Final Report

A Novel Driver Warning System with Hedging to Promote Defensive Driving

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16. Abstract

One of the major contributing factors to truck-related crashes is the presence of natural blind spots, also known as the "No Zone." While current Blind Spot Warning (BSW) systems can improve truck safety, the number of truck-related crashes continues to rise despite the growing deployment of BSW technology. Merely alerting truck drivers is insufficient to mitigate the safety risks posed by these blind spots. It is essential to enhance BSW technology to not only alert truck drivers but also encourage defensive driving among surrounding non-truck drivers. The objective of this study is to improve existing BSW technology for trucks by integrating the novel concept of "hedging." This approach involves issuing in-vehicle BSWs to both truck drivers and drivers of nearby non-trucks when they enter truck blind spots. The study aimed to provide a deeper understanding of how the Blind Spot Warning with Hedging (BSW-H) system influences driver decision-making in blind spot situations. A total of 43 participants took part in the study. Each participant drove three scenarios in a simulated network designed to mimic real-world conditions. These scenarios included a base scenario with no warning (S0), a scenario with both visual and auditory warnings (S1), and a scenario with visual-only warnings (S2). The two key performance measures evaluated in this study were the time spent in the truck's blind spot and the speed difference before and after receiving the warning. Statistical tests were performed to analyze driving behavior across the three scenarios to assess significant differences between them. The results of the analysis showed that there was a significant difference in time spent in the blind spot between Scenario S0 (no warning) and Scenario S1 (visual and auditory warnings), indicating that drivers altered their behavior when exposed to combined warnings. In the speed difference analysis, participants significantly adjusted their speed after receiving warnings in both S1 and S2. This suggests that the presence of the BSW-H system effectively influenced driving behavior.

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Abstract

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1. Introduction

Traffic safety has been a major concern in the U.S. and worldwide. Although motor vehicle travel has become safer over the past several decades, more than 30,000 people die each year as a result of car accidents. According to data from the National Highway Traffic Safety Administration (NHTSA), over 5.2 million motor vehicle crashes were reported by police in the United States in 2020. Out of these incidents, 1.6 million led to injuries, while 35,766 resulted in fatalities (1). The number of fatalities increased in 2021, with 42,939 deaths reported on U.S. roads—the highest number recorded since 2005. Pedestrian and motorcyclist fatalities rose by 12.5% and 8% respectively, reaching 7,388 (the highest in decades) and 5,932 (the highest ever recorded) (2). Reports indicate that around 43,000 people were killed on U.S. roads in 2022, approximately 10,000 more than in 2011(3). Aside from the emotional toll of loss and injury on families and friends, crashes annually result in a societal cost exceeding $340 billion (4). "We face a crisis on America's roadways that we must address together," said U.S. Transportation Secretary Pete Buttigieg in 2022. In the latest U.S. Department of Transportation (USDOT) Strategic Plan FY 2022-2026, "improving traffic safety for all road users and advancing a future without transportation-related series injuries and fatalities" is listed as the first strategic goal for the near future (5).

Among all types of traffic crashes, crashes involving trucks are particularly concerning due to their significant size and lack of maneuverability. Truck-related crashes constitute a significant safety and occupational risk to drivers. According to statistics published by National Safety Council (NSC) and NHTSA, trucks accounted for 107,000 crashes that resulted in injuries and 4,842 fatal crashes in the U.S. in 2020 alone (in which 4,965 people died) (6). In 2022, traffic crashes involving large trucks resulted in 5,936 fatalities, marking a 2% increase from the 5,821 deaths recorded in 2021. Of those killed in large truck crashes, 70% were occupants of other vehicles. While fatalities among light truck[1] occupants decreased by 0.9% from 2021 to 2022, fatalities in crashes involving large trucks[2] and the fatalities of large truck occupants rose by 2.0% and 8.5%, respectively (7). Even though large trucks account for only 4% of all registered vehicles, they

[1] Includes SUVs, pickups, and vans with gross vehicle weight ratings (GVWR) of 10,000 pounds or less.
[2] Includes commercial and non-commercial trucks with GVWRs over 10,000 pounds

represent 9% of all vehicles involved in fatal crashes (6). This disparity is a clear indication that improving the safety of trucks more generally must be a top priority in traffic safety.

One of the major factors contributing to truck-related crashes is the natural blind spots of trucks (also known as the “No Zone”) (8, 9). It has been reported that approximately 30,500 personal injuries are caused by the blind spots of trucks annually (10), and approximately 33% of all truck-related crashes in work zones are caused by improper identification of road users in trucks’ blind spots (11). Compared to crashes that involve only one truck, crashes caused by the blind spots of trucks inherently involve multiple vehicles, creating a greater risk for road users. Furthermore, due to the sheer size and weight of trucks, crashes caused by the blind spots of trucks often pose more grave threats to the smaller road users around them. According to the statistics published by the NSC (6), among all the fatalities involving trucks, the majority of deaths (roughly 71%) were occupants of the surrounding non-trucks.

Intelligent transportation system (ITS) technologies that can warn truck drivers of road users in their blind spots have been deployed over the past several decades to reduce the risk caused by blind spots. One of the most popular technologies is the Blind Spot Warning (BSW) (sometimes known as blind spot monitoring, blind spot detection, or lane-change warning) (13, 14). Briefly, BSW is used to alert the truck drivers if the space adjacent to the truck is occupied by other vehicles during lane change attempts (15). Using traffic simulations (16) and field tests (13), previous studies have found that following BSW instructions can improve truck drivers’ safety. As a result, the market size of BSW technology for trucks has been increasing over the past decade and is anticipated to grow by 961.74 million units from 2021 to 2026 (17).

However, despite the growing presence of BSW technology on trucks, the number of truck-related crashes continues to rise. It has been reported that the total number of crashes involving large trucks increased by 33% from 2011 to 2020, and the involvement rate per 100 million large truck miles traveled is also up 18% since 2011 (6). It has also been found that drivers of passenger vehicles initiated almost 83% of safety-related traffic events involving heavy trucks (18). Moreover, among all crashes caused by trucks’ blind spots, drivers of passenger vehicles initiate the vast majority (over 90%), not truck drivers (18). The statistics above indicate that only alerting truck drivers is not enough to reduce the safety risk induced by the blind spots of trucks. It is imperative to further improve current BSW technology to not only alert truck drivers but also promote defensive driving for the surrounding non-trucks as well.

Problem Statement

Blind spots refer to the areas around an automobile that are not visible to the driver directly or with the use of side or rearview mirrors (19). Due to their massive size, trucks have larger and more numerous blind spots (also called no-zones) compared to non-trucks, which are often much smaller passenger vehicles. The four major blind spots around trucks are illustrated in Figure 1 below, including the areas at the front, rear, and both sides of trucks (20). Even after adjusting all the side and rearview mirrors on a truck, it is still possible for a truck driver to completely miss non-trucks that are present in the blind spots, which could have devastating consequences for the occupants of non-trucks (19).

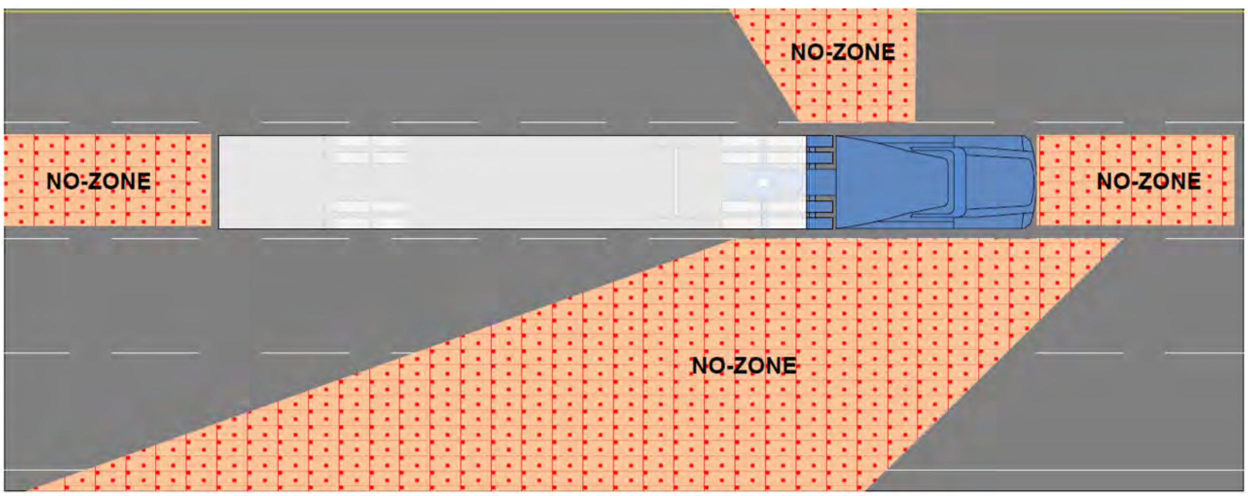

Figure 1. Illustration of four major blind spots of trucks (adopted and modified from Figure 5 in (20))

To mitigate the severe safety risks caused by the blind spots of trucks, researchers, vehicle manufacturers, and truck fleets have developed and incorporated vehicle safety systems like BSWs to monitor the obscured areas around trucks. BSWs alert the truck driver if the space adjacent to the truck is occupied by other vehicles during a lane change attempt (intended or unintended) (13). By alerting the truck drivers of the presence of non-trucks in their blind spots, BSW technology can provide adequate time for truck drivers to take precautionary actions and avoid imminent collisions between trucks and adjacent non-trucks (21).

However, warning truck drivers alone is not enough to reduce the safety risks caused by the blind spots of trucks since most blind spot crashes between trucks and non-trucks are initiated by drivers in adjacent non-trucks (18). In addition, even though truck drivers may take evasive actions in response to BSWs, the massive size of trucks means that any correcting maneuvers may cause sudden unwanted reactions from the surrounding non-trucks, potentially leading to a catastrophic chain of events. Thus, it is important to further improve BSW technology that can promote defensive driving among non-trucks in addition to truck drivers.

In this project, we aim to reduce these safety risks and promote defensive driving by incorporating the novel concept of "hedging" into current BSW technology, thus creating the improved BSW technology, **BSW-H: B**lind **S**pot **W**arning with **H**edging. The term "hedge," originating in finance, refers to an investment position intended to offset potential losses or reduce the risk of adverse price movements (22). Essentially, a hedge is a strategy that seeks to limit or reduce risk exposure. Because crash reduction and safety improvements are analogous to reducing traffic safety risk, we borrow the hedge concept from finance and apply it to reduce the risk of truck blind spots in this project. By providing BSW systems to both trucks and non-trucks, each acts as a hedge against the other. If one of them fails, the other can still act to avoid a potential collision. In other words, by incorporating a hedge in the current BSW technology, we are essentially doubling the likelihood of a safe interaction between trucks and non-trucks. The proposed BSW-H technology is illustrated in Figure 2 below.

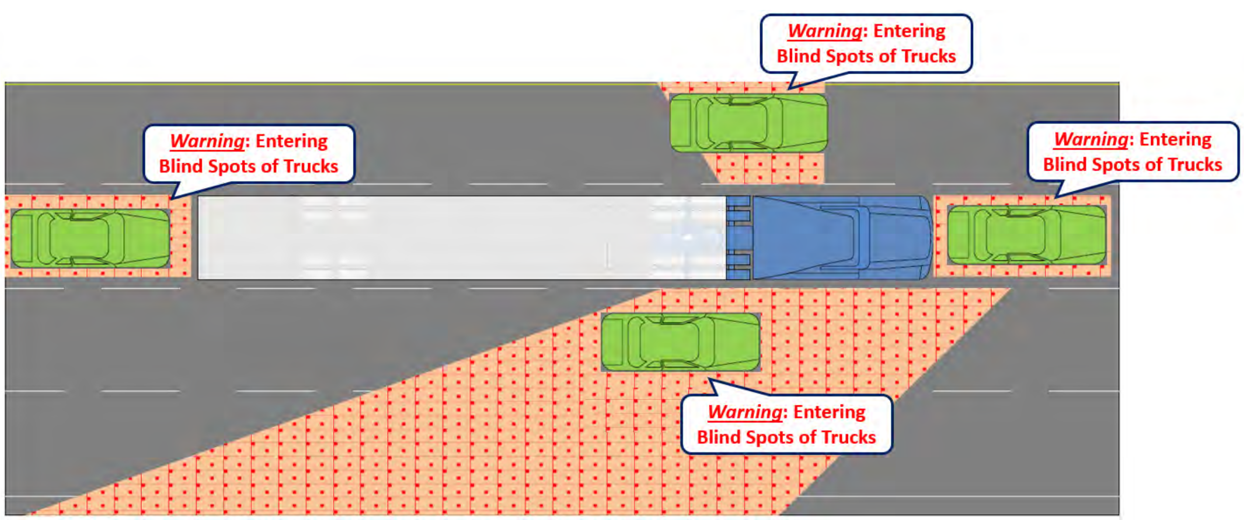

Figure 2: Illustration of proposed **B**lind **S**pot **W**arning with **H**edging

The proposed BSW-H technology supports the following key objectives:

1. ***Truck Crash Reduction***: As discussed above, traffic crashes caused by the blind spots of trucks are particularly dangerous. By issuing warnings to non-truck drivers as a hedge against the potential misidentification of non-trucks by truck drivers, the proposed BSW-H technology has the potential to reduce truck-non-truck crashes caused by blind spots.
2. ***Truck Safety Improvement***: Occupants in non-trucks are often more vulnerable to severe injuries in truck-non-truck crashes . However, from a technological perspective, the safety of non-trucks that are traveling adjacent to trucks is often overlooked in current in-vehicle driver warning systems. By issuing warnings to non-trucks via the proposed BSW-H technology, this project aims to improve the overall safety of both trucks and non-trucks.

The proposed BSW-H technology was developed in a Connected and Autonomous Vehicle (CAV) environment. Among various emerging transportation technologies, CAVs have the potential to reduce human errors (23). Connected vehicles are vehicles that are equipped with devices that allow them to communicate and share information with other vehicles, drivers, and the surrounding infrastructure. Autonomous vehicles are vehicles that can operate with little or no human interaction. Previous research conducted by the PIs has also shown that CAVs can effectively correct human errors and reduce safety risks (23, 24). Moreover, the market penetration rate of CAVs is expected to accelerate in the near future (25, 26). Using CAV technology, this project will develop a BSW-H system that can be used by the next generation of trucks and non-trucks.

The BSW-H was developed and tested using the advanced driving simulator housed in the Safety and Behavioral Analysis (SABA) lab at the National Transportation Center (NTC) at Morgan State University (MSU). The research was conducted as part of a project for the Sustainable Mobility and Accessibility Regional Transportation Equity Research (SMARTER) Center, a USDOT regional University Transportation Center (UTC). The NTC and SMARTER regularly collaborate with local, state, and federal transportation agencies, community organizations, and other universities. The PIs of this project have experience with driving simulators and human factor analysis for traffic safety evaluation (27-31).

The safety performance of the proposed BSW-H technology will be evaluated using the driving simulator at the SABA lab. Driving simulators have been used to investigate drivers' behavior and interactions with their environment since 1960. The main benefit of driving simulators is that they can provide a safe environment for driving research that can be easily configured to examine a variety of human factors. They also make it possible to manage a wider variety of experimental conditions than field tests. A driving simulator facilitates the use of various controlled traffic and environmental scenarios that are not possible with other methods. They also allow the examination of drivers' unique subjective experiences under the same events and conditions. Moreover, simulators are linked to computer systems, which can provide online data processing, formatting, and storage as well as the reduction and compact arrangement of data.

To the best of our knowledge, this project is the first study that proposes to incorporate a hedge against safety risks caused by the blind spots of trucks in current BSW technology. The proposed research will draw upon ideas from CAV technology and human factor analysis (more specifically, driver behavior analysis) and use driving simulators to evaluate the effectiveness of the proposed BSW-H technology. The results of this study have the potential to reduce crashes involving both trucks and non-trucks caused by the blind spots of trucks and prepare for the next generation of connected and autonomous trucks and non-trucks.

2. Literature Review

Blind Spot Area Around the Vehicles

Blind spot areas around a vehicle in driving refer to any areas around the vehicles that are not visible to the drivers through the rear-view mirror or side mirrors (32). These areas can pose a safety risk as they may hide other vehicles, pedestrians, or objects, leading to potential collisions or crashes. Blind spots vary depending on the size and design of the vehicle but commonly occur on the sides and rear of the vehicle. The locations of blind spots typically include:

1. Side Areas: These are areas alongside the vehicle, usually between the rear-view mirror and the side mirrors. Side blind spots can extend from the side mirrors to the vehicle's rear and may vary in size depending on the vehicle's design.
2. Rear Areas: This is the area directly behind the vehicle that is not visible to the driver through the rear-view mirror.
3. Front Areas: The front blind spot area created by the A-pillars (windshield pillars), which can obstruct the driver's view.

The Definition of Blind Spots Around Trucks

The blind spots or "No-Zone" area around the large trucks refers to the areas surrounding large trucks and buses where drivers of trucks have restricted visibility, heightening the likelihood of crashes. These blind spots around trucks and buses are called the No-Zone because they are areas that other vehicles should avoid or pass through swiftly and safely to minimize the chance of collisions. Trucks and buses have substantial No-Zones on both sides, directly behind, and right in front of them, along with reduced maneuverability and longer stopping distances (33). Several factors influence the size of blind spot areas trucks, such as the driver's height and sitting position, the vehicle's size and configuration, the design and position of the cabin, the types and placement of mirrors, and the configuration of the trailer (34). There is not much literature to specifically determine the dimensions of all blind spot areas around the trucks, but there are studies that showed the four major blind spots around the trucks. Figure 3 illustrates the four blind spot areas of a single-unit truck as published in the National Transportation Safety Board (NTSB) report in 2013 (35). The report also noted that the visibility of an object depends on its height.

Figure 3: locations of blind spots for a single-unit truck (adopted from (35))

Reed et al. (36) found that crashes where the drivers of large trucks needed to use their mirrors to complete their maneuvers (mirror-relevant crashes) comprised 20 percent of all crashes involving large-trucks (both fatal and non-fatal). Mirror-relevant crashes involving the right side of the truck (lane change/merge and right turns) were more than four times as common as those involving the left side of the truck (lane change/merge and left turns). They also identified four locations where the vision of large truck drivers needed to be improved and ranked them in the following order. Figure 4 indicates these four areas around large trucks.

1. Priority 1, which has the highest priority, is the area to the right of the large truck cab that covers an area equivalent to a right-side adjacent lane and 5 meters behind the front bumper of the large truck cab.
2. Priority 2 is the area to the right of the truck that covers an area equivalent to a right-side adjacent lane and extends from the back of the large truck cab to 5 meters behind the trailer/cargo area (second highest priority).
3. Priority 3 is the area immediately in the back of the large truck (about 5 meters); and
4. Priority 4 is the area that extends 5 meters in front of the large truck cab and one lane over to the right to include the adjacent lane.

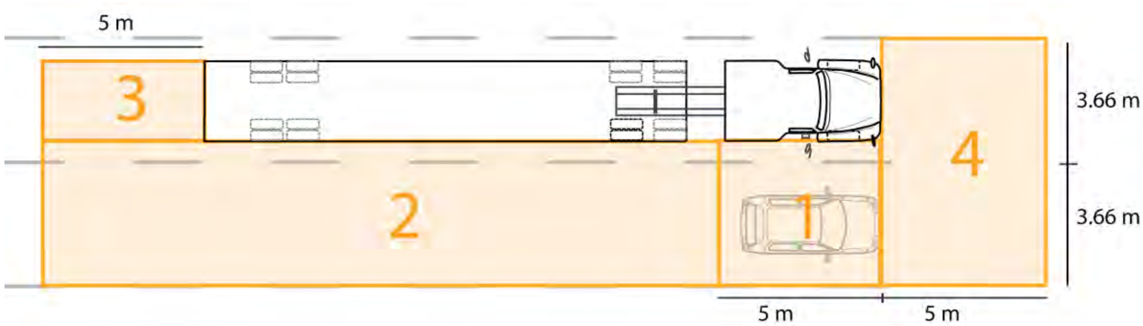

Figure 4: The prioritized zones for improvement of drivers' vision (adopted from (36))

The study conducted by Bogard et al. included seven different BSW test procedures (37). In their report, the sixth BSW test, detailed in the document as BSW-6: RV Tailgates HV (False Positive Test), is illustrated in Figure 5. In this context, HV refers to the subject vehicle, and RV represents the collision threat to the HV. This test procedure describes the right and left blind zones, both extending rearward from the truck equipped with the vehicle-to-vehicle communication system (V2V). The left blind zone terminates at the front of the HV, while the right blind zone extends beyond the front of the HV. The report does not provide specific measurements for the lengths of these blind zones.

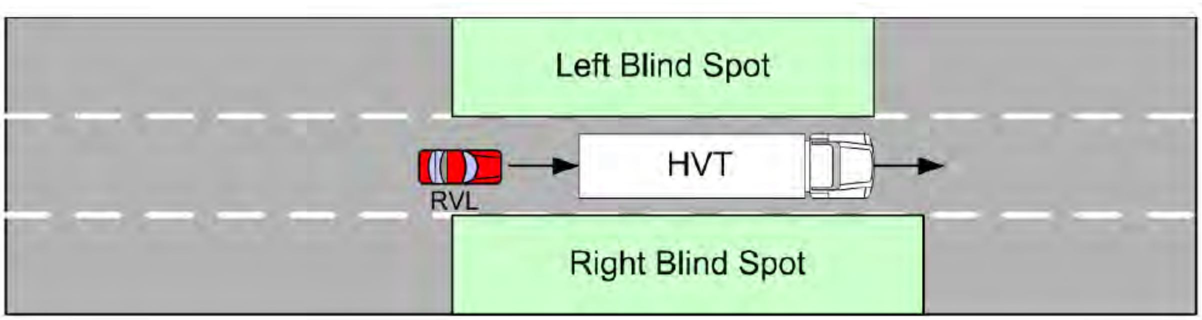

Figure 5: Depiction of the side blind spots of a large truck (adopted from (37))

In 2014, Wells and Berg (38) depicted the blind spot zones around Connected Commercial Vehicles (CCVs) differently. Their report does not provide specific measurements for the length of these zones, but it indicates that the zones begin at the rear of the trailer. They extend beyond the tractor's front bumper on the right side and to the front bumper on the left side. The following figure illustrates the blind spot areas on the left and right sides of the CCVs.

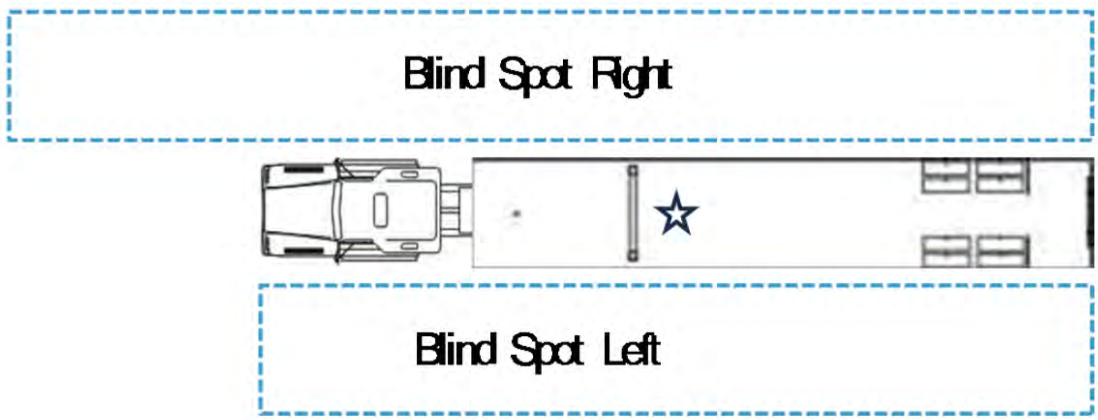

Figure 6: Blind spot areas on the sides of the CCVs (BSW/LCW Scenario) (adopted from (38))

The Federal Motor Carrier Safety Administration (FMCSA) has provided safety tips for driving around trucks. In their graphics, they illustrate that a 20-foot distance in front of the truck is considered a front blind spot, and a 30-foot distance behind the truck is identified as a rear blind spot (39). Figure 6 shows the major blind spot areas around large trucks.

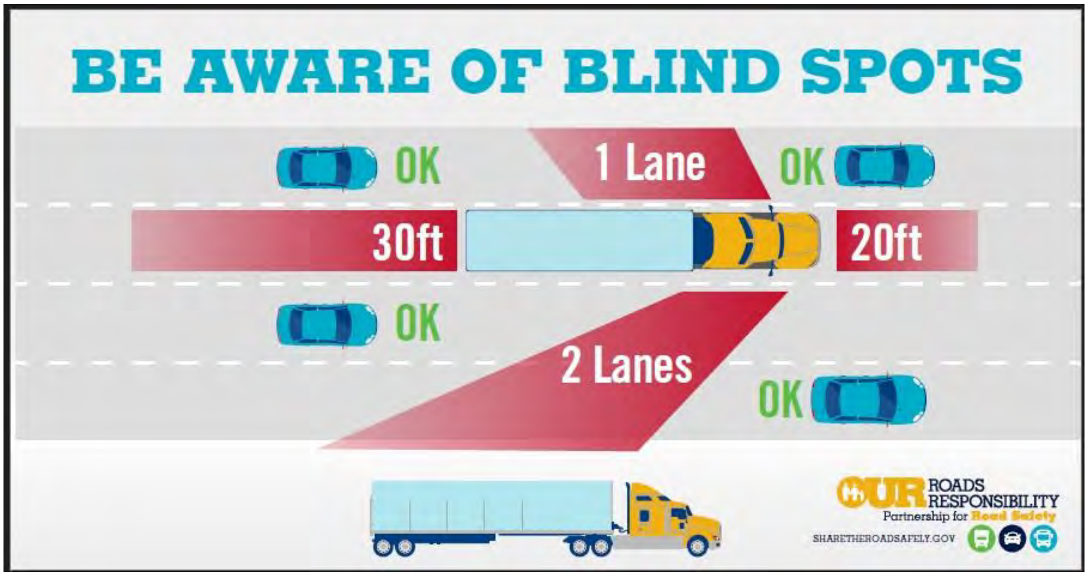

Figure 7: Illustration of four major blind spots of large trucks by FMCSA (adopted from (39))

Blind Spot Warning and Its Benefits

Drivers need to be especially cautious about blind spots during lane changes, overtaking, turning on road bends, and moving after traffic signals to avoid collisions with vehicles hidden in these areas. Since human drivers cannot always maintain such caution, crashes often occur. Therefore, a robust crash avoidance and overtaking advice system should be aware of the blind spots around vehicles and quickly alert both drivers to prevent blind spot crashes. A BSW system, also known as a blind spot detection or monitoring system, is a safety feature in vehicles designed to alert drivers of objects or vehicles in their blind spots, which are areas not directly visible through the side mirrors or rearview mirror. This system typically uses sensors, cameras, or radar mounted on the vehicle to monitor the adjacent lanes. Numerous researchers have conducted studies to assess the effectiveness and benefits of BSW systems in enhancing road user safety (41-43).

Reducing Traffic Crashes

BSW systems have consistently been shown to reduce traffic crashes across various studies. In the U.S., a 2008 study predicted that BSW systems could prevent a substantial number of large truck-related crashes, including 39,000 crashes annually, resulting in the avoidance of 457,000 injuries and 428 fatalities by 2010 (12). This early estimation was based on pre-crash scenario analyses, highlighting the potential of BSW in mitigating accidents before they occur. Further studies have corroborated these findings. For example, a 2009 in-depth clinical review estimated that BSW could prevent 5.9% of crashes involving large trucks, which is particularly significant given the high severity of such crashes (12). Similarly, research in Germany in 2009 indicated that BSW systems could potentially reduce 24.7% of truck-related crashes (12), illustrating the system's efficacy in different geographic contexts. In addition to these findings, Benson et al. reviewed the effectiveness of Advanced Driver Assistance Systems (ADAS), which include BSW as a core feature. Their research suggested that BSW systems, while contributing a smaller proportion to crash reduction compared to other technologies like forward collision warning, still had the potential to prevent up to 318,000 crashes annually in the U.S. alone. This includes a 37% reduction in injuries and a 29% reduction in fatalities from passenger vehicle crashes (44). These findings underscore the widespread applicability of BSW systems across both commercial and passenger vehicles. Further supporting these conclusions, Racine et al. proposed a more active blind spot crash avoidance system incorporating force-feedback pedals and simulators, showing that adding such features to existing BSW systems could further enhance their effectiveness in reducing crashes (45). Lastly, Blower et al.'s evaluation of various advanced collision-avoidance technologies (ACATs), including BSW, found that these systems significantly reduce the specific types of crashes they target, such as lane or road departure incidents (46). Overall, the body of research provides strong evidence that BSW systems are highly effective in reducing crashes, particularly those involving large trucks and lane-change scenarios, which are among the most dangerous on the road.

Benefits for Vulnerable Road Users (VRUs)

In addition to general crash reductions, BSW systems also provide specific benefits for VRUs, such as pedestrians, bicyclists, and motorcyclists. Wang and Wei estimated that implementing BSW systems on large trucks could prevent about 24%, 10%, and 11% of crashes involving pedestrians, bicyclists, and motorcyclists, respectively, saving 5 pedestrians, 3 bicyclists, and 15 motorcyclists annually (12). Similarly, the eIMPACT project in Europe found that BSW systems could save approximately 975 lives and prevent 2,100 injuries annually by enhancing road safety (48). These findings emphasize the importance of BSW systems in improving safety, particularly for VRUs, who are at higher risk in crashes involving large trucks.

Economic Advantages of BSW

The implementation of BSW systems also brings significant economic benefits. Khan et al. assessed the societal and private benefits of crash avoidance technologies, including BSW. They estimated that these systems could prevent up to 1.6 million crashes annually in the U.S., including 7,200 fatal crashes (49). Cicchino's study found that vehicles equipped with BSW had a 14% lower crash involvement rate in lane-change incidents, which could prevent approximately 50,000 crashes annually (50). Harper et al. estimated that BSW, along with other safety technologies, could yield annual benefits ranging from $18 billion to $202 billion (51). Isaksson-Hellman and Lindman further demonstrated that BSW-equipped vehicles had a 30% lower insurance claim cost, suggesting a reduction in crash severity (52). These studies underscore the substantial economic advantages associated with widespread adoption of BSW systems.

The integration of BSW systems into vehicles provides clear safety benefits by reducing crashes, especially those involving large trucks and VRUs. By reducing the number of collisions and fatalities, BSWs provide substantial economic benefits, including reduced crash rates, lower insurance claims, and decreased medical expenses. As BSW systems continue to evolve and become more widely implemented, they hold promise not only for improving road safety but also for generating significant societal cost savings. Future research should focus on further improving BSW technology and exploring its broader applications in connected and autonomous vehicles.

Safety Performance Measures Related to Evaluating the BSW

In previous studies, several key safety performance measures have been used to evaluate the effectiveness of BSW systems and other ADAS. These measures primarily include changes in driving behaviors such as speed reduction, lane-changing patterns, headway maintenance, and braking behavior.

Martin and Elefteriadou (2010) used speed, lane change maneuvers, and headway with the front vehicle as primary performance measures when assessing a vehicle equipped with Adaptive Cruise Control (ACC) and Lane Change Assist (LCA). Their driving simulator study revealed significant changes in these metrics, indicating how ADAS systems, including those like BSW, can alter core aspects of driving behavior (53).

Maag et al. (2012) focused on evaluating the effect of cooperative ADAS, using drivers' speed, lane changes, and interactions with hazards as key metrics. Their study found that ADAS systems influenced both the driving behavior and the emotional responses of drivers, indicating that technologies like BSW may similarly affect how drivers respond to adjacent vehicles in blind spots (54).

A different focus on headway maintenance was explored by Bao et al. (2012), who measured the time gap between vehicles in relation to a crash warning system. This study found a notable improvement in maintaining safer headway, demonstrating how warning systems, similar to BSW, could increase the time gap between vehicles in dense traffic conditions, contributing to safer lane changes (55).

Biondi et al. (2014) examined drivers' reactions to sudden beeping alerts, assessing their impact on lane-keeping and speed maintenance. They found that ADAS beeps led to startled reactions, such as lifting off the accelerator and braking, emphasizing how alert-based systems like BSW might temporarily disrupt driver control before regaining stability (56).

In a study by Jermakian et al. (2017), lane-changing behavior was evaluated using a crash warning system for teenage drivers. Performance measures included lateral drift, unsignaled lane changes, and headway maintenance, with results showing that warnings improved lane-changing behavior and reduced lateral drifts. These results highlight BSW's potential to influence similar metrics (57).

In a complementary study, Yu et al. (2021) explored the impact of an integrated collision warning system on risk compensation behavior. Hard braking was one of the key performance measures, and the study revealed that ADAS did not lead to an increase in risky compensation behavior, such as more frequent hard braking. Instead, the presence of visual-manual distractions and short headways had the most significant influence on braking behavior. This suggests that BSW systems may contribute to improved safety without increasing the likelihood of hard braking under normal conditions (58).

The impact of crash avoidance systems, including BSW, on crash prevention was emphasized by Jermakian (2011). The study used crash rates as a core measure and found that these systems could potentially prevent a significant number of crashes annually, further supporting BSW's role in enhancing road safety (59).

Tomasch and Smit (2023) demonstrated the effectiveness of aftermarket BSW systems in crash reduction, demonstrating that these systems reduced the number of warnings involving vulnerable road users, such as pedestrians and cyclists, by one-third in heavy goods vehicles and by 10% in buses. This suggests that BSW systems not only impact driver behavior but also contribute significantly to reducing the likelihood of crashes (60).

Kiefer and Hankey (2008) specifically evaluated lane-changing behavior, using the frequency of mirror checks and "over the shoulder" glances as key metrics. Their study found that BSW systems reduced unsafe lane-change attempts, with fewer instances of drivers neglecting to check blind spots, demonstrating BSW's effectiveness in promoting safer lane-change behavior (61).

Finally, Gouribhatla and Pulugurtha (2022) utilized a wide range of performance measures, including hard braking, lane departures, average speed, and brake force, in evaluating the behavioral impact of ADAS features like BSW. The study found that BSW particularly influenced brake pedal force during rural driving scenarios, indicating its role in helping drivers react more cautiously to adjacent vehicles (62).

Across these studies, common performance measures used to assess BSW effectiveness include speed reduction, lane-changing behavior, headway maintenance, braking patterns, and crash reduction. These metrics provide valuable insights into how BSW systems improve driving safety by altering key aspects of driver behavior, such as reducing unsafe lane changes and improving reaction times, while also contributing to the overall goal of reducing crashes.

Previous studies have utilized various safety performance measures to evaluate the effectiveness of ADAS and other technologies in improving driver behavior and road safety. These measures include changes in speed, lane-changing behavior, headway, hard braking, and other driving parameters. By employing driving simulators and field data, researchers have consistently demonstrated the various impacts of these technologies on the safety of roadways.

While the existing literature on BSW systems and ADAS demonstrates significant advancements in road safety and crash reduction, several limitations persist. Firstly, there is a lack of standardized guidelines defining the precise dimensions of blind spots for different types of vehicles, especially for trucks. Secondly, to the best of the author's knowledge, previous studies predominantly focus on the behavior of the host vehicle—the vehicle equipped with the BSW system—while neglecting the behavior of surrounding vehicles that may be driving in the host vehicle's blind spots. This narrow scope limits the understanding of the interaction dynamics between vehicles in real-world scenarios, thereby potentially reducing the effectiveness of BSW systems.

Considering these limitations, our study aims to address these gaps by introducing the novel concept of BSW-H. Unlike traditional BSW systems, BSW-H will issue warnings to drivers of surrounding non-trucks when they enter the truck's blind spots. This dual approach acknowledges the critical role of surrounding vehicles in blind spot-related incidents and aims to foster defensive driving practices among non-truck drivers. By leveraging Connected and Autonomous Vehicle (CAV) technology, our research will employ advanced driving simulators to evaluate the impact of BSW-H on non-truck drivers, thereby providing a comprehensive assessment of its potential to enhance overall road safety for both trucks and non-trucks.

3. Methodology

This chapter outlines the research methodology employed in this study to assess driving behavior concerning the new BSW-H system. The discussion covers the design of BSW-H for the driving simulator, scenario and network design, safety performance measures used to evaluate the effectiveness of BSW-H, and the lessons learned from the procedure.

BSW-H Design

In this research, the driving simulator functions as the User Vehicle (UV) that participants operate. When the UV enters the blind spot areas of trucks, a warning is triggered to alert drivers about their position in the truck's blind spot. The Front Vehicle (FV) refers to the truck directly ahead of the UV in the same lane, while the Surrounding Object (SO) represents trucks in other positions around the UV but not in the same lane. This section details the designed blind spot areas around trucks and the corresponding warnings created for these scenarios.

Blind Spot Area Around the Trucks

The study aims to develop a BSW-H system that warns drivers entering the blind spots around trucks. Since there is no universally accepted standard for defining the exact dimensions of these blind spots, the study references existing literature to establish these areas. The MSU driving simulator does not have predefined blind spot areas for various vehicles. However, the SABA lab's simulator software (interactive VR-Design Studio) allowed us to design the blind spot areas around trucks and incorporate visual and audio warnings for this study. The software does not allow for customization of truck dimensions, so we utilized four pre-existing truck models within the software, each approximately 12 meters in length. Three primary blind spot zones around the trucks were identified: the rear blind spot zone (Area # 1), the right blind spot zone (Area #2), and the left blind spot zone (Area #3). The blind spot at the truck's rear side extends 13 meters from the truck's rear bumper and spans the width of one lane (3.3 meters). The blind spots at the right and left sides of the truck extend from the front bumper along the truck's entire length, continuing 5 meters past the rear bumper, with a width also equal to one lane (3.3 meters). When the UV enters these defined blind spot areas, the driver receives a warning indicating they are in the truck's "No-Zone". Figure 7 illustrates the proposed blind spot areas around the trucks.

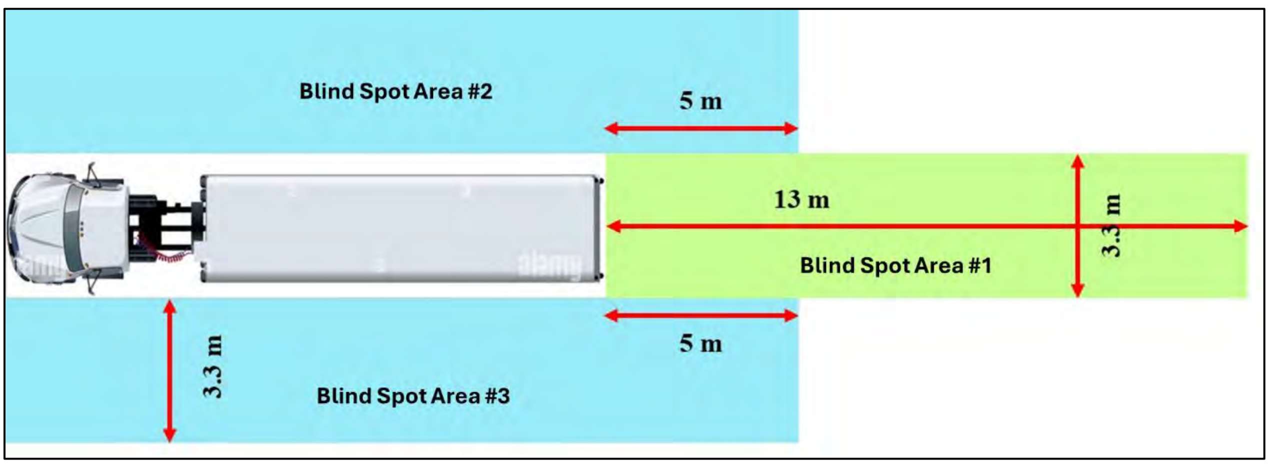

Figure 8: Proposed Blind Spot Zones Around the Trucks

Design of the Warnings

During testing, two types of warnings—visual and auditory—were sent to drivers. The visual warning consists of a blinking red text at the bottom of the driving simulator screen stating, "*Warning: Entering Blind Spots of Heavy Vehicle*". The auditory warning is a beeping sound that activates when the UV enters the truck's blind spot. While the UV remains in the blind spot, the visual warning remains displayed on the screen, and the audio warning beeps once every second. Both warnings cease immediately once the UV exits the blind spot area.

In the trajectory data log file generated by the driving simulator, there was no predefined variable for BSWs. Consequently, we faced the challenge of defining a new variable to record when the UV enters the blind spot of another vehicle, which in this case was a truck. To address this, we created a new BSW variable (column) in the CSV file. This variable logs the moment the warning message is triggered by the simulator. It then categorizes the location of each warning message using values based on the blind spot area where the warning was triggered. Blind Spot Area #1 represents the rear blind spot zone of the truck, while Blind Spot Areas #2 and #3 indicate the blind spot zones on the right and left sides of the truck, respectively. This new BSW variable allows us to pinpoint the exact time, location, and trajectory of the UV as it enters the truck's blind spot.

Although the warnings for all three blind spot zones around the trucks are identical, the log files differentiate the specific areas where the UV received the warnings. Figures 8, 9, and 10 illustrate the visual warnings received by participants for the three blind spot zones around the trucks.

Figure 9: BSW-H triggered in the Area #1 at the Rear of the Truck

Figure 10: BSW-H triggered in the Area #2 at the Right Side of the Truck

Figure 11: BSW triggered in the Area #3 at the Left Side of the Truck

Scenario Design

Three scenarios were designed to evaluate the effect of the BSW-H on participants' driving behavior as they moved through trucks' blind spots. To specifically focus on the impact of the warnings on driving performance, we used the same time of the day, traffic conditions, and weather conditions in all three scenarios. All participants drove in the same network with mild traffic and clear weather. The only differences in these three scenarios were the existence and the type of warning.

Base Scenario with no Warning (S0)

The first scenario served as the base scenario (S0). In this scenario, participants drove the network without receiving any warnings when they drove in blind spots of trucks. The data collected from the base scenario enabled us to compare the participants' driving performance with other scenarios that included BSW-H.

Scenario with Both Visual and Auditory Warnings (S1)

In the second scenario, participants received both visual and auditory warnings upon entering any of the three blind spot areas around the trucks. This consisted of a warning message displayed on the screen and an accompanying beeping sound.

Scenario with Just Visual Warning (S2)

In the third scenario, participants received only the visual warning when driving in the trucks' blind spot areas. No auditory warning was present.

Safety Performance Measures

By default, the driving simulator records vehicle trajectory data every second. For our study, we increased the precision by setting the simulator to collect trajectory data every 0.01 seconds. Additionally, we configured the simulator to record the trajectory data of all surrounding vehicles within a 300-meter radius. These adjustments, though resulting in large CSV log files (over 200 MB for a 10 km drive), provided detailed vehicle trajectory data for thorough behavioral analysis. The simulator recorded 106 variables, including trajectory data and the new BSW variable. Some of the most important variables extracted from the log file are speed, throttle, brake, distance along the road, timestamp, and the type/model of vehicles in the network. Table 1 provides definitions for some of these variables.

Table 1: Driving performance variables and their descriptions

Variables	description and units
Speed	Unit: miles per hour

Average Speed Difference (5s Interval)	The difference between an average speed of 5s after receiving the warning and 5s before receiving the warning
Time Spent in Blind Spots	The time duration between entering the blind spot of the trucks until exiting the blind spot
Throttle	The input on the acceleration pedal. It is a ratio with a value between 0 (no Throttle) and 1 (Full Throttle)
Brake	The input on the brake pedal. It is a ratio with a value between 0 (no Brake Force) and 1 (Full Brake Force)
Distance Along the Road	The distance driven from the start point of the road, Unit: meter

In our study, we utilized some of these variables to evaluate drivers' responses to the new warning system (BSW-H) while entering and navigating trucks' blind spots. Two key performance measures were employed: Time Spent in Blind Spots and Average Speed Difference before and after receiving the warning, analyzed in 5-second intervals.

Speed Difference Before/After Warning

To assess driving behavior in response to the newly introduced BSW-H, we calculated the average speed of the UV 5 seconds before and 5 seconds after receiving the warning. The average speed difference was obtained by subtracting the average speed before the warning from the average speed after the warning. This provided insights into how participants adjusted their speed after being alerted to the blind spot hazard.

Time Spent in Blind Spots

The second performance measure used to evaluate drivers' reactions to the BSW-H system was the time spent in the blind spot. This is defined as the duration from when the UV enters the blind spot zone of the host vehicle until it exits.

4. Data Collection and Processing

This section outlines the data collection procedures for this research. It details the driving simulator used, the design of the survey questionnaires, and the network developed for the study.

Driving Simulator

The data for this research was collected using the advanced driving simulator housed in the Safety and Behavioral Analysis (SABA) lab at the National Transportation Center (NTC) at Morgan State University (MSU) and the Sustainable Mobility and Accessibility Regional Transportation Equity Research (SMARTER) Center, a regional University Transportation Center (UTC).

The SABA lab's driving simulator, developed by Forum8 Company (FORUM8)[3], is a sophisticated, computer-based tool. It allows for the creation and design of various transportation network elements, including traffic signals, diverse terrains, road alignments, signage, traffic generation, and weather conditions. Additionally, it can simulate static objects such as 3D buildings and trees. This simulator enables the creation of realistic city networks, allowing drivers to choose their routes freely to reach their destinations. The simulator captures extensive data, including steering wheel control, braking, acceleration, travel times, lane-changing information, traffic mix, speed, and other metrics. SABA lab's simulator provides a comprehensive and immersive driving experience by simulating real-world conditions and environments. This capability makes it an invaluable tool for various safety-related applications. By replicating actual city networks, users can navigate through realistic urban settings, offering a more authentic and practical training environment. The driving simulator can record vehicle trajectory data at intervals of 0.01 seconds, with the default setting being every 1 second. Additionally, it can capture the trajectory data of all surrounding vehicles within a specific radius. This recorded data is then stored in CSV format on the simulator's computer. Detailed data capture further enhances its utility by allowing precise analysis of driving behaviors and traffic patterns, which can be used to improve road safety and traffic management strategies. Figure 12 indicates our driving simulator in the SABA lab.

[3] FORUM8 - 3D VR & Visual Interactive Simulation

Figure 12: SABA lab’s driving simulator at MSU

Institutional Review Board (IRB Number: 24/02-0024) approval was obtained before beginning data collection. To attract a diverse sample, flyers promoting the driving experiments were disseminated across the Morgan State University campus and throughout the Baltimore metropolitan area. These flyers were also posted on advertising websites and social media platforms.

In total, 44 participants took part in the study. Each participant was required to possess a valid driving license and was compensated at a rate of $15 per hour of driving. A group of graduate research assistants, supervised by their advisor, monitored the simulated driving sessions and administered questionnaires to the participants. The observers provided instructions on using the driving simulator and explained each scenario before the participants began.

Survey Questionnaires

Two survey questionnaires were created for the study (see Appendix A and B). The pre-simulation survey gathered sociodemographic information from participants, while the post-simulation survey evaluated their simulation experience. The pre-simulation survey collected data on participants' age, gender, ethnicity, education level, employment status, annual household income, household size, driving experience, familiarity with CAVs, knowledge of truck blind spot zones, BSW, and ADAS technologies, and whether their cars were equipped with ADAS features.

The post-simulation survey focused on participants' experiences during the study, asking them to rate their use of the BSW-H system, their reactions to it, and their assessment of its effectiveness. At the beginning of the surveys, participants were provided with explanations of BSW-H, Defensive Driving, and ADAS technologies.

Study Network

Using the VR-Design Studio software developed by Forum8, we created a virtual network modeled after a real-world environment. This network is a simulated 2-lane divided highway that based on a segment of the I-95 and I-695 highways East of Baltimore City, spanning approximately six miles. The speed limit on this highway is 55 mph; however, no speed restriction was imposed on the driving simulator, allowing participants to accelerate up to 75 mph. Speed limit signs were placed every 250 meters throughout the network. Traffic within the network was also generated by the software. As the focus of our study was on driving behavior around trucks and the effectiveness of BSW-H, only trucks were included in the network. Depending on their driving speed, participants typically took between 6 to 9 minutes to complete the network. Figure 13 illustrates the study network area map used in this research.

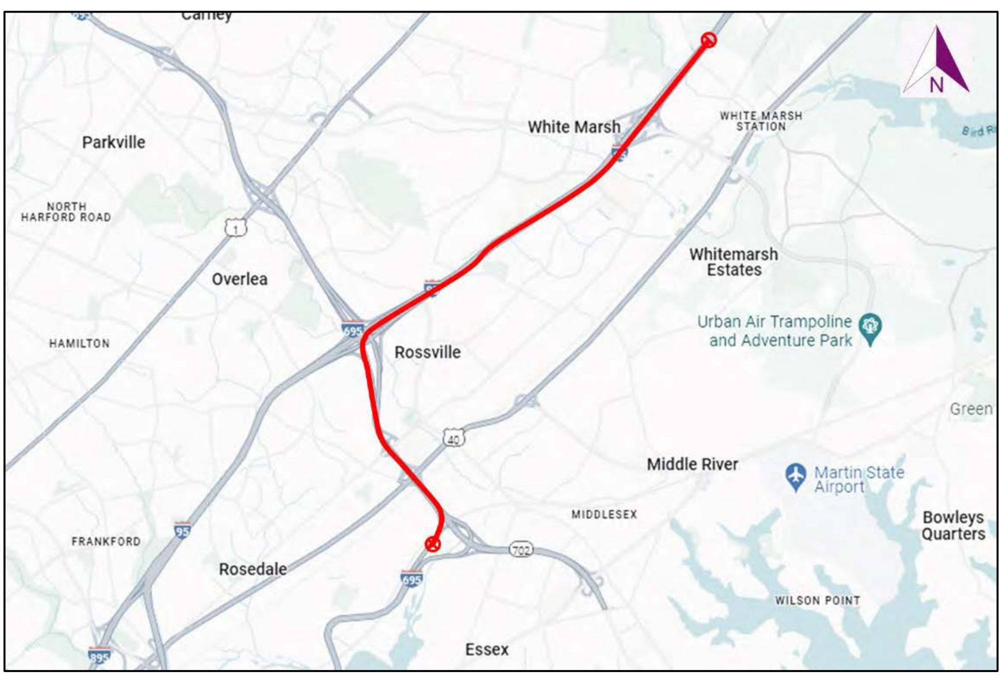

Figure 13: The Study Network

Data Processing

Forty-four participants initially took part in this experiment; however, one participant was excluded from the dataset due to experiencing dizziness and being unable to complete all three scenarios. Consequently, data analysis was conducted after cleaning the dataset and removing any outliers. After processing the data, a descriptive analysis was performed to gain insights into the characteristics of the participants. Subsequently, statistical tests were conducted to evaluate their driving behavior in response to the new BSW-H system.

Descriptive Analysis

The data from both pre-simulation and post-simulation surveys were utilized for descriptive analysis. Table 2 provides an overview of the participants' socio-demographic characteristics. Information collected includes participants' gender, age, ethnicity, employment status, and income level.

A majority of participants (51.2%) expressed a preference for a combination of visual and audible warnings, while 90.7% rated their experience as either "Excellent" or "Good." Furthermore, an overwhelming 86.0% of participants believed that BSW-H contributed to safer driving. Figures 13 and 14 present the pre-simulation and post-simulation survey results.

Table 2: Participants Socio-Demographic

Variable	Groups	Frequency	Percentage
Gender	Male	25	58.10%
	Female	18	41.90%
Age Groupe	18-25	10	23.30%
	26-35	19	44.20%
	36-45	8	18.60%
	46-55	3	7.00%
	56-65	3	7.00%
Employment Status	Full-time	20	46.50%
	Part-time	11	25.60%
	Unemployed	10	23.30%

	Not specified	2	4.70%
Annual Income	< $20000	8	18.60%
	$20,000-$29,999	11	25.60%
	$30,000-$49,999	3	7.00%
	$50,000-$74,999	7	16.30%
	$75,000-$99,999	5	11.60%
	More than $100,000	4	9.30%
	Not specified	5	11.60%
Ethnicity	White	16	37.20%
	Asian	10	23.30%
	Black or African American	11	25.60%
	Other	3	7.00%
	Not specified	3	7.00%
Employment Status	Full-time	20	46.50%
	Part-time	11	25.60%
	Unemployed	10	23.30%
	Not specified	2	4.70%

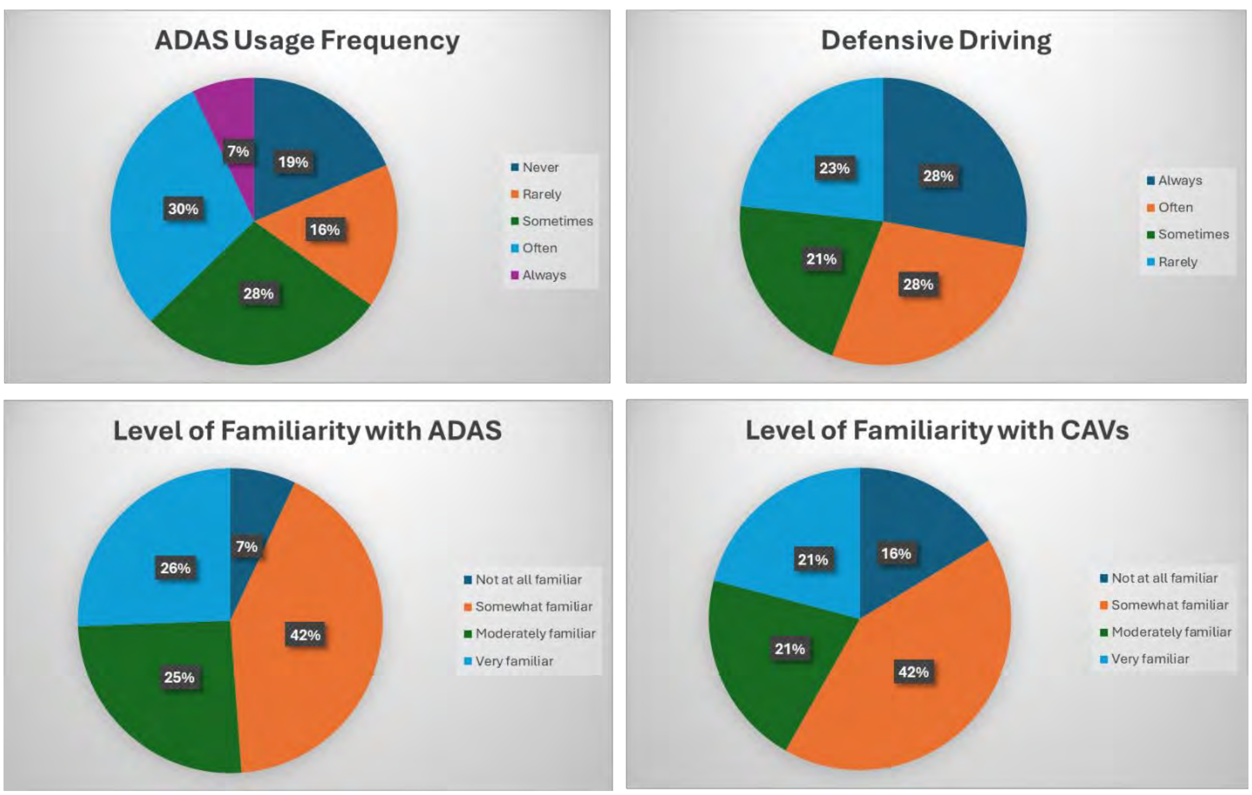

Figure 14: The results of the pre-survey

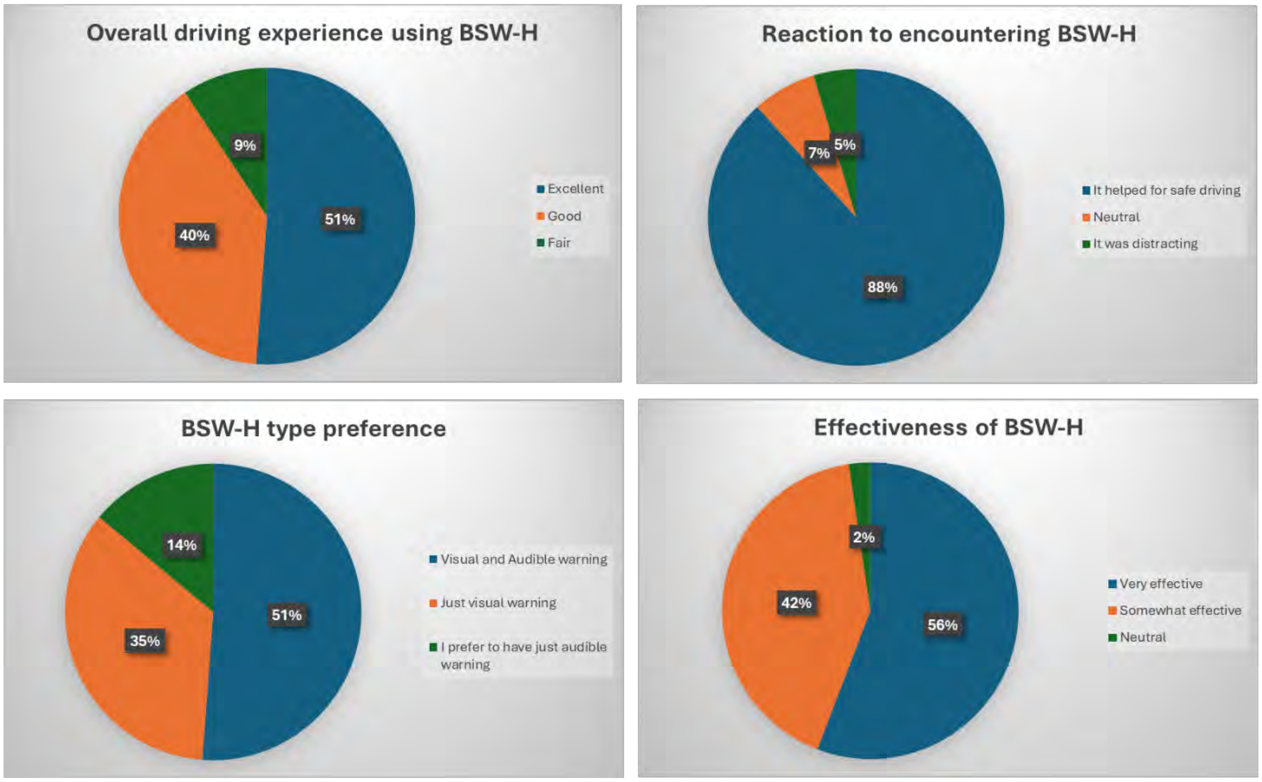

Figure 15: The results of the post-survey

5. Results & Discussions

To assess the effectiveness of the BSW-H on driving behavior, we evaluated two performance measures: the average speed difference in 5-second intervals before and after receiving the warning, and the time spent in the truck's blind spot.

For the time spent in the blind spot, as defined in the Methodology section, the duration between the UV's entry and exit from the blind spot was calculated and analyzed. Table 3 presents the summary statistics of the time spent in the trucks' blind spot zones. Figure 16 illustrates the boxplot of the time duration across the three scenarios for all participants.

Table 3: Summary statistics of time duration spent in the blind spot zones

Scenario	Count	Mean	Standard Deviation	Minimum	Median	Maximum
S0	613	2.779	1.087	0.029	2.547	9.311
S1	662	2.933	1.176	0.075	2.800	12.082
S2	657	2.900	1.281	0.097	2.691	13.567

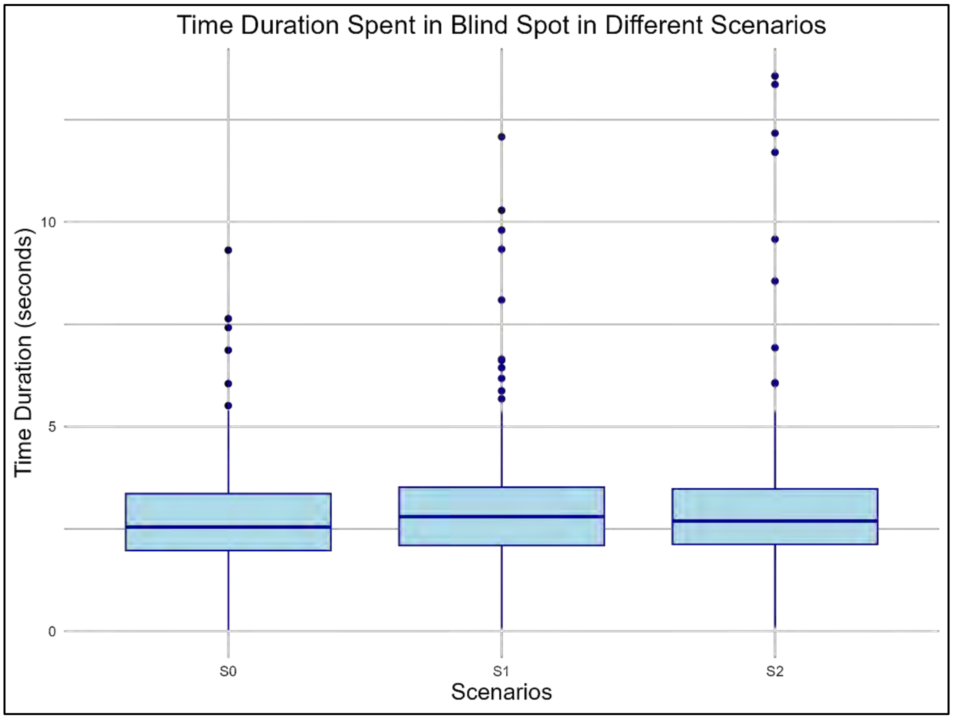

Figure 16: Boxplot of the time duration across the three scenarios

For the average speed difference analysis, we calculated the average speed 5 seconds before and 5 seconds after receiving the warning. When the UV enters the truck's blind spot area, it may take some time to exit, during which multiple warnings can be triggered. Warnings will continue until the UV exits the blind spot. For our analysis, we focused on the moment the UV first entered the blind spot and received the initial warning. This allowed us to assess the participants' driving behavior upon receiving the first warning as they entered the truck's blind spot. Table 4 presents the summary statistics of the average speed difference before and after receiving the warning in 5-second intervals, and Figure 17 shows the boxplot of the average speed difference across the three scenarios.

Table 4: Summary statistics of average speed difference before and after receiving the warning

Scenario	Count	Mean	Standard Deviation	Minimum	Median	Maximum
S0	570	0.128	1.146	-4.315	0.074	4.216
S1	610	0.258	1.192	-4.905	0.302	3.603
S2	601	0.297	1.034	-4.617	0.259	3.463

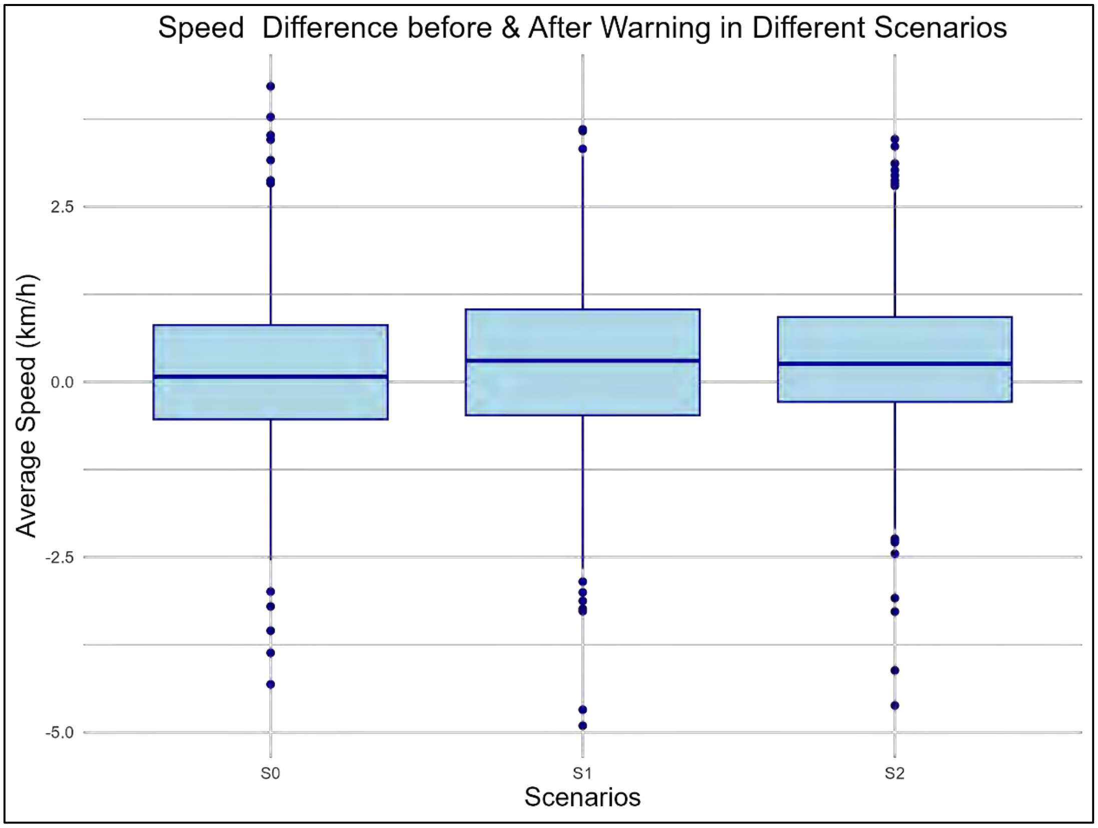

Figure 17: boxplot of the average speed difference across the three scenarios

Participants exhibited different speed behaviors in response to the BSW-H warning. In general, they could either brake to stay clear of the truck's blind spot or speed up to overtake the truck and exit the blind spot. When participants applied the brakes, it was typically when they were driving directly behind the truck in the same lane or opted to maintain a safe distance behind the truck in the adjacent lane.

The plots in Figure 18 illustrate situations where participants used the brake after receiving the BSW-H warning to avoid lingering in the truck's blind spot. The x-axes represents the time from the start of the scenario (in seconds), and the y-axes represent the speed of the UV (in km/h). The vertical red line indicates the moment the warning was triggered, the green line marks the end of the warning, the orange line shows 5 seconds before the warning was triggered, and the purple line indicates 5 seconds after the warning was triggered.

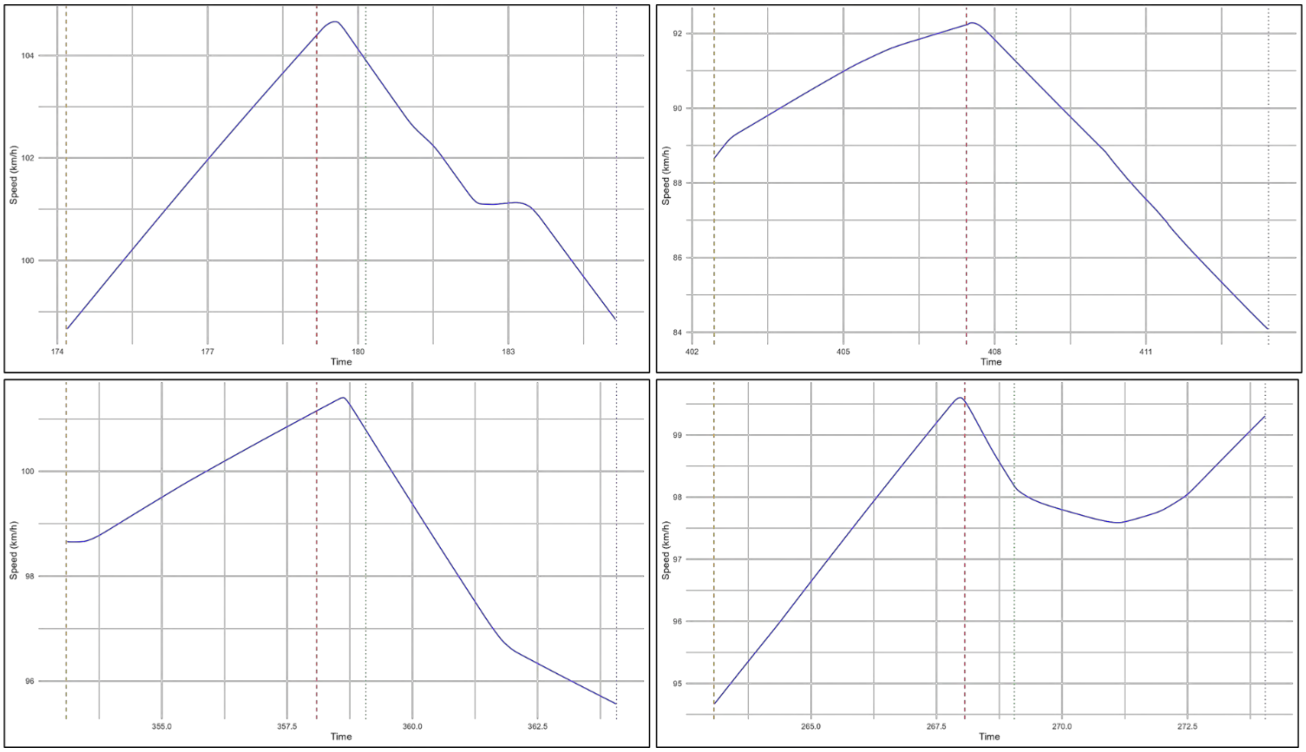

Figure 18: Examples of speed reduction after receiving the BSW-H

In response to the BSW-H warning, some participants chose to accelerate and pass the truck when given the opportunity. The following plot illustrates situations where participants increased their speed to overtake the truck after receiving the BSW-H warning.

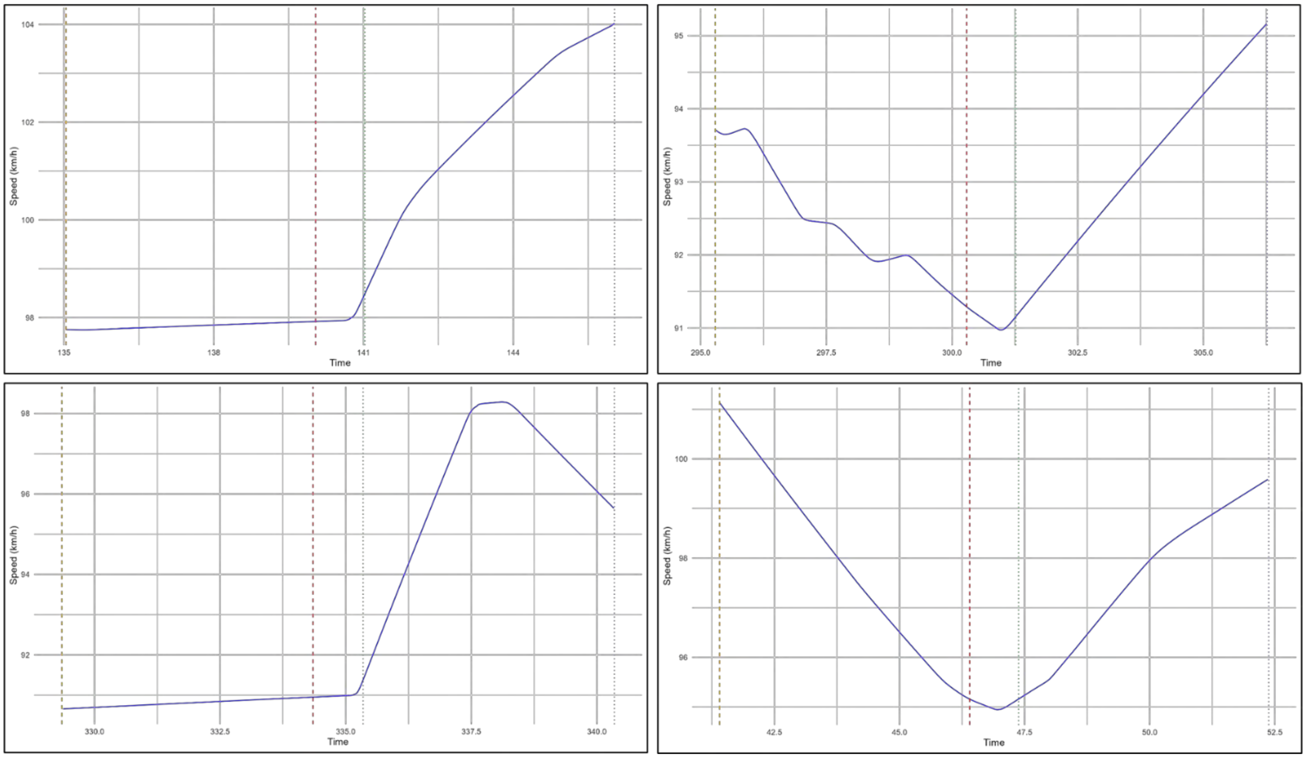

Figure 22: Examples of speed increment after receiving the BSW-H

In some cases, participants made their decision to either brake or accelerate even before receiving the BSW-H warning. One possible explanation is that participants driving smaller vehicles, likely due to prior knowledge or education, aimed to avoid lingering in the truck's "No Zone." The following plot illustrates situations where participants adjusted their speed—either increasing or decreasing—before receiving the BSW-H warning.

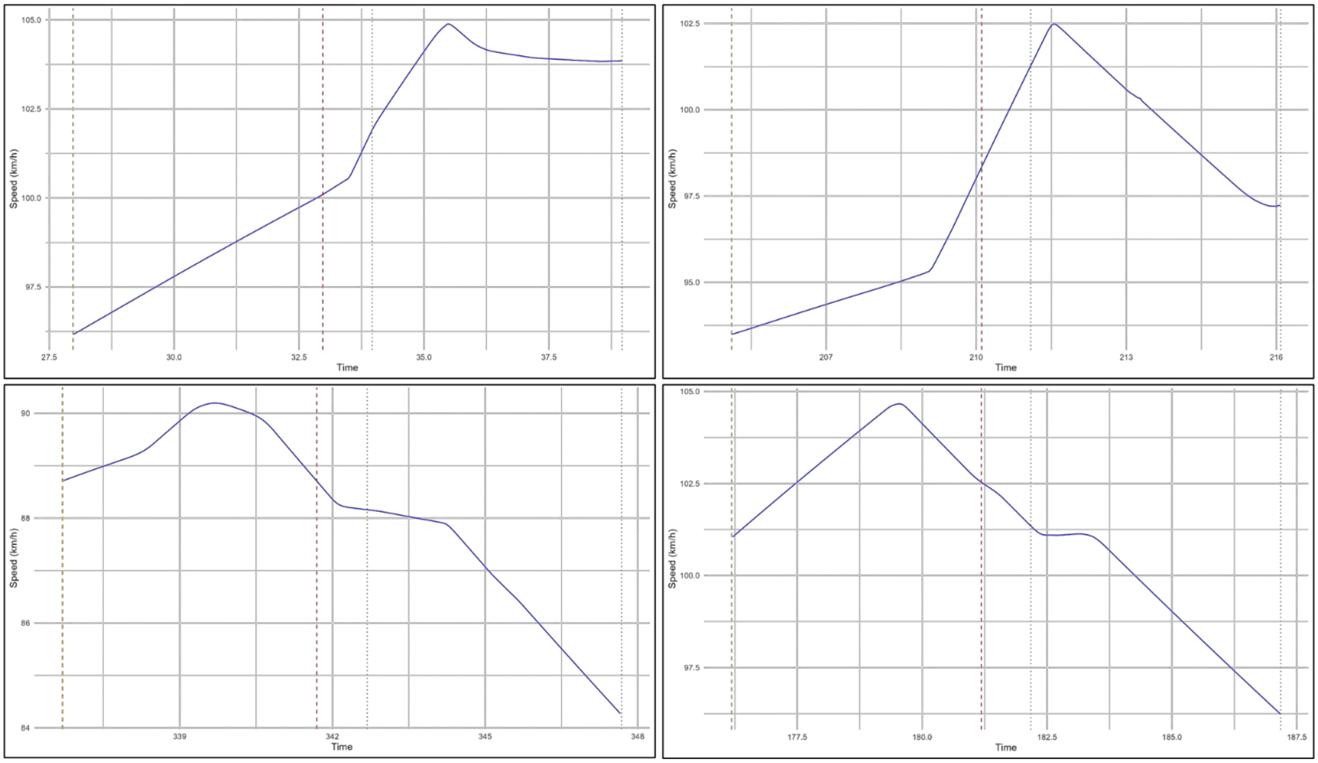

Figure 26: Examples of speed changes before receiving the BSW-H

Statistical Tests

To evaluate the impact of the newly introduced BSW-H system on driving behavior, we used two key performance measures: the *time duration spent in the truck's blind spot* and the *average speed difference* before and after receiving the warning within a 5-second interval.

To analyze these measures across the three scenarios (S0: no warning, S1: visual and auditory warnings, and S2: auditory warning only), we chose to perform an **ANOVA (Analysis of Variance)** test.

ANOVA (Analysis of Variance)

ANOVA is a statistical method used to determine whether there are any significant differences between the means of three or more independent groups. For our purposes, it helps to evaluate whether the time spent in the blind spot or the speed differences vary across the three scenarios (S0, S1, and S2).

ANOVA works by comparing the variance within each group (how much data points differ within each scenario) and between groups (how much the group means differ from each other). If the differences between the group means are large relative to the variation within groups, ANOVA indicates that at least one scenario differs significantly from the others. This test provides a global comparison to determine if any scenario has a statistically significant effect on driving behavior.

However, before conducting an ANOVA, two critical assumptions need to be verified:

- Normality of the Data Distribution:
  - The data for each scenario should follow a normal distribution.
  - To verify this, we performed the **Shapiro-Wilk Test**. The Shapiro-Wilk test compares the sample distribution to a theoretical normal distribution. It yields a p-value, which indicates whether we can assume the data to be normally distributed. If the p-value is greater than a standard significance level (usually 0.05), the data distribution is considered normal. If the p-value is smaller, it suggests that the data significantly deviates from normality, and the normality assumption is violated.
- Homogeneity of Variances:
  - The variances across the different groups should be equal (homogeneous).
  - To test this, we performed **Levene's Test**, which checks whether the variance in performance measures (such as speed difference or time duration) is similar across scenarios. Like the Shapiro-Wilk test, Levene's test produces a p-value. If the p-value is greater than 0.05, the assumption of homogeneity of variance is met. If the p-value is below 0.05, it indicates that the variances are unequal, violating this assumption.

If both the normality and homogeneity of variance assumptions are satisfied, we can proceed with the ANOVA test. A significant ANOVA result (p-value < 0.05) would indicate that at least one of the scenarios significantly impacts the driving behavior as measured by either time spent in the blind spot or speed differences (63).

Non-Parametric Alternative: Kruskal-Wallis Test

In situations where the assumptions of ANOVA (normality and homogeneity of variances) are violated, we turn to a non-parametric alternative: the **Kruskal-Wallis Test,** which is a rank-based test. This test does not assume a normal distribution or equal variances between groups, making it more flexible than ANOVA when dealing with real-world data that often do not meet strict assumptions.

In our case, it ranks the time duration spent in the blind spot or speed differences across all participants and scenarios, then compares the ranks across the three scenarios. Like ANOVA, it returns a p-value. A significant result (p-value < 0.05) from the Kruskal-Wallis test indicates that there is a statistically significant difference between at least two scenarios, but it does not specify which ones (63).

Post-hoc Analysis: Pairwise Wilcoxon Test

If either the ANOVA or Kruskal-Wallis test yields a significant result, indicating that there is a difference between the scenarios, we then perform a **post-hoc analysis** to identify which specific scenarios are different from one another. For this, we use the **Pairwise Wilcoxon Test**, a non-parametric alternative to the t-test for comparing pairs of groups (63).

The Wilcoxon test compares the driving behavior between each pair of scenarios (e.g., S0 vs. S1, S0 vs. S2, and S1 vs. S2) to determine whether the difference between them is statistically significant. To ensure the robustness of the results and to account for multiple comparisons, we apply the **Bonferroni correction**, which adjusts the p-values to prevent the risk of false positives (Type I errors).

Results of Time Duration Spent in Blind Spot Zone Analysis

Shapiro-Wilk test

First, we conducted the Shapiro-Wilk test to check whether the data followed a normal distribution.

- ✓ S0: p-value = 1.22e-15
- ✓ S1: p-value = 1.05e-22
- ✓ S2: p-value = 7.02e-29

The p-values for all scenarios are significantly below 0.05, indicating that the data for each scenario does not follow a normal distribution.

Levene's test

The Levene's test checks if the variances across groups are equal. The following is the result of Levene's test.

- ✓ F value: 0.111
- ✓ p-value: 0.895

The high p-value (0.8947) indicates that there is no significant difference in variances across the three scenarios. This suggests that the assumption of homogeneity of variances is met, even though the normality assumption is violated.

Kruskal-Wallis test

Due to the violation of the normality assumption in the Shapiro-Wilk test, we conducted the Kruskal-Wallis test as a non-parametric alternative to ANOVA. Following is the result of the Kruskal-Wallis test.

- ✓ Statistic: 7.10
- ✓ p-value: 0.029

The p-value (0.0287) is below the 0.05 threshold, indicating a statistically significant difference in the time duration across the three scenarios. This suggests that at least one of the scenarios has a significantly different mean duration compared to the others.

Pairwise Wilcoxon test

To compare the scenarios together, we conducted the pairwise Wilcoxon test. The results of the test are:

- ✓ S0 vs S1: p-value = 0.033
- ✓ S0 vs S2: p-value = 0.161
- ✓ S1 vs S2: p-value = 1.000

The p-value of 0.033 (after Bonferroni correction (63)) suggests that there is a statistically significant difference in time duration spent in the blind spot between Scenario S0 and Scenario S1.

The p-value of 0.161 indicates no statistically significant difference between Scenario S0 and Scenario S2.

The p-value of 1.000 indicates no statistically significant difference between Scenario S1 and Scenario S2.

This analysis suggests that the introduction of both visual and auditory warnings (Scenario S1) caused a significant change in the time duration that participants spent in the blind spot compared to the scenario with no warnings (S0). However, the auditory warnings alone (Scenario S2) did not significantly differ from either S0 or S1. Further analysis could explore why S1 alone produced significant differences compared to S0, but not compared to S2. Table 5 presents the summary results of the time duration analysis.

Table 5: Summary results of time duration analysis

Summary Results of Time Duration Spent in Blind Spot Zone Analysis		
Shapiro-Wilk test for Normality	S0 S1 S2	p-value = 1.22e-15 p-value = 1.05e-22 p-value = 7.02e-29
Levene's Test for Homogeneity of Variances		F value: 0.111 p-value: 0.895
Kruskal-Wallis Test (a non-parametric alternative to ANOVA)		Statistic: 7.10 p-value: 0.029
Pairwise Wilcoxon Test (Post-hoc Analysis)	S0 S1 S2	p-value = 0.033 p-value = 0.161 p-value = 1.000

Results of Speed Difference Before & After Warning Analysis

Shapiro-Wilk test

To assess if the dataset has a normal distribution, we conducted the Shapiro-Wilk test. The results are:

- ✓ S0: p-value = 0.005
- ✓ S1: p-value = 0.059

- ✓ S2: p-value = 0.004

The results indicate that the data in Scenario S1 follows a normal distribution ($p > 0.05$), which suggests that the speed differences in this scenario align with the assumption of normality. However, the data in Scenario S0 and Scenario S2 violate the normality assumption ($p < 0.05$), indicating that the speed differences in these scenarios deviate significantly from a normal distribution.

Levene's test

The p-value from Levene's test exceeds 0.05, indicating no significant variance differences among the three scenarios. This suggests that the assumption of equal variances is satisfied, despite the violation of the normality assumption.

- ✓ F value: 2.023
- ✓ p-value: 0.133

Due to violations of the normality assumption in S0 and S2, we cannot rely solely on parametric tests like ANOVA to analyze these scenarios. Instead, we must consider non-parametric alternatives, such as the Kruskal-Wallis test, which is more appropriate when the normality assumption is not met.

Kruskal-Wallis test

- ✓ Statistic: 13.2
- ✓ p-value: 0.001

The Kruskal-Wallis test result ($p < 0.05$) indicates a significant difference in speed variations across the three scenarios.

Pairwise Wilcoxon test

The pairwise Wilcoxon tests were conducted to compare the scenarios in terms of speed differences before and after receiving the warning.

- ✓ S0 vs S1: p-value = 0.011
- ✓ S0 vs S2: p-value = 0.002
- ✓ S1 vs S2: p-value = 1.000

The pairwise Wilcoxon test results reveal significant differences in average speed changes over a 5-second interval between Scenario S0 (no warning) and the other two scenarios: S1 (audio and visual warnings) and S2 (audio-only warnings). However, no significant difference was observed between Scenarios S1 and S2, suggesting that the type of warning (audio vs. audio and visual) did not significantly influence the average speed difference compared to the scenario without any warning (S0). Table 6 presents the summary results of speed difference analysis.

Table 6: Summary results of Speed Difference Analysis

Summary Results of Speed Difference Analysis		
Shapiro-Wilk test for Normality	S0 S1 S2	p-value = 0.005 p-value = 0.059 p-value = 0.004
Levene's Test for Homogeneity of Variances		F value: 2.023 p-value: 0.133
Kruskal-Wallis Test (a non-parametric alternative to ANOVA)		Statistic: 13.2 p-value: 0.001
Pairwise Wilcoxon Test (Post-hoc Analysis)	S0 S1 S2	p-value = 0.011 p-value = 0.002 p-value = 1.000

Conclusion

This study employed a driving simulator to assess the impact of the newly designed Blind Spot Warning System (BSW-H) on driving behavior. The simulator, representing the User Vehicle (UV), alerted drivers when they entered defined blind spot zones around trucks. The blind spot areas were designed based on existing literature, as there is no standardized definition. Three blind spot areas were created on the rear, right, and left sides of the truck. Drivers were prompted with visual and audio warnings when they entered each of these areas. The study incorporated three driving scenarios: no warnings (S0), both visual and auditory warnings (S1), and visual-only warnings (S2). The goal was to evaluate how drivers responded to these warnings.

Participants' driving behavior was measured through two key metrics: the time spent in the truck's blind spot and the speed difference before and after receiving the warning. The driving simulator recorded detailed trajectory data every 0.01 seconds, capturing crucial driving variables such as speed, throttle, and brake application. A total of 43 participants completed the study, and statistical analyses were conducted to assess their responses across the three scenarios. Through these analyses, this research aimed to provide insights into how the BSW-H system influences driver decision-making and safety in blind spot situations.

The analysis of the time spent in the truck's blind spot showed that the data did not follow a normal distribution, as evidenced by the Shapiro-Wilk test. Despite this, the Levene's test confirmed that variances were homogeneous across scenarios. Using the Kruskal-Wallis test, a statistically significant difference was found in blind spot time between scenarios ($p = 0.0287$). The post-hoc Pairwise Wilcoxon test revealed a significant difference between Scenario S0 (no warning) and Scenario S1 (visual and auditory warnings), suggesting that there was a significant difference in driving behavior between the two scenarios. In other words, the introduction of the combined visual and auditory warnings in Scenario S1 had an impact on the participants' behavior compared to Scenario S0. However, no significant differences were found between Scenarios S0 and S2 or between Scenarios S1 and S2, indicating that the visual & audio warnings (S1) had a stronger influence than the audio-only warning (S2).

In the analysis of speed differences before and after receiving the warning, only Scenario S1 followed a normal distribution. The Kruskal-Wallis test showed a significant difference in speed variations across the scenarios ($p = 0.00136$), with the Pairwise Wilcoxon test indicating that participants significantly altered their speed after receiving warnings in both S1 and S2. However, no significant difference was found between S1 and S2, suggesting that the type of warning did not cause any significant change in speed behavior.

Overall, the results of the statistical analyses suggest that the newly introduced BSW-H system is effective in modifying driving behavior. The time spent in the blind spot of the trucks had a significant change between the base scenario (S0) and the scenario with both visual and auditory warnings (S1). Moreover, the results of the speed difference analysis showed a significant difference between the base scenario (S0) and two warning scenarios (S1 and S2).

The results of this study provide valuable insights into how drivers react to the BSW-H system. However, employment of more participants can help to gain better understanding of the effect of BSW-H on driving behavior. Additionally, further research could examine the role of different traffic patterns, light conditions (day or night), and weather conditions on the performance of the BSW-H. Moreover, while this study focused on time spent in the blind spot and speed differences, other performance metrics, such as lane changes, reaction times, or headway distances, could provide a more comprehensive assessment of the BSW-H system's impact on driving safety.

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Appendix A

Pre-Simulation Survey Questions

"***The Blind Spot Warning with Hedging (BSW-H)*** *aims to enhance existing Blind Spot Warning (BSW) technology. With this innovative approach, we propose issuing in-vehicle blind spot warnings to drivers when they enter the blind spots of trucks.*"

1. Please select your subject number
2. What is your gender?
   a. Male
   b. Female
3. What is your age group?
   a. 18 – 25,
   b. 26-35,
   c. 36-45,
   d. 46-55,
   e. 56- 65,
   f. More than 65
4. What is your ethnicity?
   a. American Indian or Alaska Native,
   b. Asian,
   c. Black or African American,
   d. White,
   e. Other
5. What is your present educational status?
   a. High School or less,
   b. Associate degree,
   c. Undergraduate student,
   d. Graduate
   e. Postgraduate
6. Are you currently employed?

a. No,

b. Part-time,

c. full-time

7. What is your annual household income?

   a. Less than $20,000,

   b. $20,000 - $29,999,

   c. $30,000 - $49,999,

   d. $50,000 - $74,999,

   e. $75,000 - $99,999,

   f. More than $100,000

8. What is your household size?

   a. Only me

   b. 2

   c. 3

   d. 4 and more.

9. What type of driving license do you have?

   a. Permanent license for regular vehicles-class C,

   b. Permanent license for all types of vehicles class A,

   c. Learner’s Permit,

   d. Don’t have a license

10. How many years have you been driving a car?

    a. Less than 1 year

    b. Between 1 and 2 years

    c. Between 2 and 5 years

    d. More than 5 years

    e. None

11. How many cars does your household own?

    a. None

    b. 1

    c. 2

    d. 3 or more

12. Are you familiar with Connected and Autonomous Vehicles (CAVs)?
    a. Not at all familiar
    b. Somewhat familiar
    c. Moderately familiar
    d. Very familiar
13. Do you practice defensive driving in your daily drive?

Defensive driving comprises skills and tactics to reduce crash risks, including hazard awareness, safe distance maintenance, anticipating other drivers' actions, quick reactions to surprises, adherence to traffic laws, staying alert, and avoiding distractions like mobile phone use.

    a. Never
    b. Rarely
    c. Sometimes
    d. Often
    e. Always
14. Are you familiar with trucks' blind spots/no zones?
    a. Yes
    b. No
15. Have you ever heard about Blind Spot Warning (BSW)?
    a. Yes
    b. No
16. How familiar are you with Advanced Driving Assistance Systems (ADAS) technology?

"**ADAS** comprises safety features and technologies to boost vehicle safety and assist drivers, utilizing sensors and cameras to detect and mitigate potential road hazards. Examples: adaptive cruise control, lane departure warning, automatic emergency braking, and blind spot warning."

    a. Not at all familiar
    b. Somewhat familiar
    c. Moderately familiar
    d. Very familiar
17. How often do you use Advanced Driving Assistance Systems (ADAS) technology for your driving decisions?
    a. Never
    b. Rarely

c. Sometimes
d. Often
e. Always

18. Do you regularly rely on in-vehicle driver warnings during your daily drive?
    a. Yes, I frequently rely on in-vehicle driver warnings
    b. Sometimes, I use in-vehicle driver warnings depending on the situation
    c. No, I rarely or never rely on in-vehicle driver warnings
    d. I'm not sure
19. If you own a car, please provide the make and model. Additionally, specify any advanced driver assistance features (ADAS) your car may have.

For Example:

Car Model and Make: Honda Civic- 2018

ADAS: Forward Collision Warning, Lane Departure Warning, Rear Cross Traffic Warning, Blind Spot Warning, Adaptive Cruise Control, ...

Appendix B

Post-Simulation Survey Questions

"***The Blind Spot Warning with Hedging (BSW-H)*** *aims to enhance existing Blind Spot Warning (BSW) technology. With this innovative approach, we propose issuing in-vehicle blind spot warnings to drivers when they enter the blind spots of trucks.*"

1. Please select your subject number
2. How would you rate your overall driving experience using the Blind Spot Warning with Hedging (BSW-H)?
   a) Excellent
   b) Good
   c) Fair
   d) Poor
3. What was your reaction to encountering a Blind Spot Warning with Hedging (BSW-H)?
   a) It was distracting
   b) It helped for safe driving
   c) Neutral
   d) I missed it
4. Which type of Blind Spot Warning with Hedging (BSW-H) do you prefer?
   a) Visual and Audible warning
   b) Just visual warning
   c) I prefer to have just audible warning
5. How would you rate the effectiveness of Blind Spot Warning with Hedging (BSW-H) on the safety of driving?
   a) Very effective
   b) Somewhat effective
   c) Neutral
   d) Somewhat ineffective
   e) Very ineffective
6. After this experience, do you think the Blind Spot Warning with Hedging (BSW-H) will help you to drive safely?
   a) Yes
   b) No
   c) Maybe
7. Will you return for another simulation run using the driving simulator?
   a) Yes
   b) No
   c) Maybe
8. Please check the intensity of any symptom that applies to you now.
   d) General discomfort, Fatigue,
   e) Headache, Eyestrain,
   f) Blurred Vision,
   g) Salivation increase/decrease,
   h) Sweating,
   i) Dizziness,
   j) Nausea
   k) None