Informed Safety, Mobility, and Driver Comfort Enhancement Practices for Work Zones: Learnings from High-Fidelity Data

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16. Abstract

This study leverages high-fidelity observational data to analyze driver behavior and vehicle dynamics within work zones (WZs) on Tennessee's interstate highways, aiming to evaluate critical aspects of safety, mobility, and driver comfort. Data were collected over several months from GPS, IMU sensors, and video recordings on commercial vehicles traveling through two active WZs on I-40 near Jackson, Tennessee. By using precise, sensor-based measurements of speed, acceleration, heading, and lane position, this research offers a detailed, real-time perspective on how WZ conditions influence driver behavior. The observational data reveal distinct patterns, such as increased speed variability and frequency of lane changes within WZs, which are indicative of driver discomfort and potential evasive actions. The analysis also shows that specific WZ configurations, including barrier placement and lane narrowing, impact driver response differently across locations, underscoring the importance of tailored Temporary Traffic Control (TTC) strategies. This study suggests that by leveraging high-fidelity data, traffic management can adopt more adaptive measures—such as dynamic speed feedback and improved visual guidance—to enhance safety and driving experience in WZs. The findings contribute to a deeper understanding of driver-vehicle interaction under varying WZ conditions, offering valuable insights for future WZ design and management.

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Executive Summary

This research study examines the impact of work zones (WZs) on traffic safety, mobility, and driver comfort along Interstate I-40 in Tennessee. By utilizing high-fidelity vehicle dynamics data, including speed, heading, acceleration, and braking patterns, the study provides a comprehensive analysis of how WZs affect driving behavior and traffic flow. The investigation analyzed commercial vehicle dynamics at two active WZs near Jackson, Tennessee (mile markers 79 and 93.4), utilizing GPS, IMU sensors, and video recordings to capture comprehensive driver behavior data.

Key Findings

Vehicles consistently reduced speed upon approaching WZs, with average speeds dropping significantly within the WZs. Speed variability which is also an indicator of uneasiness to the driver is notably higher in WZs which is observed from frequent acceleration and deceleration. Heading data reveals frequent directional adjustment within WZs suggesting driver discomfort caused by narrow lanes, barriers, and lane shifts. Increased instances of abrupt braking and lane changes indicate elevated risks of near-crash scenarios. Reduced lane availability and the presence of construction barriers forced drivers to perform braking and evasive maneuvers. The delay caused by WZs is calculated for a sample vehicle. Over a range of two miles before and two miles after the WZ, the delay was found to be nearly 31 seconds for a commercial vehicle as compared to the situation without the WZ during a non-congested flow of traffic.

Recommendations

To mitigate the negative effects of WZs on safety and traffic flow, some of the measures have already been used in different states and their effectiveness has been reported in the literature. Deployment of dynamic speed feedback systems (DSFS) and enhanced traffic signage are effective in improving driver awareness. The presence of law enforcers and speed cameras has been found effective in ensuring compliance with speed limits. Advanced lane guidance systems minimize driver uncertainty and enhance traffic flow. Moreover, driver education campaigns help improve preparedness for navigating the WZs.

Conclusion

The study underscores the complexity of managing traffic in WZs, where disruptions to typical driving patterns increase safety risks, delays, and congestion. Implementation of these recommendations reduces crash risks by improving traffic flow predictability and driver comfort. Short-term deployment of enhanced signage and enforcement can be accomplished within 6-12 months, while longer-term infrastructure improvements should be integrated into future work

zone planning. Success metrics will include reduced speed variance, decreased sudden braking events, and improved overall safety statistics. A strategic combination of technology, enforcement, and education can significantly alleviate the challenges created by WZs. These insights aim to inform future policies and practices for creating safer, more efficient WZs, ultimately benefiting both road users and construction crews.

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Chapter 1 Introduction

1.1 Background

Work zones (WZs) have long been cited as a potential cause of road fatalities and traffic delays. According to the Federal Highway Administration (FHWA), WZs account for nearly 24 % of non-recurring congestion in freeways and 10% of overall delays. As areas of heightened complexity and reduced roadway capacity, WZs undeniably impact the flow of vehicles and can lead to adverse outcomes besides delays such as discomfort for drivers and heightened safety risks. The interruption of normal driving conditions and the presence of barriers, narrowed lanes, and altered speed limits disrupt typical traffic flow. These disruptions often contribute to rear-end collisions, sideswipes, and other crash types, primarily because of sudden braking or lane changes in response to unexpected changes in road conditions. Among the fatal crashes in WZs in 2021 as reported by FHWA, 23% involved rear-end collisions, 33% involved commercial motorized vehicles and speeding was the factor in 32% of those crashes.

To mitigate these issues, significant efforts have been made through research, policy, and engineering solutions. However, despite these advancements, the complexity of ensuring smooth traffic flow and safety in work zones continues to challenge engineers, planners, and safety experts. The rising frequency of traffic incidents and delays calls for innovative approaches that go beyond traditional traffic management strategies. Given the increasing sophistication of vehicle technology, there is now an opportunity to gain detailed insights into how vehicles behave under varying conditions in WZ. Vehicles equipped with advanced sensors and data-logging systems can record real-time information on critical factors such as speed, lane position, braking patterns, headway distances, and steering adjustments.

1.2 Objectives of the study and report organization:

This study aimed to provide critical insight into the safety, mobility, and comfort of drivers in the WZ by analyzing vehicle dynamics and driver behavior. Maximizing the efficiency of work zones requires a thorough understanding of various vehicle dynamics, driver behavior, and unsafe events that occur near a work zone. To achieve this aim, the following objectives were proposed:

- Provide a review of existing literature regarding various factors affecting safety, mobility, and comfort at WZ.
- Determine and describe performance measures selected for quantifying safety, mobility, and comfort.
- Collect high-fidelity vehicle dynamics data using various sensors.
- Calculate the performance measures from position, speed, acceleration, heading, and spacing data.

The organization of the report is as follows:

The present chapter provided the background for this study with the objectives of the study. The next chapter of the literature review provides information on the types of WZs, the past research made regarding driving behavior in WZs, and modeling driving behavior. The chapter also provides information on risk factors causing crashes in WZs. Statistics related to crashes in

Tennessee are also included in this chapter. Chapter 3 introduces the methodology adopted for data collection of the project and sensor fusion. The procedure for the collection of high-fidelity data using different sensors is discussed in this chapter. The chapter also includes information regarding the pilot study made for data collection and processing. Chapter 4 is the data collection chapter which demonstrates the area taken for this study with the vehicles instrumented for this observational study. The Result and Discussion chapter presents detailed information regarding different performance metrics obtained from high-fidelity information which were used to quantify mobility, safety, and comfort for road users. Finally, the conclusion chapter provides a summary of the study, findings, and recommendations.

Chapter 2 Literature Review

2.1 Work zone Types

Based on the duration of work, the Manual on Urban Traffic Control Device (MUTCD) categorizes WZ into five categories presented in Table 1.

Table 1: Type of work zone based on duration.

Type	Description (Work)
Long-term stationary	Occupies a 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

Temporary Traffic Control (TTC) of WZ varies with the location of work relative to the roadway as stated by MUTCD. The closer the work is to road users, a significant number of TTC devices are needed. The various locations of TTC zones are:

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

2.2 Modeling Driver Behavior

Understanding the driver behavior in and around WZ is imperative to identify control and enforcement measures. Three main approaches are available to model driver behavior near WZs: (i) traffic simulation (ii) use of driving simulators, and (iii) use of field observations. Drivers often exhibit dangerous behavior in WZs due to frustration and anger caused by congestion and travel delays. Simulation techniques, both microscopic (individual-level) and macroscopic (aggregate-level), are employed to model traffic flow and driver behavior in WZs. These techniques are especially useful in hazardous conditions where real-world observation would be difficult or dangerous. Driving simulators have gained popularity because they offer the ability to recreate realistic driving scenarios in a safe environment. These simulators have been validated in various studies for their accuracy in replicating WZ designs, road conditions, and driver reactions. When no safety risks are present, researchers use field observations to assess the impact of new WZ treatments on driver behavior. These changes are measured through traffic flow parameters like free-flow speed (FFS), deceleration, or driver violations like over-speeding or lane changes.

A naturalistic driving study observes, records, and analyzes the driver's behavior in real-world conditions without intervention. The study captures how people drive in day-to-day scenarios with all the complexities, variations, and distractions in real-life driving. The study involves using sensors, cameras, and GPS devices to capture the actions of drivers, vehicle dynamics, and the environment. The 100-car naturalistic driving study was the pioneering study on naturalistic driving that focused on capturing a crash and near-crash event (Dingus et al., 2006). In this study, a crash was defined as contact where kinetic energy is measurably transferred or dissipated due to contact with an object. A near-crash event was identified as a condition that required an evasive maneuver by the subject vehicle or other road users, animals, etc. to avoid a crash. The Strategic Highway Research Program 2 (SHRP 2) was another study (Perez et al., 2016) that collected a large amount of naturalistic driving data like driving behavior, vehicle dynamics, and environmental conditions. SHRP 2 involved 3,500 drivers across six different locations in the U.S., by monitoring the participants for a period of one to two years. The primary areas of focus were crash, near-crash, distraction, fatigue, etc. The definition of crash and near-crash were similar to the 100-car study and were referred to as safety-critical events. These events were identified by monitoring the potential window of trigger occurrence coupled with video data. Various triggers were used to help identify the safety critical events like deceleration (<= -0.65 g), acceleration (> 0.5 g), swerve (> 15 deg/s/s), etc.

2.3 Driver behavior in work zones

Driver behavior in WZs is mainly characterized by the study of a driver's behavior in compliance with (i) speed limit and speed variance, and (ii) merging behavior. Excessive speeding and large speed variances are significant contributors to crashes in WZs. Higher speeds not only increase the likelihood of crashes but also their severity, while larger speed variances raise the probability of rear-end crashes. Treatments in work zones aim to reduce over-speeding and ensure uniform traffic flow. According to the MUTCD, various TTC strategies such as traffic signs, flaggers, and Dynamic Message Signs (DMS) are used. Additional speed enforcement strategies include: (i) Law enforcement presence (ii) Speed Photo-radar Enforcement (SPE) (iii) Variable Speed Limits (VSL) (iv) Dynamic Speed Feedback Systems (DSFS). Studies in this area examine the effectiveness of these systems in managing driver behavior and improving safety.

Merging is critical in WZs as improper merge actions disrupt traffic flow and lead to safety issues, particularly in cases of lane closures. Merge behavior consists of two primary tasks: (i) Deciding where to merge (ii) Executing the merge based on gap availability in the adjacent lane.(Weng & Meng, 2011) developed models to predict merge location, probability, and distance based on traffic flow parameters, highlighting the relationship between speed flow and merge behavior. (Nassab et al., 2006) used Cellular Automata models to simulate merging strategies, suggesting that a Zipper merge and controlling speed in certain areas improve traffic flow. (Louisell et al., 2006) employed agent-based models with game theory to understand individual driver behavior and merging locations. The most common approach for modeling merge behavior is gap acceptance, where drivers decide to merge based on the availability of safe gaps between vehicles. Various strategies, such as the use of traffic signs and enforcement mechanisms, are used to regulate merging in WZs, improving traffic flow and minimizing delays.

2.4 Risk factors and behavior

Research has consistently highlighted the unique risks associated with work zones (WZs), with several studies identifying key factors that contribute to crashes and unsafe driver behaviors. (Dissanayake & Akepati, 2009) found nearly half of all work zone crashes occur within or adjacent to the work activity area and 42% of WZ crashes are rear-end collisions. The primary causes were reported as no improper action (32.1%) followed by inattentive driving (19%) and following closely (9.7%). WZs cause sudden traffic interruptions, leading to queues, slowdowns, lane changes, overtaking, and conflicts, all of which impact driver behavior (Flannagan et al., 2019).(Hamdar et al., 2016) observed higher speeds in longer WZs, which were attributed to driver impatience. They reported that an increase in activity level and an overall decrease in speed were observed. (He et al., 2016) investigated key factors affecting lane-changing behavior to be vehicle type, lane speed, and traffic volume. Risky driving behavior was associated with adverse weather, poor lighting, absence of traffic control devices, and older vehicles (Weng & Meng, 2012). They reported that middle-aged male drivers were more prone to risky behavior. In a study about the perception of risk in WZs by workers, (Debnath et al., 2015) found that adverse weather and lighting conditions, distracted driving, roadway type, and alignment are significant factors affecting risky behaviors. The most hazardous conditions were found to be wet weather, aggression toward traffic controllers, and mobile phone usage according to the study. Workers also cited the most effective countermeasure for speed compliance to be some sort of police enforcement or the presence of police cars, installation of speed humps, and driver education.

2.5 Crash Statistics of Tennessee in WZ

The number of crashes in WZ in Tennessee is found to vary across years. The count of crashes has been found above 2,000 for all years except the year 2017, where it was 1,948. Even during the Covid period, the crash counts were north of 2,000. Despite various studies being made and various engineering, enforcement, and awareness programs, the reported crashes in WZ have remained over 2,000.

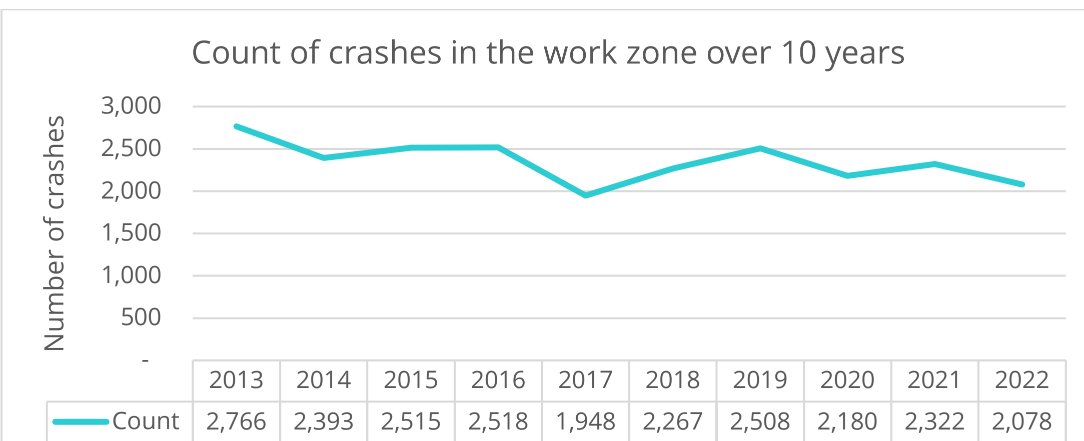

Figure 2-1: Crash count in work zone over 10 years.

Despite relatively fewer crashes in recent years as compared to earlier years, the number of deaths in crashes in WZ is rising. Before 2018, the average fatality was nearly 13 per year, which has increased to nearly 19 per year in recent years. Fatalities in 2021 and 2022 are above 20 per year.

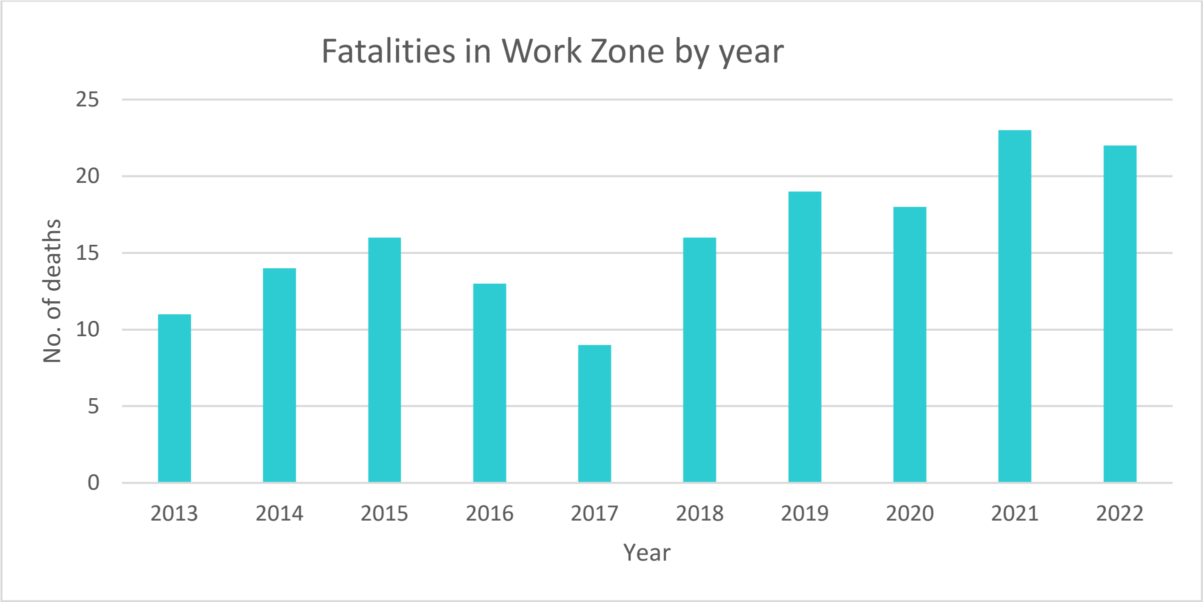

Figure 2-2: Fatalities in Work Zone by Year.

Tennessee has more than ten times the length of state roads as compared to the length of interstate, however, there is not much significant difference in the percentage of crashes in WZ among the two classifications of road. 39% of all WZ crashes in the last 10 years were recorded on state roads and 37% of all the WZ crashes in the same period were recorded on interstate highways.

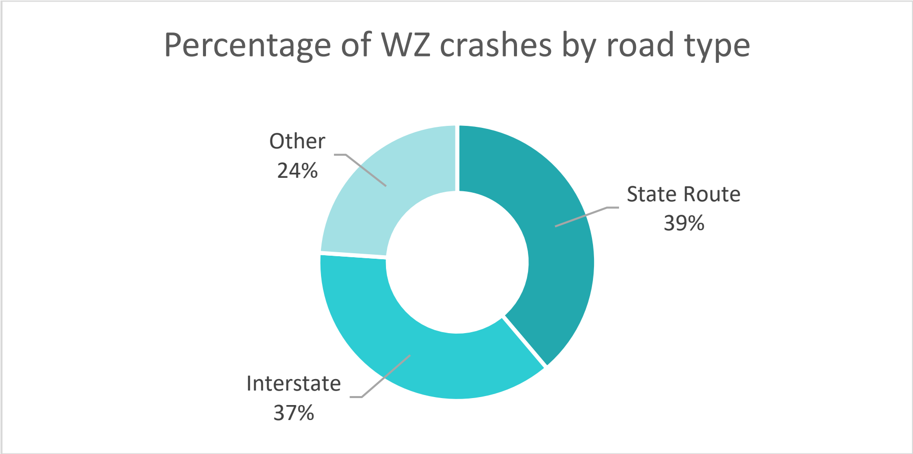

Figure 2-3: Percentage of crashes in Work Zone by type of road.

The longest interstate highway in Tennessee (I-40) is also the highway with the most no. of crashes in the year between 2013 and 2022. Despite being an interstate of less than 20 miles, a significant number of crashes have been recorded on I-240 over 10 years. Among the state routes SR001, SR003, and SR014 are the top three roadways with the highest number of crashes in the WZ.

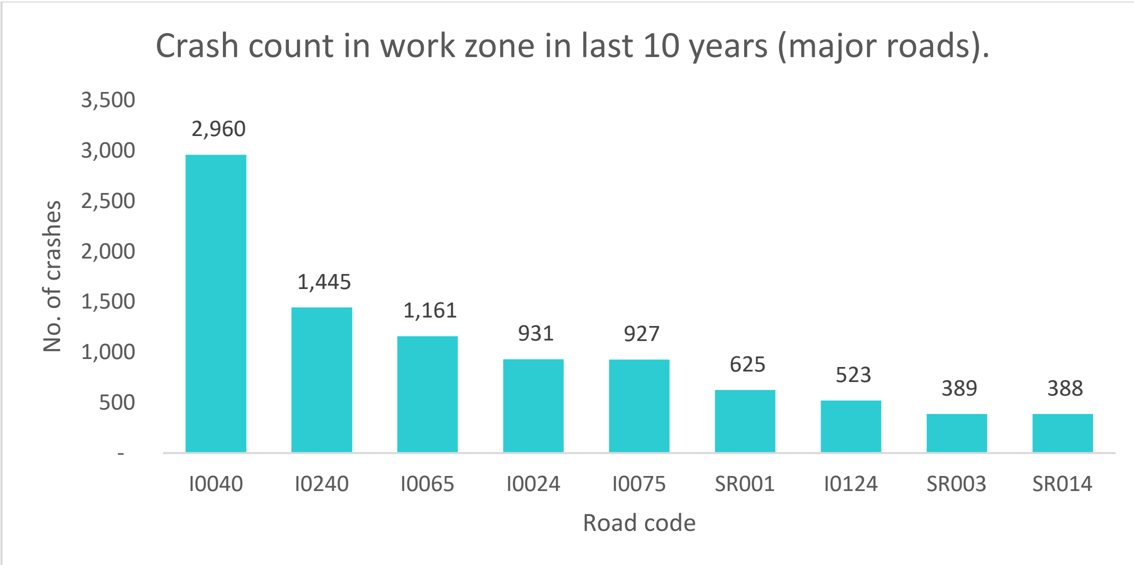

Figure 2-4: Crash count in WZ on major roads in last 10 years

This chapter reviewed the complexities of work zones (WZs), highlighting how various factors—including WZ types, Temporary Traffic Control (TTC) strategies, driver behavior, environmental conditions, and road characteristics—impact safety and efficiency. The literature indicates that while numerous traffic control strategies can reduce risks, challenges persist in promoting consistent driver behavior and ensuring safe driving conditions in WZs. By observing high-fidelity data on safety, comfort, and mobility within these zones, we can gain essential insights to help inform strategies aimed at enhancing WZ management and reducing risks for all road users.

Chapter 3 Methodology and Pilot Study

The movement of vehicles in traffic depends on surrounding vehicles. The traffic environment is dynamic and there is constant interaction between vehicles. It creates a complex network of interactions. Adjustment of positions and speed as well as following lead vehicles, making way for merging vehicles, and overtaking slower vehicles are all routine works of drivers. Drivers show signals while changing lanes to communicate with other drivers. The maneuvering of vehicles is an intricate behavior as the density, speed, lane configurations, and geometry of the road change with time and space. The movement, trajectory, and behavior of the surrounding vehicle relative to the instrumented vehicle are possible through sensor fusion. The instrumented vehicle serves as a reference point for analyzing the behavior of surrounding vehicles.

The study of the surrounding vehicles of the instrumented vehicle is possible by identifying the position and location of the surrounding vehicle in time and space. The instrumented vehicle is mounted with sensors that can store Global Positioning System (GPS) data and Inertial Measurement Unit (IMU). GPS contains information on latitude, longitude, and reduced level of the instrument with time. IMU contains information on acceleration in longitudinal and lateral directions with rotations and bearings. The instrumented vehicle is mounted with cameras that record video graphic data. Combining data from diverse sensors provides a more comprehensive understanding of the driving environment. The objective of the sensor fusion is to analyze the surrounding vehicle data from video with the instrumented vehicle as a reference.

3.1 GPS and IMU

The instrument used was Video VBOX Pro (10 Hz). It has a data logger which stores GPS data and high-quality video data. This instrument can be configured to attach up to four cameras. This study used 3 cameras, with one on the front and two on each side to record surrounding vehicle features. The data logging was made possible through an SD card. The cameras and orientation were adjusted through a preview Liquid Crystal Display (LCD). The VBOX instrument can be observed in the adjoining figure with the front-facing camera and LCD screen.

The VBOX pro instrument has an accuracy of 0.1 km/h. The update rate is 10 Hz. The maximum velocity it can register is 1600 km/hr. The accuracy of the distance is 0.05% (<50 cm per km). The resolution for distance is 1 cm and for the velocity is 0.01 km/hr. These data are provided by GPS and IMU units and are logged into the Secure Digital (SD) card. The cameras connected on the front as well as sides of the vehicle are also recorded in the SD card.

Figure 3-1: Instrument in action in the instrumented vehicle.

3.2 Video Data

The processing of video data involves many processes like detection of nearby vehicles, classification of the vehicles into vehicle type, and detection of the position of the surrounding vehicles in the image plane are all part of the processing of the video data. Calibration of the camera is a crucial step in determining the size and position of an object. Calibration of the camera can be done by measuring objects of known size at various locations within the field of view of the camera. By analyzing the variations of known objects and their positions, the position of detected classified vehicles from video data can be ascertained. The transformation of the pixel coordinate of the detected object to the real-world plan is completed by processing the video data.

3.2.1 Vehicle Detection

Computer vision is a branch of artificial intelligence that focuses on enabling computers to interpret and understand information from images or videos. This involves developing models to acquire, process, and analyze images to retrieve information. Computer vision has been in use for various applications like self-driving cars, surveillance, medical imaging analysis, robotics, and image search engines. The critical task in computer vision is object detection (vehicle detection). This involves identifying and locating objects in the images.

You Only Look Once (YOLO) is a popular real-time object detection algorithm introduced in 2016 (Redmon et al., 2016). The strength of YOLO lies in classifying objects in one pass and with higher accuracy and speed enabling it to be used for real-time applications. Its unique architecture enables object detection and classification into a single neural network. YOLO works by dividing the input image into some gird and each grid cell predicts bounding box, confidence scores, and class probabilities. The YOLO model was trained using images recorded from the video. Several images were extracted, and bounding boxes were created to train the supervised model.

3.2.2 Vehicle Tracking

Once the vehicles are detected, a tracking algorithm known as the Kalman Filter is applied to track the movement of objects across the frames. This typically involves predicting the vehicle's location, speed, and direction while accounting for occlusions and lighting condition changes. This process can be visually observed on the processed video frames. Bounding boxes surrounding vehicles are tracked over multiple frames.

3.2.3 Position of Tracked Vehicles

The local position of tracked vehicles can be estimated using their pixel coordinates obtained from video frames. This estimation involves the application of homography transformation, a technique that facilitates the mapping of points in the image plane to corresponding points on a real-world surface. By performing a perspective transformation, this process effectively converts the pixel coordinates captured by the camera into real-world coordinates, allowing for a more meaningful analysis of vehicle positions and movements.

To compute the homography matrix, points of correspondence are established between the pixel coordinates in the image and known real-world coordinates. These correspondences are crucial, as they provide the necessary data to derive the transformation matrix that links the two coordinate systems. Typically, at least four pairs of corresponding points are required to accurately compute the homography matrix. Once the corresponding points are identified, the homography matrix is calculated using methods like the Direct Linear Transform (DLT). This matrix serves as a calibration tool that converts pixel coordinates from the camera's perspective into a global coordinate system aligned with real-world surfaces.

3.3 Sensor Fusion

The process of sensor fusion first integrates IMU units and GPS units to get high-fidelity data corresponding to the pilot vehicle. When image data is integrated with the subject's inertial movement and GPS, the position of vehicles observed from cameras can be identified using transformation techniques explained in the previous section. An illustration of the locating object's position is demonstrated in the following example:

GPS data contains time stamps, longitude, and latitude. IMU data contains longitudinal and lateral speed, acceleration/deceleration along with time stamps. The video data has a time stamp as well. Now, integrating the GPS data and IMU data is straightforward as the timestamps corresponding to the GPS and IMU units must be the same. However, by utilizing current position, heading, and timestamp data from the subject vehicle and using the projected coordinate of the detected object from video data, we can estimate the position of detected objects. The detected objects are dominantly vehicles.

We can take one sample used for the estimate of the position of a vehicle using this method. Here in the following Table 2, the timestamp is given by the "Time" column. The Latitude and the longitude columns provide the GPS coordinates of the subject vehicle. The Heading column provides the orientation of movement of the subject vehicle with the north. This information corresponds to the video file with index number: 55. The "Video time" column specifies the time instant of the video file where these positions and heading have been collected So, at 16:04:48.8 the subject vehicle was at 35.6911 N 88.70984 W heading 64.53 and this position refers to 44th second of the video file indexed "55".

Time (HHMMSS.S)	latitude (deg)	longitude (deg)	Heading	Video file	Video time (s)
160448.8	35.6911	88.70984	64.53	55	44
160449.3	35.69116	88.70969	64.52	55	44.5
160449.8	35.69122	88.70955	64.47	55	45
160450.3	35.69127	88.7094	64.61	55	45.5
160450.8	35.69133	88.70926	64.62	55	46
160451.3	35.69138	88.70911	64.51	55	46.5
160451.8	35.69144	88.70897	64.52	55	47
160452.3	35.69149	88.70882	64.24	55	47.5
160452.8	35.69155	88.70868	64.32	55	48
160453.3	35.69161	88.70853	64.44	55	48.5
160453.8	35.69166	88.70839	64.7	55	49

Similarly, we have extracted the pixel coordinates of the bounding box of the tracked vehicles. Here in the following table of the output extracted from running a detection and tracking algorithm in the same video file number 55, a truck was found with id “85” being tracked from 44 seconds to 49 seconds. The coordinates x1 and y1 refer to the left top edge of the bounding box on the image plane whereas x2 and y2 refer to the right bottom edge of the bounding box on the image plane. These coordinates were used to calculate the position and movement of truck "85" over the specified time interval.

Table 2: Table showing information on nearby vehicles from the instrumented vehicle.

Video Time	Pixel coordinate, x1	Pixel coordinate, y1	Pixel coordinate, x2	Pixel coordinate, y2	Detected class	Detected id
44	488.7	750.43	640.29	907.99	truck	85
44.5	509.65	756.57	647.01	910.1	truck	85
45	526.24	758.72	653.08	911.85	truck	85
45.5	540.01	758.39	654.87	904.52	truck	85
46	554.03	761.31	659.82	901.13	truck	85
46.5	564.91	765.53	665.97	896.27	truck	85
47	581.5	765.02	676.61	896.1	truck	85
47.5	587.22	767.33	678.74	892.87	truck	85
48	591.91	769.21	679.14	890.71	truck	85
48.5	597.87	775.33	681.36	891.04	truck	85
49	601.97	772.92	683.89	883.54	truck	85

Using the principle of homography, the position of truck no. 85 was estimated by referencing the subject vehicle. From the data obtained on the image plane, the coordinates of the lower edge of the bounding box, corresponding to the detected vehicle's position at road level, were extracted. The distance and angle between the reference vehicle and truck no. 85 were then calculated. With the reference vehicle's known position and heading, trigonometric calculations were performed to estimate the real-world position of the detected truck. Since the timestamped position of the detected vehicle was also available, various metrics, such as speed, acceleration, and trajectory characteristics, could be computed to analyze its movement dynamics.

Table 3: Table showing the coordinate of the tracked vehicle after sensor fusion

Video Time	Identification of Vehicle		Data From GPS and IMU from instruments on the Truck			Detected Vehicle's Coordinate	
	Detected class	Detected id	Latitude (deg)	Longitude (deg)	Heading	Latitude (deg)	Longitude (deg)
44	truck	85	35.69110	88.70984	64.20	35.69125	88.70959
44.5	truck	85	35.69116	88.70969	64.16	35.69131	88.70942
45	truck	85	35.69122	88.70955	64.24	35.69136	88.70925
45.5	truck	85	35.69127	88.70940	64.26	35.69141	88.70907
46	truck	85	35.69133	88.70926	64.25	35.69146	88.70889
46.5	truck	85	35.69138	88.70911	64.31	35.69148	88.70877
47	truck	85	35.69144	88.70897	64.30	35.69154	88.70854
47.5	truck	85	35.69149	88.70882	64.36	35.69159	88.70837
48	truck	85	35.69155	88.70868	64.36	35.69165	88.70820
48.5	truck	85	35.69161	88.70853	64.37	35.69170	88.70804
49	truck	85	35.69166	88.70839	64.51	35.69175	88.70787

3.4 Pilot project

The main objective of this project is to study performance measures of safety, mobility, and comfort on WZ. Acquisition of high-fidelity primary data utilizing instruments is the precursor of this study. VBOX instrument that has an Inertial Measurement Unit (IMU) and Global Positioning System (GPS) need to be mounted on the vehicle. The addition of 3 cameras: one on the front and two on each side of the vehicle is also necessary to capture surrounding vehicle data. On-site pilot studies were conducted with a van from the University of Memphis.

3.4.1 Instrumental Set Up

A video VBOX instrument was installed on a university van. GPS was connected to the VBOX. One camera was installed on the front to capture video data along the direction of the travel. One camera in each direction of the vehicle was installed to capture the surrounding traffic of the vehicle. LCD preview screen was looked upon to correct the orientation of the cameras. The total setup of the hardware can be seen in the following figures.

Figure 3-2: Video VBOX installed in the van.

Figure 3-3: Preview LCD screen and front-facing camera.

Figure 3-4: Camera installed on the left side.

Figure 3-5 Camera installed on the right side.

3.4.2 Data Collection

The instrumented test vehicle was driven along Central Avenue to Highland and from Highland to Poplar Avenue. The path taken by the instrumented vehicle is shown in the map below in red color. The trip started at the bottom right corner of the map at the University of Memphis. The area represented by the grey rectangle represents the work zone.

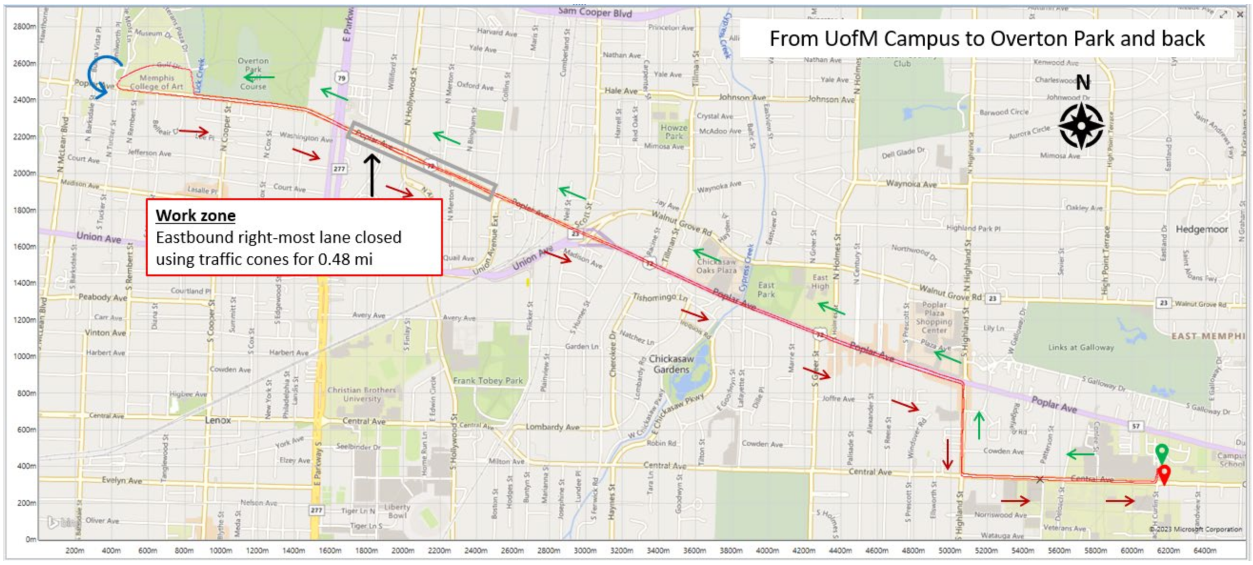

Figure 3-6: Map showing the path of the vehicle during the test run.

This section of Poplar Avenue has 3-lanes in each direction. During the day of the pilot test, the rightmost lane was closed using traffic cones as a work zone was present there. The length of the work zone was 0.48 miles. The green arrow in the above figure shows the vehicle traveling from the start at the University of Memphis to Overton Park. The vehicle then traveled back through the same path and came across the work zone while traveling east from Overton Park as indicated by red arrows. As the vehicle traversed its way back, it came across the stated work zone. IMU, GPS, and video data were logged into the SD card of the VBOX. The data contained all the information from the start to the end of the pilot study. The data were transferred from SD cards to computers for processing.

3.4.3 Data Processing

The video VBOX PRO has a software package called "VBOX Test Suite". The files obtained from the SD card are copied into a computer. The files contained have two types: one file is a video file, and the other file is a sensor data (IMU, GPS, etc.) file. The interface can be seen in the following figure. The interface consists of different sub-sections. The path taken by the vehicle is shown on the map in the bottom right corner. The red line shows the path traced by the vehicle whereas a small black cross sign shows the position of the vehicle at that instant. The panel on the left of the map shows various metrics of travel. In the following figure of the interface of the software. speed, longitudinal acceleration, and lateral acceleration of the vehicle against the distance traveled is shown. On top of these displays, is the video data recorded from the camera mounted on the vehicle. Several other pieces of information can be added and observed at the same time.

Figure 3-7: The interface of the VBOX software to visualize different attributes of the test run.

Using the GPS information available from the data logger and video data, identification of the location of WZ was made in the following figure. The information from IMU and GPS sensors was instrumental in getting the position, speed, acceleration, and heading of the instrumented vehicle. The lower portion of the following plot is obtained by plotting the speed profile along the path of travel by the test vehicle. As the pilot study comprised test vehicles passing through the inner-city area, the signalized intersections resulted in the stop-and-go of the vehicle.

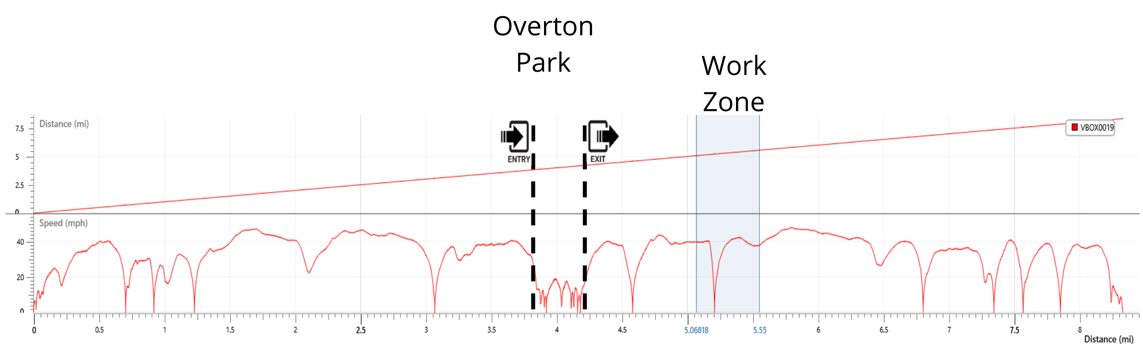

Figure 3-8: A graph showing the information of speed and distance versus time for the test run.

Chapter 4 Data Collection

4.1 Study Area

The primary objective of this project was to collect and analyze driving behavior within WZs on interstate freeways. Commercial drivers, specifically those who frequently travel through WZ areas, were identified as suitable candidates for the data collection procedure, as their driving patterns can provide valuable insights into the interaction between traffic and WZ conditions. These drivers often encounter various WZ scenarios, making them ideal for observing behaviors related to speed, lane changes, and safety.

Figure 4-1: Map of Tennessee showing interstate I-40 and Madison County.

In the case of this study, data regarding work zones on Tennessee's interstate highways were already available, providing a foundation for selecting specific sites. Two active WZ locations were identified on Interstate 40 (I-40), near Jackson, Tennessee, where construction work was ongoing. The first WZ location was situated near Mile Marker (MM) 79, and the second location was between MM 93 and MM 94 (taken as 93.4 afterward). These sites were selected due to their accessibility, active construction status, and the availability of commercial traffic passing through.

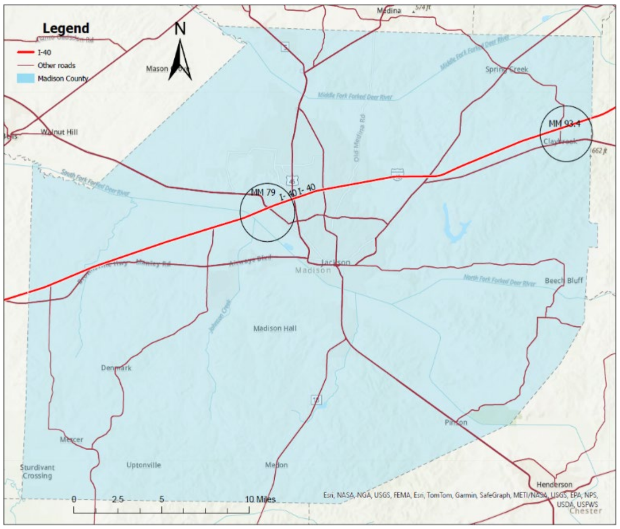

Figure 4-2: Map of Madison County showing WZ at MM79 and MM93.4

The nature of work observed in MM79 consisted of upgrading the inner lane of the road. Concrete barriers were placed to segregate construction work from traffic. The nature of work in MM93.4 was the maintenance of the exit and the entry lane. Construction work was being performed on the shoulder part of the right lane.

4.2 Instrumentation of vehicles

Commercial vehicle drivers that travel through the above-mentioned sites were contacted for the data collection. Four commercial vehicles were selected for data collection. The duration of data collection ranged from mid-March 2003 to early October 2023. The trucks collected data while traveling between facilities in Nashville and Memphis. The instrumental setup for the trucks can be seen in the following figures. The instrument to record inertial movement and GPS was placed inside the truck. The front-facing camera was installed in the middle of the front glass. Two cameras facing the left and right sides captured the lateral movement as well as surrounding traffic and lateral clearances.

Figure 4-3: VBOX installed on a truck

Figure 4-4: Front camera on the truck

Figure 4-5: Right side camera

Figure 4-6: Left side camera

The data collected were uploaded to the cloud in intervals of two weeks. The total no. of sample data collected from the trucks in the two WZs along the two direction of travel is presented in table below. These tracks were obtained after removing (filtering out) tracks that did not have continuous data or were missing video data. The variation in the number of samples is due to various reasons such as drivers often forgetting to switch on the data logging system and sometimes due to power cable or camera connections shifted due to vibration in the vehicle. These problems were often dealt with at the time of data transfer, however, still the problem would persist.

Table 4: Frequency of data collection in the two WZ by different trucks

	Traveling to Nashville		Traveling from Nashville	
	MM 79	MM93.4	MM 79	MM93.4
Truck 1	13	13	8	8
Truck 2	34	58	30	31
Truck 3	57	60	10	56
Truck 4	30	31	27	31

The following images are extracted from the video captured from the truck while navigating through the WZ. The first row of the pictures belongs to WZ at MM 79 in I0040 and the second row of the picture belongs to WZ at MM 93.4. The first column of the picture is while the truck is traveling to Nashville from Memphis and the second column represents the picture while the vehicle is traveling from Nashville to Memphis. Detected vehicles can also be seen in the images with concrete barriers on the side of the road to segregate the WZ.

Figure 4-7: Image extracted from a vehicle in WZ at MM 79 (Memphis to Nashville)

Figure 4-8: Image extracted from a vehicle in WZ at MM 79 (Nashville to Memphis)

Figure 4-9: Image extracted from a vehicle in WZ at MM 93.4 (Memphis to Nashville)

Figure 4-10: Image extracted from a vehicle in WZ at MM 93.4 (Nashville to Memphis)

Chapter 5 Result and Discussion

5.1 Mobility

The speed profile of a vehicle can point out several important aspects of travel. While a sudden decrease in speed may imply braking action by the vehicle. The underlying causes could be various and some of these can be uncovered from video data as well. Sometimes the driver may accelerate and increase speed as the road may have favorable conditions to have higher speed which again can be verified from video data.

Most of the plots in this chapter have been drawn for a single vehicle. While the plots can be made for all vehicles in all the WZs, the cluttering of various information on the same figure resulted in a graphic that was confusing. For example, the map in the following figure represents the region around Jackson, Tennessee. The colored area along the length of the I-40 represents the longitudinal speed profile of a subject vehicle. We can observe the location of WZ near MM 79 which is in the middle area (longitude: -88.8876° to -88.8678° and latitude:35.6516° to 35.6591°) of the figure. Initially, the speed is represented by a green color (around 63-66 mph). During the transition, a dark blue color (50-55 mph) can be observed which persists through WZ. After crossing the WZ, the subject vehicle regains its speed.

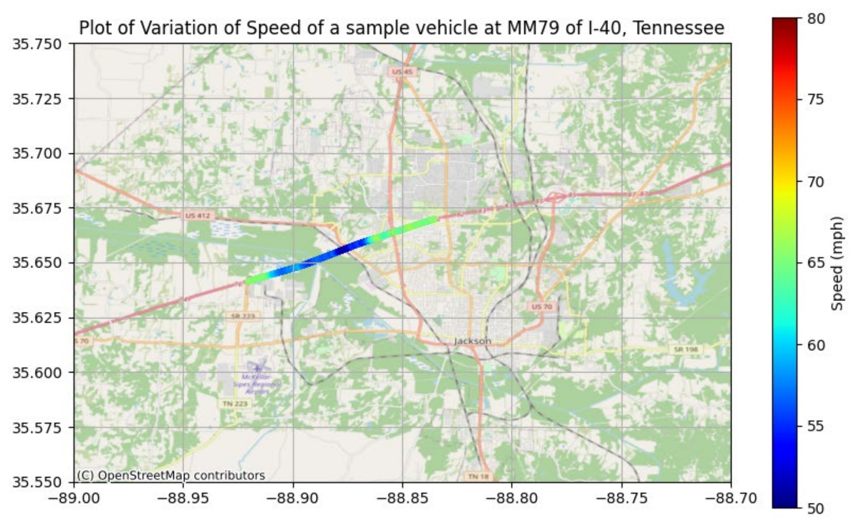

Figure 5-1: Speed Variation along the path of travel in WZ at MM 79 (Memphis to Nashville)

The speed profile for the same vehicle was plotted for the WZ located at Mile Marker (MM) 93.4, covering a stretch from two miles before to two miles after the WZ. The work zone, spanning from longitude -88.6413° to -88.6261° and latitude 35.7158° to 35.7205°, is depicted in the figure below. This profile reveals a distinct reduction in speed within the work zone, while the vehicle maintains a relatively constant speed in the areas preceding and following the WZ.

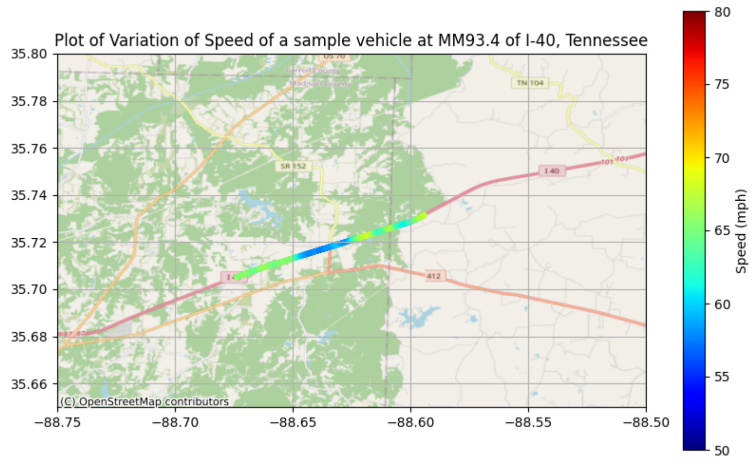

Figure 5-2: Speed Variation along the path of travel in WZ at MM 93.4 (Memphis to Nashville)

A sample plot of the longitudinal speed profile of a subject vehicle while traveling from Nashville to Memphis at MM93.4 as shown in the figure below is similar to the speed profile at the same location for travel along Memphis to Nashville. There's a slight speed drop in the WZ area which is regained even before the end of the WZ area.

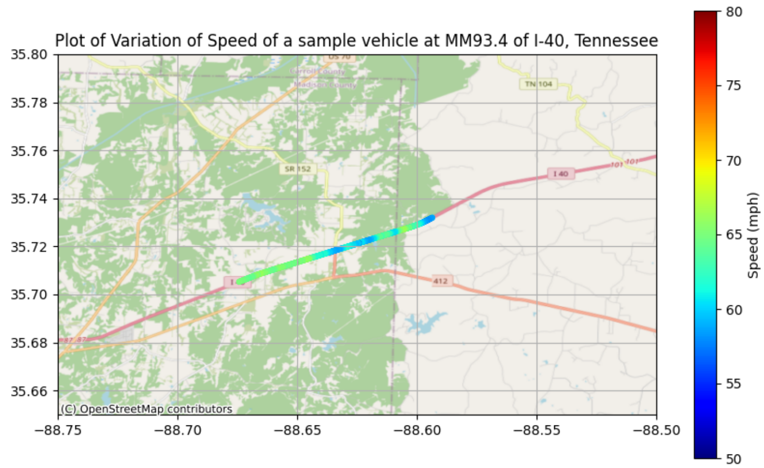

Figure 5-3: Speed Variation along the path of travel in WZ at MM 93.4 (Nashville to Memphis)

Similarly, the speed profile of the vehicle was plotted in WZ at MM79 while the vehicle traveled from Nashville to Memphis. This plot seems different than when the vehicle traveled in the opposite direction. The effect of WZ was visible nearly 2 miles before the WZ. A drop in speed was observed at nearly 2 miles before WZ. The vehicle traveled at a speed of around 55 mph through the WZ and then by the end of the WZ, the vehicle regained its original speed of 65 mph.

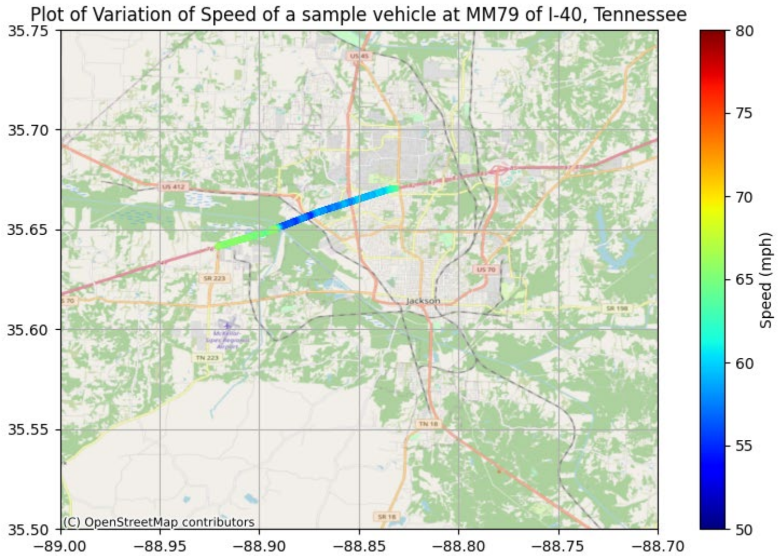

Figure 5-4: Speed Variation along the path of travel in WZ at MM 79 (Nashville to Memphis)

The nature of WZs in the two areas has caused different effects on the vehicle. Despite both the WZs being two-lane roads, the speed drop in the case of MM79 is more pronounced than MM93.4. One simple inference from these four longitudinal speed profiles can be the effect of concrete barriers. The WZ at MM79 had concrete barriers on the inner lane whereas WZ at MM93.4 had concrete barriers in the outer lane.

The speed data along a longitudinal profile from 2 miles before the WZ to 2 miles after the WZ was plotted to observe patterns and variations of speed by distance in a WZ for a single vehicle over multiple days. The following figure exhibiting the heatmap of speed in the WZ at mile marker 79 for truck no. 1 clearly shows the speed variation within the WZ. The x-axis represents the length of the roadway in feet, starting at zero (2 miles before the WZ where the first work zone in 2 miles sign is placed). The y-axis represents different days of travel. The color gradient is yellow for 50 mph, with green in between and dark blue for 75 mph speed.

The figure below presents a heatmap illustrating vehicle speeds across three distinct sections: *Before the WZ*, *Within the WZ*, and *After the WZ*. In the *Before WZ* section, vehicle speeds gradually decrease as indicated by a shift from dark green in the leftmost part of the figure to a greenish-yellow closer to the boundary with the WZ. This transition suggests drivers are preparing to slow down as they approach the work zone. The *WZ* itself represents the most critical area in the displayed stretch, with speeds depicted in a yellowish color, indicating moderate to low speeds (50–60 mph). This color shift reflects the heightened caution or restrictions often observed in work zones. Finally, in the *After WZ* section, vehicle speeds increase once more, represented by a return to dark green and blue colors. This color transition signifies that speeds have resumed to near-normal levels, approaching 65 mph as drivers leave the work zone. The heatmap captures the impact of the WZ on vehicle speed, highlighting a reduction in speed within the WZ, followed by a return to typical speeds afterward.

Figure 5-5: Speed heatmap of vehicles at WZ on I-40

The speed profile provides a preliminary understanding of mobility patterns around the WZ. To assess driver comfort, we can examine key descriptive statistics of speed, such as the mean and standard deviation, at various locations relative to the WZ. A higher standard deviation of speed often suggests reduced driver comfort, as it indicates more frequent acceleration and deceleration, a behavior typical around WZs where drivers adapt to changing conditions.

Table 5: Descriptive statistics of trucks in the vicinity of WZ

Location	Average Speed (mph)	Standard Deviation of Speed
2 miles before WZ	63.19	2.07
1.3 miles before WZ	58.34	2.67
0.6 mile before WZ	56.49	1.15
WZ starts	53.97	5.72
WZ Mid	50.87	4.10
WZ End	52.46	2.42
0.6 mile after WZ	59.41	3.93
1.3 miles after WZ	61.40	2.81
2 miles after WZ	64.09	1.80

As shown in the table, average speed gradually decreases as vehicles approach the WZ, starting at 63.19 mph, two miles before the WZ, and reaching 53.97 mph at the start of the WZ. Within the WZ, vehicles maintain lower speeds, with an average speed of 50.87 mph at the midpoint. After the WZ, speeds increase, returning to normal levels two miles beyond the WZ at 64.09 mph. The standard deviation of speed is notably higher within the WZ, reflecting greater variability in speed and a likely reduction in driver comfort as drivers navigate this area. In contrast, speed variability is lower in the sections both before and after the WZ, suggesting steadier, more comfortable driving conditions in these areas.

These descriptive statistics provide insights into the impact of the WZ on vehicle speed and driver behavior, highlighting areas where drivers may experience more frequent acceleration and deceleration.

WZs often contribute to traffic delays and congestion. Congested traffic conditions can be observed directly from video footage, while delays can be quantified through data and graphs that relate distance, speed, and time. The figure below illustrates the impact of the WZ on vehicle travel. The green line represents the actual distance traveled by a vehicle within the WZ, while the red line shows the hypothetical distance it would have covered without the WZ. This graph spans a four-mile stretch, extending two miles before and two miles after the WZ. The vertical gap between the two lines—amounting to 2,200 feet—indicates the distance by which the vehicle trails behind due to the WZ. This difference underscores the delay imposed by the WZ, offering a visual and quantitative measure of its effect on traffic flow and mobility.

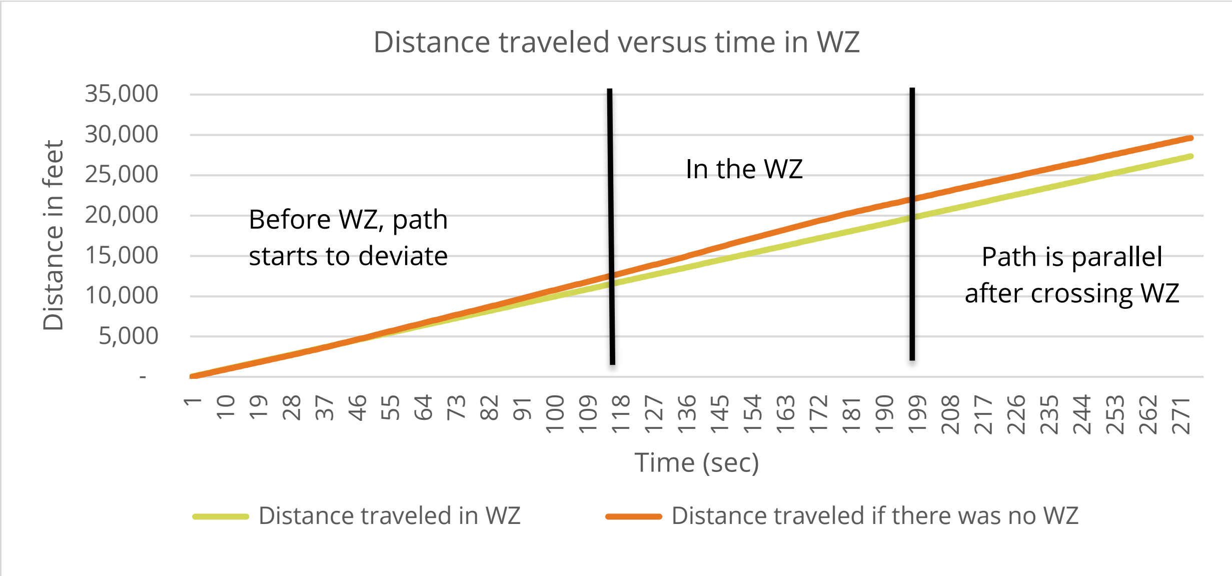

Figure 5-6: Distance vs time (Real path and imaginary path)

Sensor fusion data was utilized to assess the impact of the WZ on increased travel time. To simplify the analysis, a single vehicle was tracked to study the WZ's effect and quantify the delay caused by the WZ. The average speed of the vehicle under normal conditions, unaffected by the WZ, was calculated as 65 mph by averaging its speed four miles upstream of the WZ.

In the following graph, the top straight red line represents the vehicle's expected average speed in the absence of the WZ, while the curved cyan line shows the actual speed observed as the vehicle navigates through the WZ. The area between these lines represents the delay induced by the WZ. By integrating this area, the delay incurred over the span of two miles before to two miles after the WZ was calculated to be approximately 31 seconds. This analysis provides a clear depiction of how the WZ affects travel time, illustrating the impact on traffic flow and mobility in real-world conditions.

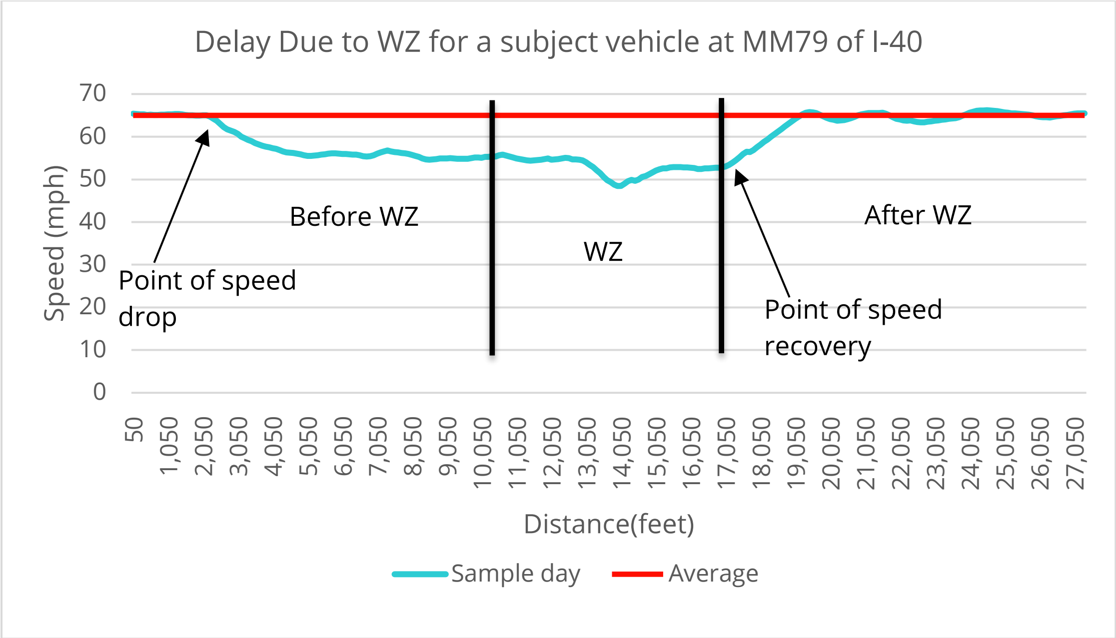

Figure 5-7: Delay due to WZ (Speed vs. distance plot)

5.2 Comfort

Frequent lane changes, abrupt accelerations, and decelerations are behaviors that often signal a driver's discomfort or lack of confidence, particularly in complex driving environments like WZs. Discomfort may stem from various factors, including narrow lanes, nearby construction activities, or the presence of barriers. When drivers feel uneasy, they tend to brake, accelerate, or make directional adjustments more frequently. These patterns can be meticulously tracked through data collected by onboard instruments, providing valuable insights into driver behavior.

This study leverages heading data (bearing) from fused datasets to assess drivers' comfort levels as they navigate through WZs. Heading data, which measures the vehicle's orientation relative to true north, serves as a proxy for understanding drivers' directional stability and helps reveal subtle shifts in comfort. By analyzing the average heading across multiple vehicles, we establish a baseline or "moving average" model of a typical vehicle's heading as it progresses through the WZ. This moving average profile represents the expected or "normal" trajectory within the zone, providing a benchmark to which individual vehicle behaviors can be compared.

In the accompanying figure, scattered points represent the recorded heading data from 134 vehicle trajectories, with a solid line marking the average path within the WZ. The WZ extends from approximately 10,500 feet to 17,000 feet along the observed route. Before entering the WZ, a shift in heading from 70 to 65 degrees reflects an oncoming road curve. A second curve at around 16,500 feet further illustrates the natural shifts drivers encounter. However, the increased fluctuations within the WZ—most visible along the 65-degree heading—highlight drivers' unease as they navigate through this section. Comparing these fluctuations to the moving average allows us to pinpoint the areas in the WZ that may require improvements to enhance driver comfort and stability.

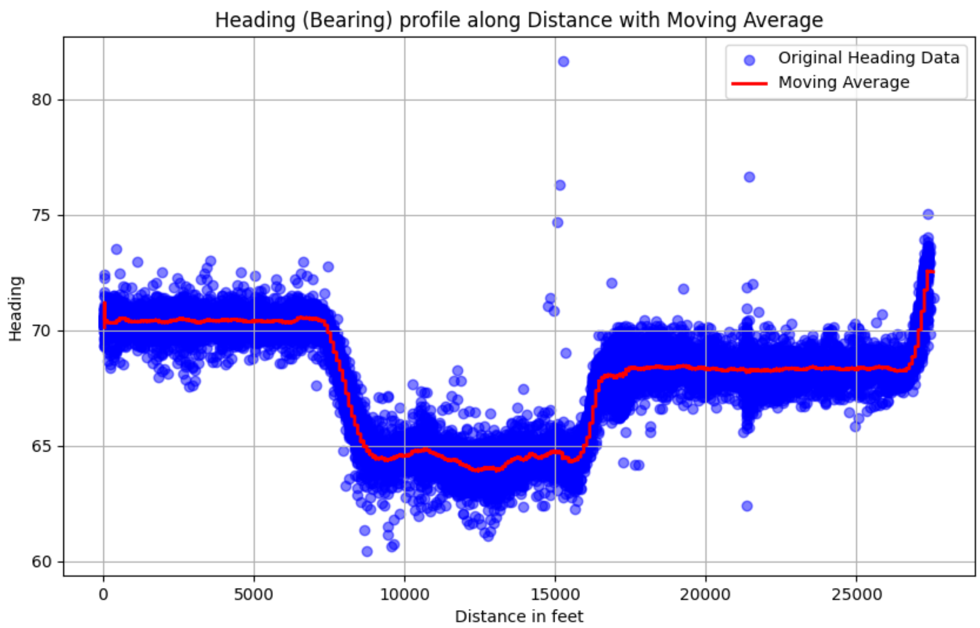

Figure 5-8: Heading (Bearing) of vehicles in the WZ at MM 79.

For individual assessments, a single vehicle's heading data can be plotted alongside this moving average. Significant deviations from the average profile may indicate areas within the WZ that contribute to driver unease. For instance, if a vehicle's heading data shows erratic or frequent shifts relative to the moving average, it suggests that the driver had to adjust course more often, possibly due to uncomfortable/confusing road conditions.

Figure 5-9: Comparison of heading between average value and single path

5.3 Safety

Acceleration and deceleration are critical indicators for assessing safety performance, especially in zones where driving patterns are influenced by external factors such as road construction. One particularly useful measure is a jerk, the rate of change of acceleration over time, which can highlight sudden shifts in driving behavior. Analyzing jerks allows us to detect abrupt changes that might signal evasive maneuvers or discomfort, both of which have implications for road safety.

In the graph below, the cumulative acceleration of a vehicle is plotted with time along the x-axis. The figure is divided into three distinct sections by two lines marking the entry and exit of the WZ. Before entering the WZ, the vehicle's acceleration profile remains relatively steady, with minimal fluctuations, indicating smooth and uninterrupted driving. At around the 50-second mark, a clear trend of deceleration begins, suggesting that the driver is preparing to adjust to the WZ.

Upon entering the WZ, acceleration remains relatively constant, indicating that the driver maintains a steady speed through this controlled section. This behavior suggests caution, likely in response to WZ conditions. Exiting the WZ, the vehicle begins to accelerate once more, suggesting that the driver feels comfortable resuming a higher speed.

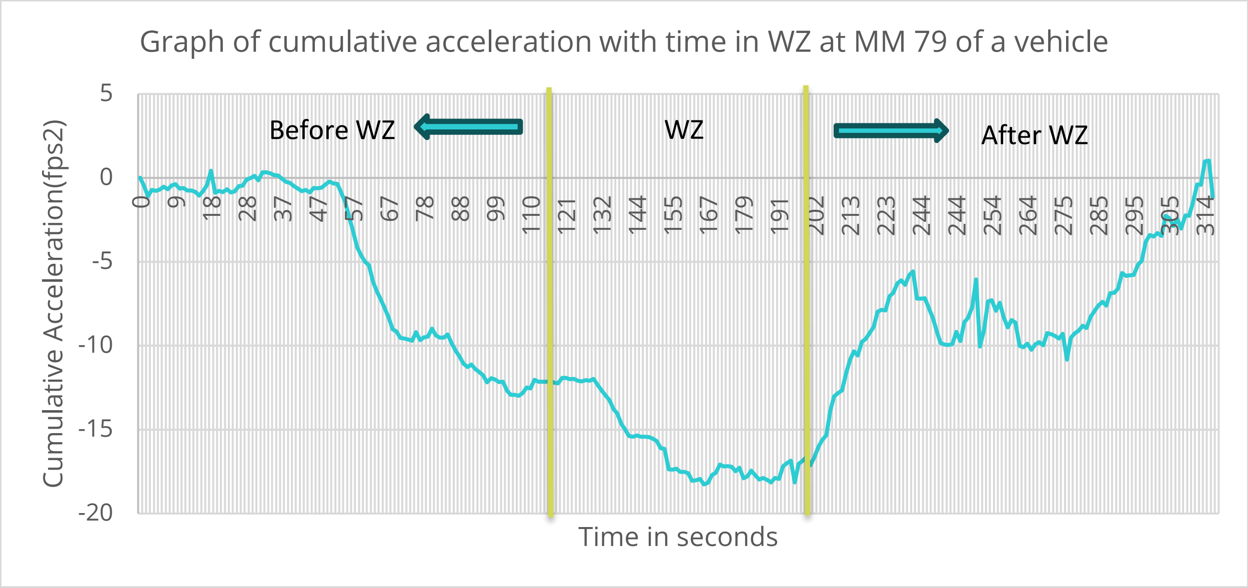

Figure 5-10: Graph of cumulative acceleration with time in WZ

Different studies have defined criteria for identifying evasive maneuvers, which are often considered surrogate safety measures. These maneuvers, typically characterized by sharp deceleration or quick swerving, can help pinpoint near-crash events. A high deceleration rate within a brief time frame usually signifies sudden braking, potentially in response to an unexpected obstacle or a perception of hazard. By examining cumulative acceleration data alongside jerk, researchers can gain insight into the conditions that trigger these evasive responses, allowing for a more comprehensive understanding of safety dynamics within WZs.

5.4 Discussions

The findings of this study underscore the multifaceted challenges involved in managing traffic within WZs. These challenges stem from disruptions to typical driving patterns, which result in increased safety risks, delays, and congestion. Addressing these challenges requires a balanced approach that incorporates short-term, medium-term, and long-term strategies, tailored to specific conditions within WZs.

In the short term, enhanced signage and enforcement mechanisms can be rapidly deployed to address immediate safety and mobility concerns. Signs should communicate clear and consistent messages, focused on areas where lane shifts or reduced capacity create confusion for drivers(Datta et al., 2016). Different researchers have established that even the presence of unmanned law enforcement vehicles is also helpful against risky driving behaviors, such as speeding and abrupt lane changes (Hallmark et al., 2023). Sometimes, WZs can be hotspots for crashes and as such having automated speed cameras can be helpful as speed and speed variation are the causal factors in many of the crashes occurring in WZs. The presence of law enforcement or automated speed cameras can significantly mitigate risks during active construction periods and is highly recommended if the WZs start to become crash black spots.

Medium-term strategies should involve deploying smart advanced technology solutions, such as variable message signs, variable speed limits, DSFS, and lane guidance systems(Brewer et al., 2006; Fisher et al., 2021; Fontaine, 2006). Real-time feedback and messages to the drivers have been found effective in helping drivers adjust their behavior in response to changing WZ conditions (Heutinck et al., 2006). These systems help drivers maintain uniform speed profiles and reduce speed variance, minimizing the likelihood of rear-end collisions. Lane guidance can further enhance driver confidence and safety by providing clear navigation cues in complex or heavily constrained WZ environments.

In the long term, infrastructure improvements should be integrated into the planning and design of future WZs. Such improvement should include but not be limited to the use of adaptive traffic management systems capable of dynamically responding to congestions and delay patterns. By leveraging the use of intelligent transportation systems, WZ planning can facilitate real-time monitoring and provide actionable insight to optimized traffic flow. Additionally, consideration should be given to alternative construction or schedules that minimize disruption to peak traffic periods.

Evaluation of the effectiveness of these measures requires well-defined success metrics. Key indicators include speed variance reductions, fewer sudden braking or lane changes, and an overall decline in crash rates within WZs. Longitudinal studies can be conducted to assess these interventions' sustained impact and identify areas for further improvement. The importance of educating drivers on safe behaviors is also very important as WZs are hotspots of crashes. Public awareness campaigns and targeted driver training programs can improve preparedness, fostering safer interactions with changing road scenarios.

In this study, high-fidelity data revealed critical driving behaviors in and around WZs, including reduced speeds, frequent speed fluctuations, lateral swerving, frequent braking and acceleration, and delays caused by WZs. This behavior shows a reduction in mobility, safety, and comfort. Disruptive traffic flow, leading to a decrease in safety and efficiency is evident here.

Addressing these challenges through targeted interventions and strategies can significantly enhance the safety, mobility, and comfort in the WZs. These insights contribute to developing resilient and adaptive traffic management strategies for complex environments.

Chapter 6 Conclusion

This comprehensive study on WZs along I-40 highlights several critical insights into how these areas impact traffic safety, mobility, and driver comfort. By leveraging vehicle-mounted sensor technology and video data, the research revealed that work zones impose a significant burden on traffic flow and create hazardous conditions for drivers. The key findings are as follows:

1. **Impact on Mobility**: Vehicles consistently reduced speed as they approached the work zones, with the greatest reductions occurring at the start and middle of the zones. The average speed dropped significantly in work zones, with a corresponding increase in speed variability. This variability is a crucial indicator of driver discomfort, as frequent changes in speed (both deceleration and acceleration) suggest that drivers are struggling to maintain a smooth flow through the work zone.

2. **Comfort and driving behavior**: The analysis of heading data revealed that drivers frequently adjusted their trajectories, indicating discomfort, particularly in areas where lane shifts or narrow lanes were present. The occurrence of sudden braking and lane-changing events increased within the work zones, pointing to elevated risks of near-crash incidents. These behaviors are likely driven by driver uncertainty about work zone configurations and reduced road capacity.

3. **Safety**: The study identified a higher probability of unsafe events, such as sudden braking, within work zones. These events are often triggered by the need to merge, respond to reduced lane availability, or navigate around barriers. The increased frequency of such maneuvers underscores the importance of clearly marked lanes and better communication of work zone layouts to drivers.

4. **Impact on Traffic Flow**: Delays were quantified by comparing vehicle speeds before, during, and after the work zones. The study found that work zones not only slow down traffic but also lead to cumulative delays due to slower speeds and increased braking. For example, the delay caused by traversing a work zone was calculated to be around 31 seconds for a commercial vehicle traveling through the monitored sections. While this may seem minimal, the compounding effect on overall traffic flow and congestion becomes significant, especially during peak hours.

Based on these findings, the report advocates for the implementation of enhanced traffic management strategies within WZs. The observed speed variability and frequent braking highlight the need for DSFS, which can provide real-time speed feedback guidance and reduce abrupt speed changes. Similarly, the erratic heading changes and discomfort observed in driver behavior underline the importance of improved signage and lane guidance systems, which can offer clear navigation cues and minimize confusion. Furthermore, the high-speed variance observed within WZs validates the need for enforcing speed limits. Law enforcement or automated speed cameras have been in practice and produced significant results in deterring speed and mitigating crash risks.

In conclusion, WZs remain a complex challenge for traffic engineers, safety experts, and policymakers. This study provides evidence that work zones disrupt typical driving patterns and introduce significant safety risks. However, with the right mix of technology, enforcement, and driver education, the negative impacts of work zones on traffic flow and safety can be minimized. The insights gathered from this study contribute to the ongoing efforts to create safer, more efficient work zones, ultimately benefiting both drivers and construction workers on Tennessee's highways.

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Appendices

Link to the data