
# Strategies for Improved Driver Behavior within Work Zones

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16. Abstract

Work zones (WZs) are among the most hazardous roadway environments due to restricted geometry, temporary traffic control, and increased driver workload, which often lead to speeding and elevated crash frequency as well as severity. A section of roadway of nearly 8 miles long on I-65, in Robertson County, near the Kentucky state border, where additional lanes were being added, was identified as the study location. The posted speed limit of the WZ was 55 mph. This study evaluates the effectiveness of speed feedback mechanisms: Dynamic Speed Feedback Signs (DSFS), Speed Wizard (SW), and combinations of SW with Portable Changeable Message Signs (PCMS), in mitigating speeding behavior within freeway WZs. High-resolution vehicle trajectory data were collected through a multi-camera video system and analyzed using three complementary models: a Generalized Ordered Logit (GOL) model to identify determinants of speeding severity, a Bayesian Generalized Additive Model (BGAM) to examine non-linear speed adjustments, and a Spatial Lag Model (SLM) to assess inter-vehicle dependencies and spatial spillover effects. Results showed that DSFS and SW were the most effective interventions, significantly reducing mean speeds and severe speeding violations by at least 8%. Despite the speed limit of 55 mph, 75% of the vehicles travel at speeds higher than the posted limit. After crossing the feedback sign, the speed of the vehicle tended to stabilize around 58 mph, while higher speed vehicles decelerated and lower speed vehicles accelerated. Spatial effect on the driving behavior was found statistically significant, which showed speed reductions extended to neighboring vehicles, indicating collective behavioral adaptation. Overall, the findings demonstrate that speed feedback systems are highly effective, data-driven countermeasures for enhancing driver compliance and safety in WZs.

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| Enhancing work zone crash severity analysis: The role of synthetic minority oversampling technique in balancing minority categories | Muhammad Adeel, Asad J Khattak, Sabyasachee Mishra, Diwas Thapa | Accident Analysis & Prevention | (Adeel et al., 2024) |
| Enhancing safety in work zones: the influence of speed feedback on driving behavior | Pawan Neupane, Diwas Thapa, Sabyasachee Mishra, Jason R Quicksall | Journal of Safety Research | (Neupane et al., 2025) |
| To balance or not to balance? Applying a machine learning technique to oversample severe injury crashes in work zones | Muhammad Adeel, Asad J Khattak, Sabyasachee Mishra, Diwas Thapa | 104th Annual Meeting of the Transportation Research Board | (Adeel et al., 2025) |
| Effect of Speed Feedback Mechanism on Speed and Headway Distributions in Long Work Zones | Pawan Neupane, Sabyasachee Mishra, Jason R Quicksall | 104th Annual Meeting of the Transportation Research Board | TRBAM-25-06263 |
| Trajectory-based Analysis of the Effectiveness of Speed Feedback in Work Zones | Pawan Neupane, Muhammad Adeel, Asad J. Khattak, Sabyasachee Mishra, Jason R Quicksall | 105th Annual Meeting of the Transportation Research Board | TRBAM-26-05374 |

# Executive Summary

The primary objective of this research was to evaluate driver speed behavior and compliance within freeway work zones (WZs) under varying roadways, environmental, and operational conditions. Excessive speeding within WZs is one of the most prevalent and dangerous driver behaviors, increasing both the frequency and severity of crashes. Despite improvements in WZ design and signage, many drivers fail to adjust their speeds appropriately when approaching or passing through construction zones.

To address this persistent safety issue, the study focused on the use of speed feedback systems, including Dynamic Speed Feedback Signs (DSFS), Speed Wizard (SW), and combinations of SW with Portable Changeable Message Signs (PCMS) as behavioral interventions to improve compliance and reduce variability.

The research developed three complementary analytical models:

1. A Generalized Ordered Logit (GOL) model to assess the determinants of speeding severity.
2. A Bayesian Generalized Additive Model (BGAM) to analyze non-linear speed adjustments between the start and end of observation areas; and
3. A Spatial Lag Model (SLM) to quantify spatial interdependence in speed behavior across vehicles.

By combining these models with trajectory-level vehicle data obtained from multiple synchronized cameras, this research presents a comprehensive behavioral, temporal, and spatial assessment of driver responses to speed feedback mechanisms in real-world WZ environments.

WZs represent a unique and complex traffic environment where geometric constraints, temporary signage, and human factors intersect. National crash databases consistently report elevated crash rates in WZs, especially in the activity area where driver workload and environmental complexity are highest. Traditional speed control measures, such as police patrols or automated enforcement, are often impractical or cost-prohibitive for continuous operations. Therefore, non-enforcement-based behavioral feedback systems have gained prominence as viable, cost-effective countermeasures.

Speed feedback signs operate on a psychological feedback principle, providing drivers with immediate, personalized speed information relative to posted limits. Such systems rely on voluntary compliance rather than punitive enforcement, making them effective in promoting short-term behavioral adjustment. However, their long-term and spatial effects, such as how drivers react downstream of feedback, remain less explored. This study's multi-camera setup provides a rare opportunity to examine both immediate and sustained behavioral responses.

A WZ in I-65 in Robertson County, near the state border with Kentucky, was identified as the location for data collection, where an additional lane was being added to the freeway. High-resolution vehicle trajectory data were collected using five longitudinally placed cameras covering the WZ corridor. The cameras were solar-powered and were mounted on 20-foot-high poles. The system was equipped with remote connection features that uploaded the data to the cloud continuously. Nearly two and a half months of continuous data were collected by the cameras.

The videos were processed through You Only Look Once (YOLO) object detection and ByteTrack tracking algorithms, followed by homography transformations to convert image coordinates into real-world metrics. Data was categorized by lane, vehicle type, feedback condition, and environmental context. The resulting dataset enabled the estimation of individual and collective speed patterns across different areas of WZ relative to speed feedback mechanisms.

Across all analyses, results consistently demonstrated that feedback mechanisms effectively reduce speeding tendencies, but their impact differs by type, lane position, and spatial proximity. Drivers exposed to DSFS or SW exhibited significant speed reductions immediately after feedback, with observable spillover benefits extending to nearby vehicles. However, mixed treatments (SW+PCMS) produced smaller effects, suggesting cognitive overload or diminished attention when multiple stimuli compete for driver focus. The presence of spatial dependence further indicates that speed behavior is contagious; drivers adapt to the prevailing flow patterns of nearby vehicles, emphasizing the importance of collective dynamics in WZ safety management.

## *Key Findings*

- Dynamic Speed Feedback Signs and Speed Wizard are the most effective feedback systems for reducing speeding violations. Both produced statistically significant reductions across all models, while the combination (SW+PCMS) was less effective in reducing vehicle speeds and speeding violations. The severe (>15 mph) and moderate (10-15 mph) speeding violations are reduced by at least 8% and the speed is also reduced by more than 5% in each feedback deployment.
- Spatial spillover effects amplify the impact of feedback systems. The SLM results revealed strong spatial interdependencies where speed reduction due to the feedback system spills over.
- Lane position and vehicle type are significant behavioral determinants. Vehicles traveling on inner lanes exhibited higher speeds than vehicles on outer lanes. Trucks not only traveled more slowly but also contributed to overall traffic calming as compared to cars.
- Non-linear adaptation to information feedback occurs around a critical threshold speed (~58 mph). The BGAM analysis showed that vehicles exceeding this threshold tend to decelerate in the work zone, while slower vehicles accelerate, indicating natural self-stabilization after crossing speed feedback signs.
- Environmental and temporal factors influence compliance. Weekend and clear-weather conditions were associated with higher probabilities of severe speed violations, while rain and overcast conditions were associated with lower speeds due to perceived risk. The results are generalizable to other long-distance and long-duration work zones in Tennessee.

## *Key Recommendations*

- Prioritize DSFS/SW deployment in long-distance and long-duration WZs, which have been found to increase crash frequency by a significant amount. DSFS consistently achieved the largest reductions in both direct and indirect speed effects. Agencies should deploy DSFS units in high-speed and high-volume corridors, particularly in taper and activity areas, to maximize compliance. DSFS combines visual salience and feedback ambiguity, effectively prompting drivers to self-correct without explicit enforcement.

- Avoid Excessive Information Layering. The combination of SW + PCMS showed diminished effectiveness, indicating potential driver desensitization. Messages should remain concise and uniform to reduce cognitive overload.
- Implement Lane-Specific Monitoring and Enforcement. Since left-lane traffic is more prone to higher-order speeding, targeted enforcement (e.g., lane-specific radar monitoring or automated detection) can effectively control aggressive driving behavior.
- Adopt Context-Aware Enforcement Policies. Temporal (weekend) and environmental (weather) variations in speeding behavior warrant adaptive enforcement, possibly integrating real-time traffic, lighting, and weather data to prioritize deployment schedules. Providing context-aware enforcement policies enables the deployment of scarce resources, while the violations are more frequent or more severe.
- Integrate Spatial Analytics into Safety Evaluation. For selected work zones, agencies should incorporate spatial econometric models in post-implementation assessments to quantify direct and spillover effects, ensuring a comprehensive evaluation of feedback treatments and enforcement strategies.

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## Glossary of Key Terms and Acronyms

| Acronym | Full Form |
|---|---|
| **AADT** | Annual Average Daily Traffic |
| **AIC** | Akaike Information Criterion |
| **ASE** | Automated Speed Enforcement |
| **BIC** | Bayesian Information Criterion |
| **BGAM** | Bayesian Generalized Additive Model |
| **DMS** | Dynamic Message Sign |
| **DSFS** | Dynamic Speed Feedback Sign/System |
| **FHWA** | Federal Highway Administration |
| **GOL** | Generalized Ordered Logit |
| **HMC** | Hamiltonian Monte Carlo |
| **MCMC** | Markov Chain Monte Carlo |
| **MUTCD** | Manual on Uniform Traffic Control Devices |
| **NDS** | Naturalistic Driving Study |
| **PCMS** | Portable Changeable Message Sign |
| **POA** | Proportional Odds Assumption |
| **SHRP** | Second Strategic Highway Research Program |
| **SLM** | Spatial Lag Model |
| **SPE** | Speed Photo-Radar Enforcement |
| **SW** | Speed Wizard |
| **TDOT** | Tennessee Department of Transportation |
| **TTC** | Temporary Traffic Control |
| **VSL** | Variable Speed Limit |
| **WZ** | Work Zone |

# Chapter 1 Introduction

Work Zones (WZs) are indispensable for maintaining and improving roadway infrastructure, but simultaneously pose substantial challenges to safety and traffic operations. The Fatality Analysis Reporting System (FARS) reported over 100,000 WZ crashes in the United States in 2023 (FHWA, 2023), underscoring the urgency of effective traffic control and driver-behavior management strategies. Narrow right of way, shifting lane alignments, and temporary signage create an unfamiliar driving environment that often leads to elevated crash frequency and severity (Nnaji et al., 2020; Thapa & Mishra, 2021). Empirical evidence suggests that the activity area where active construction, workers, and equipment are present is particularly hazardous, accounting for nearly 40-70 percent of total WZ crashes (Dissanayake & Akepati, 2009a; Garber & Zhao, 2002).

Speeding remains one of the most critical contributors to crash risk in WZs, affecting both the frequency and the severity of incidents(Khattak et al., 2002; Sorensen et al., 2015). While Automated Speed Enforcement (ASE) and police patrols have been effective deterrents(Benekohal et al., 2009a), such strategies are not always viable due to regulatory constraints and limited enforcement resources. Consequently, speed feedback systems, such as the Dynamic Speed Feedback System (DSFS), Speed Wizard (SW), and Portable Changeable Message Signs (PCMS), have emerged as promising non-intrusive tools to enhance compliance and influence driver cognition. These systems rely on voluntary behavioral correction rather than punitive enforcement, providing immediate, context-specific feedback that encourages safer driving behavior.

However, previous evaluations of speed feedback effectiveness have been limited in scope, typically relying on aggregated or point-based speed measurements that obscure how driver behavior evolves over space and time. Moreover, few studies have accounted for the influence of surrounding vehicles, even though driver responses are strongly shaped by peer behavior within dense traffic streams. This gap in knowledge underscores the need for high-resolution, trajectory-based analyses that can capture both individual and collective responses to feedback interventions.

## *1.1 Study Motivation*

To address the shortcomings, the present study applies a trajectory-based framework using high-resolution vehicle movement data collected through a network of longitudinal cameras deployed within the activity area of freeway WZ. This design allows for the reconstruction of continuous vehicle trajectories, providing detailed insight into how speeds evolve before, during, and after exposure to feedback systems. By combining computer-vision-based trajectory extraction with advanced econometric and spatial modeling, the study investigates not only the direct effect of feedback signs on individual drivers but also spillover effects influencing surrounding vehicles through localized interactions and visual cues.

The research thereby moves beyond traditional aggregate approaches, incorporating spatial dependence via a Spatial Lag Model (SLM) and examining behavioral adaptation using a Generalized Ordered Logit (GOL) model, and a Bayesian Generalized Additive Model (BGAM). Together, these methods enable a comprehensive assessment of how feedback devices influence driver speed choice, compliance, and stability within complex, high-risk WZ environments.

## *1.2 Research Objectives*

The overarching goal of this project is to analyze and model driver speed behavior within WZs under varying roadway, environmental, and operational conditions, with emphasis on understanding the effects of speed feedback systems and spatial dependencies.

Specific objectives include:

1. To examine the determinants of speeding severity using a GOL model, identifying factors that influence minor, moderate, and severe speed violations.
2. To model non-linear behavioral adjustments in speed before and after encountering feedback mechanisms using a BGAM.
3. To evaluate spatial dependencies and spillover effects in driver speeds using an SLM, quantifying how drivers' speeds are influenced by the behavior of surrounding vehicles.
4. To compare the effectiveness of different speed feedback treatments: DSFS, SW, and combination in mitigating speeding behavior and promoting compliance.
5. To provide evidence-based recommendations for improving WZ safety management, feedback placement, and enforcement strategies in accordance with Federal Highway Authority (FHWA) and Tennessee Department of Transportation (TDOT) policy frameworks.

## *1.3 Scope of the Study*

This study focuses on a controlled freeway WZ environment designed to capture real-world driver behavior under varying operational scenarios. Data were collected using multiple high-resolution sensing systems and video-based tracking techniques, ensuring precise measurements of vehicle speed, lane position, and trajectory.

The analysis encompasses three distinct levels:

- End of Observation Area: Behavioral severity analysis utilizing the GOL model to understand driver-level violation outcomes.
- Start and End of Observation Area: Non-linear speed change analysis using BGAM to identify how feedback exposure modifies speed behavior.
- Full Trajectory (Spatial Analysis): SLM to quantify inter-vehicle dependencies and feedback spillover across adjacent lanes and zones.

The study includes both passenger cars and trucks, distinguishing between lane-based operations (left vs. right), temporal conditions (weekday vs. weekend), and weather categories (clear vs. overcast). The feedback treatments were alternated systematically to ensure balanced representation and robust statistical comparisons.

## *1.4 Research Approach*

The research employed a multi-stage analytical framework integrating behavioral econometrics, Bayesian inference, and spatial statistics:

1. Data aggregation and preprocessing: Speed, lane, vehicle class, and feedback type data were aggregated by minute and spatially aligned with WZ layout and signage locations.
2. Modeling Frameworks: The GOL model assessed proportional odds violations and estimated the likelihood of speed violation severity levels. The BGAM model captured non-linear relationships between baseline and post-feedback speeds. The SLM identified spatial dependence across vehicles using Moran's I and Anselin-Kelejian diagnostics.
3. Validation: Each model was validated using standard goodness of fit and information criteria (AIC/BIC), convergence diagnostics, and residual tests for spatial independence.
4. Interpretation: The combined results were synthesized to draw meaningful behavioral, operational, and policy insights.

This integrated approach ensures that both individual driver responses and broader traffic system dynamics are captured, offering a holistic understanding of speed regulation in WZs.

## *1.5 Report Organization*

The remainder of this report contains a literature review that summarizes prior studies on driver behavior and speed feedback systems relevant to WZ safety in Chapter 2. Chapter 3 details the methodology, containing details of data collection, processing, and modeling approaches used in the analysis. The results of the different models and their interpretation are presented in Chapter 4. Finally, Chapter 5 summarizes the overall insights, policy implications and provides actionable recommendations.

# Chapter 2 Literature Review

## 2.1 Work Zone Types

Depending on the duration of work, the Manual of Uniform Traffic Control Devices (MUTCD) categorizes work zones (WZs) into four distinct categories presented in TABLE I.

**TABLE I WORK ZONE TYPES BY DURATION**

| Type | Description |
| --- | --- |
| Long-term stationary | Occupies the location for more than 3 days |
| Intermediate-term stationary | Occupies a location for more than one daylight period up to 3 days, or nighttime work lasting more than an hour |
| Short-term stationary | Daytime work that occupies a location for more than an hour within a single daylight period |
| Short duration | Occupies a location for up to an hour |
| Mobile | Moves intermittently or continuously |

In addition to the definition of WZ types, the MUTCD also provides standards and guidelines for deploying safety signs and systems for Temporary Traffic Control (TTC). WZs can also be categorized based on their location relative to the roadway as follows.

i. Outside the shoulder,
ii. On the shoulder with no encroachment,
iii. On the shoulder with minor encroachment,
iv. Within the median, and
v. Within the traveled way.

## 2.2 Modeling Driver Behavior Near Work Zones

To identify WZ control and enforcement measures, it is important to understand driver behavior in and around WZs. There are three main approaches to modeling driver behavior near WZs. These are (i) the use of traffic simulation, (ii) the use of driving simulators, and (iii) the use of field observations. Drivers show hazardous and aggressive behavior in WZs, which is an outcome of frustration and anger arising from congestion and travel delay. Therefore, researchers and practitioners rely on traffic simulation to study driver behavior when passing through WZs, particularly during hazardous conditions. Microscopic and macroscopic simulation tools are useful in this regard when modeling traffic flow at aggregate and individual levels, respectively (e.g., Berthaume, 2015; Gan et al., 2021; Hou & Chen, 2019, 2020). These simulation techniques have also proven quite useful in investigating driver behavior that would not be observed otherwise in the real world. For example, researchers have relied on simulation techniques to study the impact of Connected and Autonomous Vehicles (CAVs) and their features on driver behavior and WZ safety (e.g., Algomaiah & Li, 2021, 2022; Bashir & Zlatkovic, 2021). Recently, driving simulators have been increasingly used to study driving behavior. They have gained popularity in recent years because of their ability to simulate realistic driving conditions in a safe environment. Their usage has been bolstered by studies that have validated their ability to imitate WZ design, road conditions, and driver reaction (e.g., see Bella, 2005; Bham et al., 2014; Mathur et al., 2010; Zhang et al., 2020). In instances where the effect of new WZ treatments is of interest to researchers and no risk is prevalent, researchers rely on field observations. In this approach, the changes in driver behavior are analyzed after applying the WZ treatment. In most cases, these changes are quantitatively assessed based on the change in certain traffic flow parameter(s), such as Free-Flow Speed (FFS), deceleration, etc., or some violations such as overspeeding, lane change maneuvers, etc. (e.g., Benekohal et al., 2010; Mishra et al., 2021; Thapa & Mishra, 2021).

## *2.3 Driver Behavior in Work Zones*

Based on the literature, driver behavior in WZs is mainly characterized by their compliance with (i) average speed and speed variance, and (ii) merge behavior. Overspeeding and large speed variances in WZs are major contributors to WZ crashes. Higher speeds increase the likelihood of crashes and their severities (Osman et al., 2016, 2018; K. Zhang & Hassan, 2019). Larger speed variances are associated with an increased probability of rear-end crashes. Therefore, WZ treatment focuses on controlling overspeeding and maintaining a uniform traffic flow. The MUTCD defines the use of various TTC approaches, such as the use of traffic signs, flaggers, and Dynamic Message Signs (DMS), to accomplish this. In addition to this, there are other speed enforcement systems and strategies, such as the presence of law enforcement, Speed Photo-radar Enforcement (SPE), Variable Speed Limit (VSL), and Dynamic Speed Feedback System (DSFS). A review of studies that have investigated the effects of employing these systems and strategies is discussed in the next sections.

Driver merge behavior is critical to traffic flow in WZs, as it has direct implications on traffic flow and safety. Inappropriate merge behavior is affected by the speed flow relationship, as it increases travel delay from lane closure (Weng & Meng, 2011). According to a study (Weng & Meng, 2011), merging behavior comprises two distinct tasks. In the first task, the driver determines where to merge, and in the second, the merge action is executed based on the adequacy of the gap in the adjacent through lane. Accordingly, the authors modeled merge behavior using traffic flow parameters as the predictors in three models that corresponded to (i) the location of merge using a log-normal distribution, (ii) a binary logit-based model for merge probability, and (iii) a log-normally distributed merging distance. Other studies have sought to study merge behavior through the identification of merge locations and merge probabilities. For example, Nassab 2006 used Cellular Automata with several rules of lane change to model merge behavior and found the optimal strategy to increase traffic flow when using the Zipper merge (Nassab et al., 2006). The authors reported that the safety gap near the entry of the blocked lane and limiting the maximum allowable speed within a certain region of the WZ could increase traffic flow in WZs. Louisell, et al. 2006 used an agent-based model with game theory to model individual driver behavior and driver interactions, respectively, to determine merging locations (Louisell et al., 2006). The most common approach used to model merge probability is gap acceptance models that assume drivers' decision to merge is dependent on the availability of a safe gap between the lead and following vehicles (Lee, 2006; Toledo et al., 2007; Weng & Meng, 2011). Several strategies are used to enforce appropriate merge behavior.

## 2.4 Work Zone Risk Factors and Driver Behavior

Dissanayake and Akepati 2009 identified WZ characteristics for states part of the Smart Work Zone Deployment Initiative (SWZDI) (Dissanayake & Akepati, 2009b). Their analysis found that almost half of all WZ crashes occurred within or adjacent to work activity. Notably, about 42% of all WZ crashes were rear-end crashes. The primary factor resulting in crashes was taking no improper action (32.1%), followed by inattentive driving (19%) and following closely (9.7%).

WZs cause sudden interruptions in traffic flow, resulting in queues, slowdowns, maneuvers (lane change and overtake), and conflicts. These collectively affect driver behavior (Flannagan et al., 2019). Therefore, road, driver, and environmental characteristics all have an impact on driver behavior. Driver behavior across the literature has been studied alongside WZ, vehicle, environmental, and driver characteristics. (Hamdar et al., 2016) studied driver behavior for various WZ scenarios related to length, barrier type, and level of activity (Hamdar et al., 2016). They reported higher average vehicle speeds along longer WZs, which could be attributed to drivers' growing impatience when navigating through longer lane closures. A difference in time headways and mean space was observed when using different barriers. With the increase in activity level, an overall decrease in speed was also observed. He, et al. 2015 investigated drivers' lane change maneuvers and found vehicle type, lane speed, and volumes to be significant determinants of a lane change in WZs (He et al., 2016). Weng and Meng 2012 investigated the effects of environment, vehicle, and driver characteristics on risky driving behavior at WZs (Weng & Meng, 2012). The authors reported that adverse weather and lighting conditions, the absence of traffic control devices, and old vehicles were associated with risky driving behavior. The authors also found risky driving behavior was observed on single and multilane roads when the lighting conditions were unfavorable and favorable, respectively. Middle-aged male drivers were most likely to exhibit risky driving behavior. After surveying workers (Debnath et al., 2015) identified adverse weather and lighting conditions, distracted driving, roadway type, and alignment as the major risks in WZs. According to the workers, the most hazardous conditions were working in wet weather (skid resistance, reduced visibility), driver frustration and aggression toward traffic controllers, and distracted driving from mobile phone use (Debnath et al., 2015). In terms of time of day, peak hours, and non-daylight hours (dawn, dusk, and night) are considered the most hazardous conditions by workers. Reasons cited for non-daylight hours being the most hazardous were the higher number of drunk drivers and reduced visibility. Similarly, working on freeways and hilly/curved roads was considered risky by workers. Finally, according to the workers, the most effective countermeasures for speed compliance were police enforcement, presence of police cars regardless of the presence of an officer, installation of speed bumps, and WZ-oriented driver education.

## 2.5 Control and Enforcement Strategies

In terms of driver behavior, researchers have extensively studied speed compliance in WZs since overspeeding and speed variation are the main contributors to WZ crashes, most of which are rear-end crashes (Debnath et al., 2014; Hajbabaie, Ramezani, et al., 2011; Meng et al., 2010). The major causes of rear-end crashes are speed variations and queue formation. Therefore, most traffic control strategies in WZs are designed to prevent overspeeding and reduce speed variance by providing motorists with regulatory information or warnings. The traditional approach used to control and guide traffic (and thus, driver behavior) is to use barriers, flaggers, and signs before or in the WZ. The standards and guidelines for their placement and usage are defined under Temporary Traffic Control (TTC) in Part 6 of MUTCD.

There are several traffic control approaches and strategies that are not covered under TTC in MUTCD. These methods can be divided into two broad categories: (i) regulatory methods and (ii) warning strategies. These methods are presented in Table with their discussion as follows.

TABLE II WORK ZONE CONTROL AND ENFORCEMENT STRATEGIES

| Methods | Description |
|---|---|
| **Regulatory strategies** | |
| Speed Photo Radar Enforcement | Identifies motorists driving over the speed limit and issues citations. |
| Police presence | Police officer(s) present on-site to stop and fine speeding vehicles. |
| **Warning strategies** | |
| Traffic barriers | Concrete or water-filled barriers to separate WZ from traffic |
| Ghost police vehicle | A police car is present on-site without a police officer. |
| Dynamic Message Signs (DMS) | Displays regulatory, warning, or informative messages to drivers. |
| Variable Speed Limit (VSL) | Uses sensors to detect changing roads, weather, or traffic conditions and displays a safe speed limit to approaching motorists. |
| Variable Advisory Speed System (VASS) | Displays the speed limit downstream to inform motorists of the change in speed limit. |
| Dynamic Speed Feedback System (DSFS) | Detects and displays the speed of the approaching vehicle to the driver. |

## 2.6 Regulatory Strategies

*i. Speed Photo-Radar Enforcement*

Speed Photo-Radar Enforcement (SPE) uses radar and cameras to detect the speed and registration plates of an oncoming vehicle, respectively. The driver of a vehicle is issued a citation when a pre-specified speed threshold is crossed. An automated version of SPE also exists.

SPE was first implemented in the US by the Illinois DOT (Benekohal et al., 2009b, p. 20, 2010). Over the years, the system has been adopted by several states across the US due to its ability to reduce speeds and improve WZ safety (Ravani et al., 2015). During its first implementation in Illinois, excessive speeding over 10 mph was eliminated, and a reduction in violations of posted speed limits was reduced form from 39.8% to 8.3% (Benekohal et al., 2009b, p. 20, 2010). Furthermore, a reduction in speed by as much as 57% after the removal of SPE, also called the halo effect, has been reported (Benekohal et al., 2010). (Adenaiya, 2017) reported a 10% reduction in speed violations over 6-10 mph after implementing SPE. Similarly, (Retting et al., 2008) also reported a 20% reduction in speed violations exceeding 10 mph along with some halo effects. The halo effects of SPE have been found to extend over several months. (Joerger, 2010; Oregon Department of Transportation, 2015) observed a 27.3% reduction in speeding where SPE was initially installed. SPE systems have also been proven to improve WZ crashes by reducing speed variations. Ambros et al., 2020 found a reduction in speed variance by 2 kmph, along with a 10% reduction in speeding and a 17% reduction in crash rates.

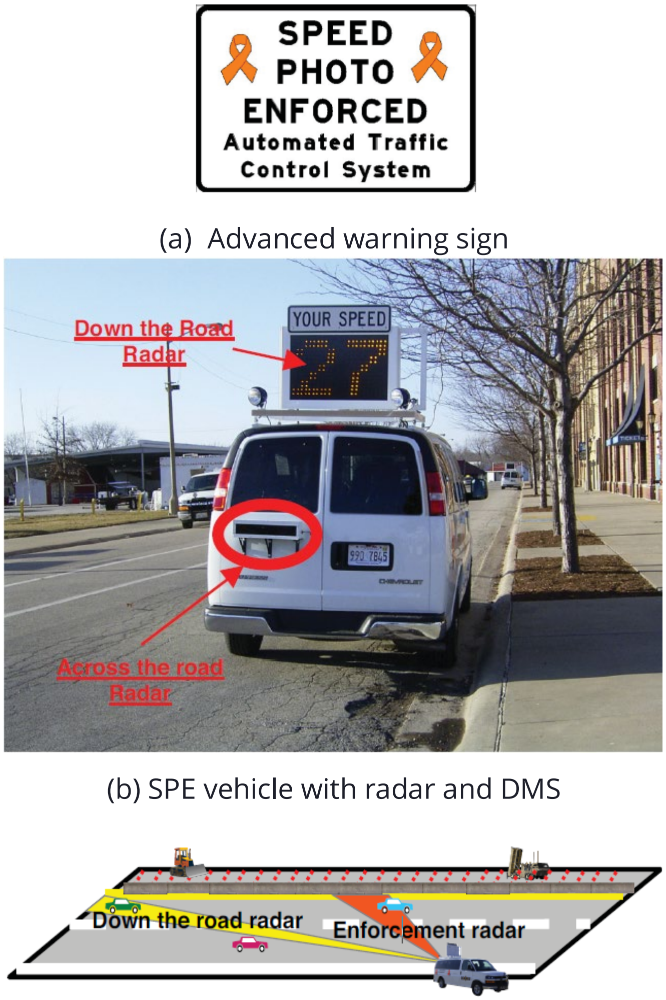



**Figure 2-1 SPE tested by Illinois DOT (Taken from Benekohal et al., 2009).**

*ii. Police presence*

Police presence or patrol within or before a WZ is an effective method of speed control and enforcement. It is also one of the most common practices for speed control (Maze et al., 2000) and has been reported to reduce WZ crashes by as much as 41% (Chen & Tarko, 2012). Police presence in WZ can be either as a patrol or a parked vehicle with or without officers. When testing the effect of a stationary police car on travel speed on urban and rural highways, (Richards et al., 1985) reported speed reduction ranging from 8-27%. The effect of a circulating police car was, however, much less (a reduction of 2-3 mph in the rural highway when circulating versus 7 mph when stationary). (Sisiopiku & Patel, 1999) studied the change in vehicle speed before and after the presence of law enforcement on interstates in Michigan. The authors reported a decrease in average speed by 5mph in the presence of law enforcement; however, the average speed increased by 2.7 mph soon after passing them. Moreover, the authors reported no lasting "halo" effects from police enforcement after 1-3 hours.

Police presence has proven to be even more effective when used alongside other enforcement techniques. When comparing different speed control techniques, (Hajbabaie, Medina, et al., 2011) found that the use of a speed feedback display with a police car was more effective in reducing mean vehicle speed than using the techniques individually (Hajbabaie, Medina, et al., 2011). Similarly, (Zech et al., 2005) reported that the use of rumble strips with police presence was more effective in reducing speed compared to using rumble strips or police presence alone (Zech et al., 2005). This strategy also reduced speed variances by about 25%. According to Ravani, et al. 2018 report that any police presence could reduce the 85th percentile speed of motorists. However, an increased speed variance should also be expected, particularly on urban roads when employing police enforcement strategies (Ravani & Wang, 2018).

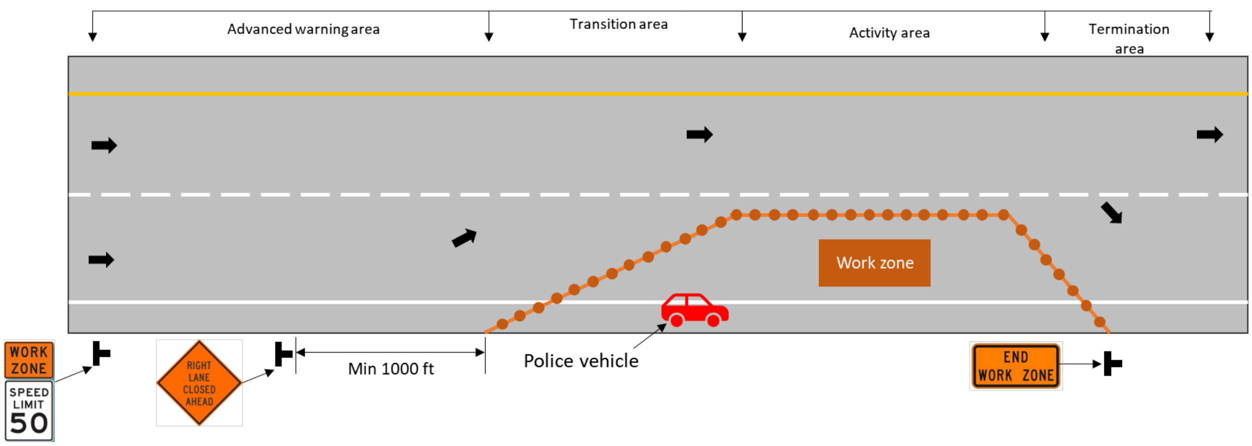



**Figure 2-2 Work zone setup with a police vehicle.**

## 2.7 Warning Strategies

*i. Lane width reduction using traffic barriers*

Lane width reduction is done by narrowing the lane and creates a funneling effect that results in the reduction of FFS. The lane reduction is done either using lane marking or physical barriers. While reducing lane width increases WZ safety, it must be noted that lane width reduction hurts the traffic throughput (Benekohal et al., 2004). The Highway Capacity Manual provides the standard reductions in FFS for various lane widths. (Chitturi & Benekohal, 2005) investigated the effect of lane width reductions and found that 10, 7, 4.4, and 2.1 mph reductions were appropriate for 10, 10.5, 11, and 11.5 ft wide lanes, respectively (Chitturi & Benekohal, 2005). Lane reduction using traffic cones has been shown to reduce speed by up to 16% (Richards et al., 1985). Researchers comparing the reduction in speed with and without lane reduction have reported considerable changes in speed when lanes are physically narrowed. (Paolo & Sar, 2012) reported an 18.7 kmph reduction in mean speed on highways with 30 kmph and 50 kmph posted speed limits when two travel lanes were reduced, versus a 3 kmph reduction when temporary speed limits were posted (Paolo & Sar, 2012). When studying the impact of lane closure, construction activity, and lane width reduction on FFS on an interstate in Missouri, (Bham & Mohammadi, 2011), reported lane reduction had the most prominent impact during construction activity, with a reduction of 8.5 and 11.1 mph for cars and trucks, respectively. Furthermore, the authors reported that tubular markers resulted in a greater reduction of FFS compared to lane markings.


**Figure 2-3 Dynamic Message Sign**

*ii. Dynamic Message Signs*

DMSs are used to display regulatory and warning messages to motorists. In WZs, they are used to display information regarding incident management, route diversion, adverse weather or traffic warning, traffic control, travel delays, speed control, etc. These messages can either be prerecorded or dynamic. Dynamic messages in DMS are displaced based on downstream conditions collected using roadway sensors. DMS are also called Changeable Message Signs.
Messages in DMS have been observed to encourage motorists to reduce speed, merge early, and maintain a safe headway. (Almallah et al., 2021). The length and wording of messages in DMS and their effect on driver behavior have been subject to considerable research. (B. R. Ullman et al., 2007; G. L. Ullman et al., 2005) reported that displaying sequential messages was comparable to

a single large display. According to a study (Zech et al., 2008), the type of messages has a different effect on driver compliance near WZ. The authors reported the message "WORK ZONE|MAX SPEED|45 MPH|BE|PREPARED|TO STOP" resulted in most compliance with speeds reduced by up to 6.7 mph. Notably, graphics are more effective than text messages in increasing driver compliance (Bai et al., 2011; Huang & Bai, 2019; Messina et al., 2011). Researchers have also been interested in the location of DMS relative to WZ. The literature suggests that more vehicle slowdowns occur near DMSs that are closest to the WZ (Strawderman et al., 2013). Thapa, et al. 2019 after studying the effect of various warning signs at the advanced warning area on driver behavior, found that drivers farther away from the WZ were less likely to respond to DMS. Similarly, drivers traveling above the speed limit were more likely to comply with DMS signs. The researchers also found that reduced speed >=4 prompted more effective responses from drivers at lane ends and speed limit signs. Similarly, according to Xu, et al. 2018, instructing drivers to "Go Straight" further ahead and suggesting to them to "Change Lane" at a point closer to a WZ is more effective in reducing speed, acceleration, and lateral vehicle movement (Xu et al., 2018). Driver compliance has been found to increase with the distance between a DMS and WZ (Strawderman et al., 2013).

*iii. Variable Speed Limit*

In contrast to a prespecified speed limit on roadways, the Variable Speed Limit (VSL) system regulates safe limits on WZ based on prevailing and changing conditions by displaying them to motorists. The speed limits are determined to reduce congestion, prevent queuing, and maintain safe vehicle speed. Moreover, VSL is mostly used in WZs and roadway segments that require better speed regularization and harmonization to alleviate recurring bottlenecks and improve throughout. (Kwon et al., 2007) developed a system that matched upstream and downstream speed to improve traffic flow and found an improvement in throughput of up to 7%. 2012). A study by Wilson & Saito, 2012 demonstrated that VSL could improve traffic flow by increasing the mean speed and decreasing speed variance (Wilson & Saito, 2012). Through the use of real-time data feed, VSLs are capable of providing considerable benefits by delaying congestion and improving speed compliance (Fudala & Fontaine, 2010). However, greater VSL speed compliance during high traffic demand has been shown to reduce traffic throughput (Radwan et al., 2011). Furthermore, according to researchers, VSL seems to have a greater impact on traffic safety (crash reduction) than on traffic flow (Lu & Shladover, 2014).


**Figure 2-4 Example of variable speed limit (Source: WSDOT)**

*iv. Dynamic Speed Feedback System*

Dynamic Speed Feedback System (DSFS), as the name suggests, provides drivers with feedback regarding their speed against the posted speed limit using text such as "YOUR SPEED IS xxx". DSFS are placed in advanced warning areas to draw the attention of motorists when they exceed a certain speed limit. Compared to other automated systems that detect traffic conditions and display messages, DSFS are cheaper and easier to use (Mattox et al., 2007). According to (Flynn et al., 2020), DSFS is very effective in reducing the speed of passenger vehicles. Gambatese et al., 2015 reported a 23% decrease in 85$^{th}$ percentile speed in WZs when using portable DSFS mounted on a truck, with a 48% reduction in speeding (Gambatese & Jafarnejad, 2015).

*v. Dynamic Lane Merge System*

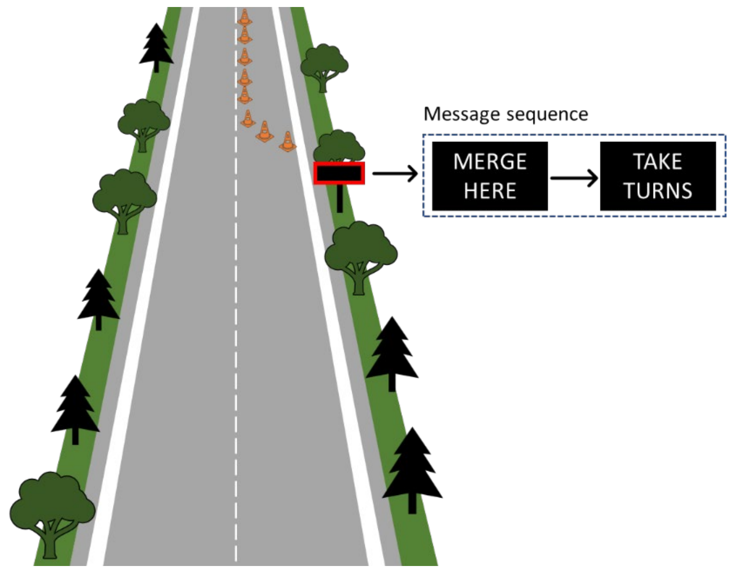
Dynamic Lane Merge Systems (DLMS) are designed to regulate driver merge behavior by informing them of safe merge locations. The merge locations are estimated by detecting traffic flow and end-of-queue location downstream and using algorithms to calculate the best merge location to increase traffic throughput by reducing speed variance. DLMS has been proven to improve WZ safety by discharging queues at a uniform rate (Wei & Pavithran, 2006). DLMS also removes the need for adequate vehicle gaps between vehicles when merging, which can reduce side-swipe crashes (Wei & Pavithran, 2006).

There are two types of Dynamic Lane Merge Systems, Dynamic Early Lane Merge Systems (DELMS) and Dynamic Late Lane Merge Systems (DLLMS). Based on field testing, researchers have recommended using DELMS in rural congested roadways to reduce driving aggression and DLLMS in urban roadways to reduce queues. DLLMS remains based on driver compliance, as it is based on the zipper merge approach. According to (T. Datta et al., 2004), DELMS can improve traffic flow and reduce aggressive driving behavior near WZs. Considering user costs and safety benefits, DELMS provides a benefit-cost ratio of 1.96 if installed at a


**Figure 2-5 Dynamic Speed Feedback**

location for at least 60 days (T. Datta et al., 2004). The advent of Connected and Autonomous Vehicles (CAVs) has enabled the Cooperative Late Merge System (CLMS). Simulations have shown that CLMS could provide superior performance to traditional lane merge systems with a high compliance rate in moderate to high traffic demand (Algomaiah & Li, 2021, 2022).

Researchers have also pointed out the importance of message working when using lane merge systems. Dutta, et al. 2001 studied driver behavior and maneuvers when using the late lane merge system in Michigan and found that the message "Do Not Pass/When Flashing" was confusing to some drivers since it is not typically used in WZs (T. K. Datta et al., 2001).




(a) Example of late merger system with zipper merge

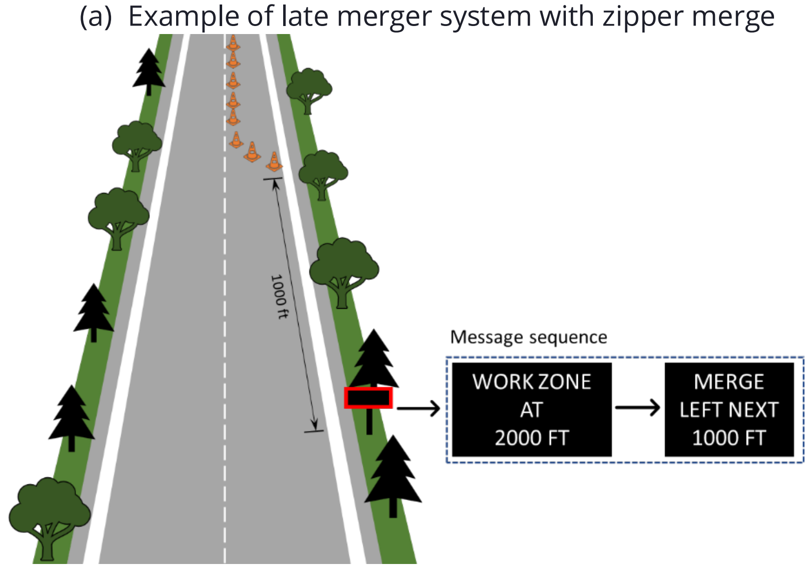



**Figure 2-6 Dynamic lane merge systems**

(b) Example of an early merge system

*vi. Connected and Autonomous Vehicle technologies*

The advent of Connected and Autonomous Vehicle (CAV) technologies has introduced innovative approaches to control and enforce driver behavior. CAV-enabled cooperative features facilitated by Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication have the potential to eliminate the need for signals, signs, in-vehicle warning systems, and DMS to inform drivers. For example, cooperative adaptive cruise control and lane merge systems will eliminate the need for DMS, VSL, DSFS, and DLMS, help with queue management, and improve WZ safety by eliminating rear-end crashes. (Bashir & Zlatkovic, 2021) using simulation demonstrated that at a mere 25% penetration rate, the CAV-based queue warning system could increase the time to collision by 4 times. In the same context, (Khazraeian et al., 2017) state that only 6% CAV penetration is adequate to estimate end-of-queue location with an average accuracy of 96%. Similarly, (Algomaiah & Li, 2021, 2022) have shown that the CAV-enabled lane merge system is superior to all other lane merge systems in reducing delays and queue length. Therefore, it is safe to conclude that WZ-related treatments in the future will most likely employ CAV technologies.

Contrary to the "cooperative" feature, another potential area for future development is the development of individual-centric WZ treatments, such as customized messages aimed toward less compliant individuals. (Flannagan et al., 2019) analyzed the Second Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (NDS) dataset and suggested "nudging" the drivers from selfish to altruistic behavior so that the overall traffic throughput in work zones is improved. The authors found that some drivers traveled at higher average speeds and speed variance. These drivers created risky situations. This could be mitigated by "nudging" them to demonstrate more cooperative and altruistic behavior. A previous study has reported that compliance from individual drivers is necessary to maintain stable traffic flow (Davis, 2016). Therefore, they recommend that future WZ treatments must be individual-centric. In cases where this is not practical, stable flow and full compliance can be achieved by using CAVs. In particular, only 1/3$^{rd}$ of compliant vehicles can result in fully compliant traffic, according to the research (Davis, 2016).

# Chapter 3 Methodology

The field data for this study were collected to analyze traffic behavior and safety performance within freeway WZs using high-resolution, video-based trajectory data. The primary objective was to obtain information on speed at various cross-sections before and after speed feedback mechanisms, to characterize speed variations and car-following patterns.

To achieve this, a multi-camera longitudinal monitoring system was deployed along an active double-lane freeway work zone, instrumented to capture the full progression of vehicles through the activity region of the WZ.

## 3.1 Site Configuration and Camera Deployment

Data on planned WZs were obtained from the TDOT. A WZ along Interstate 65, Roberson County, part of the ongoing widening project between SR-25 and SR–109 initiated in 2021, was selected for data collection. Specifically, a straight section of the activity area between SR-25 and SR-52 was chosen for analyzing driver behavior. On September 14, 2023, five cameras were installed on 20-foot poles along the site to capture vehicle movements within WZ. Each camera was positioned to ensure at least 100 feet of overlapping coverage with the adjacent camera, enabling continuous tracking of vehicles across the field of view. The video recordings captured traffic traveling southbound on I-65 throughout the study period. The location of the study area is illustrated in the Figure 3-1: Map of Tennessee showing the location of the study area.

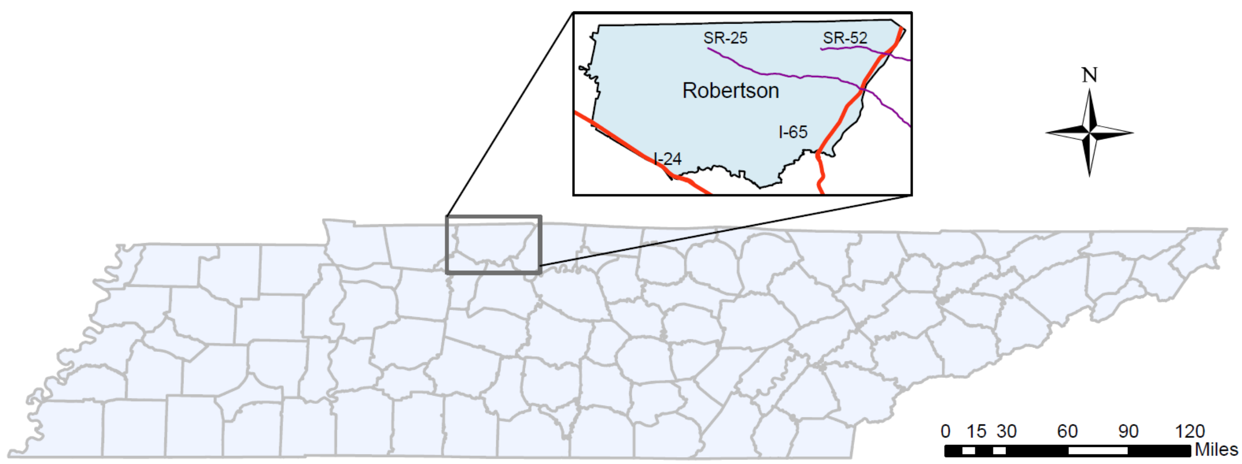



**Figure 3-1: Map of Tennessee showing the location of the study area**

The spatial configuration and placement details of all five cameras and the feedback sign used in the study are presented in Figure 3-2: Arrangement of the equipment for the experiment. The first camera was positioned at 36°34'25.52"N, 86°37'01.69"W, approximately 58 feet from the right edge of the pavement. The second camera, located at 36°34'21.54"N, 86°37'04.42"W, was placed 61 feet from the pavement edge and 467 feet from the first. The third camera was mounted at 36°34'17.14"N, 86°37'07.19"W, 60 feet from the right edge and 493 feet from the second camera. The fourth camera, installed at 36°34'12.37"N, 86°37'10.09"W, stood 49 feet from the pavement edge and 546 feet from the third. The fifth camera was positioned at

36°34'07.00"N, 86°37'13.70"W, 61 feet from the right pavement edge and 600 feet from the fourth. The alignment and spacing ensured continuous capture of vehicle movements along the monitored segment. Solar panels powered all cameras to enable uninterrupted recording. Additionally, feedback signs were installed at 36°34'21.29"N, 86°37'03.73"W, about 6 feet from the right edge of the roadway. As the work was ongoing, the arrangement of cameras was governed by the space available for erection without disturbing construction activity.

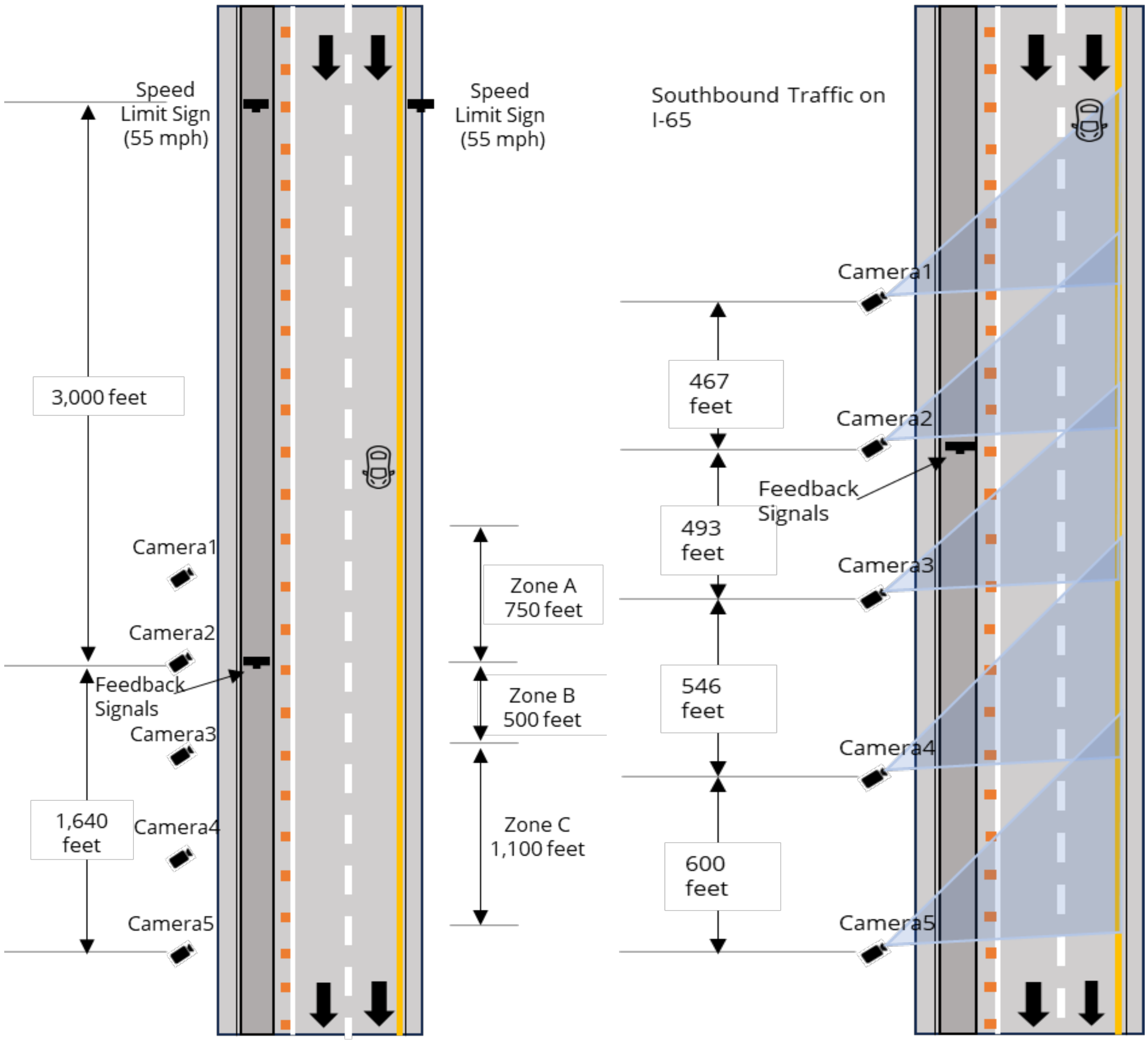
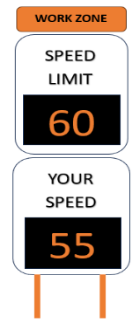
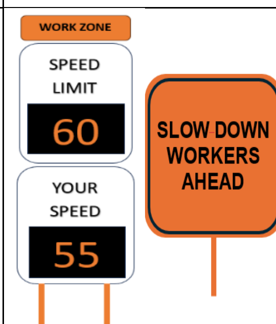



**Figure 3-2: Arrangement of the equipment for the experiment.**

The objective of recording the videographic data was to observe the naturalistic driving behavior of motorists as they traversed the WZ, particularly after being exposed to the feedback signs. The recordings aimed to capture real-world driver responses to the feedback messages, such as speed adjustments, headway maintenance, and overall compliance with the displayed information. The details of the schedule of feedback signals are presented in the Table III.

**Table IIIII Schedule Of Installation Of the Equipment**

| Equipment | Date | Action (Installed/ Removed) | Message Shown | Days | Sample of display |
|---|---|---|---|---|---|
| DSFS | 10/3/2023 | Installed | "YOUR SPEED XX" | 13 |  |
| | 10/16/2023 | Removed | | | |
| SW | 10/26/2023 | Installed | "SPEED LIMIT 55, YOUR SPEED XX" | 14 |  |
| | 11/9/2023 | Removed | | | |
| SW and PCMS | 11/13/2023 | Installed | "SPEED LIMIT 55, YOUR SPEED XX" (SW) | 8 |  |
| | | | "SLOW DOWN WORKER AHEAD" (PCMS) | | |
| | 11/21/2023 | Removed | | | |

## *3.2 Data Processing*

The data collected from the cameras was uploaded to the cloud using remote sensing equipment in the cameras. The data was then downloaded to the local system. Each video file ranged from 5 minutes to 10 minutes in length. 2,877 images were extracted from the video file representing diverse conditions of traffic flow. The images were split into a 2,517-train set (87%), a 240-validation set (8%), and a 120-test set (4%). The images were used to fine-tune You Only Look Once (YOLO) (Jocher et al., 2022; Redmon et al., 2016).

The use of YOLO enables the production of a bounding box surrounding the vehicles. The trained model provides pixel coordinates of bounding box vertices for each detected vehicle in the video frames. The tracking of the bounding box across successive frames was done by using another algorithm named ByteTrack (Y. Zhang et al., 2022). A sample of the detected vehicles, their bounding box with their IDs and confidence, is demonstrated in Figure 3-3.

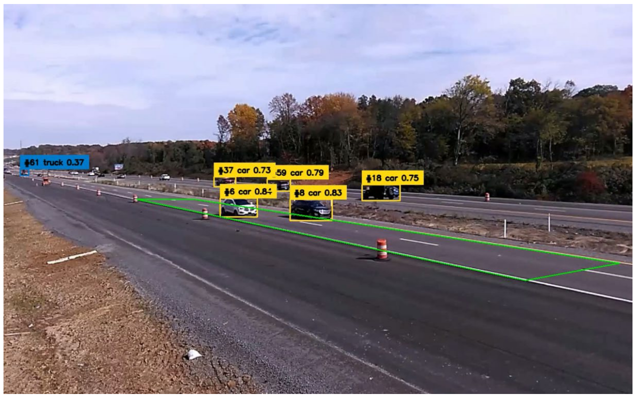



**Figure 3-3 Sample of an image showing vehicles with their IDs and their bounding boxes.**

The bounding box obtained from object detection exists on an oblique image plane and must be projected onto a horizontal (ground) plane to derive real-world positions. This conversion process, known as homography transformation, a variant of perspective transformation, establishes a geometric relationship between the image plane and the physical road surface using four known real-world coordinates that lie on the same plane, as shown in the Figure 3-3, by the green rectangular quadrilateral.

The transformation can be mathematically expressed as:

$$\begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} \sim \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{bmatrix} u \\ v \\ 1 \end{bmatrix}$$

Where, $(u, v)$ represent pixel coordinates, and $(X, Y)$ denote real-world coordinates.

To estimate the elements of the 3X3 transformation matrix H, each pair of corresponding image and real-world points contributes to two linear equations derived from projective geometry. These equations collectively form a homogenous linear system of the form:

$$A * h = 0$$

Where, $A$ is a matrix built from the known point correspondences, and $h$ is a column vector containing the nine elements of $H$. Since the solution is defined up to scale, at least four pairs of corresponding points (yielding eight equations) are required. The system is typically solved using singular value decomposition, which identifies the solution that minimizes overall error.

The resulting vector is reshaped into the 3X3 homography matrix $H$, which enables mapping from image to world coordinates. To ensure accurate localization, the lower corner of each vehicle's bounding box was used as the reference point, as it lies closest to the road surface and is least influenced by perspective transformation. These transformed coordinates from successive frames form the basis for constructing vehicle trajectories across the monitored segment.

The raw vehicle trajectories extracted from the video data required further refinement to enhance accuracy, coherence, and reliability. For this purpose, a comprehensive consistency analysis framework adapted from the methodology proposed (Punzo et al., 2011) was employed. This framework evaluates trajectory validity across three main dimensions: internal consistency, platoon consistency, and physical consistency. Internal consistency verifies that each vehicle's kinematic behavior, such as variations in speed, acceleration, or heading, remains physically plausible and free of abrupt fluctuations. Platoon consistency examines whether vehicles traveling in proximity exhibit synchronized and realistic car-following behavior, ensuring coherent movement patterns within traffic streams. Physical consistency evaluates overall trajectory metrics, confirming that speed and acceleration values lie within empirically valid bounds observed in highway environments.

## *3.3 Analysis Methodology*

Despite the continuous process of data capturing, uploading, and downloading, the overall workflow was constrained by the limited volume of data successfully uploaded to the cloud due to restrictions in the remote upload system. Thus, three different tiered analyses were used for the study.

### 3.3.1 Analysis at the End of Observation Area

Analysis of the speeding behavior based on observations at the end of the observation area (captured by the fifth camera) was made in this section. Based on a previous study (Gargoum et al., 2016; Mannering, 2009) Speed violations were classified relative to the 55-mph speed limit:

- **Minor:** 60–65 mph (5–10 mph over)
- **Moderate:** 65–70 mph (10–15 mph over)
- **Severe:** > 70 mph (> 15 mph over)

These natural speed orders were used to study the influence of covariates on these ordinal speed levels using the Generalized Ordinal Logit model. In an ordinal regression model (Eluru et al., 2008), the violations ($y_i$) are assumed to be associated with underlying latent variables ($y_i$*) given by:

$$y_i^* = X_i\beta + \varepsilon_i, \text{ for } i=1,2,3....N \qquad ...(1)$$

Where, $X_i$ is the vector of explanatory variables, β is the vector of unknown parameters to be estimated, and $\varepsilon_i$ is the random error term, assumed to follow a logistic distribution. The observed ordinal outcome $y_i^*$ corresponds to the categorized speed violation:

$$y_i = j, \text{ if } \psi_{j-1} < y_i^* < \psi_j, \text{ for } j = 1, 2....,J \qquad ...(2)$$

Where, $\psi_j$ are threshold parameters separating the ordered categories of violations: **(1)** minor (60–65 mph), **(2)** moderate (65–70 mph), and **(3)** severe (> 70 mph).

Under the GOL framework, the threshold parameter is expressed as:

$$\psi_j = \alpha_j + Z_i\delta_j \qquad ...(3)$$

where $Z_i$ includes the subset of covariates that violate the POA, and $\delta_j$ represents the deviation from proportional odds across the thresholds. The probability of an observation belonging to a category $j$ is given by:

$$\pi_{ij} = \frac{\exp(\alpha_j + \delta_j Z_i - X_i\beta)}{1 + \exp(\alpha_j + \delta_j Z_i - X_i\beta)} - \frac{\exp(\alpha_{j-1} + \delta_{j-1} Z_i - X_i\beta)}{1 + \exp(\alpha_{j-1} + \delta_{j-1} Z_i - X_i\beta)} \qquad ...(3)$$

This model formulation allows the effect of each covariate to differ between low and high severity thresholds, capturing nuanced behavioral responses to WZ conditions and feedback systems. More details of the methodology and analysis can be found in (Neupane et al., 2025).

*Descriptive Statistics*

A total of 22,950 individual vehicle trajectories were extracted from the processed video data collected under four experimental conditions: Base (no feedback), DSFS, SW, and Combined (SW and PCMS). To maintain uniformity in external conditions, one hour of daytime traffic during daytime from multiple weekdays and weekends was sampled for each configuration, resulting in approximately 16 hours of comparable traffic observations. The descriptive statistics of the data collected are presented in TABLE IV.

**TABLE IV COUNT AND PERCENTAGE OF VEHICLES AND DESCRIPTIVE STATISTICS OF THE SPEED OF VEHICLES**

| | Base | | Combined | | DSFS | | SW | |
|---|---|---|---|---|---|---|---|---|
| Categorical Variables | | | | | | | | |
| | 3,864 | 16.84% | 6,705 | 29.22% | 5,037 | 21.95% | 7,344 | 32.00% |
| Lane | | | | | | | | |
| Left | 1,959 | 8.54% | 2,966 | 12.92% | 2,515 | 10.96% | 3,519 | 15.33% |
| Right | 1,905 | 8.30% | 3,739 | 16.29% | 2,522 | 10.99% | 3,825 | 16.67% |
| Vehicle Type | | | | | | | | |
| Car | 2,843 | 12.39% | 3,946 | 17.19% | 3,472 | 15.13% | 4,811 | 20.96% |
| Truck | 1,021 | 4.45% | 2,759 | 12.02% | 1,565 | 6.82% | 2,533 | 11.04% |
| Headway Violation | | | | | | | | |
| No Violation | 2,916 | 12.71% | 5,470 | 23.83% | 3,854 | 16.79% | 5,888 | 25.66% |
| Violation | 948 | 4.13% | 1,235 | 5.38% | 1,183 | 5.15% | 1,456 | 6.34% |
| Day | | | | | | | | |
| Weekday | 2,418 | 10.54% | 4,994 | 21.76% | 3,092 | 13.47% | 4,289 | 18.69% |
| Weekend | 1,446 | 6.30% | 1,711 | 7.46% | 1,945 | 8.47% | 3,055 | 13.31% |
| Weather | | | | | | | | |
| Sunny | 3,111 | 13.56% | 5,783 | 25.20% | 1,615 | 7.04% | 6,957 | 30.31% |
| Overcast | 753 | 3.28% | 922 | 4.02% | 3,422 | 14.91% | 387 | 1.69% |
| Speed (Continuous Variable) | | | | | | | | |
| Average | 62.71 | | 58.90 | | 59.26 | | 60.64 | |
| Std Dev | 9.94 | | 10.51 | | 8.89 | | 9.37 | |
| Q1 | 56.06 | | 52.24 | | 53.53 | | 54.41 | |
| Median | 62.55 | | 59.11 | | 58.81 | | 60.60 | |
| Q3 | 69.13 | | 65.33 | | 64.87 | | 66.40 | |

(Notes: Total no. of vehicles’ trajectories extracted: 22,950, Base = No feedback)

The descriptive analysis indicated that vehicle distribution across lanes was balanced, with approximately 47.8% of vehicles traveling in the left lane. Passenger cars were the predominant vehicle type overall, showing the highest share during the Speed Wizard (SW) condition. The dataset comprised a larger proportion of weekday observations (64.5%), while sunny weather represented most environmental conditions (76.1%). In addition, tailgating behavior, identified as a headway violation below 1.5 seconds, was incorporated as one of the covariates in the ordered speed-violation analysis.

An interesting pattern emerged from the descriptive statistics concerning speed limit compliance. Across all feedback conditions, the first quartile of speed remained close to the posted 55 mph limit, while the median speed exceeded it by about 5 mph. Approximately 21% of vehicles maintained a headway shorter than 1.5 seconds, indicating frequent tailgating behavior. Overall, a substantial share of drivers exceeded the speed limit and followed other vehicles too closely.

The dependent variable of the GOL model is illustrated in TABLE V.

**TABLE V REPRESENTATION OF THE DEPENDENT VARIABLE OF THE GOL MODEL**

| Level of Violation | Count | % with normal speed | % without normal speed (GOL model) |
|---|---|---|---|
| Normal (Speed < 60 mph) | 11,413 | 49.73% | |
| Minor (Speed between 60-65 mph) | 4,768 | 20.78% | 41.33% |
| Moderate (Speed between 65-70 mph) | 3,489 | 15.20% | 30.24% |
| Severe (Speed above 70 mph) | 3,280 | 14.29% | 28.43% |

### 3.3.2 Analysis at the Start and End of the Observation Area

This approach of analysis aimed at investigating the traffic characteristics and speed drop between the start (observation at camera 1) and the end (observation at camera 5). The analysis involved two main phases: the modeling of speed and headway distributions and the estimation of speed changes through a BGAM.

First, standard probability distributions were fitted separately to the observed headway and speed data. The goodness of fit was verified using the Kolmogorov-Smirnov test, and the Gaussian Kernel Density model was applied to explore the conditional distribution of vehicle speed across varying headway intervals under different feedback scenarios. The primary treatment variables included the three speed feedback signs. Control variables such as lane position, vehicle type, day of the week, and weather conditions were also included in the analysis.

The response variable in the model represented the change in speed from the first area to the last area. Given the nonlinear nature of speed behavior, the BGAM framework was selected for its flexibility in capturing complex relationships. The model incorporated both linear (categorical) and smooth (continuous) predictors. Speed before encountering feedback was treated as a nonlinear continuous variable, while other covariates were binary categorical variables. The general form of BGAM is given by:

$$g(E(Y)) = \beta_0 + f_1(x_1) + f_2(x_2) + f_3(x_3) + \cdots f_m(x_m) \quad ...(5)$$

Where $g(.)$ is the lnk function, $Y$ represents the response variable, $\beta_0$ is the intercept, and $f_1$, $f_2, f_3 ... f_m$ are smooth functions of the predictor variables $x_1, x_2, x_3, ... x_m$.

The model was estimated by Hamiltonian Monte Carlo sampling, which employs the No-U-Turn Sampler algorithm to generate the posterior distribution of parameters. HMC is an advanced sampling technique that leverages gradient information from the log-posterior to propose efficient transitions between parameter values. Compared to traditional Markov Chain Monte Carlo methods, HMC yields faster convergence and superior exploration of complex parameter spaces. Its efficiency makes it particularly suitable for models like BGAM, which combine nonlinear smooth terms and multiple covariates.

### *Descriptive Statistics*

The dataset comprises observations from 12,327 vehicles, recorded across multiple feedback conditions in the WZ. Approximately 67% of the observations occurred on weekdays, while 20% were recorded under rainy or cloudy conditions. About 76.5% of the data were collected while some type of speed feedback was active. The vehicle composition showed that passenger cars dominated the traffic stream, followed by trucks. Lane distribution was relatively balanced, with slightly higher usage of the left lane. The details of the descriptive statistics for the second study are illustrated in TABLE VI.

**TABLE VI DESCRIPTIVE STATISTICS FOR THE SECOND STUDY**

| | | Installed Feedback | | | |
|---|---|---|---|---|---|
| **Variables** | | **Base** | **DSFS** | **SW** | **Combined** |
| **Categorical Variable** | | Count (%) | Count (%) | Count (%) | Count (%) |
| Vehicle Type | car | 2,122(17.21) | 2,347(19.04) | 1,666(13.52) | 2,026(16.44) |
| | truck | 782(6.34) | 1,692(13.73) | 676(5.48) | 1,016(8.24) |
| Day | Weekday | 1,554(12.61) | 3,390(27.5) | 1,549(12.57) | 1,589(12.89) |
| | Weekend | 1,350(10.95) | 649(5.26) | 793(6.43) | 1,453(11.79) |
| Weather | Rainy | 753(6.11) | 921(7.47) | 793(6.43) | 378(3.07) |
| | Sunny | 2,151(17.45) | 3,118(25.29) | 1,549(12.57) | 2,664(21.61) |
| Lane | Left | 1,629(13.21) | 2,393(19.41) | 1,379(11.19) | 1,733(14.06) |
| | Right | 1,275(10.34) | 1,646(13.35) | 9,63(7.81) | 1,309(10.62) |
| **Continuous Variable** | | | | | |
| Speed at Area 1 | | | | | |
| | Average (mph) | 66.88 | 64.26 | 66.34 | 66.42 |
| | Standard Deviation | 10.69 | 10.80 | 8.65 | 12.62 |
| Speed at Area 2 | | | | | |

|  | | Installed Feedback | | | |
|---|---|---|---|---|---|
| Variables | | Base | DSFS | SW | Combined |
|  | Average (mph) | 63.99 | 61.08 | 61.00 | 60.59 |
|  | Standard Deviation | 9.62 | 11.56 | 8.65 | 8.47 |

(Notes: Total no. of vehicles' trajectories extracted: 12,327, Base = No feedback)

### 3.3.3 Analysis Involving the Trajectories

A fuzzy logic-based vehicle re-identification system was used to stitch trajectories across multiple camera zones, employing temporal, spatial, lane-sequence, and class similarity criteria to generate globally consistent trajectories. The final dataset was then smoothed using recursive low-pass and Gaussian filters to remove noise.

Changepoint analysis, a statistical tool used to identify points in a sequence of data where structural changes occur, was applied to the trajectory data. Based on the analysis, three regions for study were identified. The zones were established based on distance from the speed limit sign:

- Zone A (Before): 2,250-3000 ft downstream of the speed limit sign and represents normal driving behavior before exposure to the feedback message.
- Zone B (After): 3,000-3,500 ft downstream of the speed limit sign and covering the immediate downstream section where drivers first react to the feedback.
- Zone C (Sustain): 3,500-4,450 ft downstream of the speed limit sign representing the extended downstream area where speed adaptation stabilizes.

A Spatial Lag Model was developed to capture how drivers' speeds were influenced not only by roadway and vehicle characteristics but also by the speeds of nearby vehicles. This approach explicitly modeled spatial interdependence among drivers, an essential aspect of behavior within WZ traffic. The spatial Lag Model is specified as:

$$Y = \rho WY + X\beta + \varepsilon \quad \text{.........(6)}$$

Where,

$Y$ = the vector of observed speeds.

$WY$ = spatial dependence, with $W$ representing the spatial weight matrix.

$X$ = matrix of explanatory variables such as vehicle class, treatment type, and location within the WZ.

$\beta$ = regression coefficients associated with the explanatory variables, as in normal regression.

$\rho$ = quantifies the strength of spatial dependence or the degree of influence of nearby vehicles.

$\varepsilon$ = error or residuals.

Four one-hour traffic sample stitched trajectories were extracted, each representing the four different conditions: base, DSFS, SW, and combined, from 12 pm to 1 pm. The details of the descriptive statistics of the speed of the vehicle across three different zones from the changepoint analysis and feedback types are illustrated in TABLE VII.

**TABLE VII DESCRIPTIVE STATISTICS OF VEHICLE SPEEDS ACROSS DIFFERENT ZONES AND FEEDBACK TYPES**

| S. No. | Feedback | Zone | Mean Speed (mph) | Std. Dev. of Speed | No. of Vehicles | Remarks |
|---|---|---|---|---|---|---|
| 1 | Base/No Feedback | Zone A (Before) | 58.35 | 13.01 | 578 | |
| 2 | Base/No Feedback | Zone B (After) | 64.32 | 13.27 | | Base |
| 3 | Base/No Feedback | Zone C (Sustain) | 60.01 | 12.62 | | |
| 4 | DSFS | Zone A (Before) | 60.42 | 13.37 | 642 | |
| 5 | DSFS | Zone B (After) | 60.80 | 11.95 | | Treatment |
| 6 | DSFS | Zone C (Sustain) | 52.59 | 12.81 | | |
| 7 | SW | Zone A (Before) | 56.99 | 19.69 | 612 | |
| 8 | SW | Zone B (After) | 61.07 | 15.89 | | Treatment |
| 9 | SW | Zone C (Sustain) | 56.10 | 11.40 | | |
| 10 | SW & PCMS | Zone A (Before) | 58.87 | 9.99 | 623 | |
| 11 | SW & PCMS | Zone B (After) | 63.10 | 16.34 | | Treatment |
| 12 | SW & PCMS | Zone C (Sustain) | 53.99 | 11.43 | | |

# Chapter 4 Results and Discussion

To comprehensively assess driver behavior and safety outcomes under different roadway and operational conditions, three complementary analytical frameworks were developed: analysis at the end of the observation area (the GOL model), analysis at the start and end of the observation area (the BGAM model), and analysis involving the trajectories (the SLM model).

## *4.1 Results of Analysis at the End of Observation Area*

To investigate the determinants of severity levels in driver responses, a GOL model was used to estimate its parameters (Eluru & Yasmin, 2015). The identification of variables that violated the Proportional Odds Assumption (POA) and determining the optimal model specification, Brant's test, and Wald's test were employed (Brant, 1990; Williams, 2006). An ordered logit model was also estimated as a comparison with the GOL model. The result is provided in TABLE VIII.

**TABLE VIII PARAMETER ESTIMATION FOR THE GOL MODEL FOR SPEED LIMIT VIOLATION**

| | Ordered Logit | | Generalized Ordered Logit | |
|---|---|---|---|---|
| Variables | Coefficient | Std. Error | Coefficient | Std. Error |
| Ordinal variable (following proportional odds) | | | | |
| Lane (Base = Right) | 1.26 | 0.09 | 1.26 | 0.09 |
| Vehicle type (Base = Truck) | 0.65 | 0.09 | 0.65 | 0.09 |
| DSFS | -0.72 | 0.08 | -0.72 | 0.08 |
| SW | -0.54 | 0.06 | -0.53 | 0.06 |
| Combined (SW+PCMS) | -0.36 | 0.06 | -0.36 | 0.06 |
| Lane*Vehicle type | -0.41 | 0.11 | -0.40 | 0.11 |
| Nominal Variables (violating proportional odds) | | | | |
| Threshold (intercept) | | | | |
| Minor \| moderate & severe. | 0.71 | 0.09 | 0.71 | 0.09 |
| Minor & moderate \| severe. | 2.12 | 0.09 | 2.13 | 0.10 |
| Day (Base = Weekday) | | | | |
| | 0.60 | 0.05 | | |
| Minor \| Moderate | | | -0.53 | 0.05 |
| Minor & moderate \| severe | | | -0.68 | 0.06 |
| Weather (Base = Sunny) | | | | |
| | -0.61 | 0.08 | | |

| | Ordered Logit | | Generalized Ordered Logit | |
|---|---|---|---|---|
| Variables | Coefficient | Std. Error | Coefficient | Std. Error |
| Minor \| moderate & severe | | | 0.60 | 0.08 |
| Minor & moderate \| severe | | | 0.68 | 0.11 |
| Headway Violation (Base = No violation) | | | | |
| | 0.20 | 0.05 | | |
| Minor \| moderate & severe | | | -0.09 | 0.05 |
| Minor & moderate \| severe | | | -0.32 | 0.05 |
| Leading vehicle (Base = Truck) | | | | |
| | 0.11 | 0.05 | | |
| Minor \| moderate & severe | | | -0.16 | 0.06 |
| Minor & moderate \| severe | | | -0.04 | 0.06* |
| Weekday*Weather | | | | |
| | 0.64 | 0.11 | | |
| Minor \| moderate & severe | | | -0.82 | 0.13 |
| Minor & moderate \| severe | | | -0.68 | 0.14 |
| No. of observations | 9,231 | | 9,231 | |
| Null log-likelihood | -10,010.00 | | -10,010.00 | |
| AIC-value | 18,869.41 | | 18,846.15 | |
| Log-likelihood at convergence | -9,421.00 | | -9,405.07 | |

The model coefficients were derived using the maximum likelihood estimation approach, with variable selection guided by a stepwise regression procedure at a 0.05 significance level. Model selection was determined based on the Akaike Information Criterion (AIC) and the log-likelihood at convergence. Interaction terms between predictors were incorporated when their inclusion resulted in a meaningful improvement by a reduction in AIC and log-likelihood values.

The GOL model demonstrated a superior fit compared to the standard ordered logit model, as reflected in its improved log-likelihood value. The GOL model demonstrated a superior fit compared to the standard ordered logit model, as reflected in its improved log-likelihood value. As described in the methodological framework, certain variables satisfied the POA, while others did not. Variables conforming to POA influenced the linear component of the model, where a positive (negative) coefficient indicates a higher (lower) probability of higher-order violations. Conversely, variables violating POA affected the threshold component, where a positive (negative) coefficient increases (decreases) the threshold, reducing (increasing) the likelihood of higher-order violations.

The analysis revealed that lane position, vehicle type, and feedback mechanisms significantly influenced the likelihood of speed limit violations. Drivers traveling in the left lane were considerably more prone to higher-order speed violations than those in the right lane, consistent across all levels of violation severity. Similarly, passenger cars were more likely to engage in higher-order violations compared to trucks, indicating that smaller and more agile vehicles tend to display riskier driving behavior. Among the feedback mechanisms, the DSFS was the most effective in mitigating speeding behavior, followed by SW and combined feedback systems. Interestingly, the combined feedback was slightly less effective than the SW alone, suggesting potential driver desensitization when feedback types coexist.

Several contextual variables, day of week, weather, headway violation, and leading vehicle, were found to violate the POA, implying that their effects vary across different levels of speed violation severity. Weekend driving was associated with higher probabilities of severe speed violations, while adverse weather conditions (rain or overcast) generally reduced the likelihood of severe violations, possibly due to increased caution under poor visibility and surface conditions. However, drivers exhibiting headway violations (tailgating) were more likely to commit severe speeding offenses, supporting evidence from previous research linking unsafe following distances to aggressive driving tendencies. The influence of the leading vehicle type was modest, indicating that following a car tends to induce moderate speeding behavior, while following a truck encourages more conservative speeds.

Interaction effects further highlighted complex relationships between driving and environmental factors. The lane-vehicle type interaction demonstrated that while both left-lane driving and passenger cars independently increase the likelihood of higher-order violations, their combined effect is somewhat mitigated, indicating adaptive behavior under certain conditions. In contrast, the weekday-weather interaction revealed that driving on weekends under adverse weather conditions significantly increases the risk of severe speed violations. This suggests that reduced traffic and perceived familiarity with conditions may foster riskier behavior, even in less favorable weather. These insights underscore the importance of targeted interventions, such as dynamic lane control, focused enforcement on left-lane traffic, and public awareness campaigns emphasizing the dangers of speeding during inclement weather and weekends, to enhance overall roadway safety.

Marginal effects of the independent variables that impact the probability of the outcome in a GOL econometric framework provide insight into how the probability of the level of violation changes with a change in the independent variables. In practical terms, marginal effects show how likely a driver is to transition from a lower category of violation (e.g., minor) to a higher category (e.g., moderate or severe) when a certain factor changes, such as moving from the right lane to the left lane, encountering adverse weather, or being exposed to a feedback system. For variables that violate the POA, marginal effects vary across thresholds, indicating that their influence is not uniform across all levels of violation severity. Thus, analyzing marginal effects in the GOL model provides a more intuitive and nuanced understanding of how and to what extent specific roadway drivers or environmental factors alter the likelihood of higher-order speed violations. TABLE IX presents the marginal effect of the covariates for the ordered likelihood of violations.

**TABLE IX MARGINAL EFFECT OF CONTROL VARIABLES**

| Variable | Level | contrast | estimate | Std. Error | P>\|z\| |
|---|---|---|---|---|---|
| Lane | Minor | L - R | -0.22 | 0.01 | 0.00 |
| | Moderate | | 0.06 | 0.00 | 0.00 |
| | Severe | | 0.16 | 0.01 | 0.00 |
| Type | Minor | Car - truck | -0.08 | 0.01 | 0.00 |
| | Moderate | | 0.02 | 0.00 | 0.00 |
| | Severe | | 0.06 | 0.01 | 0.00 |
| Weekday | Minor | End - Day | -0.15 | 0.01 | 0.00 |
| | Moderate | | 0.00 | 0.01 | 0.99* |
| | Severe | | 0.15 | 0.01 | 0.00 |
| Weather | Minor | Clear - overcast | 0.06 | 0.02 | 0.00 |
| | Moderate | | 0.00 | 0.01 | 0.76* |
| | Severe | | -0.06 | 0.01 | 0.00 |
| Leading Vehicle | Minor | | -0.04 | 0.01 | 0.00 |
| | Moderate | Car - truck | 0.03 | 0.01 | 0.02 |
| | Severe | | 0.01 | 0.01 | 0.50* |
| Headway Violation | Minor | Violation – No Violation | -0.02 | 0.01 | 0.09* |
| | Moderate | | -0.04 | 0.01 | 0.00 |
| | Severe | | 0.06 | 0.01 | 0.00 |

A positive marginal effect indicates an increase in the likelihood of a particular violation level, whereas a negative effect indicates a decrease. Among the traffic and vehicle-related factors, cars were significantly more likely to commit higher-order speed violations compared to trucks. A car in place of a truck increased the probability of moderate violations by 0.02 and severe violations by 0.06, while decreasing the probability of minor violations by 0.08. This result is consistent with earlier studies (Antin et al., 2011; Benekohal et al., 2009b) that have shown passenger cars are more prone to risky driving behaviors due to their smaller size, faster acceleration, and greater maneuverability. In contrast, trucks tend to move more slowly and are operated by professional drivers and are subject to stricter operational regulations. These findings suggest that targeted speed awareness campaigns and differentiated speed enforcement strategies could be effective in managing risky driving behavior, particularly among passenger vehicles. The influence of the leading vehicle type also emerged as significant; drivers following cars were more likely to commit higher-order violations compared to those following trucks, suggesting that a greater presence of heavy vehicles can indirectly help moderate overall traffic speeds.

Roadway and environmental characteristics also played a substantial role in influencing speeding tendencies. The lane of travel was the most influential variable, with vehicles in the left (inner) lane significantly more likely to exhibit higher-order violations. The probability of severe violations increased by 0.16 and moderate violations by 0.06 for vehicles in the left lane, while minor violations decreased by 0.22. This confirms previous research (Hoogendoorn, 2005), which found that inner-lane traffic typically moves at higher speeds due to overtaking and maintaining flow in faster lanes. These findings imply that lane-specific enforcement and monitoring, particularly in inner lanes, could be an effective strategy to control speeding behavior/ Deploying speed cameras or targeted patrols in inner lanes could deter habitual speeding and improve overall compliance.

Temporal and environmental factors, such as day of the week and weather conditions, also influenced the likelihood of speeding violations. Weekend driving was associated with a higher probability of severe speed violations (0.15), potentially due to leisure travel, social activities, and relaxed driving attitudes. This finding supports the need for day-specific interventions, such as enhanced enforcement and public safety messaging on weekends. In contrast, adverse weather conditions such as rain or overcast skies were associated with a 0.06 decrease in severe speeding violations, indicating that drivers tend to reduce speeds under poor visibility and slippery road conditions. This aligns with previous findings (Ahmed & Ghasemzadeh, 2018) showing inclement weather naturally discourages aggressive driving. Consequently, law enforcement and safety agencies should prioritize speed enforcement during clear weather, when drivers are more likely to underestimate risks and engage in higher-order speed violations.

The marginal effect of different speed feedback treatments is presented in the Figure 4-1 Marginal effect of feedback signs.

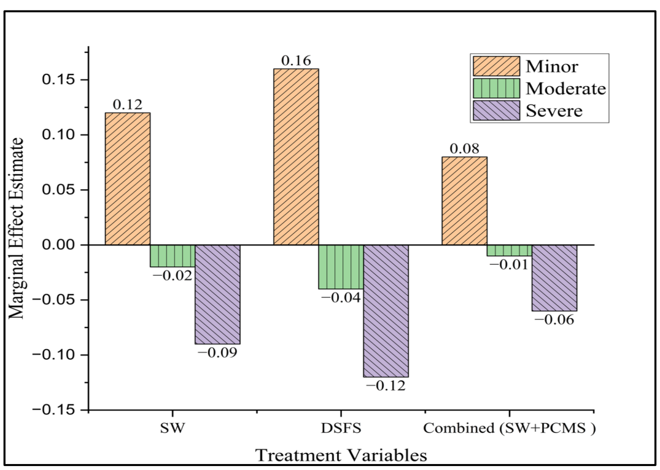



**Figure 4-1 Marginal effect of feedback signs**

The study's experimental design varied the type of feedback mechanism to assess its influence on driver speeding behavior. Consistent with earlier research (Fisher et al., 2021), all feedback devices used in the study were effective in reducing higher-order speeding violations. The DSFS emerged as the most effective treatment, reducing the likelihood of severe speeding violations by 0.12, followed by SW at 0.09 and the combined at 0.06. Moderate-order speeding violations also decreased across all feedback configurations, as shown in the marginal effects plot. These results reinforce the effectiveness of real-time and static feedback systems in mitigating speeding behavior within controlled environments such as WZs.

In summary, the results of the GOL model highlight the multifaceted nature of speeding behavior, shaped by roadway design, vehicle type, driver characteristics, and environmental conditions. The findings underscore that infrastructure-related factors, such as lane position and feedback mechanisms, play a dominant role in moderating speed, while driver-related factors, including vehicle type and following behavior, contribute to the variation in speeding tendencies across severity levels. Contextual influences, including time of day, day of the week, and weather, further reveal that speeding is not a uniform phenomenon but one that fluctuates with situational awareness and perceived driving comfort. Collectively, the results emphasize that effective speed management and enforcement strategies must be both context-sensitive and spatially targeted. Measures such as inner-lane monitoring, deployment of feedback signs, and weekend-specific enforcement can significantly enhance compliance and safety outcomes. By integrating behavioral, environmental, and operational insights, transportation agencies can design more adaptive interventions that not only reduce individual speeding behavior but also generate wider safety benefits across the traffic stream.

## *4.2 Results of Analysis at the Start and End of Observation Area*

The second analysis was aggregated at one-minute intervals after being classified by lane, vehicle type, feedback type, and observation area. The speed change between Area 1 and Area 2 was modeled using the BGAM, where SA1 was treated as the only continuous predictor. This continuous variable was with a smoothing term to capture potential non-linear effects, while categorical factors such as lane, vehicle type, day, weather, DSFS, SW, and combination were treated as binary variables. The result of the analysis is demonstrated in TABLE X.

**TABLE X MODEL OUTPUT FROM THE BGAM MODEL**

| | Estimate | Est. Error | l-95% CI | u-95% CI | R hat | Bulk ESS | Tail ESS |
|---|---|---|---|---|---|---|---|
| **Regression Coefficients** | | | | | | | |
| Intercept | 5.36 | 0.36 | 4.64 | 6.07 | 1 | 10,694 | 11,418 |
| DSFS | 2.06 | 0.39 | 1.3 | 2.81 | 1 | 11,266 | 11,765 |
| SW | 2.97 | 0.34 | 2.29 | 3.64 | 1 | 11,234 | 11,599 |
| Combination | 0.74 | 0.33 | 0.08 | 1.38 | 1 | 10,154 | 11,076 |
| Smooth SA1 (sSA1) | 24.67 | 9.04 | 6.95 | 42.74 | 1 | 7,976 | 7,675 |
| Lane (Right = 0) | -5.54 | 0.32 | -6.17 | -4.91 | 1 | 18,058 | 12,574 |
| Vehicle Type (Truck = 0) | -1.29 | 0.24 | -1.76 | -0.82 | 1 | 18,417 | 12,141 |
| Day (Weekday = 0) | -2.6 | 0.27 | -3.14 | -2.07 | 1 | 15,275 | 11,357 |
| Weather (Sunny = 0) | 3.06 | 0.3 | 2.48 | 3.64 | 1 | 17,452 | 12,492 |
| **Smoothing Spline Hyperparameters** | | | | | | | |
| sSA1 Std. Dev(sdsSA1) | 14.44 | 5.28 | 6.25 | 26.72 | 1 | 4,681 | 6,418 |
| **Further Distributional Parameters** | | | | | | | |
| Residual Std. Dev. | 5.21 | 0.08 | 5.05 | 5.37 | 1 | 19,395 | 11,689 |

The results indicated that all variables were statistically significant within their credible intervals, and the Rhat statistic, a convergence diagnostic, confirmed that all parameters achieved satisfactory convergence. A positive coefficient denotes a reduction in SA2 compared to SA1, whereas a negative coefficient implies an increase in SA2 relative to SA1.

The non-linear component of the model, represented by SA1, was modeled using a smoothing spline to account for potential non-linearity between initial speed and subsequent speed change. The standard deviation of the smoothing term sds(SA1) suggests substantial variability in speed change explained by SA1, with a credible interval (0.67,39.13) indicating uncertainty in this effect. This demonstrates that the initial speed has a strong, non-linear influence on the speed change. The further analysis of the non-linear marginal of SA1 on the speed change showed that SA2 would increase if the SA1 was less than 58.07 mph and decrease if the SA1 was more than 58.07 mph. However, the speed change increased in both directions as the SA1 was further from 58.07 mph in either direction.

The results revealed significant differences based on roadway and traffic characteristics. Vehicles in the left lane recorded a coefficient of -5.54, indicating higher speeds relative to the right lane, while cars traveled faster than trucks by approximately 1.3 mph. Similarly, weekend driving was associated with higher speeds (-2.60), suggesting more aggressive driving patterns during weekends, whereas rainy or overcast conditions led to a notable reduction in speed (3.06), as drivers exercised greater caution.

The results also demonstrated that all feedback mechanisms, DSFS, SW, and the combination, had significant positive effects, confirming that feedback systems effectively reduce speeds after drivers encounter them. Among these, SW produced the largest reduction, followed by DSFS, while the combined feedback approach had a comparatively smaller impact, likely due to information overload.

In summary, the BGAM effectively captured both the linear and non-linear relationships influencing speed behavior in WZs. The model's strong convergence diagnostics and significant parameter estimates confirm its robustness and reliability. The findings emphasize that SA1 plays a crucial role in determining subsequent speed adjustments, exhibiting a distinctly non-linear pattern where drivers tend to self-correct when traveling notably above or below a critical threshold of approximately 58 mph, despite the speed limit of 55 mph. Furthermore, roadway and driver-related characteristics such as lane position, vehicle type, day of the week, and weather significantly affect speed patterns, reflecting variations in driver intent and situational awareness. The consistent positive effects of feedback systems, particularly SW and DSFS, demonstrated their effectiveness in promoting compliance and reducing vehicle speeds within WZs. Collectively, these results underscore the value of integrating behaviorally responsive feedback technologies and context-aware enforcement strategies to sustain safe and uniform speeds, ultimately enhancing the operational safety of dynamic roadway environments.

## *4.3 Results of Analysis Involving the Trajectories*

The SLM was developed to examine how vehicle speeds are influenced by various speed feedback treatments while accounting for spatial dependencies that arise from driver interactions within traffic streams. Before model estimation, Moran's I test was conducted to assess the presence of spatial autocorrelation in vehicle speeds, and the results confirmed significant spatial dependence (p<0.05). This finding justified the use of a spatial econometric approach, as it indicates that drivers' speeds are not independent but rather influenced by the speeds of surrounding vehicles. The dependent variable in the model is the instantaneous speed of each vehicle observed at one of three locations: Zone A (baseline), Zone B (adjacent to feedback), and Zone C (downstream of feedback). Control variables include distance relative to the speed limit sign, vehicle type, and lane of travel, while the treatment variables correspond to the different feedback mechanisms. Categorical variables were converted into binary indicator variables for inclusion in the model. Given the reality of vehicle platooning, following behavior, and the mutual influence among drivers, spatial dependence is an essential consideration in modeling real-world speed dynamics. The results of the SLM are presented in the following TABLE XI.

**TABLE XI MODEL RESULTS FROM THE SPATIAL LAG MODEL**

| Variable | Coefficient | Std. Error | t-statistic | p-value |
|---|---|---|---|---|
| Constant | 35.864 | 6.757 | 5.307* | <0.001 |
| DSFS (Base = No Feedback) | -3.341 | 0.337 | -9.891* | <0.001 |
| SW (Base = No Feedback) | -3.04 | 0.341 | -8.913* | <0.001 |
| SW & PCMS (Base = No Feedback) | -2.395 | 0.343 | -6.966* | <0.001 |
| Distance (ft) relative to speed limit sign | 0.0017 | 0.0006 | 2.802* | 0.005 |
| Truck (Base = car) | -2.543 | 0.242 | -10.241* | <0.001 |
| Right lane (Base = Left) | -2.851 | 0.248 | -11.783* | <0.001 |
| Zone B (Base = Zone A) | 1.205 | 0.52 | 2.316* | 0.021 |
| Zone C (Base = Zone A) | -4.054 | 1.122 | -3.613* | <0.001 |
| Spatial dependence ($\rho$) | 0.391 | 0.127 | 3.090* | 0.002 |
| **Model Fit Statistics** | | | | |
| Sample size | | 12,508 | | |
| Akaike Information Criterion (AIC) | | 64,511 | | |
| Bayesian Information Criterion (BIC) | | 64,585 | | |

The results presented in the table confirm that all key parameters are statistically significant at the 5% level, and the model fit indices (AIC = 64,5111; BIC = 64,585) indicate satisfactory performance. The spatial lag coefficient is positive and highly significant, demonstrating that vehicle speeds are spatially correlated. The Anselin-Kelejian test further confirmed that there was no significant spatial error dependence (p=0.662), indicating that the SLM adequately captures the spatial structure in the data. A positive coefficient in this model denotes an increase in vehicle speed, while a negative coefficient indicates a reduction. The positive spatial relationship reinforces the behavioral premise that drivers unconsciously synchronize their speeds with adjacent traffic, emphasizing the importance of considering collective dynamics rather than isolated vehicle behavior in safety analysis.

The treatment variables representing speed feedback signs: DSFS (-3.341), SW (-3.04), and combination (-2.395) were all statistically significant and negative, confirming that all feedback systems effectively reduce vehicle speeds as intended. The DSFS exhibited the greatest magnitude of reduction, reaffirming its role in effective treatment for encouraging compliance and improving safety. An interesting pattern was observed across spatial zones: immediately downstream of the feedback sign (Zone B), speeds were slightly higher (1.205, p =0.021) compared to the baseline zone (Zone A), suggesting a brief transitional adjustment period where drivers react to feedback before stabilizing their speeds. However, a substantial reduction in speed was observed in Zone C (coef. = -4.05, p<0.001), indicating a sustained behavioral effect of the feedback sign further downstream. Collectively, these findings highlight that spatial factors and driver interactions play a pivotal role in shaping speed behavior and that dynamic feedback systems are highly effective in reducing speeds and enhancing safety in WZs.

The decomposition of effects into direct and indirect (spatial spillover) components provides valuable insights into how both local conditions and neighboring vehicle behavior influence speeds within WZs. The direct effects represent the influence of each explanatory variable on an individual vehicle's own speed, whereas the indirect effects capture how changes in that variable for surrounding vehicles affect the subject vehicle's speed, illustrating the interconnected nature of traffic flow. These effects are summarized in TABLE XII.

**TABLE XII DIRECT AND INDIRECT EFFECTS FROM THE SLM MODEL**

| Variable | Direct Effect | Indirect Effect (Spatial Spill) | Total Effect |
|---|---|---|---|
| DSFS | -3.341 | -2.151 | -5.492 |
| SW | -3.04 | -1.957 | -4.997 |
| SW & PCMS | -2.395 | -1.542 | -3.937 |
| Distance | 0.002 | 0.001 | 0.003 |
| Truck | -2.543 | -1.637 | -4.18 |
| Right lane | -2.852 | -1.836 | -4.687 |
| Zone B | 1.205 | 0.776 | 1.98 |
| Zone C | -4.054 | -2.61 | -6.663 |

Among the control variables, distance from the speed limit sign exhibited a small but positive direct effect, indicating that vehicles tend to accelerate gradually as they travel farther downstream in the corridor. The positive indirect effect suggests that this gradual increase extends beyond individual drivers, influencing nearby vehicles as well, likely due to visual cues or collective movement patterns. This observation aligns with earlier research (Ardeshiri & Jeihani, 2014) reporting similar increases in speed with greater distance downstream. In contrast, Zone B, located immediately after the feedback signs, showed positive effects for both direct and indirect components, implying a temporary rise in speed immediately downstream of the feedback. However, Zone C, farther from feedback, displayed a significant speed reduction, likely due to a delayed driver response as they process the feedback and adjust their speed accordingly. Vehicle type was another significant factor: trucks were associated with lower speeds in both direct and indirect effects, confirming that heavy vehicles not only travel more slowly but also contribute to reducing the overall speed of surrounding traffic. This aligns with previous findings (Gao et al., 2020) that higher proportions of large vehicles help maintain lower freeway speeds.

All feedback treatments (DSFS, SW, and combination) produced negative direct and indirect effects, indicating their strong potential to reduce speeds for both the treated drivers and those nearby. The DSFS had the largest overall effect (direct: - 3.341; indirect: - 2.151), reaffirming its superior ability to influence driver behavior throughout the corridor. While the combination also reduced speeds (direct: - 2.395; indirect: - 1.542), it was less effective than SW alone, likely due to information overload, which may limit driver responsiveness. This suggests that the simultaneous presentation of multiple feedback types should be carefully calibrated to prevent desensitization and ensure consistent compliance.

Overall, the results underscore that speed feedback systems not only lower individual vehicle speeds but also generate measurable spillover effects, promoting more uniform traffic behavior across the WZ. The observed reduction exceeding 5% illustrates the broader safety benefits for these interventions, especially in areas with high driver interaction. From an implementation perspective, strategically placing feedback signs at regular intervals, particularly in downstream segments, can help maintain sustained speed reductions and minimize post-feedback acceleration. Furthermore, the presence of spatial dependence highlights that traditional non-spatial models may underestimate the true extent of traffic control effects. Therefore, future studies and policy evaluations should incorporate spatial econometric approaches to fully capture the distributed impacts of speed management strategies in WZs.

## *4.4 Discussion*

This study employed three complementary analytical frameworks: GOL, BGAM, and SLM to capture distinct yet interconnected dimensions of driver behavior in WZs. Together, these models offer a holistic understanding of how roadway, environmental, vehicle, and feedback-related factors influence speeding behavior, both individually and collectively. The integration of these three approaches provides a comprehensive behavioral and spatial interpretation of driver responses to varying WZ conditions.

The GOL model focused on analyzing the determinants of different severity levels of speeding violations at the end of the observation area, thereby highlighting the conditions under which drivers are most likely to engage in minor, moderate, or severe speed limit violations. The results emphasize that speeding is a multifactorial behavior shaped by lane choice, vehicle type, feedback mechanisms, and environmental context. Drivers in the left (inner) lane were consistently more likely to commit higher-order violations, corroborating existing evidence that faster-moving traffic and overtaking maneuvers tend to occur in inner lanes. The increased odds of severe violations in the left lane underscore the importance of lane-specific enforcement, such as targeted monitoring using speed cameras or dynamic lane control, to mitigate excessive speeding in high-flow zones. Similarly, vehicle type emerged as a critical determinant, with cars exhibiting a greater propensity for higher-order violations than trucks, likely due to differences in acceleration capability, vehicle agility, and perceived maneuvering freedom. These findings reinforce that vehicle composition on highways directly influences speed patterns, suggesting that a higher proportion of heavy vehicles could serve as a moderating factor for average speeds within WZs.

The effectiveness of speed feedback treatments was another major insight from the GOL analysis. Across all feedback types, DSFS and SW devices significantly reduced the likelihood of higher-order violations, confirming their utility in improving driver compliance. Interestingly, the combination of SW and PCMS was less effective than SW alone, indicating a potential for cognitive overload when multiple feedback types are presented simultaneously. This suggests that drivers may become less responsive when inundated with multiple stimuli, highlighting the importance of message clarity and signal simplicity in feedback design. The analysis also revealed that weekend driving and favorable weather conditions were associated with riskier speeding behavior. The higher incidence of severe violations during weekends likely reflects reduced traffic enforcement and greater leisure-oriented travel, while drivers in clear weather may underestimate risks, leading to overconfidence and excessive speed. In contrast, adverse weather conditions such as rain prompted more cautious driving, reducing the probability of severe violations. Collectively, these findings underline that both contextual awareness and perceptual judgment play essential roles in shaping driver responses.

The BGAM results further emphasized the importance of lane position, vehicle type, and temporal-environmental context in shaping these responses. Vehicles in the left lane and cars consistently exhibited higher speeds, whereas trucks and right-lane traffic maintained lower speeds, likely due to safety considerations near work activity areas. Similarly, speeds were higher on weekends and lower during rainy or overcast conditions, mirroring the findings from the GOL model but with finer temporal granularity. The feedback variables were again found to be significant; SW produced the largest mean reduction in speed (-2.97 mph), followed by DSFS (-2.06 mph) and the combined treatment (-0.74 mph). The smaller effect of the combined feedback mechanism reinforces the earlier observation that information saturation may reduce behavioral responsiveness. Overall, the BGAM highlighted the non-linear and context-sensitive nature of driver speed adjustment, demonstrating that feedback treatments not only influence overall speed levels but also modulate how drivers adapt to feedback depending on their baseline speed and situational awareness.

The spatial model provided a third and critical dimension to the analysis by incorporating spatial interdependence among vehicles, a factor often overlooked in traditional studies of speed behavior. The significant and positive spatial lag coefficient confirmed that vehicle speeds exhibit spatial autocorrelation, meaning that the speeds of nearby vehicles influence drivers’ speeds. This finding is consistent with the concept of platooning behavior, where drivers subconsciously synchronize their speed with surrounding traffic to maintain flow continuity or perceived safety. The absence of spatial error dependence, as confirmed by the Anselin-Kelejian test, validates the adequacy of the spatial lag specification in capturing the underlying spatial dynamics. The positive coefficient for distance from the speed limit sign suggests a gradual downstream acceleration, while the negative coefficients for truck and right-lane variables reinforce the trend of slower, more cautious driving in proximity to work activity areas.

The SLM also revealed critical insights into spatial spillover effects, distinguishing between direct effects and indirect effects. Feedback signs again demonstrated strong negative effects on both components, underscoring their role in reducing individual speeds and influencing collective behavior. For instance, the DSFS reduced speeds not only for the driver directly exposed to the sign (direct effect = -3.341) but also the indirect effect (-2.151), producing a total reduction exceeding 5 mph. This spatial diffusion of behavior, where nearby drivers slow down even without direct exposure to feedback, highlights a powerful spillover safety benefit that extends beyond the point of installation. Similar patterns were observed for SW and combination, although the magnitude was smaller. The speed increase observed in Zone B (immediately after feedback) likely represents a transitional phase before the feedback's effect stabilizes, whereas Zone C demonstrated sustained reductions, reflecting the longer-term behavioral impact of the treatments.

Practically, these findings carry substantial implications for transportation policy and WZ management. The evidence from all three models demonstrates that speed feedback systems, particularly DSFS and SW, are highly effective tools for reducing excessive speeds and improving compliance. Their combined direct and spillover effects suggest that deploying them strategically at regular intervals along WZ corridors can help maintain safe and consistent speeds, minimize abrupt accelerations or decelerations, and enhance overall operational safety. The results also emphasize the importance of spatially informed design by accounting for interdependence among vehicles: transportation planners can better predict collective behavioral responses and identify optimal feedback placements to increase corridor-wide safety benefits.

In summary, the integration of the GOL, BGAM, and SLM models provides a comprehensive behavioral, temporal, and spatial understanding of speed regulation in WZs. The GOL model captures the discrete transition between levels of speeding severity, the BGAM demonstrates the non-linear behavioral adjustments over short spatial intervals, and the SLM reveals the networked nature of driver responses that extend beyond individual decision-making. Collectively, these models illustrate that speeding behavior is not an isolated phenomenon but a complex, context-driven, and spatially interactive process. Future research should build upon these findings by exploring multi-level spatial-temporal models and real-time monitoring approaches to dynamically assess driver responses and optimize feedback strategies. The holistic integration of behavioral analysis, spatial econometrics, and feedback-based interventions offers a promising pathway for advancing data-driven safety management and enhancing driver compliance in complex roadway environments such as WZs.

# Chapter 5 Conclusion

## 5.1 Purpose and Summary of the Study

The primary objective of this research was to evaluate driver speed behavior and compliance within freeway WZs under varying roadways, environmental, and operational conditions. The study specifically examined how different speed feedback mechanisms: DSFS, SW, and combination (SW+PCMS), influenced driver decision-making and speed regulation.

To achieve a comprehensive understanding, three complementary analytical frameworks were developed:

- The GOL model examined the severity levels of speed limit violations at the end of the observation area.
- The BGAM analyzed speed adaptation between the start and end of the observation area while accounting for non-linear relationships.
- SLM captured spatial interdependence among vehicles to assess how driver speeds are influenced by the behavior of nearby traffic.

Together, these models provide an integrated behavioral, temporal, and spatial view of speed regulation in WZs, highlighting how infrastructure design, driver characteristics, and feedback technologies interact to influence compliance and safety.

## 5.2 Major Findings

### 5.2.1 Findings from the GOL Model

The GOL model identified key factors influencing the severity of speeding violations. Drivers traveling in the left lane and those operating passenger cars exhibited a significantly higher likelihood of severe violations, while trucks and right-lane drivers showed more conservative behavior. Among the feedback mechanisms, DSFS produced the strongest reduction in violation severity, followed by SW, whereas the combined (SW+PCMS) configuration was less effective, likely due to information overload or diminished driver attention.

Environmental and temporal variables such as weekend driving and clear weather increased the probability of higher-order violations, while adverse weather conditions reduced the likelihood of severe speeding, suggesting greater driver caution in lower-visibility conditions. These findings confirm that speeding behavior is context-dependent and shaped by both roadway design and driver perception.

### 5.2.2 Findings from the BGAM

The BGAM framework analyzed the dynamic relationship between initial and subsequent speeds. The continuous predictor, SA1, demonstrated a non-linear effect on the speed change between the start and end of the experiment area. Drivers traveling below approximately 58 mph tended to accelerate after encountering feedback, while those exceeding that threshold tended to decelerate, indicating self-corrective driving behavior.

Roadway and driver-related factors remained significant: vehicles on the left and cars maintained higher speeds, while trucks and right-lane vehicles demonstrated lower speeds. SW and DSFS again emerge as the most effective mechanisms, reducing speeds substantially after exposure.

The combined treatment produced smaller effects, likely due to perceptual saturation. Overall, the BGAM confirmed that drivers adaptively adjust their speeds based on their baseline velocity, roadway position, and contextual awareness.

### 5.2.3 Findings from the SLM

The SLM analysis introduced the spatial dimension, confirming that driver speeds are not independent but spatially correlated. The significant spatial lag coefficient revealed that drivers tend to synchronize their speeds with surrounding traffic, a behavior consistent with platooning and collective flow dynamics.

The feedback variables demonstrated significant negative effects: DSFS, SW, and combination, confirming their strong influence in lowering speeds. Interestingly, immediately downstream of feedback (Zone B), speeds showed a temporary increase (possibly a transitional adjustment), while Zone C reflected sustained speed reductions, indicating the long-term behavioral effect of feedback mechanisms.

The decomposition of effects into direct and indirect (spatial spillover) components showed that feedback systems not only reduce the speed of the driver exposed to them but also influence neighboring vehicles. The DSFS exhibited the highest total reduction (-5.49 mph), followed by SW (-5.00 mph), demonstrating broad spillover benefits throughout the traffic stream.

## *5.3 Broader Significance and Impact*

The integrated results from all three models highlight that speeding in WZs is a multifaceted, spatially interactive behavior rather than an isolated driver decision. The combination of econometric, non-linear, and spatial frameworks provides a more complete understanding of driver response to feedback mechanisms and environmental cues.

From a practical standpoint, this study reinforces that speed feedback systems, especially DSFS and SW, are among the most effective, low-cost tools for reducing excessive speeds and improving compliance. Their influence extends beyond individual drivers, creating collective safety improvements across vehicle platoons. The findings also demonstrate the value of incorporating spatial analysis into transportation safety research, as it captures the diffusion of behavioral changes across the traffic stream, something traditional models often overlook.

The broader significance extends to federal and state transportation safety initiatives, such as the FHWA's *Work Zone Safety and Mobility Rule* and *Strategic Highway Safety Plan*. By quantifying both individual and spillover effects of feedback systems, this research supports data-driven decision making for targeted enforcement, intelligent feedback deployment, and evidence-based policy formation.

## *5.4 Recommendations*

The following recommendations are proposed to enhance WZ safety and driver compliance:

1. **Prioritize DSFS Deployment in High-Risk WZs.**
   DSFS consistently achieved the largest speed reductions. Agencies should install DSFS units in high-speed or high-volume corridors, particularly near taper zones and active work areas, as well as long-duration WZs.

2. **Avoid Excessive Information Layering.**
   The combination of SW + PCMS showed diminished effectiveness, indicating potential driver desensitization. Messages should remain concise and uniform to reduce cognitive overload.
3. **Implement Lane-Specific Monitoring and Enforcement.**
   Since left-lane traffic is more prone to higher-order speeding, targeted enforcement (e.g., lane-specific radar monitoring or automated detection) can effectively control aggressive driving behavior.
4. **Adopt Context-Aware Enforcement Policies.**
   Temporal (weekend) and environmental (clear weather) variations in speeding behavior warrant adaptive enforcement, possibly integrating real-time traffic, lighting, and weather data to prioritize deployment schedules.
5. **Integrate Spatial Analytics into Safety Evaluation.**
   Agencies should incorporate spatial econometric models in post-implementation assessments to quantify direct and spillover effects, ensuring a comprehensive evaluation of feedback treatments and enforcement strategies.
6. **Future Research and Implementation.**
   Further field validation is recommended using connected-vehicle and high-resolution trajectory data to develop real-time adaptive feedback systems capable of dynamic message adjustments based on current traffic conditions.

## *5.4 Conclusion*

This study advances the understanding of driver speed regulation in WZs by linking behavioral modeling with spatial analytics. It provides empirical evidence that drivers' responses to feedback systems are both individual and collective, influenced by road geometry, lane configuration, and environmental context. The integration of GOL, BGAM, and SLM frameworks represents a methodological innovation that bridges behavioral economics, traffic operations, and spatial modeling.

The findings carry clear implications for federal and state transportation policy, supporting initiatives under the *Vision Zero* initiative and *Work Zone Data Initiative* aimed at reducing fatalities and improving WZ mobility. Ultimately, this research underscores that well-designed, data-informed, and spatially strategic feedback systems can foster safer, more adaptive, and more sustainable roadway environments for both workers and drivers alike.

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