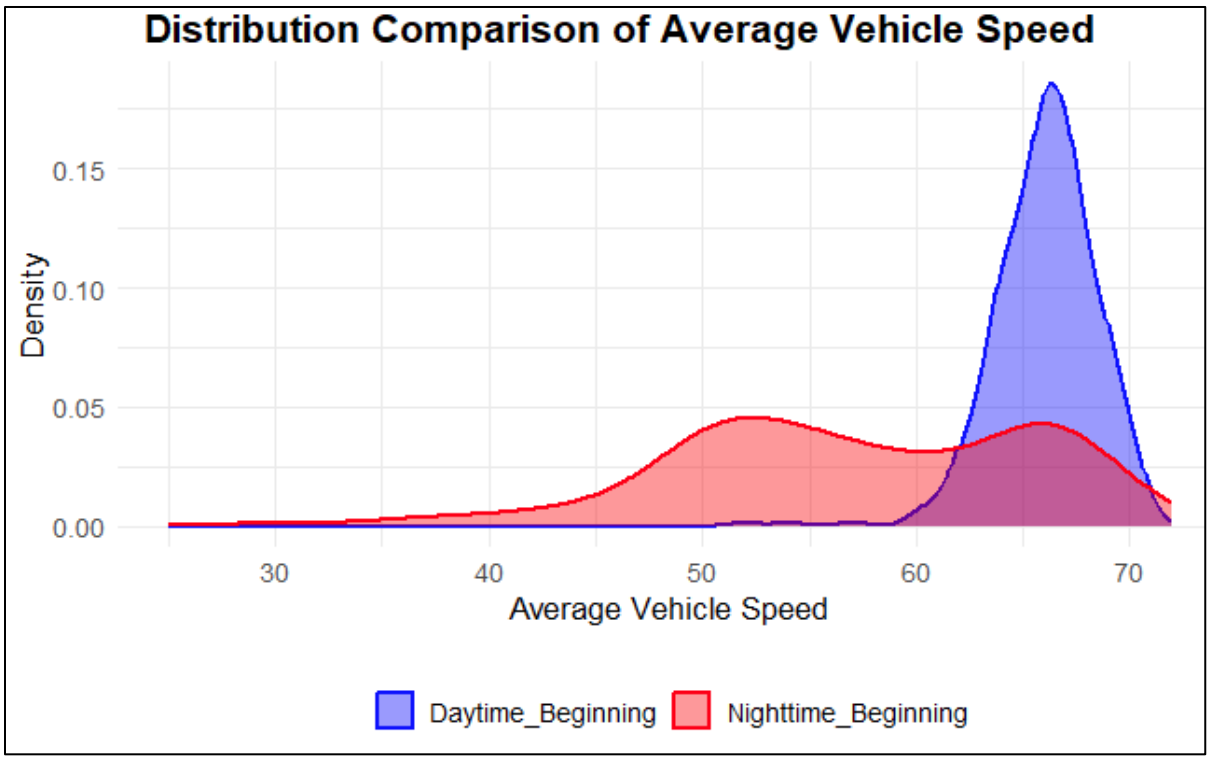


Figure 88. Average vehicle speed distribution for the beginning of the work zone (lane 2)

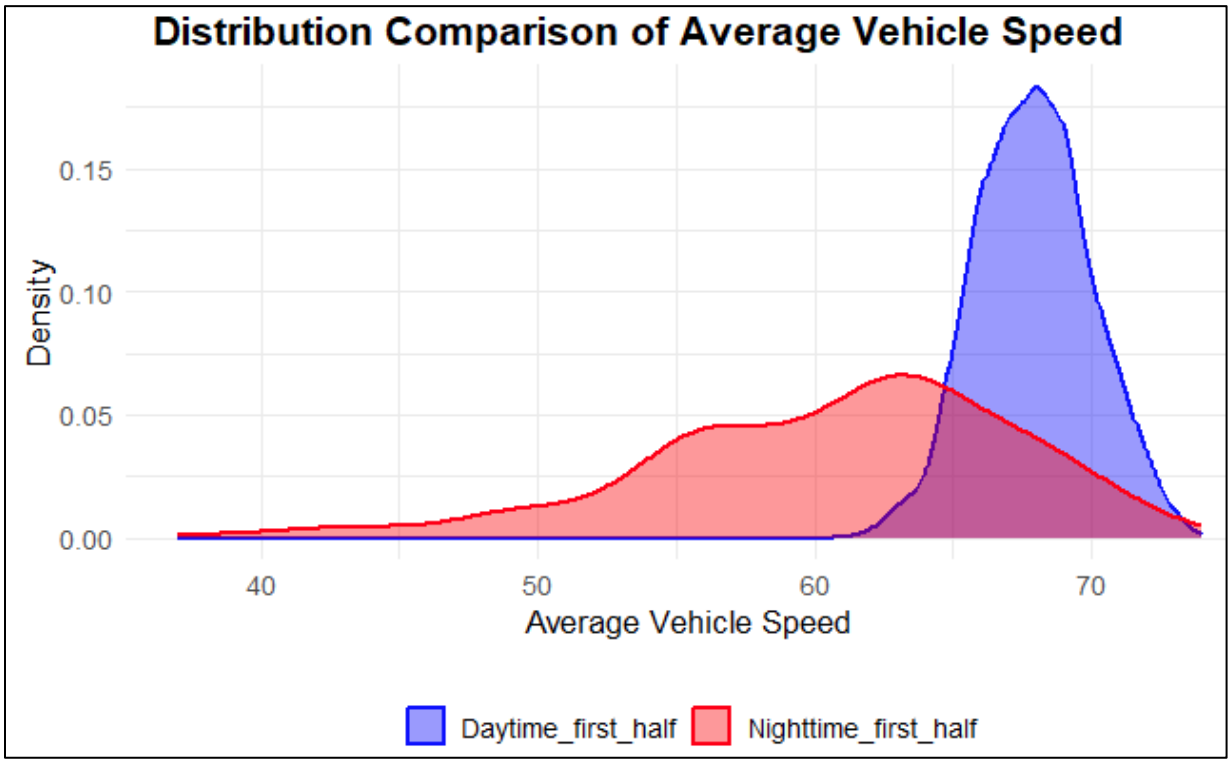


Figure 89. Average vehicle speed distribution for the first half of the active work zone (lane 2)

6.12. 23 Summary of Category One: Analysis of Average Vehicle Speed for Construction with the Presence of Blue Lights in the Work Zone

This section provides a comprehensive summary based on the hypothesis tests conducted in this category and the insights gained from them.

6.12.23.1 Average Vehicle Speed for Individual Work Zone Locations and Lanes with the Presence of Blue Lights (Hypothesis 1-Hypothesis 9)

The hypothesis tests (Hypothesis 1-Hypothesis 3) showed that average vehicle speeds followed a consistent pattern under construction with the presence of blue lights. During weekday daytime, speeds remained higher at the beginning of the work zone and in the first half of the active work zone but declined in the second half of the active work zone. During weekday nighttime, the same trend was observed. However, the reductions in the second half of the active work zone were more significant, suggesting a stronger response under blue light conditions. Weekend nighttime results aligned with weekday nighttime patterns, indicating lower speeds toward the end of the work zone and reflecting consistent speed reductions as drivers progressed through the work zone.

Lane-based results within this hypothesis group (Hypothesis 4-Hypothesis 9) showed that both Lane 1 and Lane 2 exhibited relatively stable speeds at the beginning and in the first half of the active work zone, followed by clearer reductions in the second half of the active work zone. Although this general trend was observed in both lanes, Lane 2 generally exhibited slightly lower speeds than Lane 1 across the work zone segments. These findings indicated that speed reduction intensified as drivers progressed through the work zone, regardless of lane.

6.12.23.2 Average Vehicle Speed Differences Between Lanes under Construction with the Presence of Blue Lights (Hypothesis 10-Hypothesis 15)

The hypothesis tests (Hypothesis 10-Hypothesis 15) comparing speeds between lanes showed consistent speed separation between Lane 1 and Lane 2. During weekday daytime, Lane 1 maintained higher average vehicle speeds across the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone. Lane 2 reflected lower and more concentrated speeds. This pattern suggested that drivers in Lane 2 tended to maintain lower and more consistent speeds throughout the work zone.

During weekday nighttime, speed differences between the lanes became more distinct. Lane 1 continued to have higher speeds, while Lane 2 showed lower speeds, indicating a stronger response to the presence of blue lights under nighttime conditions. Weekend nighttime results showed a similar pattern. Lane 1 maintained slightly higher speeds while Lane 2 exhibited lower and more consistent speeds. This pattern may also reflect driver expectations regarding construction schedules, as construction activity is often less common during weekends, which may lead drivers to perceive lower risk and maintain slightly higher speeds despite the presence of blue lights.

6.12.23.3 Average Vehicle Speed Differences Between Daytime and Nighttime under Construction with the Presence of Blue Lights (Hypothesis 16-Hypothesis 22)

The hypothesis tests (Hypothesis 16-Hypothesis 22) comparing daytime and nighttime conditions showed significant differences in speed behavior based on time of day. At the beginning of the

work zone, weekday daytime speeds were higher, while weekday nighttime speeds shifted toward lower values, indicating earlier speed adjustments during nighttime conditions. In the first half of the active work zone, nighttime speeds showed greater reductions across this segment, reflecting increased caution as drivers entered the active construction area.

In the second half of the active work zone, weekday nighttime speeds remained lower and more consistent than daytime speeds, indicating sustained speed reductions deeper into the active work zone. Lane-based comparisons also complemented these findings. Lane 1 showed larger reductions between daytime and nighttime as drivers progressed through the work zone. In contrast, the differences in Lane 2 became smaller in the later segments of the active work zone, suggesting that speed reduction in Lane 2 occurred earlier and was maintained throughout the remainder of the work zone.

6.12.23.4 Insights from the Analysis

The findings from this category indicated that blue lights might have influenced speed behavior by encouraging gradual and consistent reductions as drivers progressed through the work zone. Speed adjustments were limited at the entry points but became more evident in the later stages, particularly within the second half of the active work zone.

The analysis also showed that time of day played a critical role in shaping driver response. Nighttime conditions were associated with stronger and more consistent speed reductions, suggesting that increased visibility of blue lights may have enhanced driver awareness and caution.

Lane-based comparisons further indicated that speed patterns varied between lanes, with Lane 2 generally exhibiting lower and more consistent speeds than Lane 1 across the work zone segments. This suggested that driver response to blue lights and construction activity may differ depending on lane position and traffic flow dynamics.

Overall, the category demonstrated that blue lights functioned as a significant visual signal that shaped speed behavior progressively rather than immediately. Their influence appeared strongest under nighttime conditions and in the active work zone segments.

6.13 Category Two: Comparative Analysis of Average Vehicle Speed Between Construction in the Presence of Blue Lights and Construction in the Absence of Blue Lights in the Work Zone

This category focuses on analyzing the comparative effect of construction with the presence of blue lights and construction without the presence of blue lights in the selected work zone on average vehicle speed. Based on the results from the preliminary analysis (Section 6.11), a total of eleven hypothesis tests were proposed and conducted to assess the differences in average vehicle speed under these two construction conditions. This included comparing traffic volume by considering several factors, including lanes, individual three work zone locations, and daytime and nighttime. **Table 85** summarizes the test results for the eleven hypotheses under this category. More details about each hypothesis test, including the individual hypothesis statements, data pre-processing, results analysis, and discussion (following the roadmap explained in

Table 5 or

Table 6), are presented in the following sections. An overall summary and key insights are provided at the end of the section.

Table 85. Summarized results of the category two hypothesis tests for average vehicle speed

Number	Details	Results
Hypothesis 1	Overall, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	Significant difference
Hypothesis 2	Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	Significant difference
Hypothesis 3	Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	Significant difference
Hypothesis 4	Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 5	Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)	Significant difference
Hypothesis 6	Lane 1, Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	No significant difference
Hypothesis 7	Lane 2, Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	Significant difference
Hypothesis 8	Lane 1, Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	Significant difference
Hypothesis 9	Lane 2, Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights	Significant difference
Hypothesis 10	Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Lanes for Individual Work Zone Locations	Significant difference
Hypothesis 11	Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Lanes for Individual Work Zone Locations	Significant difference

6.13.1 Hypothesis 1: Overall, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

H_0: *There is no significant difference in the average vehicle speed for the overall work zone between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

H_1: *There is a significant difference in the average vehicle speed for the overall work zone between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

Data Collected: For the analysis, the data were divided into two categories:

- Construction with the presence of blue lights - 26784 observations
- Construction without the presence of blue lights - 7488 observations

An illustration of the dataset is depicted in **Table 86**.

Table 86. Data points for average vehicle speeds for construction with the presence of blue lights vs. construction without the presence of blue lights

Average Vehicle Speed Lane 1 (mph)	Average Vehicle Speed Lane 2 (mph)
65	70
72	55
X	X
X	X
68	60
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test yielded a p-value of less than 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed between construction with the presence of blue lights and construction without the presence of blue lights.

According to the descriptive statistics, the median vehicle speed was 65 mph during construction with the presence of blue lights and 68 mph during construction without the presence of blue lights. Although the medians were close, the density plot in **Figure 90** illustrates a more concentrated peak at higher speeds for construction without the presence of blue lights, while construction with the presence of blue lights displayed a shift toward lower speeds with a broader spread. This supported the statistical results and suggested that blue lights might have contributed to more cautious driving behavior, reflected in lower and more varied speeds during construction.

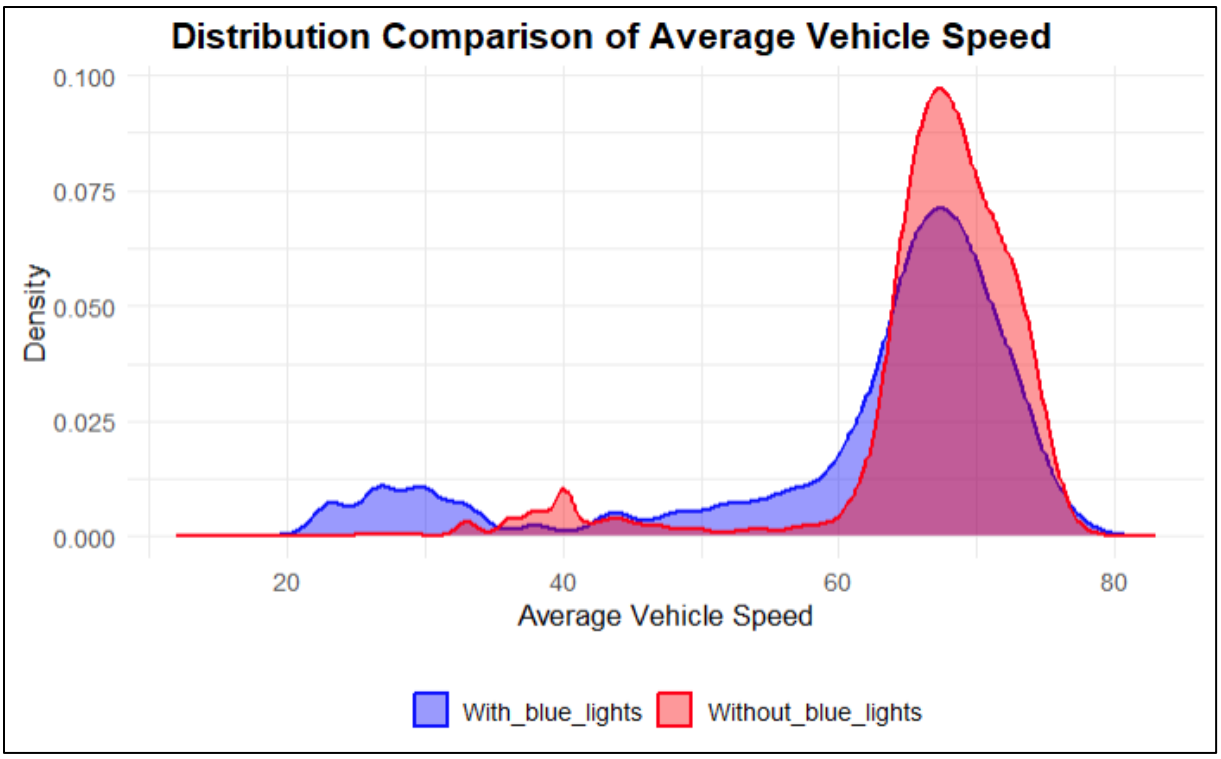


Figure 90. Average vehicle speed distribution with and without blue lights

6.13.2 Hypothesis 2: Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

H_0: *There is no significant difference in average vehicle speed between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

H_1: *There is a significant difference in average vehicle speed between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

Data Collected: For the analysis, the data were divided into two categories:

- Construction with the presence of blue lights - 2592 observations
- Construction without the presence of blue lights - 5760 observations

An illustration of the dataset is depicted in **Table 29**.

Table 87. Data points for average vehicle speed for construction with the presence of blue lights vs. construction without the presence of blue lights

Average vehicle speed for Construction with the Presence of Blue Lights (mph)	Average vehicle speed for Construction without the Presence of Blue Lights (mph)
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test.

Analysis Results: The Mann-Whitney U test yielded a p-value of 0.007592, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed during the daytime between construction with the presence of blue lights and construction without the presence of blue lights. According to the descriptive statistics, the median average vehicle speed was 68 mph for both conditions. The IQR was 6 for construction with the presence of blue lights and 6 for construction without the presence of blue lights, suggesting very similar variability. Although the medians were the same, the density plot in **Figure 91** illustrates a more concentrated distribution for construction without the presence of blue lights, while construction with the presence of blue lights showed a slightly wider spread. This supported the statistical results and suggested that blue lights might have influenced driver behavior by reducing consistency in vehicle speeds during daytime construction.

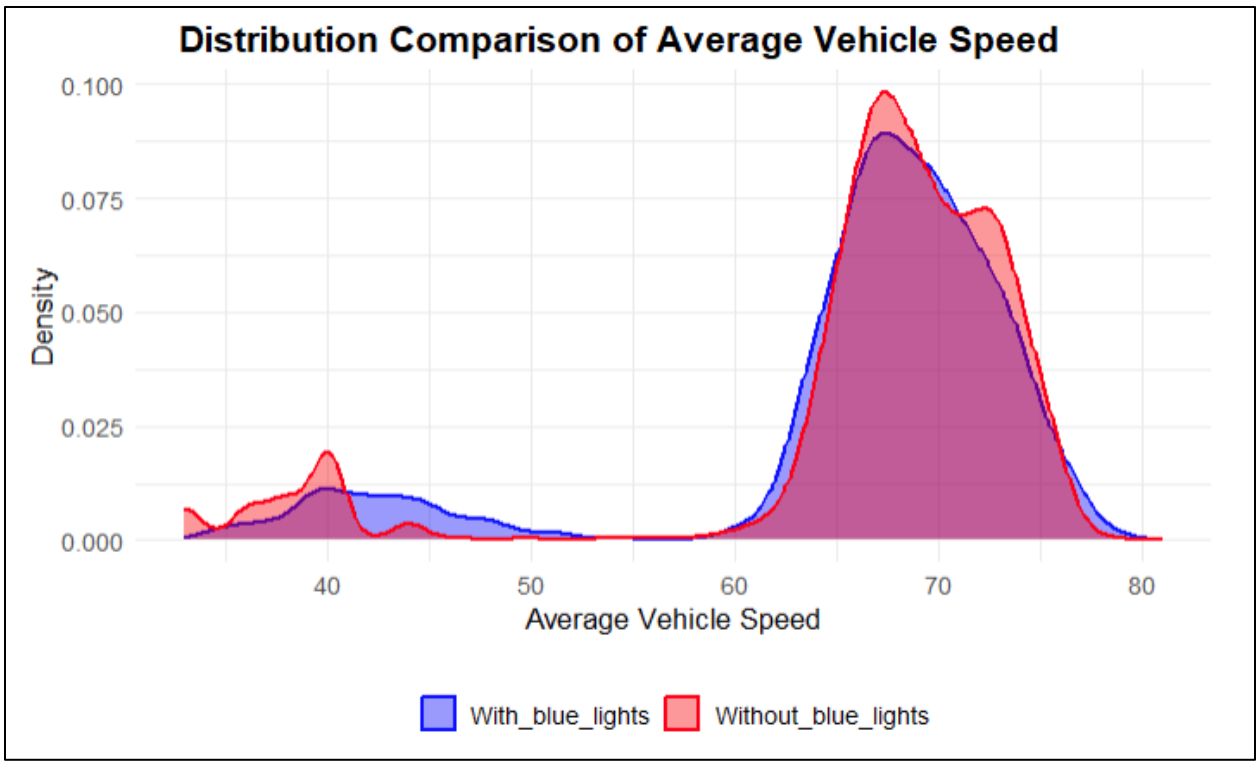


Figure 91. Average vehicle distribution with and without blue lights

6.13.3 Hypothesis 3: Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

H₀: *There is no significant difference in average vehicle speed between construction with the presence of blue lights and construction without the presence of blue lights during nighttime.*

H₁: *There is a significant difference in average vehicle speed between construction with the presence of blue lights and construction without the presence of blue lights during nighttime.*

Data Collected: For the analysis, the data were divided into two categories:

- Construction with the presence of blue lights - 24192 observations
- Construction without the presence of blue lights - 1728 observations

An illustration of the dataset is depicted in **Table 88**.

Table 88. Data points for average vehicle speed for construction with the presence of blue lights vs. construction without the presence of blue lights

Average Vehicle Speed for Construction with the Presence of Blue Lights (mph)	Average Vehicle Speed for Construction without the Presence of Blue Lights (mph)
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test.

Analysis Results: The Mann-Whitney U test yielded a p-value of less than 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed during nighttime between construction with the presence of blue lights and construction without the presence of blue lights.

According to the descriptive statistics, the median average vehicle speed was 65 mph for construction with the presence of blue lights and 68 mph for construction without the presence of blue lights. The IQR was 10 with blue lights and 5 without blue lights, indicating slightly greater variability in speeds when blue lights were present. Although the medians were close, the density plot in **Figure 92** shows that construction without the presence of blue lights had a sharper concentration at higher speeds, while construction with the presence of blue lights was more concentrated at slightly lower speeds. This supported the statistical results and suggested that blue lights might have influenced drivers to reduce speed and created more variability in speed patterns during nighttime construction.

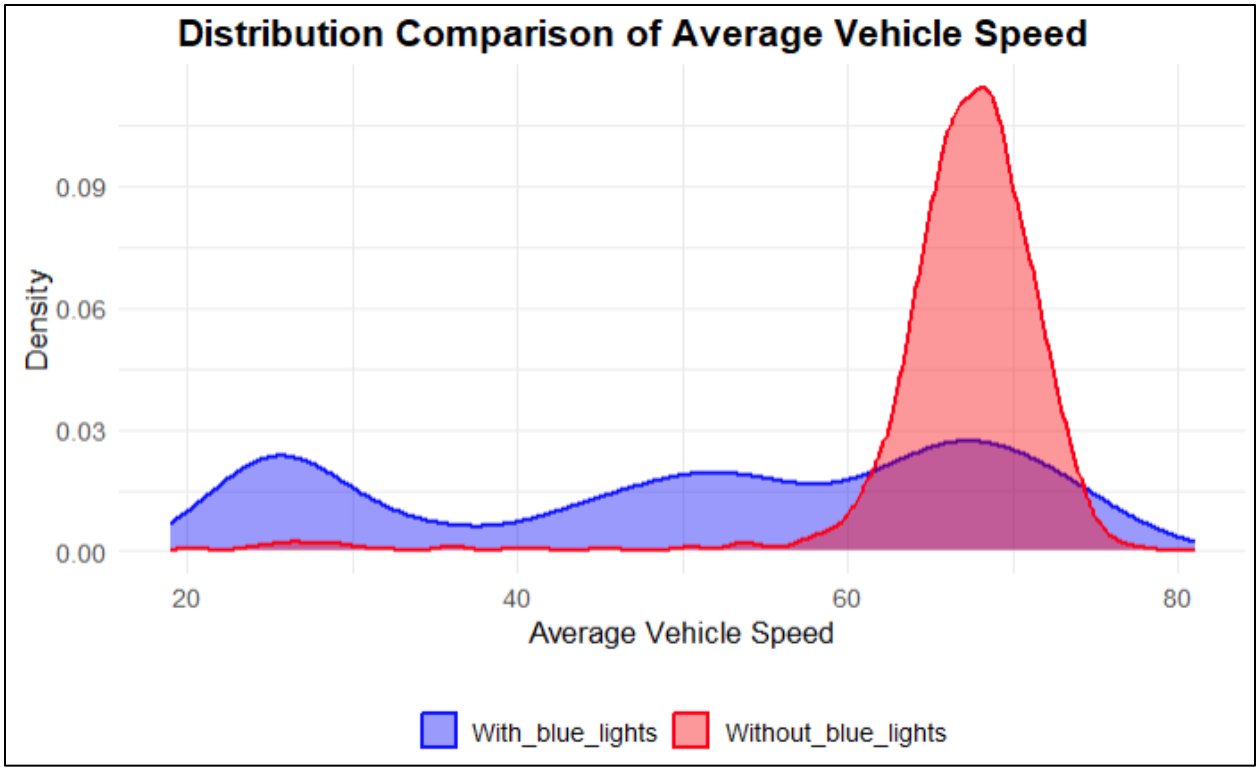


Figure 92. Average vehicle speed distribution with and without blue lights

6.13.4 Hypothesis 4: Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis aimed to compare vehicle speeds during daytime in the presence and absence of blue lights for three individual work zone locations - the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone. The null and alternative hypotheses formulated for this test are as follows:

***H_0**: There is no significant difference in the average vehicle speed during the daytime in the presence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

***H_1**: There is a significant difference in the average vehicle speed during the daytime in the presence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

Data Collected: For hypothesis testing, the vehicle speed data during daytime were categorized into six conditions:

- **With Blue Light Beginning (WB_Beg)** - Construction with the presence of blue lights at the beginning of the work zone, 864 observations
- **Without Blue Light Beginning (WOB_Beg)** - Construction without the presence of blue lights at the beginning of the work zone, 1920 observations
- **With Blue Light First Half (WB_1stH)** - Construction with the presence of blue lights in the first half of the active work zone, 864 observations
- **Without Blue Light First Half (WOB_1stH)** - Construction without the presence of blue lights in the first half of the active work zone, 1920 observations
- **With Blue Light Second Half (WB_2ndH)** - Construction with the presence of blue lights in the second half of the active work zone, 864 observations
- **Without Blue Light Second Half (WOB_2ndH)** - Construction without the presence of blue lights in the second half of the active work zone, 1920 observations

An illustration of the dataset is depicted in **Table 89**.

Table 89. Data points for daytime average vehicle speed differences between construction with the presence of blue lights and construction without the presence of blue lights for individual work zone locations

WB_Beg (mph)	WOB_Beg (mph)	WB_1stH (mph)	WOB_1stH (mph)	WB_2ndH (mph)	WOB_2ndH (mph)
45	47	40	55	67	52
38	33	37	31	28	47
X	X	X	X	X	X
X	X	X	X	X	X
X	X	X	X	X	X
41	44	25	17	34	64

Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Methods: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of 3.105456e-219, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it can be concluded that there was a statistically significant difference in average vehicle speed between construction with the presence of blue lights and construction without the presence of blue lights for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during daytime. The results from the post hoc pairwise comparisons are shown in **Table 90**.

Table 90. Post hoc pairwise comparison results

Comparison	p-value
WB_Beg - WOB_Beg	<0.0001
WB_1stH - WOB_1stH	0.6766
WB_2ndH - WOB_2ndH	<0.0001

Post Hoc Pairwise Comparisons:

Beginning of the work zone: For the beginning of the work zone, the comparison between construction with and without blue lights, which included the data from the green columns in **Table 89** yielded a p-value of <0.0001. The median speed was 68 mph for both conditions, but slight differences in distribution were observed.

First half of the active work zone: For the first half of the active work zone, the comparison between construction with and without blue lights, which included the data from the blue columns in **Table 89** yielded a p-value of 0.6766, indicating no statistically significant difference. The median speeds were 70 mph with blue lights and 69 mph without blue lights.

Second half of the active work zone: For the second half of the active work zone, the comparison, which included the data from the orange columns in **Table 89** yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 65 mph with blue lights and 66 mph without blue lights.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different between construction with the presence of blue lights and construction without the presence of blue lights for location comparisons during daytime. The post hoc comparisons also provided insights into location-specific differences, showing that the effect of blue lights was evident at the beginning of the work zone and the second half of the active work zone, while no significant difference appeared in the first half of the active zone.

In **Figure 93**, the density plot shows overlapping peaks but with subtle shifts for the beginning of the work zone. Construction without the presence of blue lights displayed a slightly sharper peak at higher speeds, while construction with the presence of blue lights spread more evenly, extending toward lower speeds. This indicated that blue lights encouraged small speed reductions when drivers entered the work zone.

In **Figure 94**, the difference was greater for the second half of the work zone. Construction without the presence of blue lights was tightly clustered around higher speeds, while construction with the presence of blue lights shifted toward lower values, producing a wider spread. This highlighted that drivers reduced their speeds more noticeably near the end of the work zone when blue lights were present.

Overall, the results suggested that construction with the presence of blue lights influenced speed behavior primarily at the beginning of the work zone and the second half of the active work zone. The absence of significant change in the first half of the active work zone indicated that drivers may have already adapted their speeds after entry, with additional adjustments emerging as they approached the work zone exit.

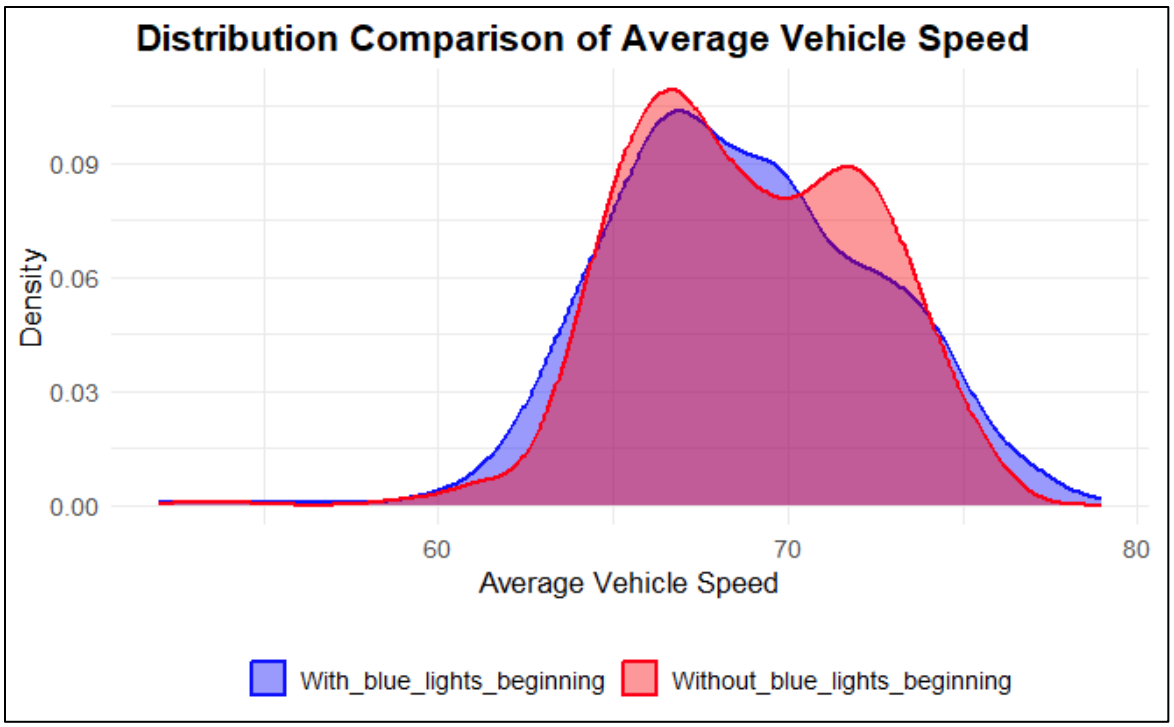


Figure 93. Average vehicle speed distribution for the beginning of the work zone

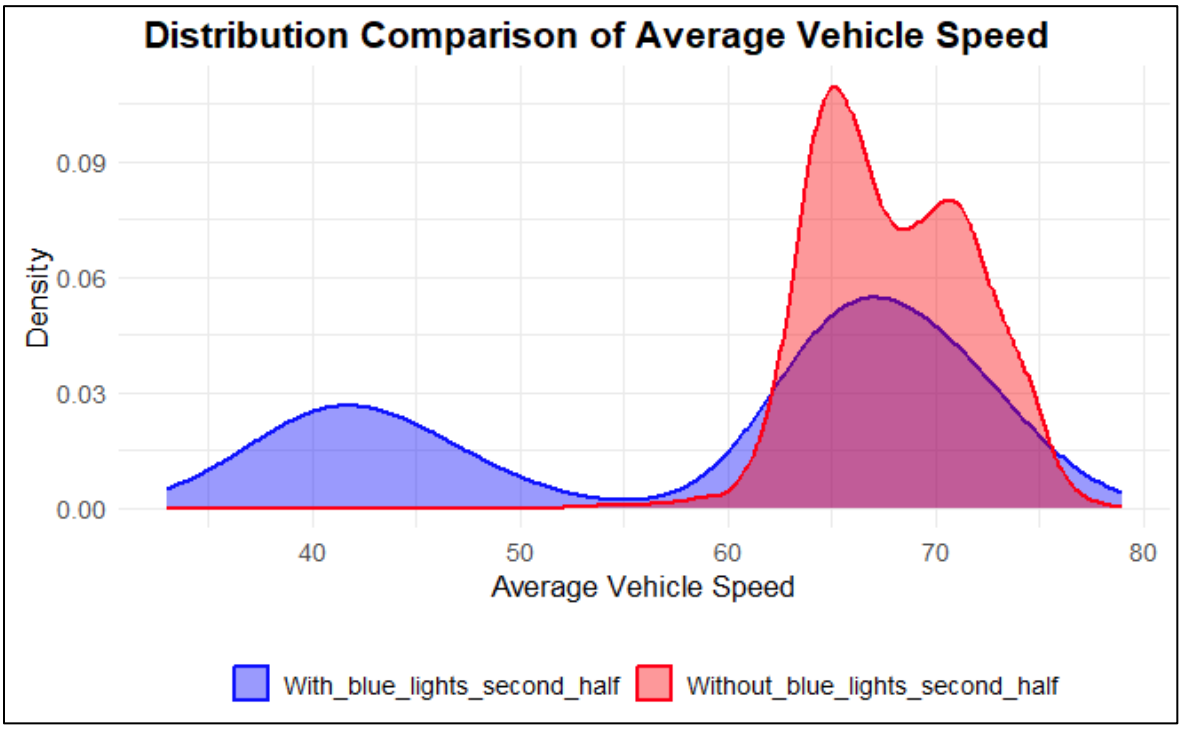


Figure 94. Average vehicle speed distribution for the second half of the active work zone

6.13.5 Hypothesis 5: Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Work Zone Locations (Beginning of the Work Zone vs. First Half of the Active Work Zone vs. Second Half of the Active Work Zone)

This analysis evaluated whether vehicle speeds differed during nighttime construction with and without blue lights for three specific work zone locations: the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone. The null and alternative hypotheses are as follows:

***H_0**: There is no significant difference in the average vehicle speed during the nighttime in the presence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

***H_1**: There is a significant difference in the average vehicle speed during the nighttime in the presence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

Data Collected: For this hypothesis, vehicle speed data during nighttime construction with and without blue lights were categorized into six conditions:

- **With Blue Light Beginning (WB_Beg)** - Construction with the presence of blue lights at the beginning of the work zone, 8064 observations
- **Without Blue Light Beginning (WOB_Beg)** - Construction without the presence of blue lights at the beginning of the work zone, 576 observations
- **With Blue Light First Half (WB_1stH)** - Construction with the presence of blue lights in the first half of the active work zone, 8064 observations
- **Without Blue Light First Half (WB_1stH)** - Construction without the presence of blue lights in the first half of the active work zone, 576 observations
- **With Blue Light Second Half (WB_2ndH)** - Construction with the presence of blue lights in the second half of the active work zone, 8064 observations
- **Without Blue Light Second Half (WB_2ndH)** - Construction without the presence of blue lights in the second half of the active work zone, 576 observations

An illustration of the dataset is depicted in **Table 91**.

Table 91. Data points for nighttime average vehicle speed differences between construction with the presence of blue lights and construction without the presence of blue lights for individual work zone locations

WB_Beg (mph)	WOB_Beg (mph)	WB_1stH (mph)	WOB_1stH (mph)	WB_2ndH (mph)	WOB_2ndH (mph)
45	47	40	55	67	52
38	33	37	31	28	47
X	X	X	X	X	X
X	X	X	X	X	X
X	X	X	X	X	X
41	44	25	17	34	64

Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Methods: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value close to 0, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it can be concluded that there was a statistically significant difference in average vehicle speed between construction with the presence of blue lights and construction without the presence of blue lights for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone during nighttime. The results from the post hoc pairwise comparisons are presented in **Table 92.**

Table 92. Post hoc pairwise comparison results

Comparison	p-value
WB_Beg - WOB_Beg	<.0001
WB_1stH - WOB_1stH	<.0001
WB_2ndH - WOB_2ndH	<.0001

Post Hoc Pairwise Comparisons:

Beginning of the work zone: The comparison between construction with and without blue lights, which included the data from the green columns in **Table 91** yielded a p-value of <0.0001. The median speed was 66 mph with blue lights and 67 mph without blue lights.

First half of the active work zone: The comparison between construction with and without blue lights, which included the data from the blue columns in **Table 91** yielded a p-value of <0.0001. The median speed was 66 mph with blue lights and 69 mph without blue lights.

Second half of the active work zone: The comparison between construction with and without blue lights, which included the data from the orange columns in **Table 91** yielded a p-value of <0.0001. The median speed was 63 mph with blue lights and 66 mph without blue lights.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different between construction with the presence of blue lights and construction without the presence of blue lights for location comparisons during nighttime. The post hoc comparisons also provided insights into location-specific differences, showing that blue lights influenced speed behavior at the beginning, first half, and second half of the active work zone.

In **Figure 95**, for the beginning of the work zone, construction without the presence of blue lights produced a sharp, narrow peak centered at higher speeds, while construction with the presence of blue lights spread out more broadly and shifted toward lower speeds. This indicated that drivers quickly reduced speed at the entry when blue lights were visible. In **Figure 96**, for the first half of the active work zone, construction without the presence of blue lights remained clustered around higher speeds, while construction with the presence of blue lights showed a broader distribution and greater shift toward lower speeds. This suggested that drivers maintained reduced speeds deeper into the active area. In **Figure 97** for the second half of the active work zone, construction without the presence of blue lights was concentrated at higher speeds, while construction with the presence of blue lights displayed multiple peaks, with clear density toward lower values. This highlighted stronger and sustained reductions in speed near the end of the work zone.

Overall, the results suggested that construction with the presence of blue lights consistently reduced speeds throughout the work zone, with the greatest impact seen at the beginning of the work zone and second half of the active work zone. These findings indicate that blue lights effectively guided drivers to slow down, potentially improving safety conditions in active nighttime construction zones.

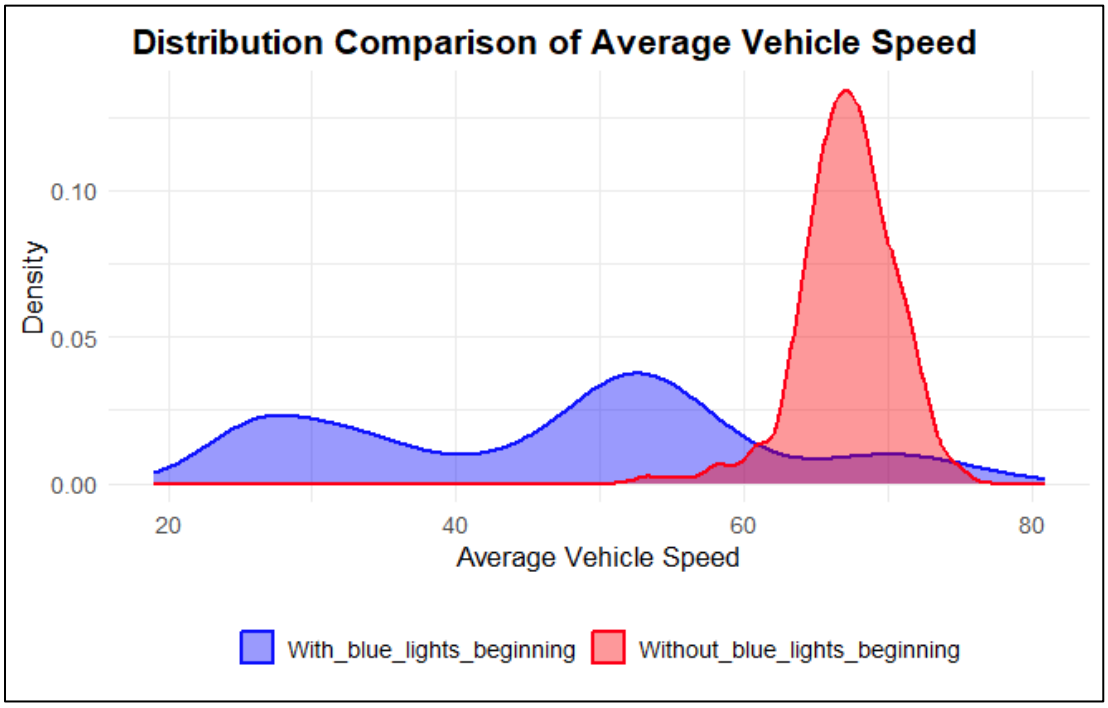


Figure 95. Average vehicle speed distribution for the beginning of the work zone

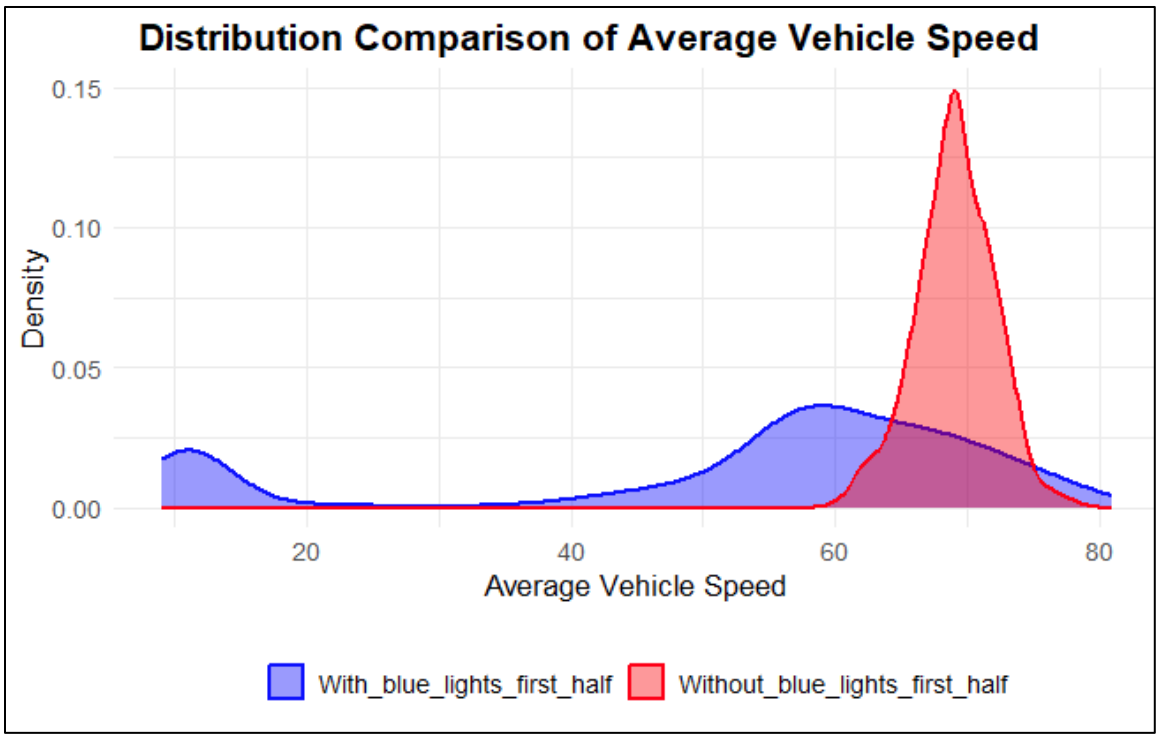


Figure 96. Average vehicle speed distribution for the first half of the active work zone

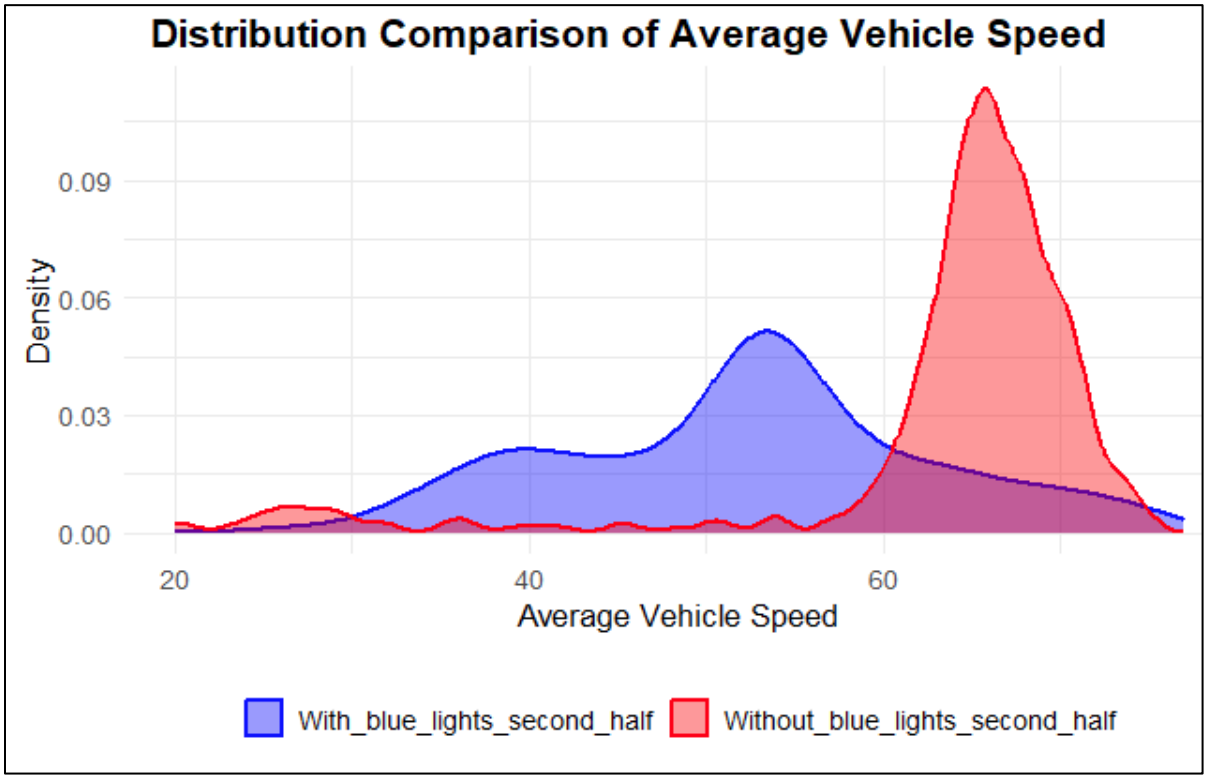


Figure 97. Average vehicle speed distribution for the second half of the active work zone

6.13.6 Hypothesis 6: Lane 1, Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

***H_0**: There is no significant difference in the average vehicle speed within lane 1 between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

***H_1**: There is a significant difference in the average vehicle speed within lane 1 between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

Data Collected: For the analysis, the data were divided into two categories:

- Daytime lane 1 construction with the presence of blue lights - 1296 observations
- Daytime lane 1 construction without the presence of blue lights - 2880 observations

An illustration of the dataset is depicted in **Table 93**.

Table 93. Data points for average vehicle speed for construction with the presence of blue lights vs. construction without the presence of blue lights - daytime, lane 1

Average Vehicle Speed for Construction with the Presence of Blue Lights (mph)	Average Vehicle Speed for Construction without the Presence of Blue Lights (mph)
75	65
81	44
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test yielded a p-value of 0.8814, which was greater than the significance level ($\alpha = 0.05$). Therefore, there was insufficient evidence to reject the null hypothesis. This indicated that there was no statistically significant difference in average vehicle speed within Lane 1 between construction with the presence of blue lights and construction without the presence of blue lights during the daytime. According to the descriptive statistics, the median average vehicle speed was 71 mph during construction with the presence of blue lights and 70 mph during construction without the presence of blue lights.

6.13.7 Hypothesis 7: Lane 2, Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

***H_0**: There is no significant difference in the average vehicle speed within lane 2 between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

***H_1**: There is a significant difference in the average vehicle speed within lane 2 between construction with the presence of blue lights and construction without the presence of blue lights during the daytime.*

Data Collected: For the analysis, the data were divided into two categories:

- Daytime lane 2 construction with the presence of blue lights - 1296 observations
- Daytime lane 2 construction without the presence of blue lights - 2880 observations

An illustration of the dataset is depicted in **Table 94**.

Table 94. Data points for average vehicle speed for construction with the presence of blue lights vs. construction without the presence of blue lights - daytime, lane 2

Average Vehicle Speed for Construction with the Presence of Blue Lights (mph)	Average Vehicle Speed for Construction without the Presence of Blue Lights (mph)
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test yielded a p-value of less than 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed within Lane 2 between construction with the presence of blue lights and construction without the presence of blue lights during the daytime. According to the descriptive statistics, the median average vehicle speed was 66 mph for both conditions. Although the medians were the same, the density plot in **Figure 98** illustrated subtle distributional differences. Speeds during construction without the presence of blue lights showed a sharper, more concentrated peak, while construction with the presence of blue lights displayed a slightly broader spread. This supported the statistical results and suggested that the significance might have been driven by minor shifts in the distribution rather than meaningful changes in central tendency, indicating that blue lights might had minimal influence on daytime speeds in Lane 2.

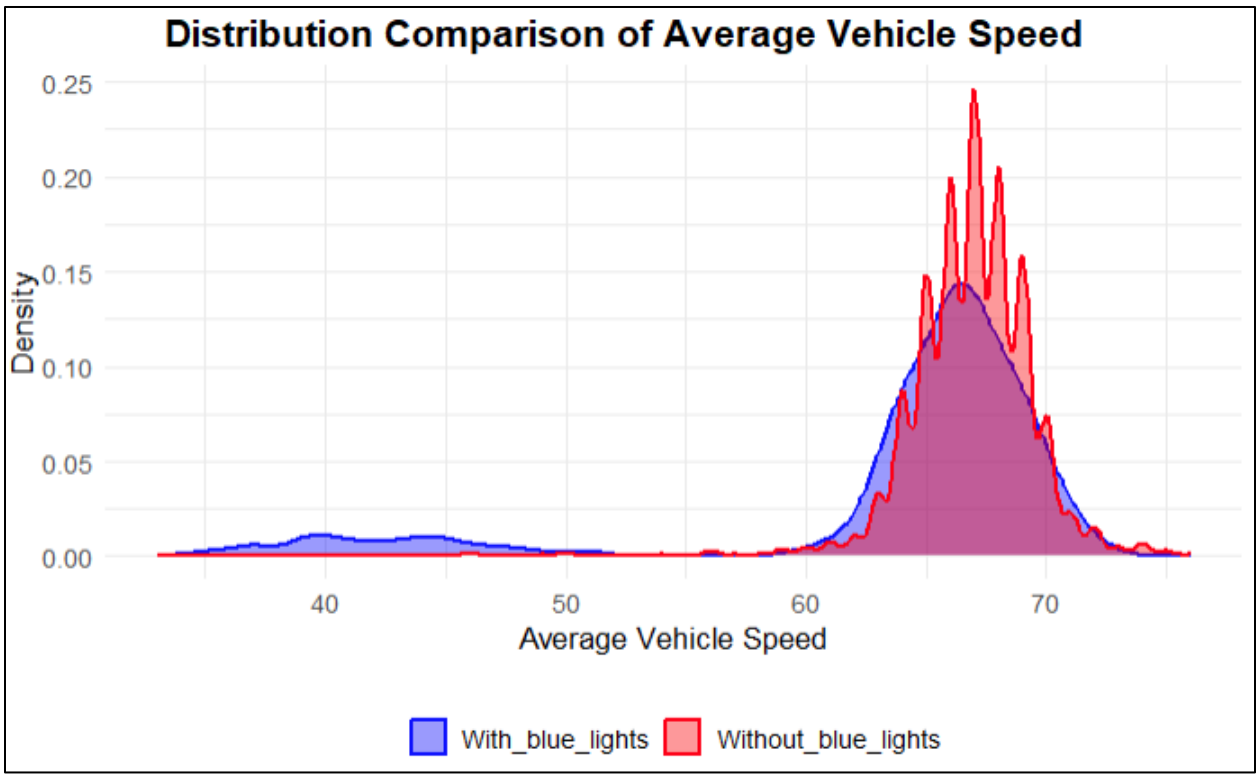


Figure 98. Average vehicle speed distribution with and without blue lights

6.13.8 Hypothesis 8: Lane 1, Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

***H_0**: There is no significant difference in the average vehicle speed within lane 1 between construction with the presence of blue lights and construction without the presence of blue lights during the nighttime.*

***H_1**: There is a significant difference in the average vehicle speed within lane 1 between construction with the presence of blue lights and construction without the presence of blue lights during the nighttime.*

Data Collected: For the analysis, the data were divided into two categories:

- Nighttime lane 1 construction with the presence of blue lights - 12096 observations
- Nighttime lane 1 construction without the presence of blue lights - 864 observations

An illustration of the dataset is depicted in **Table 95**.

Table 95. Data points for average vehicle speeds for construction with the presence of blue lights vs. construction without the presence of blue lights - nighttime, lane 1

Average Vehicle Speed for Construction with the Presence of Blue Lights (mph)	Average Vehicle Speed for Construction without the Presence of Blue Lights (mph)
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test yielded a p-value of less than 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed within Lane 1 between construction with the presence of blue lights and construction without the presence of blue lights during nighttime. According to the descriptive statistics, the median average vehicle speed was 66 mph during construction with the presence of blue lights and 69 mph during construction without the presence of blue lights. The IQR was 14 for construction with the presence of blue lights and 4 for construction without the presence of blue lights, indicating greater variability when blue lights were used. The density plot in **Figure 99** illustrates that speeds without the presence of blue lights were concentrated around higher values, while speeds with the presence of blue lights showed a broader distribution and extended further toward lower ranges. This supported the statistical results and suggested that blue lights might have contributed to reducing and dispersing speeds during nighttime on Lane 1.

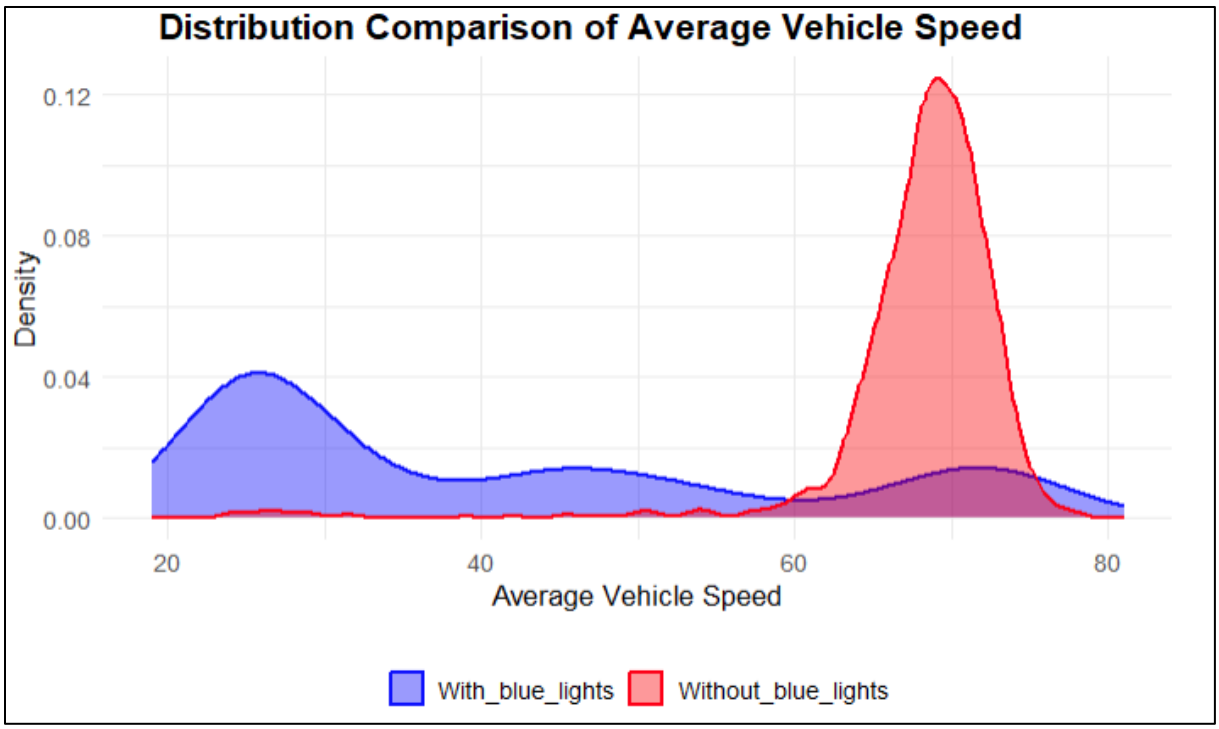


Figure 99. Average vehicle speed distribution with and without blue lights

6.13.9 Hypothesis 9: Lane 2, Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights

This analysis examines whether vehicle speed differs between ongoing construction with blue lights and ongoing construction without blue lights in lane 2 during the nighttime. The null and alternative hypotheses for this test are as follows:

***H_0**: There is no significant difference in the average vehicle speed within lane 2 between construction with the presence of blue lights and construction without the presence of blue lights during the nighttime.*

***H_1**: There is a significant difference in the average vehicle speed within lane 2 between construction with the presence of blue lights and construction without the presence of blue lights during the nighttime.*

Data Collected: For the analysis, the data were divided into two categories:

- Nighttime lane 2 construction with the presence of blue lights - 12096 observations
- Nighttime lane 2 construction without the presence of blue lights - 864 observations

An illustration of the dataset is depicted in **Table 96**.

Table 96. Data points for the average vehicle speed for construction with the presence of blue lights vs. construction without the presence of blue lights - nighttime, lane 2

Average Vehicle Speed for Construction with the Presence of Blue Lights (mph)	Average Vehicle Speed for Construction without the Presence of Blue Lights (mph)
75	65
81	44
X	X
X	X
58	17
Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.	

Analysis Methods: Mann-Whitney U test

Analysis Results: The Mann-Whitney U test yielded a p-value of less than 2.2e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed within Lane 2 between construction with the presence of blue lights and construction without the presence of blue lights during nighttime. According to the descriptive statistics, the median average vehicle speed was 64 mph during construction with the presence of blue lights and 66 mph during construction without the presence of blue lights. The IQR was 7 for construction with the presence of blue lights and 4 for construction without the presence of blue lights, suggesting that speeds were slightly more variable under the blue light condition. Although the medians were close, the density plot in **Figure 100** illustrates that speeds without the presence of blue lights were concentrated around higher values, while speeds with the presence of blue lights showed a broader distribution and extended further toward lower ranges. This supported the statistical results and suggested that blue lights might have contributed to lowering and dispersing speeds during nighttime in Lane 2.

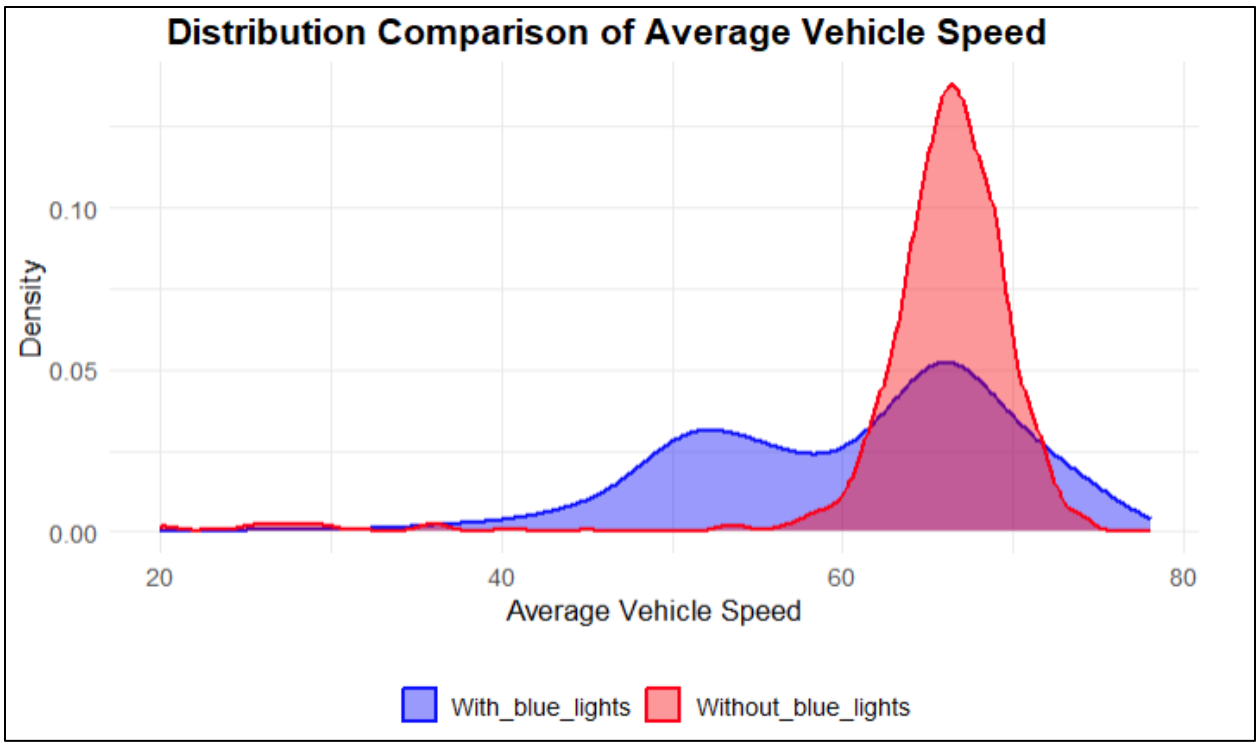


Figure 100. Average vehicle speed distribution with and without blue lights

6.13.10 Hypothesis 10: Daytime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Lanes for Individual Work Zone Locations

This analysis compared vehicle speed during the daytime between lane 1 and lane 2 for construction with blue lights and construction without blue lights for individual work zone locations. The analysis spanned three work zone locations-the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone-and two lanes: lane 1 and lane 2. The null and alternative hypotheses are as follows:

***H_0**: There is no significant difference in average vehicle speed during the daytime for individual lanes in the presence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

***H_1**: There is a significant difference in average vehicle speed during the daytime for individual lanes in the presence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

Data Collected: For hypothesis testing, the average vehicle speed data during the daytime were categorized into the following conditions:

- **Lane 1 With Blue Lights Beginning (L1_WB_Beg)** - Lane 1, construction with the presence of blue lights at the beginning of the work zone, 432 observations
- **Lane 1 Without Blue Lights Beginning (L1_WOB_Beg)** - Lane 1, construction without the presence of blue lights at the beginning of the work zone, 960 observations
- **Lane 1 With Blue Light First Half (L1_WB_1stH)** - Lane 1, construction with the presence of blue lights at the first half of the active work zone, 432 observations
- **Lane 1 Without Blue Light First Half (L1_WOB_1stH)** - Lane 1, construction without the presence of blue lights at the first half of the active work zone, 960 observations
- **Lane 1 With Blue Light Second Half (L1_WB_2ndH)** - Lane 1, construction with the presence of blue lights at the second half of the active work zone, 432 observations
- **Lane 1 Without Blue Light Second Half (L1_WOB_2ndH)** - Lane 1, construction without the presence of blue lights at the second half of the active work zone, 960 observations
- **Lane 2 With Blue Lights Beginning (L2_WB_Beg)** - Lane 2, construction with the presence of blue lights at the beginning of the work zone, 432 observations
- **Lane 2 With Blue Lights Beginning (L2_WOB_Beg)** - Lane 2, construction without the presence of blue lights at the beginning of the work zone, 960 observations
- **Lane 2 With Blue Light First Half (L2_WB_1stH)** - Lane 2, construction with the presence of blue lights at the first half of the active work zone, 432 observations
- **Lane 2 With Blue Light First Half (L2_WOB_1stH)** - Lane 2, construction without the presence of blue lights at the first half of the active work zone, 960 observations
- **Lane 2 With Blue Light Second Half (L2_WB_2ndH)** - Lane 2, construction with the presence of blue lights at the second half of the active work zone, 432 observations
- **Lane 2 Without Blue Light Second Half (L2_WOB_2ndH)** - Lane 2, construction without the presence of blue lights at the second half of the active work zone, 960 observations

An illustration of the dataset is depicted in **Table 97**.

Table 97. Data points for daytime average vehicle speed differences between construction with the presence of blue lights and construction without the presence of blue lights for individual lanes for individual work zone locations

L1_WB_ Beg (mph)	L1_ WOB_Beg (mph)	L1_WB_ 1stH (mph)	L1_ WOB_ 1stH (mph)	L1_WB_ 2ndH (mph)	L1_ WOB_ 2ndH (mph)	L2_WB_ Beg (mph)	L2_ WOB_Beg (mph)	L2_WB_ 1stH (mph)	L2_ WOB_ 1stH (mph)	L2_WB_ 2ndH (mph)	L2_ WOB_ 2ndH (mph)
22	25	65	87	41	12	23	29	30	35	12	27
42	12	55	62	41	78	32	65	20	11	9	47
X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X
41	53	49	67	23	25	64	11	20	27	30	48

Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of <2.22e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed during the daytime for individual lanes between construction with the presence of blue lights and construction without the presence of blue lights for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone. The results from the post hoc pairwise test are shown in **Table 98**.

Table 98. Post hoc pairwise comparison results

Comparison	p-value
L1_WB_Beg - L1_WOB_Beg	<.0001
L1_WB_1stH - L1_WOB_1stH	1
L1_WB_2ndH - L1_WOB_2ndH	<.0001
L2_WB_Beg - L2_WOB_Beg	1
L2_WB_1stH - L2_WOB_1stH	0.8721
L2_WB_2ndH - L2_WOB_2ndH	1

Post Hoc Pairwise Comparisons:

Lane 1 - Beginning of the Work Zone: The comparison between construction with the presence of blue lights and construction without the presence of blue lights, which included the data from the green columns in **Table 97** yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 71 mph with blue lights and 71 mph without blue lights.

Lane 1 - First Half of the Active Work Zone: The comparison between construction with the presence of blue lights and construction without the presence of blue lights, which included the data from the purple columns in **Table 97** yielded a p-value of 1, indicating no statistically significant difference. The median speed was 72 mph with blue lights and 72 mph without blue lights.

Lane 1 - Second Half of the Active Work Zone: The comparison between construction with the presence of blue lights and construction without the presence of blue lights, which included the data from the light blue columns in **Table 97** yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 68 mph with blue lights and 70 mph without blue lights.

Lane 2 - Beginning of the Work Zone: The comparison between construction with the presence of blue lights and construction without the presence of blue lights, which included the data from the orange columns in **Table 97** yielded a p-value of 1, indicating no statistically significant difference. The median speed was 66 mph with blue lights and 67 mph without blue lights.

Lane 2 - First Half of the Active Work Zone: The comparison between construction with the presence of blue lights and construction without the presence of blue lights, which included the data from the deep blue columns in **Table 97** yielded a p-value of 0.8721, indicating no statistically

significant difference. The median speed was 68 mph with blue lights and 68 mph without blue lights.

Lane 2 - Second Half of the Active Work Zone: The comparison between construction with the presence of blue lights and construction without the presence of blue lights, which included the data from the light red columns in **Table 97** yielded a p-value of 1, indicating no statistically significant difference. The median speed was 64 mph with blue lights and 65 mph without blue lights.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different between construction with the presence of blue lights and construction without the presence of blue lights for lane and location comparisons during daytime. The post hoc comparisons also provided insights into lane-wise differences, showing that the effects appeared in Lane 1 at the beginning and the second half of the work zone, while Lane 2 did not show significant changes.

In **Figure 101**, the density plot shows that construction without the presence of blue lights had a sharper concentration at higher speeds, while construction with the presence of blue lights displayed a wider spread that extended toward lower speeds. This suggested that drivers reduce their speeds when first entering the work zone under blue light conditions.

In **Figure 102**, a similar pattern appears. Construction without the presence of blue lights remained concentrated at higher speeds, while construction with the presence of blue lights shifted toward lower speeds. This indicated that the influence of blue lights continued to affect driver behavior deeper into the work zone.

Overall, the results suggested that construction with the presence of blue lights reduced speeds in Lane 1 at both the beginning and the second half of the work zone, while Lane 2 remained unaffected. This pattern might have occurred because drivers in Lane 1 were closer to observing blue lights and perceived a closer proximity to active construction, which led to a stronger behavioral response. The presence of these speed reductions was sufficient to produce a statistically significant overall ART ANOVA result, even though the effect did not appear for all lane and location combinations. This highlighted that the influence of blue lights was concentrated in the lane adjacent to the active construction area during daytime.

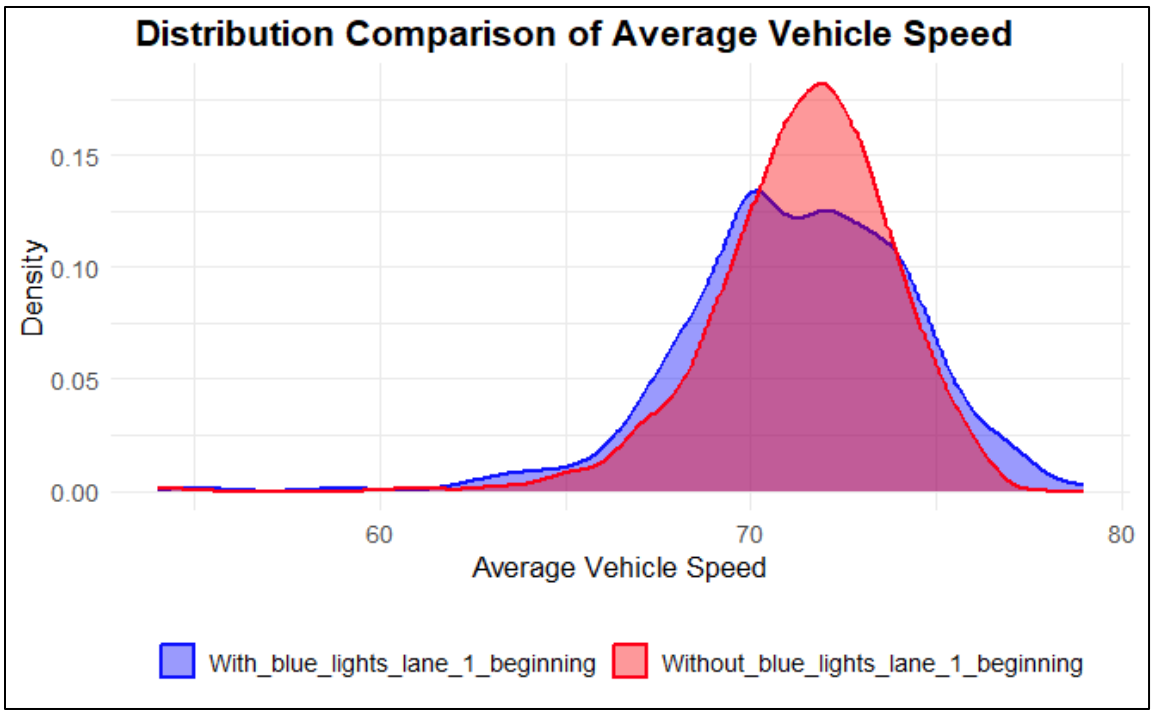


Figure 101. Lane 1 - Beginning of the work zone

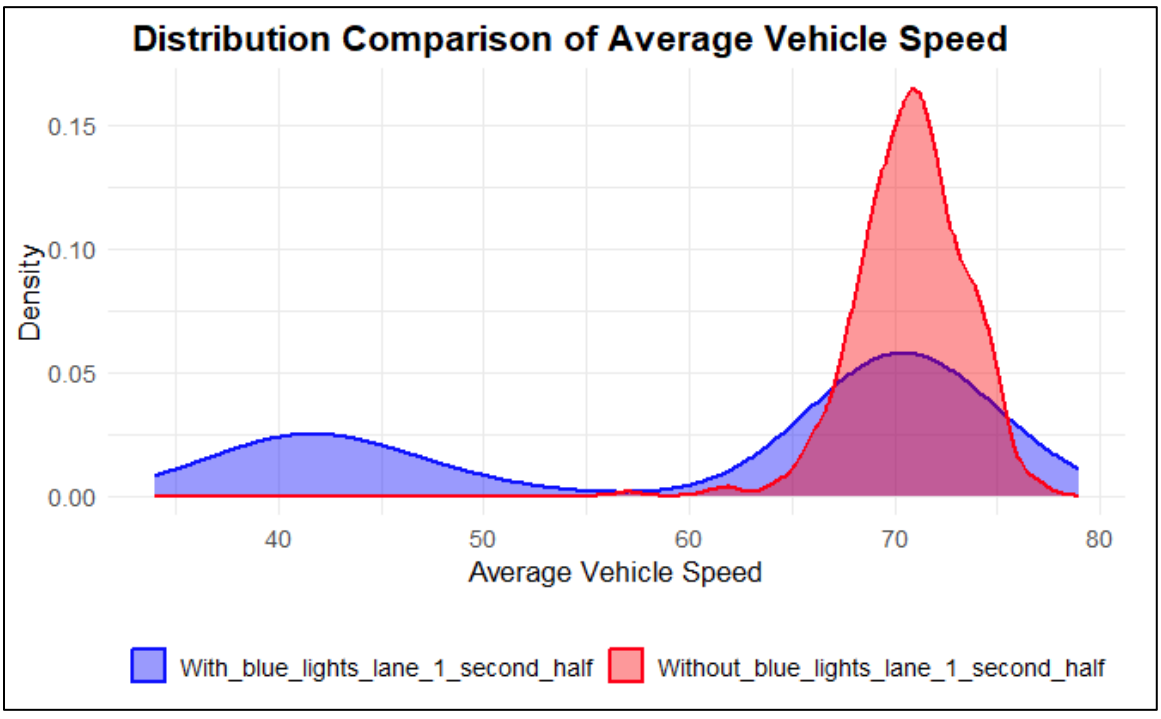


Figure 102. Lane 1 - Second half of the active work zone

6.13.11 Hypothesis 11: Nighttime, Construction with the Presence of Blue Lights vs. Construction without the Presence of Blue Lights for Individual Lanes for Individual Work Zone Locations

This analysis compared vehicle speed during nighttime between lane 1 and lane 2 for construction with blue lights and construction without blue lights for individual work zone locations. The analysis spanned three work zone locations-the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone-and two lanes: lane 1 and lane 2. The null and alternative hypotheses are as follows:

***H_0**: There is no significant difference in the average vehicle speed during the nighttime for individual lanes in the presence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

***H_1**: There is a significant difference in the average vehicle speed during the nighttime for individual lanes in the presence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone compared to the absence of blue lights during construction work for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone.*

Data Collected: For hypothesis testing, the vehicle speed data during nighttime were categorized into the following conditions:

- **Lane 1 With Blue Lights Beginning (L1_WB_Beg)** - Lane 1, construction with the presence of blue lights at the beginning of the work zone, 4032 observations
- **Lane 1 Without Blue Lights Beginning (L1_WOB_Beg)** - Lane 1, construction without the presence of blue lights at the beginning of the work zone, 288 observations
- **Lane 1 With Blue Light First Half (L1_WB_1stH)** - Lane 1, construction with the presence of blue lights at the first half of the active work zone, 4032 observations
- **Lane 1 Without Blue Light First Half (L1_WOB_1stH)** - Lane 1, construction without the presence of blue lights at the first half of the active work zone, 288 observations
- **Lane 1 With Blue Light Second Half (L1_WB_2ndH)** - Lane 1, construction with the presence of blue lights at the second half of the active work zone, 4032 observations
- **Lane 1 Without Blue Light Second Half (L1_WOB_2ndH)** - Lane 1, construction without the presence of blue lights at the second half of the active work zone, 288 observations
- **Lane 2 With Blue Lights Beginning (L2_WB_Beg)** - Lane 2, construction with the presence of blue lights at the beginning of the work zone, 4032 observations
- **Lane 2 With Blue Lights Beginning (L2_WOB_Beg)** - Lane 2, construction without the presence of blue lights at the beginning of the work zone, 288 observations
- **Lane 2 With Blue Light First Half (L2_WB_1stH)** - Lane 2, construction with the presence of blue lights at the first half of the active work zone, 4032 observations

- **Lane 2 With Blue Light First Half (L2_WOB_1stH)** - Lane 2, construction without the presence of blue lights at the first half of the active work zone, 288 observations
- **Lane 2 With Blue Light Second Half (L2_WB_2ndH)** - Lane 2, construction with the presence of blue lights at the second half of the active work zone, 4032 observations
- **Lane 2 Without Blue Light Second Half (L2_WOB_2ndH)** - Lane 2, construction without the presence of blue lights at the second half of the active work zone, 288 observations

An illustration of the dataset is depicted in **Table 99**.

Table 99. Data points for nighttime average vehicle speed differences between construction with the presence of blue lights and construction without the presence of blue lights for individual lanes for individual work zone locations

L1_WB_ Beg (mph)	L1_ WOB_Beg (mph)	L1_WB_ 1stH (mph)	L1_ WOB_ 1stH (mph)	L1_WB_ 2ndH (mph)	L1_ WOB_ 2ndH (mph)	L2_WB_ Beg (mph)	L2_ WOB_Beg (mph)	L2_WB _1stH (mph)	L2_ WOB_ 1stH (mph)	L2_WB_ 2ndH (mph)	L2_ WOB_ 2ndH (mph)
22	25	65	87	41	12	23	29	30	35	12	27
42	12	55	62	41	78	32	65	20	11	9	47
X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X
41	53	49	67	23	25	64	11	20	27	30	48

Note: The 'X' marks in the table represent similar data points of the same type (average vehicle speed). These placeholders indicate that the dataset includes additional values consistent with the displayed pattern.

Analysis Strategy: ART ANOVA test with post hoc pairwise comparisons.

Analysis Results: The overall ART ANOVA test yielded a p-value of <2.22e-16, which was smaller than the significance level ($\alpha = 0.05$). This provided sufficient evidence to reject the null hypothesis. Therefore, it was concluded that there was a statistically significant difference in average vehicle speed during nighttime for individual lanes between construction with the presence of blue lights and construction without the presence of blue lights for the beginning of the work zone, the first half of the active work zone, and the second half of the active work zone. The results from the post hoc pairwise test are shown in **Table 100**.

Table 100. Post hoc pairwise comparison results

Comparison	p-value
L1_WB_Beg - L1_WOB_Beg	<.0001
L1_WB_1stH - L1_WOB_1stH	<.0001
L1_WB_2ndH - L1_WOB_2ndH	<.0001
L2_WB_Beg - L2_WOB_Beg	0.6944
L2_WB_1stH - L2_WOB_1stH	<.0001
L2_WB_2ndH - L2_WOB_2ndH	<.0001

Post Hoc Pairwise Comparisons:

Lane 1 - Beginning of the Work Zone: The comparison between construction with the presence of blue lights and construction without the presence of blue lights, which included the data from the green columns in **Table 99** yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 66 mph with blue lights and 69 mph without blue lights.

Lane 1 - First Half of the Active Work Zone: The comparison between construction with the presence of blue lights and construction without the presence of blue lights, which included the data from the purple columns in **Table 99** yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 68 mph with blue lights and 70 mph without blue lights.

Lane 1 - Second Half of the Active Work Zone: The comparison between construction with the presence of blue lights and construction without the presence of blue lights, which included the data from the light blue columns in **Table 99** yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 64 mph with blue lights and 67 mph without blue lights.

Lane 2 - Beginning of the Work Zone: The comparison between construction with the presence of blue lights and construction without the presence of blue lights, which included the data from the orange columns in **Table 99** yielded a p-value of 0.6944, indicating no statistically significant difference. The median speed was 66 mph with blue lights and 66 mph without blue lights.

Lane 2 - First Half of the Active Work Zone: The comparison between construction with the presence of blue lights and construction without the presence of blue lights, which included the

data from the deep blue columns in **Table 99** yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 64 mph with blue lights and 68 mph without blue lights.

Lane 2 - Second Half of the Active Work Zone: The comparison between construction with the presence of blue lights and construction without the presence of blue lights, which included the data from the light red columns in **Table 99** yielded a p-value of <0.0001, suggesting a significant difference. The median speed was 62 mph with blue lights and 65 mph without blue lights.

Discussion: The ART ANOVA results confirmed that average vehicle speeds were significantly different between construction with the presence of blue lights and construction without the presence of blue lights for lane and location comparisons during nighttime. The post hoc comparisons also provided lane-wise insights, showing consistent reductions in Lane 1 for all three locations and more selective effects in Lane 2, especially in the active segments.

Figure 103 illustrates that construction without the presence of blue lights produced a sharper peak at higher speeds, while construction with the presence of blue lights displayed a wider spread that extended toward lower speeds. This showed that drivers began reducing their speeds when entering the work zone under blue light conditions. In **Figure 104**, the separation becomes clearer. Construction without the presence of blue lights remained clustered around higher speeds, while construction with the presence of blue lights shifted downward. This suggested that the influence of blue lights reinforced speed reductions deeper into the active zone. **Figure 105** also illustrates a strong difference. Construction without the presence of blue lights peaked at higher levels, while construction with the presence of blue lights shifted prominently toward lower speeds. This indicated stronger compliance with reduced speeds near the exit of the active zone under blue light conditions. In **Figure 106**, the difference also appears noticeable. Construction with the presence of blue lights produced a slightly flatter and wider distribution, while construction without the presence of blue lights maintained a sharper peak at higher speeds. This suggested that blue lights encouraged reductions in Lane 2 speeds near the active zone. In **Figure 107**, the separation becomes stronger. Construction without the presence of blue lights remained narrowly concentrated at higher speeds, while construction with the presence of blue lights extended toward lower speeds. This indicated that drivers in Lane 2 also adjusted their speeds as they moved closer to the work zone exit.

Overall, the results suggested that the impact of blue lights was most consistent in Lane 1, where drivers steadily reduced their speeds throughout the work zone. Lane 2 showed smaller but significant reductions in the active segments, highlighting that the presence of blue lights influenced driver caution even in the farther lane from the work zone during nighttime conditions.

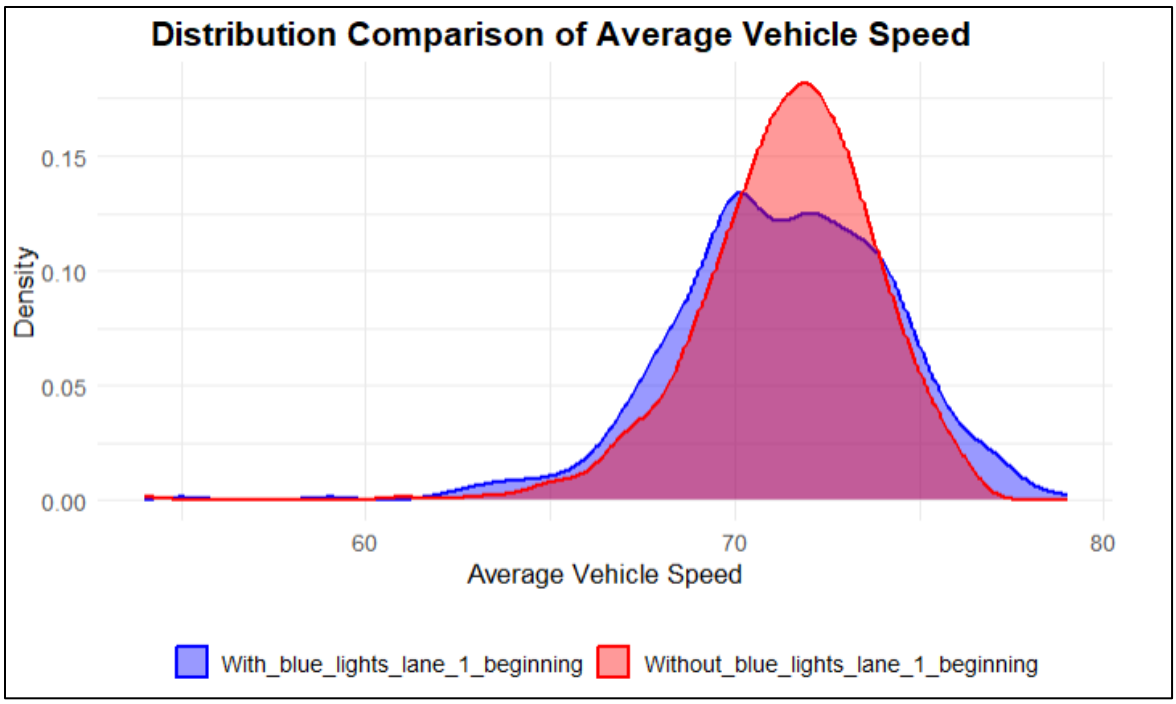


Figure 103. Lane 1 - Beginning of the work zone

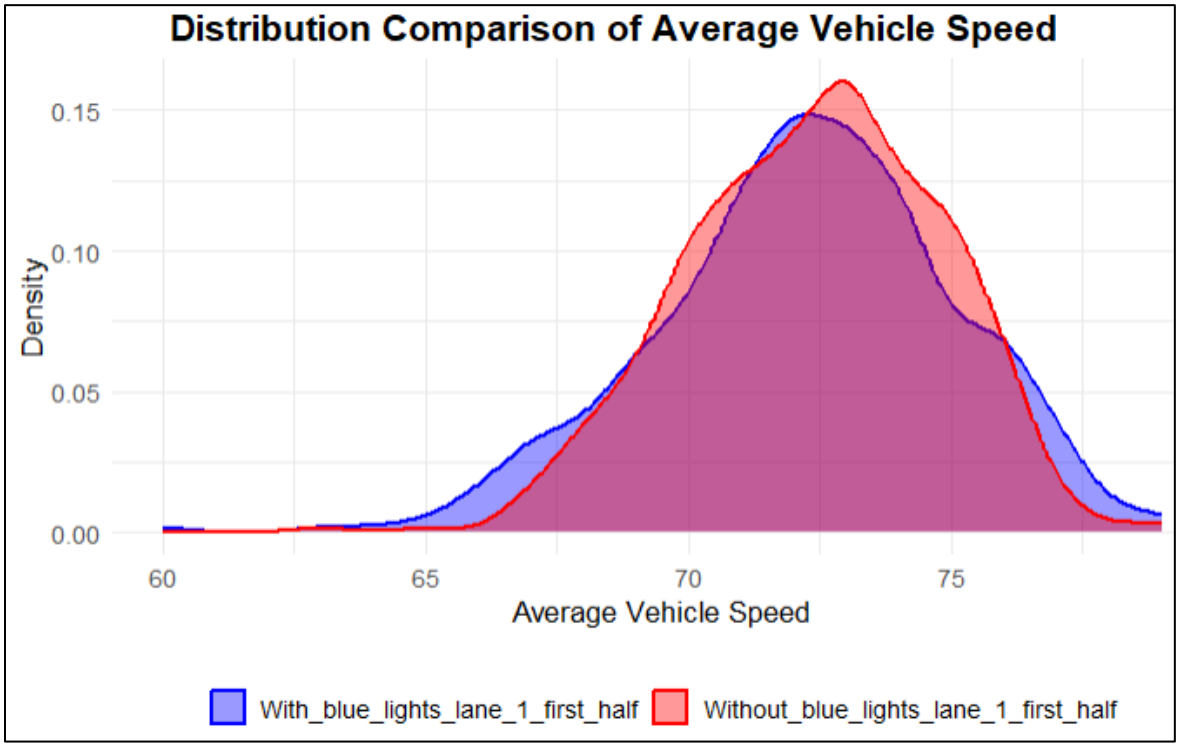


Figure 104. Lane 1 - First half of the active work zone

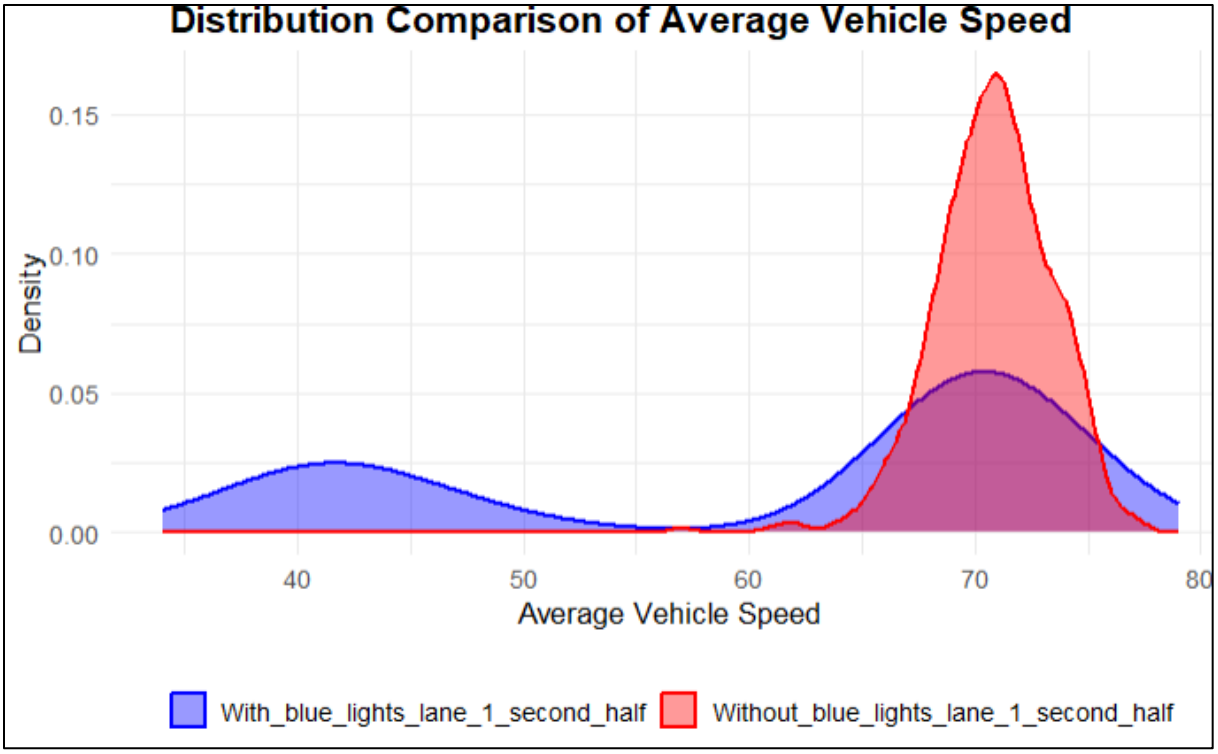


Figure 105. Lane 1 - Second half of the active work zone

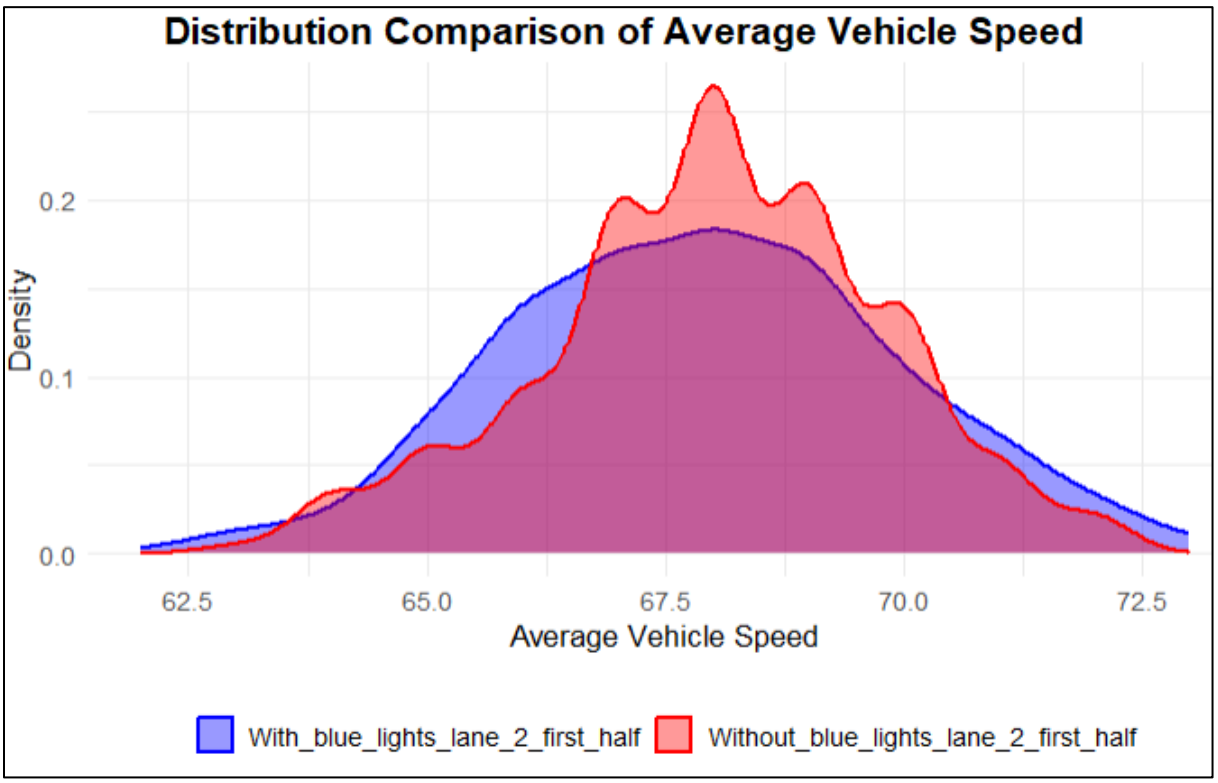


Figure 106. Lane 2 - First half of the active work zone

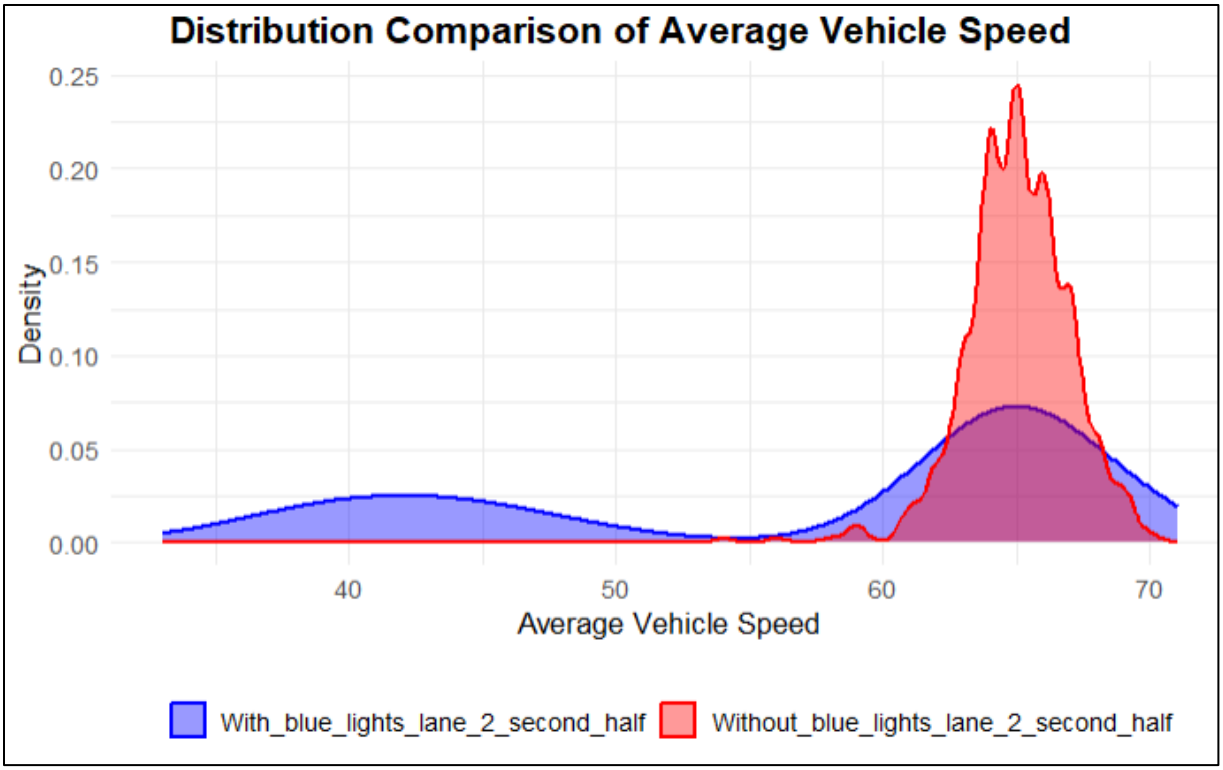


Figure 107. Lane 2 - Second half of the active work zone

6.13.12 Summary of Category Two: Comparative Analysis of Average Vehicle Speed Between Construction in the Presence of Blue Lights and Construction in the Absence of Blue Lights

This section provides a comprehensive summary based on the hypothesis tests conducted in this category and the insights gained from them.

6.13.12.1 Overall Average Vehicle Speed with and without the Presence of Blue Lights (Hypothesis 1-Hypothesis 3)

The hypothesis tests (Hypothesis 1-Hypothesis 3) showed that construction with the presence of blue lights was associated with lower average vehicle speeds compared to construction without the presence of blue lights. When separated by time of day, daytime differences were limited, indicating that the influence of blue lights on speed reduction during daytime was relatively small. At nighttime, clearer differences were observed, as vehicle speeds under construction with the presence of blue lights were lower compared to construction without the presence of blue lights. This indicated stronger speed reductions when blue lights were more visible during nighttime conditions.

6.13.12.2 Average Vehicle Speed at Individual Work Zone Locations with and without the Presence of Blue Lights (Hypothesis 4-Hypothesis 5)

The hypothesis tests (Hypothesis 4-Hypothesis 5) examining work zone locations showed that the influence of blue lights varied by time of day. During daytime conditions, speed reductions in the presence of blue lights were most evident at the beginning of the work zone and in the second half of the active work zone, while little difference was observed in the first half of the active work

zone. During nighttime conditions, lower vehicle speeds in the presence of blue lights were observed for all work zone locations, although the amount of the speed reduction varied by location.

6.13.12.3 Lane-based Average Vehicle Speed with and without the Presence of Blue Lights (Hypothesis 6-Hypothesis 9)

The hypothesis tests (Hypothesis 6-Hypothesis 9) on lane-based speed behavior showed limited differences between construction with and without the presence of blue lights during daytime conditions. Lane 1 did not show a statistically significant difference, while Lane 2 showed a statistically significant difference with only minor distributional changes. At nighttime, construction with the presence of blue lights was associated with lower speeds in both lanes, with the effect being more significant in Lane 1. These findings indicated stronger nighttime responses to the presence of blue lights in the lane closer to construction activity.

6.13.12.4 Lane-based Average Vehicle Speed for Individual Work Zone Locations with and without the Presence of Blue Lights (Hypothesis 10-Hypothesis 11)

The hypothesis tests (Hypothesis 10-Hypothesis 11), combining lane and location effects, showed that during daytime conditions, the influence of blue lights was mainly in Lane 1, particularly at the beginning of the work zone and in the second half of the active work zone. Lane 2 showed minimal differences for the individual work zone locations during daytime conditions. During nighttime conditions, lower speeds in the presence of blue lights were observed in Lane 1 for all work zone locations, while Lane 2 showed speed reductions mainly within the active work zone segments.

6.13.12.5 Insights from the Analysis

The findings indicated that the presence of blue lights influenced average vehicle speed, with limited effects during daytime conditions and stronger reductions during nighttime conditions. Speed behavior was further shaped by work zone location and lane use, with effects observed in specific work zone segments during daytime, and more consistent speed reductions throughout the work zone during nighttime conditions once drivers encountered the blue lights. Lane-level results indicated that the strongest speed adjustments occurred in Lane 1, the lane closer to construction activity, while Lane 2 showed smaller but noticeable reductions within the active work zone segments during nighttime conditions. Overall, this category demonstrated that blue lights may have served as a visual signal that encouraged earlier driver awareness and more consistent speed reductions, particularly under nighttime conditions.

Chapter 7. Discussion

This project contributes to investigating the practices and initiatives for effective blue light implementation for work zone safety. To comprehend the "Blue Light Law" legislated by the state of Mississippi, this project was conducted through a systematic literature review, a meticulously designed survey from the results of the literature review, and field data collection and analysis to evaluate the effectiveness of blue light implementation in work zones.

The discussion section is structured around three main components of the project: the systematic literature review, the survey results, and the field data analysis. Each component provided the perspectives and insights on the role of blue lights in work zone safety. The literature review highlighted prior research and theoretical foundations, the survey captured practitioner experiences and perceptions, and the field data analysis offered real-world behavioral insights. These parts provided a comprehensive understanding of how blue lights might influence and contribute to work zone safety.

7.1 Discussion of Systematic Literature Review

The literature review indicates that blue lights are mainly used for law enforcement due to varying state regulations on warning lights. State DOTs, including those in Texas, Florida, and Oregon, have conducted studies on blue light usage in work zones, suggesting an emerging interest in this area. Therefore, this project can meaningfully contribute to understanding and implementing blue lights for work zone safety. The literature analysis also categorized results on installation platforms, light location, and driver behavior, offering a quick overview of warning light implementation practices. It was found that blue lights helped drivers recognize work zones and encouraged speed reduction and lane changes. This information is highly beneficial for deploying blue lights as warning lights in work zones. Moreover, the findings from multiple state DOT studies supported the theoretical foundation for using blue lights in work zones by linking them to improvements in driver attention, speed compliance, and risk perception. The Florida DOT observed that stationary police vehicles with flashing blue lights led to a significant reduction in the percentage of speeding drivers within work zones, reinforcing the role of visibility and perceived enforcement in influencing behavior (Gan et al., 2018). The Ohio DOT emphasized that drivers were most responsive when they perceived a higher level of risk, and that highly visible elements such as sequential flashing lights and enforcement presence (often mimicked by blue lights) were among the most effective speed-reduction tools (Sommers & McAvoy, 2013). The Oregon DOT found that adding blue lights to construction equipment consistently prompted earlier and greater slowing in advance of work zones, especially in the taper area, aligning with theories on visual notice and driver expectancy (Gambatese et al., 2019). Meanwhile, these findings highlighted that the effectiveness of blue lights in work zones is supported by established human factors principles, including visibility and psychology, which help explain their impact on driver behavior and potential to improve work zone safety outcomes.

Overall, the literature review findings support the potential of blue lights for safety enhancement and identify that blue lights are currently not fully utilized relative to their perceived benefits.

Moreover, there is limited censure in the existing literature regarding the detailed use of blue lights for work zone safety, which further supports the case for expanded exploration and adoption.

7.2 Discussion of Survey Analysis Results

The survey results suggested practical insights into how blue lights might be implemented for work zone safety (Assafi et al., 2025). The survey focused on categories including demographics, current progress at the organizational level, reaction to blue lights, light deployment, effectiveness, and configuration. A structured overview of the survey findings is presented in **Table 101**, which summarizes the responses by category and highlights their insights for practitioners and researchers. Participants primarily included professionals from relevant backgrounds, ensuring responses aligned closely with current blue light scenarios. Additionally, the survey yielded suggestions from these professionals beyond those explicitly asked in the questionnaire. This can serve as a resource for designing future studies on blue light usage for work zone safety. The survey results indicated that organizational progress concerning blue light usage is currently marginal, encompassing research, regulations, and guidelines. Advancing research and establishing comprehensive rules and regulations for blue light usage can mark an initial step forward. Furthermore, participants showed greater attentiveness in work zones with blue lights on police vehicles compared to other applications. Therefore, integrating blue lights with police vehicles when deploying them for work zone safety could enhance effectiveness. The survey also provided insights into the optimal location and configuration of blue light installations. Most respondents preferred placing blue lights at the beginning of work zones, and they found the visor lighting style most effective for motorists. These findings are crucial for informing policies on blue light implementation. While some respondents noted adverse effects, most considered blue lights non-distracting within work zones. This suggests that implementing blue lights for work zone safety is viable, as participants generally accept them as standard warning sign configuration. The survey also identified operational challenges for implementing blue light for work zone safety, such as limited organizational policies, a lack of regulations, and communication gaps between law enforcement and construction teams. Overall, the results from the survey highlight the strong potential of implementing blue light for improving work zone safety, but more future efforts are needed to provide decision-makers with a clearer trajectory from a policy or operational standpoint.

Table 101. Summary of the survey findings and insights

Survey Category	Key Findings	Insights/Implications
1. General Demographics	57% of respondents were from the South of the U.S.; 90% worked in state DOTs.	The majority of respondents are closely tied to state-level transportation practices (DOTs), indicating the reliability of insights for state policy guidance.
2. Organizational Progress	Only 13% reported ongoing research on blue lights; 37% had existing policies on blue light in place.	There is limited formal development of blue light practices, suggesting a need for more research and standardized regulation.
3. Reactions to Blue Lights	87% stayed alert when facing flashing lights; 89% assumed law enforcement presence in the work zone when observing blue lights.	Blue lights enhance perceived law enforcement presence, promoting alertness and cautious behavior among drivers.
4. Blue Light Deployment	68% preferred placement at the beginning of a work zone; 24% suggested using blue lights all the time throughout the project duration.	Deployment at work zone entry points and during the full project duration is considered most effective for visibility and safety, according to the respondents.
5. Effectiveness of Blue Lights	83% believed blue lights help reduce speed; 40% rated them excellent for ensuring work zone regulations.	Findings suggest blue lights are viewed as effective tools for both speed control and regulatory compliance. Their perceived effectiveness indicates potential for broader use as visual enforcement cues, enhancing driver awareness and supporting safer work zones.
6. Light Configuration	Among the warning light color configurations in work zones, about 22% of respondents identified blue lights as being used as warning lights. Among the color combinations expected on law enforcement vehicles in active work zones, 51% of respondents expected to see blue lights, 32% stated blinking lights were most effective in getting attention in the work zone, 21% found flashing blue lights in the work zone as distracting, and 59% were undecided whether blue lights cause distraction.	The results indicate that while blue lights are generally seen as effective for attracting drivers' attention in work zones, concerns about distraction remain. This suggests the need to optimize flashing patterns and intensity to balance visibility with minimal distraction.

7.3 Discussion of Field Data Analysis Results

The field data analysis examined how traffic volume and average vehicle speed might have been influenced by the presence of blue lights in the work zone. These analyses were organized into two parts. The first focused on traffic volume, identifying how lanes are used and location within the work zone might have been affected. The second examined average vehicle speed, exploring how driver adjustments varied by time of day, lane, and location. Overall, these analyses provided

practical evidence on how blue lights might have shaped real-world traffic behavior in active construction areas.

7.3.1 Discussion of Traffic Volume Analysis Results

The field data analysis on traffic volume suggested evidential support that the presence of blue lights might have influenced driver behavior within the work zone. Across both categories of analysis, a consistent pattern appeared where Lane 2 carried more vehicles, while Lane 1 showed reduced or more variable volumes. This indicated that drivers might have shifted away from the lane closest to the active construction area. This behavior was more persistent during nighttime when the visibility of the blue lights was greater. The placement of one blue light at the beginning of the work zone and the other moving within the active work zone might have guided these choices. The placement of the first blue light might have prompted earlier lane changes, while the second blue light might have influenced drivers to remain in the lane farthest from the active work zone.

Location-based results showed that these shifts varied within the different work zone locations. During the daytime, traffic volume differences were most visible in the active work zone area, while the beginning of the work zone showed little change. At nighttime, the presence of blue lights appeared to influence earlier adjustments at the entry point of the work zone, and these patterns continued into the first half and the second half of the active work zone. In addition, overall nighttime traffic volumes might be lower as fewer drivers travel during nighttime hours compared to daytime travel periods. This overall reduction in traffic flow may also have contributed to the observed differences in lane usage during nighttime conditions.

The comparative results between construction with the presence of blue lights and construction without the presence of blue lights also suggested that the blue lights might have been associated with lower traffic volumes, with the strongest effects observed at nighttime. Moreover, volumes in the lanes adjacent to the active work zone also decreased during the presence of blue lights compared to conditions without blue lights. These findings suggested that the presence of blue lights might have played an important role in influencing traffic distribution under construction conditions.

7.3.2 Discussion of Average Vehicle Speed Analysis Results

The field data analysis on average vehicle speed suggested evidential support that the presence of blue lights might have shaped drivers' behavior in ways that varied by location within the work zone, lane choice, and time of day. Drivers tended to travel faster at the beginning of the work zone and in the first half of the active work zone, but speeds declined in the second half of the active work zone. These reductions were more noticeable during nighttime, suggesting that the visibility of the blue lights might have influenced caution and encouraged lower speeds in the active work zone areas.

Lane-based comparisons highlighted further distinctions. Lane 1 generally carried higher speeds, while Lane 2 showed lower speeds, particularly during nighttime conditions. This pattern may be associated with the higher traffic volumes observed in Lane 2, which could lead to more stable and

slightly lower speeds due to increased vehicle interactions. In contrast, Lane 1 carried fewer vehicles and therefore displayed slightly higher speeds. In addition, Lane 1 was closer to the active construction area where merging and lane-changing activity occurred. These maneuvers may have created a temporary speed increment, which could also contribute to the higher and more variable speeds observed in this lane. Differences between daytime and nighttime also aligned with this trend. Daytime speeds were more consistent and higher, while nighttime speeds were lower, indicating that drivers tended to adopt more cautious speeds during nighttime conditions. Furthermore, the presence of blue lights was generally associated with lower speeds throughout the work zone, suggesting that the visual signal encouraged drivers to reduce speed when approaching and traveling through the construction area.

The comparative analysis between construction with the presence of blue lights and construction without the presence of blue lights also supported these insights. Overall, speeds under construction with the presence of blue lights were lower, with the most visible effect during nighttime. Location-specific results suggested that the presence of blue lights might have encouraged reductions at the beginning of the work zone and again in the second half of the active work zone, while the first half showed little change during daytime. At nighttime, however, both lanes and all locations reflected speed reductions, with Lane 1 showing more consistent speed reductions throughout the work zone and Lane 2 showing smaller reductions mainly within the active work zone segments.

Overall, these results suggested that the placement and movement of the blue lights might have prompted drivers to slow down earlier at the entry and maintain lower speeds further along the work zone. The first blue light at the beginning of the work zone might have created initial awareness, while the second blue light moving within the active work zone might have reinforced speed reductions in the active construction areas.

7.3.3 Overall Insight and Other Discussion

The findings from the field data analysis suggested that blue lights might have functioned as a behavioral cue that influenced both lane selection and speed regulation within the work zone. Their presence appeared to encourage drivers to increase distance from active construction areas and adopt more cautious driving patterns. The influence was more during nighttime, indicating that visibility conditions strengthened their behavioral impact. The placement strategy of blue lights in the work zone appeared to support both early awareness and sustained compliance through the work zone. These patterns indicated that blue lights may serve as a practical visual intervention to enhance driver attentiveness and improve traffic flow distribution under construction conditions.

It is important to interpret these findings within the operational setting of the work zone. Law enforcement personnel were not instructed to pull over speeding vehicles during the work zone construction. Although the blue lights were turned on, the absence of enforcement actions may have influenced driver perception and reduced the potential impact of the lights compared to real enforcement conditions. Upon conversation with the on-site law enforcement official, it was found that the instructions for ticketing were supposed to be provided by the contractor side. As the officers were off duty and were there due to their voluntary sign-up, ticketing was not enforced for

speeding in the work zone. This could also influence the regular motorists in the work zone area, as they might get the notion that they might not get ticketed for speeding in this work zone.

In addition, the work zone lacked adequate shoulder space, making the placement of law enforcement vehicles more challenging and at times risky. This condition restricted vehicle movement and limited the flexibility of blue light deployment. This is also another reason for not enforcing ticketing, as the lack of a shoulder area might create traffic congestion if vehicles were pulled over.

Chapter 8. Conclusions, Limitations, Recommendations, and Implementation Plans

8.1 Conclusions

This project investigated the implementation practices and initiatives related to using blue lights in work zones across the U.S. by combining a systematic literature review, a nationwide survey of transportation professionals, and field data analysis. These three components provided insights into existing research, practitioners' perceptions, perceived effectiveness, implementation practices, operational challenges of blue light deployment, and real-world behavioral outcomes. The key conclusions from this project are as follows:

i. **Literature Review:** The systematic literature review suggested that blue lights, especially when combined with enforcement presence, might influence driver behavior by improving speed compliance and encouraging lane changes. However, most prior studies primarily focused on behavioral outcomes without providing detailed procedures for implementation. This highlighted a lack of standardization in deployment practices and an ongoing need for more structured evaluation of blue light applications.

ii. **Survey Results:** The survey results suggested that most transportation professionals perceived blue lights as effective in improving driver alertness and compliance in work zones. Respondents favored deploying blue lights at the start of work zones and supported their continuous use throughout construction projects. Attention was strongest when blue lights were mounted on police vehicles, reinforcing the importance of enforcement cues. Some concerns were also raised about possible distraction, weak inter-agency coordination, and limited regulatory guidance, which indicated the need for clearer policies and stronger collaboration among stakeholders.

iii. **Field Data Analysis:** The field data analysis suggested that the presence of blue lights might have been associated with changes in both traffic volume distribution and average vehicle speed in active work zones. Drivers tended to avoid Lane 1 (closest to construction) and drove more in Lane 2, especially at nighttime when blue lights were more visible. Average speeds declined more consistently during nighttime conditions, with reductions strongest at the beginning and in the active work zone segments. These results suggested that the placement and movement of blue lights might have guided lane preferences and encouraged lower speeds, contributing to safer traffic behavior under construction conditions.

Overall, the combined findings from the literature, survey, and field data analyses suggested that blue lights might serve as an effective visual tool for enhancing work zone safety. While their potential benefits were supported across multiple dimensions, achieving consistent effectiveness will likely require standardized deployment strategies, optimized placement, and stronger regulatory frameworks. As interest in blue light usage continues to grow in the U.S., this project is expected to provide actionable information for MDOT (and maybe other state DOTs and transportation agencies) to develop and refine policies and guide the effective integration of blue lights in active work zones for safety enhancement.

8.2 Limitations

While this project provided important insights into the use of blue lights for work zone safety, several limitations should be acknowledged. Recognizing these limitations is important for properly interpreting the results and identifying areas for future recommendations.

I. **Restricted placement of blue lights:** The placement of the two blue lights was constrained by county regulations prohibiting law enforcement vehicles from crossing county lines. Their positioning and movement were further influenced by contractor convenience and operational considerations. As a result, blue light #1 covered a smaller area compared to blue light #2, and the configurations were not modified during the project in order to maintain the integrity and safety of the existing work zone setup. As the blue light locations were not kept fixed consistently throughout the project, their movement within the work zone limited the ability to isolate and accurately evaluate the specific effect of location on driving behavior. A more controlled setup, in which blue light positions remain constant for a defined period, would have allowed a clearer assessment of how placement influences traffic volume and speed adjustments.

II. **Field data availability:** The dataset had fewer observations for daytime construction with blue lights compared to nighttime conditions, and fewer nighttime observations for construction without blue lights. Although sufficient data were available for analysis, the imbalance reflected the construction schedule and may have influenced comparative findings. In addition, multiple work zones were initially identified with the assistance of MDOT for potential blue light implementation and field data collection. However, due to operational and logistical constraints, including work zone scheduling and the limited availability of law enforcement personnel to support blue light deployment, only a single work zone was selected for detailed field investigation. Investigating multiple work zones with varying configurations, traffic conditions, and enforcement characteristics would strengthen the validity of future investigations.

III. **Survey sample size and distribution:** The survey included 67 transportation professionals, with a majority of respondents concentrated in the southern U.S. The voluntary nature of participation may have led to regional clustering. Broader participation across diverse geographic regions in the U.S. would enable a more comprehensive understanding of the investigated problem through the availability of a larger dataset.

These limitations highlight the need for future studies to expand data collection across different regions, work zone conditions, and enforcement scenarios. Such efforts could provide more comprehensive evidence on how blue lights influence driver behavior and support the development of standardized implementation strategies.

8.3 Recommendations and Implementation Plan

Building on the findings, conclusions, and limitations of this project, this section outlines the key implementation-oriented recommendations intended to support MDOT in transforming the insights into practice, where applicable. The recommendations and implementation plans are discussed below:

i. **Considerations for Standardized Deployment Practices:** The findings suggested that the effectiveness of blue lights depended on their placement, operating duration, and visibility conditions. Based on these insights, MDOT could consider the development of internal guidance or reference materials outlining recommended practices for blue light deployment in work zones. These guidelines could address placement at work zone entry points, use during nighttime operations, and coordination with existing traffic control devices.

ii. **Coordination with Law Enforcement:** Survey and literature findings indicated that blue lights were most effective when drivers associated them with the presence of law enforcement. MDOT could consider exploring coordination approaches with law enforcement agencies to clarify roles, expectations, and operational constraints related to blue light usage in work zones. Such coordination could help address challenges related to jurisdictional boundaries, enforcement authority, and deployment feasibility.

iii. **Expansion of Pilot Testing and Field Evaluation:** The field data analysis was limited to a single work zone and specific operating conditions. To build on these results, MDOT could consider supporting future pilot deployments in additional work zones with varying roadway types, traffic volumes, and lighting conditions. Pilot testing in multiple settings could provide further insight into how blue lights perform under different operational contexts and support more robust evaluation of their safety impacts.

iv. **Strengthening Inter-Agency Collaboration:** Operational challenges identified through the survey highlighted the importance of coordination among transportation agencies, contractors, and law enforcement. MDOT could consider facilitating structured communication frameworks that clarified responsibilities related to blue light deployment, maintenance, and enforcement visibility. Improved collaboration could support smoother implementation and reduce uncertainty during work zone operations.

v. **Broader Stakeholder Engagement and Feedback:** The survey sample primarily reflected perspectives from state transportation professionals. MDOT could consider supporting future outreach efforts that incorporate feedback from contractors, work zone maintenance personnel, and drivers. Broader stakeholder engagement could provide additional insights into operational challenges, perceived effectiveness, and acceptance of blue light use in work zones.

Overall, these recommendations and implementation plans are expected and aim to assist MDOT in considering how the findings of this project can be applied to practical guidance, pilot applications, and coordination strategies for work zone operations. By applying these recommendations in a phased manner, MDOT may further evaluate the role of blue lights as a visual safety tool while addressing operational constraints and stakeholder needs. Such efforts can support informed decision-making and contribute to more consistent and effective work zone safety practices.

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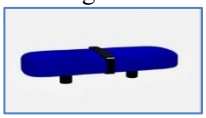
Appendix A

Table 102. Survey categories, representative questions, and provided options

Survey Category	Subcategory	Representative Questions with Provided Options
1. General Demographics (3 questions included)	No subcategory	What organization do you currently represent? a) Federal transportation agency b) State DOT c) Non-State DOTs d) Others, and please list:
2. Organizational Progress (6 questions included)	Research Perspective	Has your organization conducted any research studies regarding the use of blue lights for work zone safety? a) Yes b) No c) I am not sure
		Does your organization consider proposing and developing research studies regarding the use of blue lights for work zone safety? a) Yes b) No c) I am not sure
	Regulations/ Guidelines/ Strategies Perspective	In the state where you are working, blue light uses are allowed (select all that apply): a) Only allowed for law enforcement (during an emergency or traffic stop) b) Also can be used for work zone notifications, i.e., additional and dedicated law enforcement presence in road construction work zones c) Also allowed for non-law enforcement vehicles to use blue lights for warning purposes d) I am not sure
		Does your organization have formal regulations/guidelines/ strategies for implementing blue lights in work zones? a) Yes b) No c) I am not sure
3. Reactions to Blue Lights (7 questions included)	Attention, Awareness, and Assumptions	How does the presence of a police vehicle with flashing blue lights in a work zone affect your level of attention and awareness? a) I am more alert and pay more attention while passing the police vehicle, and continue to be alert while in the work zone. b) I am more alert and pay more attention while passing the police vehicle, and then revert to my normal driving habits. c) The presence of a police vehicle with flashing blue lights has no effect on me.
		How does the presence of a police vehicle with blue lights off in a work zone affect your level of attention and awareness? a) I am more alert and pay more attention while passing the police vehicle, and continue to be alert while in the work zone. b) I am more alert and pay more attention while passing the police vehicle, and then revert to my normal driving habits. c) The presence of a police vehicle with blue lights off in a work zone has no effect on me.

		If you see a vehicle (such as a police vehicle) with flashing blue lights sitting in a work zone, do you assume that: a) The officer just finished writing a ticket and is about to move along. b) The officer is on break. c) The officer is sitting in the work zone to ensure the work zone safety is enforced. d) None of the above
	Actions	What action would you take when seeing flashing blue lights in a work zone? Select all that apply. a) Stop b) Slow down c) Proceed without changing speed d) Increase speed e) Change lane (if applicable) f) None of the above
		What action would your coworker (who is the driver) take when he/she see flashing blue lights in a work zone? a) Stop b) Slow down c) Proceed without changing speed d) Increase speed e) Change lane (if applicable) f) None of the above
		If you are exceeding the posted speed limit and see a police vehicle with flashing blue lights in the work zone, do you: a) Slow down to below the posted speed limit b) Slow down to match the posted speed limit c) Slow down slightly but still above the posted speed limit d) Do not slow down and continue your regular speed e) Stop completely f) None of the above
4. Blue Light Deployment (5 questions included)	Location Relative to Work Zone and Typical Time to Deploy	When is the most typical time to deploy vehicles (such as police vehicles) with flashing blue lights in a work zone for safety? Select all that apply. a) Weekday - day frequently b) Weekday - day occasionally c) Weekday - night frequently d) Weekday - night occasionally e) Weekday - rush hour frequently f) Weekday - rush hour occasionally g) Weekend - day frequently h) Weekend - day occasionally i) Weekend - night frequently j) Weekend - night occasionally k) All the time of a day
		Which is the most typical location of placing a vehicle (such as police vehicles) with flashing blue lights in work zones? a) Beginning of the lane closure in the work zone b) Inside the work zone near the workers c) Inside the work zone away from the workers d) End of the lane closure in the work zone e) I am not sure
	Work Zone Types and Features	Which types of work zones are vehicles (such as police vehicles) with flashing blue lights used for? Select all that apply. a) Short-term work zones (1 hour to 3 days of construction) b) Lone-term work zones (more than 3 days of construction)

		c) Moving work zones (0-60 minutes of construction) d) Any work zone
		What criteria do you use (or propose to use) when deploying vehicles (such as police vehicles) with flashing blue lights in work zones for safety? Select all that apply. a) Road volume b) Classification of the road c) Congestion d) Any work zone e) Other, and please list:
5. Effectiveness of Blue Lights (8 questions included)	Benefits and Adverse Effects	What are the potential benefits of deploying vehicles (such as police vehicles) with flashing blue lights in work zones? Select all that apply. a) Reducing high speeds b) Improving safety conditions for workers and motorists c) Ensuring that work zone safety regulations are followed d) Not applicable e) Others, and please list:
		What are the potential adverse effects of deploying vehicles (such as police vehicles) with flashing blue lights in work zones? Select all that apply. a) Accidents might occur due to vehicles suddenly slowing down below the speed limit b) Motorist slowing down too quickly, leading to more congestion c) Motorist "rubber necking" d) Officers writing tickets in the work zone causing significant backups e) None f) Others, and please explain:
	General Opinions	In your opinion, has the use of vehicles (such as police vehicles) with flashing blue lights in work zones been effective in which of the following? • Reducing speed: a) Yes b) No c) Undecided • Improving safety conditions for workers and motorists: a) Yes b) No c) Undecided • Ensuring work zone safety regulations are followed: a) Yes b) No c) Undecided
	Strategic Initiatives	Were there any problems encountered during the work zone enforcement (using police vehicles with flashing blue lights)? Select all that apply. a) Lack of communication between enforcement and construction personnel b) Location of ticketing in the work zone c) Too few or too many police vehicles d) A reduced speed limit that was too slow or too fast for work zones e) Not applicable f) Others, and please list:

		Select the additional strategic initiatives that could be implemented to further improve the effectiveness of vehicles (such as police vehicles) with flashing blue lights in work zones. Select all that apply. a) Better communication and communication methods between officers and work zone workers b) Adjusting the number of police vehicles with flashing lights (more or less) c) Creating a more effective method of distributing tickets within the work zone d) Requiring work zone safety training for officers e) Others, and please explain: _____
6. Light Configuration (10 questions included)	Colors	Which of the warning light colors/combinations have you encountered in active work zones? Select all that apply. a) Blue b) Red c) Green d) Amber/Yellow e) Blue and red combination f) White and red combination g) None of the above
		What color lights do you expect to see on a vehicle (such as police vehicles) in a work zone? Select all that apply. a) Red b) Blue c) Green d) Amber e) Combination of some colors f) None of the above
	In Getting Attention	Two styles of warning lights are shown below. Which one do you think is more effective in attracting your attention while approaching a work zone? a) Visor light bars  b) Beacon lights  c) No difference
		Which one(s) do you think is more effective for blue lights to attract your attention while approaching a work zone? a) Blinking lights b) Rotating lights c) Oscillating lights d) No difference to me e) I am not sure
	In Alerting Drivers	In general, do you find single-color flashing warning lights (i.e., flashing blue lights) or alternating-color warning lights (i.e., a warning light flashing back and forth between red and blue) are more effective in alerting drivers? a) Single color warning lights b) Alternating color warning lights

		c) No difference between the two options d) Neither of these options is effective
		Which of the following warning light colors/combinations do you consider the most useful and helpful? Select all that apply. Please note that "most useful and helpful" here means which color or color combination makes you alert and cautious in a work zone. a) Blue b) Red c) Green d) White e) Blue and red combination f) I do not consider any of the warning light colors and combinations useful or helpful.
	In Causing Distraction	Do you find flashing blue lights in work zones distracting? a) Yes b) No c) Undecided
		Which of the following, if any, would you consider distracting while you are approaching or within a work zone? a) Blue lights off b) Slowly flashing lights c) Rapidly flashing lights d) I do not find any of the options distracting. e) All of them are distracting for me.

Appendix B

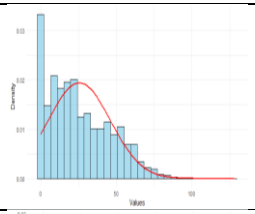
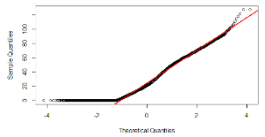
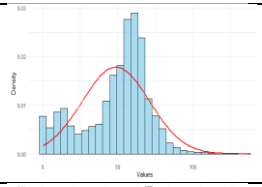
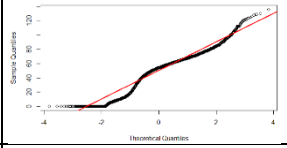
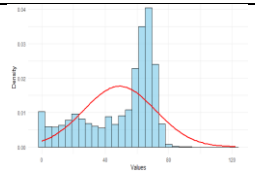
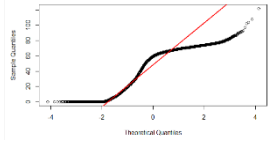
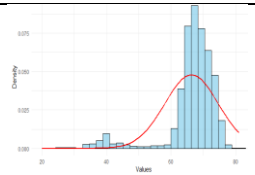
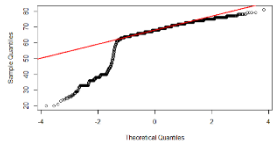
Normality Testing of the Data

For this project, the data collected for the volume and average speed were checked for normality. The data points were divided based on the work zone conditions (i.e., construction with the presence of blue lights and construction without the presence of blue lights) for volume and average speed metrics. The normality check of the data points for each variable under the work zone location and conditions was performed. Shapiro-Wilk (SW) and Kolmogorov-Smirnov (KS) tests for normality testing are commonly used (Hanusz & Tarasińska, 2015). However, the SW test was not suitable for the data set in this project, as it has a sample size limitation of 3-5000 (Ahmad et al., 2015). Thus, the KS normality test was selected and conducted. The following hypotheses were used for checking the normality of the data at the significance level, $\alpha = 0.05$ (Neumann et al., 2020):

H_0: *The data follows a normal distribution (p-value > 0.05);*
H_1: *The data do not follow a normal distribution (p-value ≤ 0.05).*

The summary of the normality test is depicted in **Table 103Error! Reference source not found.**. According to the results of the normality test, the p-value for all the work zone conditions is < 0.05. This suggests there is sufficient evidence to reject the null hypothesis and accept the alternative hypothesis. Therefore, it can be concluded that the data under all work zone conditions do not follow a normal distribution. Moreover, the histogram with the overlaid bell curve visually illustrates the shape of the data distribution in comparison to a normal distribution. In all cases, noticeable skewness and deviation from the bell curve are observed, indicating that the data are not normally distributed. The Q-Q plots further support this by showing significant departures from the reference line, particularly in the tails. These visualizations complement the statistical test results and reinforce the conclusion to reject the null hypothesis of normality. The appropriate statistical tests to analyze the data were determined based on the results of the normality test.

Table 103. Summary of the normality test of the collected data

Metric	Work Zone Condition	Data Points	p-value	Histogram with Bell Curve	Q-Q plot	Decision
Volume	Construction with the presence of blue lights	26784	< 2.2e-16			Null hypothesis rejected. Data is **not normally distributed.**
	Construction without the presence of blue lights	7488	< 2.2e-16			Null hypothesis rejected. Data is **not normally distributed.**
Average Speed	Construction with the presence of blue lights	26784	< 2.2e-16			Null hypothesis rejected. Data is **not normally distributed.**
	Construction without the presence of blue lights	7488	< 2.2e-16			Null hypothesis rejected. Data is **not normally distributed.**