Project Report

Managing the Traffic Impacts of Highway Infrastructure Constructions

A Framework for Construction Planning

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Managing the Traffic Impacts of Highway Infrastructure Constructions: A Framework for Construction Planning

A Report to

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by

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Executive Summary

Highway infrastructure construction projects often necessitate temporary traffic pattern changes, such as lane or road closures, which can impact mobility, safety, and the environment. This report presents a systematic framework and tool designed to assist transportation agencies in evaluating and comparing alternative construction plans. The framework integrates cost analysis to quantify the traffic effects of work zones, enabling more informed decision-making. Utilizing data and methodologies from the Highway Capacity Manual (HCM), Highway Safety Manual (HSM), and Motor Vehicle Emission Simulator (MOVES), the study develops a monetization approach for assessing the traffic impacts of work zone on road users. The analysis focuses on highway projects, accounting for factors such as road type, lane configurations, and the presence of drivable medians or shoulders.

The developed framework can be used to estimate travel delay, crash frequency, and fuel consumption due to work zones, providing a structured methodology to assess total costs. A spreadsheet tool has been designed to facilitate impact calculations by converting estimated changes in mobility, safety, and environmental factors into monetary terms using value-of-time metrics, crash cost estimates, and fuel price data. While the tool serves as a practical resource for highway construction planning, its applicability may evolve with shifts in traffic patterns, such as the increased adoption of electric and automated vehicles. Future refinements may be necessary to reflect emerging transportation trends and technological advancements.

Key Words: Work Zone, Traffic Impact, Mobility, Safety, Environment, Spreadsheet Tool.

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Table of Contents

List of Figures

List of Tables

1. Introduction

Building and maintaining roads and bridges is generally the responsibility of state and local governments. According to the 2015 Conditions and Performance Report, issued by the USDOT, approximately 20 percent of the highway mileage on federal-aid highways in the United States failed to meet the criteria for acceptable pavement; in urban areas, there were 25 percent of arterial roads and 40 percent of collector roads in poor conditions (FHWA, 2017). According to the data on the conditions of US bridges released by FHWA, in 2015, more than 80,000 bridges nationwide were found to be functionally obsolete, which means they do not meet the current design or engineering standards. Many of these bridges are on major highway networks; for example, more than 20 percent of bridges on urban Interstate Highways are functionally obsolete (Memmott, 2007). With a large number of roads and bridges that are either structurally deficient or functionally obsolete, a large number of construction activities or work zones on the road or roadside will persist.

That being said, this research project looks into highway infrastructure projects that could temporally change the traffic patterns during construction, such as pavement resurfacing that requires lane closure. In order to mitigate the unwanted or unintended impacts of work zones, transportation agencies and construction managers are responsible for designing and implementing effective construction scenarios or plans for highway infrastructure projects.

Different construction plans have both pros and cons, which may create challenges for transportation agencies to determine which plan would be the most suitable one for a project. Though studies have offered methods to estimate the impacts of a highway infrastructure construction project (or work zone) on the traffic (Abdelmohsen & El-Rayes, 2016; Kim et al., 2024), it remains unclear how to assemble these estimated/expected impacts (of constructions on the traffic) to inform decision-making during construction planning. This project is to establish a framework to guide transportation agencies and highway construction managers to systematically evaluate and compare construction plans.

2. Review of Related Work

Work zones are always set to repair or reconstruct roads and bridges. Work zones usually need to close the shoulder, one or more lanes, one direction of roads, or the whole roads. For consumers (i.e., travelers) and construction planners, different types of work zones (i.e., different degrees of lane closure) will have different impacts on their costs. For example, for travelers, the work zone that only closes the shoulders might slightly impact their travel time or crash rate. However, closing the shoulder might be the worst plan for construction planners because it has the longest working duration. Therefore, it is important to evaluate the work zone traffic impacts, which are reflected by the cost impact to travelers and construction benefit and cost to accomplish the trade-off between consumers and construction planners.

This literature review concentrated on work zone traffic impact. Three different aspects (i.e., mobility impacts, safety impacts, and environmental impacts) are considered critical parts of traffic impacts. Except highways or freeways are closed for repair or reconstruction, construction activities can influence traffic by reducing capacity, free-flow speed, or both (Highway Capacity Manual, 2010). Mobility impacts indicate how traffic (e.g., capacity, travel time) is affected by different types of highway or freeway work zones. More specifically, based on previous literature (Weng & Meng, 2013), mobility impacts are represented by capacity and delay. Safety impacts are the impacts of work zones on traffic safety. In this literature review, we will majority discuss the crash rate in the work zone. In addition, as we said before, the speed of roads will decrease because of the work zone, and the fuel consumption and gas emissions will increase (the lower the speed, the higher fuel consumption and gas emissions). In other words, considering the work zone traffic impacts, we focus on travelers rather than other objects. The following sections separately discuss these three aspects (i.e., mobility impacts, safety impacts, and environmental impacts).

2.1 Scholarly Research Perspectives

2.1.1 Mobility Impacts

Mobility impacts are one of the work zone traffic impacts' aspects. It reflects the impact of the regular traffic flow by work zones. With work zone activities, the most obvious phenomenon is speed reduction. Because work zone activities always need to close one or more lanes available for traffic. Vehicles have to merge to the available lanes before entering the work zone or decreasing their speed to avoid potential collision when other vehicles try to merge. Simultaneously, based on the speed-flow relationship, speed reduction will let the decreasing of road capacity. Reduction of road capacity increases traffic delay (Weng & Meng, 2013). Thus, learning and exploring how to estimate work zone capacity and delay from previous studies is necessary to evaluate work zone mobility impacts.

TABLE 1 Factors affecting work zone capacity

Factors	References
Heavy vehicle percentage	Al-Kaisy and Hall (2003), Heaslip et al. (2009), Kim et al. (2001), Sarasua et al. (2006), Weng and Meng (2011, 2012), Zheng et al. (2011)
Work zone grade	Al-Kaisy et al. (2000), Kim et al. (2001), Weng and Meng (2012), Zheng et al. (2011)
Work zone intensity	Adeli et al. (2003), Heaslip et al. (2009), Kim et al. (2001), Weng and Meng (2011, 2012), Zheng et al. (2011)
Road type	Weng and Meng (2011, 2012)
Number of opened lanes	Adeli et al. (2003), Sarasua et al. (2006), Weng and Meng (2011, 2012), Zheng et al. (2011)
Number of closed lanes	Kim et al. (2001), Weng and Meng (2011, 2012), Zheng et al. (2011)
Work zone duration	Weng and Meng (2011, 2012)
Work time	Adeli et al. (2003), Al-Kaisy and Hall (2003), Heaslip et al. (2009), Weng and Meng (2011, 2012)
Lane Width	Adeli et al. (2003), Weng and Meng (2012), Zheng et al. (2011)
Lane closure location	Al-Kaisy and Hall (2003), Kim et al. (2001), Weng and Meng (2011, 2012)
Work zone length	Adeli et al. (2003), Kim et al. (2001), Weng and Meng (2012), Zheng et al. (2011)
Weather condition	Al-Kaisy et al. (2000), Al-Kaisy and Hall (2003), Heaslip et al. (2009), Weng and Meng (2011, 2012)
Driver composition	Al-Kaisy et al. (2000), Al-Kaisy and Hall (2003), Heaslip et al. (2009), Weng and Meng (2012), Zheng et al. (2011)
Work zone speed	Heaslip et al. (2009), Weng and Meng (2011, 2012)
Ramp	Adeli et al. (2003), Weng and Meng (2012), Zheng et al. (2011)
State/City	Weng and Meng (2011, 2012)
Work zone layout	Adeli et al. (2003), Zheng et al. (2011)
Sign distance	Heaslip et al. (2009)
Lateral distance	Kim et al. (2001), Zheng et al. (2011)

Commonly, researchers not only consider the work zone speed, but they also consider multiple different factors as the potential predictor to estimate work zone capacity (

TABLE 1). Most literature considered Heavy vehicle percentage as the key factor affecting the work zone capacity (Al-Kaisy & Hall, 2003; Heaslip et al., 2009; Kim et al., 2001; Sarasua et al., 2006; Weng & Meng, 2011, 2012; Zheng et al., 2011). The reasons are that trucks occupy more space on the roadway and usually move slower than passenger cars. Thus, a higher percentage of heavy vehicles tend to reduce work zone capacity, whether short-term or long-term work zone. Work zone grade was often concerned with heavy vehicle percentage in work zone capacity estimating (Al-Kaisy et al., 2000; T. Kim et al., 2001; Weng & Meng, 2012; Zheng et al., 2011). The existence of grades might influence the traffic flow in the work zone, especially when heavy vehicles are present (considering the weight and inertia). Work zone intensity was also identified as a famous factor in work zone capacity estimating (Adeli et al., 2003; Heaslip et al., 2009; Kim et al., 2001; Weng & Meng, 2011, 2012; Zheng et al., 2011). Researchers claimed that the heavier the work zone intensity, the lower capacity occurs in the work zone. Furthermore, because urban freeways' work zone capacity is usually higher than rural freeways' work zone capacity, some research included road type in their work zone capacity model (Weng & Meng, 2011, 2012). The number of open or closed lanes was widely applied in estimating work zone capacity (Adeli et al., 2003; Kim et al., 2001; Sarasua et al., 2006; Weng & Meng, 2011, 2012; Zheng et al., 2011). Besides, work zone duration was also included in some works (Weng & Meng, 2011, 2012). Weng and Meng (2013) summarized in their review paper that long-term work zone capacity is usually higher than short-term work zone capacity. Considering travelers' attention might decrease during nighttime, nighttime maintenance, and construction could reduce the work zone capacity at that time period. Therefore, some studies chose work time as one of the predictors (Adeli et al., 2003; Al-Kaisy & Hall, 2003; Heaslip et al., 2009; Weng & Meng, 2011, 2012). In addition, lane width could also affect the work zone capacity because it would affect the speed (Adeli et al., 2003; Weng & Meng, 2012; Zheng et al., 2011). Lane closure location, which represents whether the right or left lane is closed because of the work zone, was applied by some studies to estimate work zone capacity (Al-Kaisy & Hall, 2003; Kim et al., 2001; Weng & Meng, 2011, 2012). Some researchers also used work zone length as the factor that affects work zone capacity (Adeli et al., 2003; Kim et al., 2001; Weng & Meng, 2012; Zheng et al., 2011). Kim et al. (2001) claimed that a longer work zone could reduce work zone capacity. Heaslip et al. (2009) found that work zone capacity would not vary with the length of the work zone. Furthermore, weather conditions (Al-Kaisy et al., 2000; Al-Kaisy & Hall, 2003; Heaslip et al., 2009; Weng & Meng, 2011, 2012), driver composition (Al-Kaisy et al., 2000; Al-Kaisy & Hall, 2003; Heaslip et al., 2009; Weng & Meng, 2012; Zheng et al., 2011), work zone speed (Heaslip et al., 2009; Weng & Meng, 2011, 2012), ramp (Adeli et al., 2003; Weng & Meng, 2012; Zheng et al., 2011), state or city (Weng & Meng, 2011, 2012), work zone layout (Adeli et al., 2003; Zheng et al., 2011), sign distance (Heaslip et al., 2009), and lateral distance (Kim et al., 2001; Zheng et al., 2011) were also supposed that are useful in work zone capacity estimation.

After variable selection, a reasonable and efficient model is critical to estimating work zone capacity. Three different types of methods were used to estimate work zone capacity (

TABLE 2): parametric approaches, non-parametric approaches, and simulation approaches (Weng & Meng, 2013).

TABLE 2 Approaches of work zone capacity estimation

Approaches	References	Models or tools
Parametric approaches	Al-Kaisy et al. (2000)	Multi-regression approach
	Kim et al. (2001)	A multiple regression approach
	Al-Kaisy and Hall (2003)	A generic multiplicative approach
	Sarasua et al. (2006)	Derived from speed-flow relationship
	Racha et al. (2008)	Derived from speed-flow relationship
	Highway Capacity Manual (2010)	Two distinct guidelines
	Elefteriadou (2016)	Empirical function
Non-parametric approaches	Adeli et al. (2003)	A neural-fuzzy logic approach
	Karim and Adeli (2003)	Radial basis function neural network
	Weng and Meng (2011)	A decision tree approach
	Zheng et al. (2011)	A neural-fuzzy logic approach
	Weng and Meng (2012)	An ensemble tree approach
Simulation approaches	Arguea (2006)	Improved CORISM
	Chatterjee et al. (2009)	VISSIM
	Heaslip et al. (2009)	A hybrid approach integrating the simulation and mathematical methods
	Heaslip et al. (2011)	CORSIM

Parametric approaches are a kind of approach in which a predictor takes a predetermined form. To estimate work zone capacity, as parametric approaches, the multiple regression (Al-Kaisy et al., 2000; Kim et al., 2001), the generic multiplicative approach (Al-Kaisy & Hall, 2003), models derived from the speed-flow relationship (Racha et al., 2008; Sarasua et al., 2006), and the empirical function (Elefteriadou, 2016; Highway Capacity Manual, 2010) are widely used. To investigate freeway capacity in the long-term work zone, Al-Kaisy et al. (2000) developed a multi-regression model. Using a field dataset from Ontario, Canada, they found significant variation in freeway capacity in the work zones. Furthermore, they proved that temporal variation, grade, day of work, and weather conditions influenced freeway work zone capacity. Kim et al. (2001) also conducted a multiple regression model to suggest a new methodology that could estimate the work zone capacity. In addition, they also tried to investigate which independent factors would affect the capacity reduction in work zones. Twelve work zone sites' (work zone sites with lane closure on four normal lanes in one direction) traffic and geometric data were collected. Finally, compared with other models, they claimed that their analytical models developed predicted within 1% capacity of the study work zones. Without multiple regression, Al-Kaisy and Hall (2003) developed a generic multiplicative approach to provide a guideline for freeway capacity estimation at the reconstruction site. Same as before, they still used data collected from Ontario, Canada. They found that the heavy vehicle and driver composition have the most significant effect on capacity. Some researchers prefer models derived from the speed-flow relationship. Sarasua et al. (2006) used traffic flow data collected from 34 work zone sites on South Carolina interstate highways to build a model derived from the speed-flow relationship to develop capacity thresholds for work zone lanes. Based on the same aim, Racha et al. (2008) conducted a non-linear hyperbolic model, which is also derived from the speed-flow relationship according to the traffic flow data from 22 work zone sites. Different from other parametric models, various editions of HCM provided some empirical functions. Highway Capacity Manual (2010) described an equation of short-term work zone capacity. Moreover, for the long-term work zone, Highway Capacity Manual (2010) indicated that 1750 vphpl should be the capacity when the lane closure status is two-to-one lane closure. When three-to-two lane closure, 1860 vphpl should be used. Elefteriadou (2016) provided an empirical function based on the known queue discharge rate. Although parametric approaches were widely used to estimate work zone capacity, there are some limitations of parametric approaches. For instance, models to estimate long-term work zone capacity cannot be used to predict short-term work zone capacity, and vice versa, because the capacity of the long-term work zone is usually higher than the short-term work zone (Weng & Meng, 2013). In addition, parametric approaches' prediction ability depends on the data quality. If the data is not good enough, the model will also perform badly.

Considering the limitation of parametric approaches, many studies adopted non-parametric approaches to develop a universal work zone capacity estimation method. Early this century, Adeli et al. (2003) developed a neuro-fuzzy logic model because they claimed that any mathematical function could not describe work zone capacity. They claimed that this model improved the estimation accuracy compared with other models. Zheng et al. (2011) used the Dutch case to compare work zone capacity estimation methods and found that the neuro-fuzzy logic model performed best. Some machine learning methods were also adopted to estimate work zone capacity. Karim and Adeli (2003) developed radial basis function neural network models to estimate work zone capacity and delay. Weng and Meng (2011, 2012) developed a decision tree model and an ensemble tree-based model to predict work zone capacity accurately. Compared with parametric approaches, non-parametric approaches can deal with the non-linear relationship between factors and work zone capacity. Besides, non-parametric approaches have a higher prediction accuracy than parametric approaches. In recent, machine learning models, with the development of model interpretability, can provide different insights into which and how factors affect work zone capacity. However, non-parametric approaches are also data-driven methods. The data quality is still a critical factor that affects the model performance.

Except for parametric approaches and non-parametric approaches, researchers also used simulation tools to estimate work zone capacity (Arguea, 2006; Chatterjee et al., 2009; Heaslip et al., 2009, 2011). CORSIM and VISSIM are the majority of tools. Even though simulation approaches can avoid potential problems caused by data, these methods/tools are not suitable for our project. It is wasting time to create every work zone scenario in the simulation tool. Therefore, if we have enough data, non-parametric approaches are the best way to estimate work zone capacity.

Compared with work zone capacity, the delay is a more direct mobility impact. The delay caused by work zones is defined as the difference between travel time on a roadway segment without work zones and the actual longer travel time in work zones. Like work zone capacity estimation methods, there are three types of work zone delay estimation approaches (TABLE 3): macroscopic analytical approaches, macroscopic simulation approaches, and microscopic simulation approaches.

TABLE 3 Approaches of work zone delay estimation

Approaches	References	Models or tools
Macroscopic analytical approaches	Martinelli and Xu (1996)	Deterministic queuing approach
	(Jiang, 1999)	An enhanced deterministic queuing approach taking into account deceleration and acceleration delay
	Schonfeld and Chien, (1999)	Deterministic queuing approach
	Jiang (2001)	A queue-discharge rate table is used to improve the queuing delay estimation accuracy
	Du et al. (2016)	ANN
	Tang and Chien (2008)	Deterministic queuing approach
	Meng and Weng (2013)	An improved deterministic queuing model
	Kamyab et al. (2020)	Random Forest, XGBoost, ANN
Macroscopic simulation approaches	Chitturi and Benekohal (2004)	FRESIM, QuikZone, and QUEWZ
Microscopic simulation approaches	Wu (2000)	INTEGRATION
	Chien et al. (2002)	CORSIM
	Yang et al. (2008)	A hybrid method integrating a macroscopic analytical model with a microscopic simulation tool
	Meng and Weng (2010)	CA model

Macroscopic analytical approaches are the most widely used approaches in work zone delay estimation. More specifically, most studies used the deterministic queuing approach to analyze work zone delay (Jiang, 1999; Martinelli & Xu, 1996; Schonfeld & Chien, 1999; Tang & Chien, 2008). Jiang (1999) used traffic flow data collected from Indiana four-lane freeways to analyze the traffic flow characteristics of the freeway work zone. To minimize work zone length and cycle time based on delay, a deterministic queuing approach is conducted by Schonfeld and Chien (1999). Considering the time cost of work zones for highway maintenance projects, Tang and Chien (2008) also developed a deterministic queuing model to estimate work zone delay. Meng and Weng (2013) improved the deterministic queuing model based on cumulative arrivals and departures to estimate the total queuing delay. Moreover, machine learning methods are also applied to analyze work zone delay (Du et al., 2016; Kamyab et al., 2020). Du et al. (2016) developed an artificial neuro-network model based on New Jersey freeway work zone data to estimate work zone delay. Kamyab et al. (2020) conducted different supervised machine learning models (i.e., Random forest, XGBoost, and Artificial neuro network) combined with historical lane closure information to forecast Spatiotemporal mobility (work zone delay) for future lane closures. The advantages and drawbacks of macroscopic analytical approaches are the same as parametric and non-parametric approaches in work zone capacity estimation.

Simulation can also be used in the analysis of work zone delay. CORSIM, FERSIM, and INTEGRATION are the most frequently used tools (Chien et al., 2002; Chitturi & Benekohal, 2004; Wu, 2000). Meng and Weng (2010) applied a cellular automata (CA) model to characterize driver acceleration-deceleration behavior to evaluate traffic delay. However, the estimated traffic delay from these tools does not vary with different work zone configurations (Weng & Meng, 2013).

In conclusion, whether estimating work zone capacity or delay, based on large and at least average-level datasets, non-parametric approaches (macroscopic analytical approaches) are a relatively better choice to evaluate work zone mobility impacts.

2.1.2 Safety Impacts

Work zone safety impacts include crash severity, crash rate, location of crash occurrence, time of crash occurrence, etc. Combined with our objective (vehicle or driver) and quantifiable degree of safety impact, in this section, we will mainly talk about the crash rate.

Although there are too many scholarly papers concentrate on work zone crashes, limited to the database, we can only find a few studies that mention work zone crash rate (Garber & Woo, 1990; Graham et al., 1978; Hall & Lorenz, 1989; Jin et al., 2008; Juergens, 1962; Khattak et al., 2002; La Torre et al., 2017; Pigman & Agent, 1990; Rista et al., 2017; Rouphail et al., 1988; Sisiopiku et al., 2015; Tsyganov et al., 2003). Compared with non-work zones or pre-work zones, there is no consistent variety of work zone crash rates. Juergens (1962) found that the work zone crash rate increased by 7 to 24% for 10 work zone sites. Rouphail et al. (1988) reported that the work zone crash rate increased by 88% for long-term work zones. After the work zone, the crash rate decreased by 34%. For the short-term work zone, the crash rate seems like a constant rate of 0.8 accidents/mile-day. Hall and Lorenz (1989) showed that during the construction period, the crash rate would increase by 26%. Garber and Woo (1990) indicated that for multilane highways and two-lane urban highways in Virginia, the work zone crash rate would increase 57-168%. Khattak et al. (2002) reported that the work zone crash rate is 21.5% higher than the pre-work zone period. Sisiopiku et al. (2015) indicated that the highest crash rate in the work zone occurs between 10:00 AM and 4:00 PM in Alabama. La Torre et al. (2017) found that, during the construction period, the fatal and injury crashes increased 33% more than the pre-work zone period. The property damage-only crashes increased by 65% during the pre-work zone period. Rista et al. (2017) reported that with every 1% increase in project duration, the crash rate would increase by 0.9%. Furthermore, when shoulder closure, there is no statistically significant difference in crash rate between the construction period and pre-work zone period. In the two-lane freeways, single-lane closure would lead to a 21.2% increase in crash rate. In freeways that have more than two lanes, single-lane closure would lead to an 11.8% increase in crash rate. For multilane closure, the crash rate increased by 13.9% compared with the pre-work zone period.

However, some studies showed contrasting results (i.e., the crash rate decreased during the work zone period or no difference with the pre-work zone period). Graham et al. (1978) indicated that although 79 work zone sites experienced an overall crash rate increase of 6.8%, 31% of projects' crash rates decreased. Pigman and Agent (1990) claimed that 14 of 19 work zone sites had a higher crash rate than before. Tsyganov et al. (2003) found that some work zones have lower crash rates than before. Jin et al. (2008) also claimed no statistical significance between work zone crash rate and non-work zone crash rate at the 95% confidence level.

2.1.2 Environmental Impacts

Overview of previous studies, few studies discussed the fuel consumption and gas emission connected with work zones. Since the work zone may slow or congest traffic, fuel consumption under traffic congestion is the same as work zone traffic conditions. The majority method to estimate fuel consumption is using the motor vehicle emission simulator (MOVES) (Kim et al., 2018; Mehrabani et al., 2021; Papson et al., 2012; Treiber et al., 2008). Treiber et al. (2008) reported that when travelers meet traffic congestion, fuel consumption will increase by 80%, and travel time will increase by 4 times. Therefore, they concluded that the influence of travel time on travel time is distinctly greater than that of fuel consumption. Papson et al. (2012) found that when the LOS shifted from LOS E to LOS B, the nitrogen oxide emissions were reduced by 15% per vehicle, and particulate matter emissions were reduced by 17%, while control delay increased by 40%. Furthermore, they claimed that the largest emission sources were cruising and acceleration which accounted for more than 80% of total emissions under all scenarios. Kim et al. (2018) studied work zone Fuel consumption and greenhouse gas emissions from on-road vehicles. They indicated that, for the freeway scenarios, greenhouse gas emissions and fuel consumption increased by 86% and 85% compared with the non-work zone.

3. Project Objective and Scope

3.1 Project Objective

The objective of this research project is to establish a framework to comprehensively evaluate the impacts of highway infrastructure constructions or work zones on mobility, safety, and the environment. The framework is expected to assist transportation agencies in construction planning for highway infrastructure projects that involve alternating existing traffic patterns during the construction (such as lane or road closures). A cost analysis is integrated into the framework for transportation agencies and construction managers to quantitatively compare alternative construction plans.

3.2 Project Scope

This research project examines highway infrastructure projects that would temporarily change traffic patterns during construction, such as pavement resurfacing that requires lane or road closure. The framework developed in this project is expected to be valuable for projects on most highway facilities in Alabama. The framework will consider the land use (rural or urban), highway class (freeway or local), lane number, presence of drivable shoulders or medians, and other attributes of the construction sites (if deemed important by ALDOT).

The construction impacts discussed in this project are limited to the impacts on traffic flows. Other construction impacts, such as dust generation, noise pollution, operations with vegetation removal, and air pollution (from the work zone), are not addressed in this project.

4. Scenarios Creation

A general approach pertaining to the scenario creation of work zones is to propose or develop all possible scenarios by considering the number of lanes and the possibility of medians and shoulders on freeways. Using the Highway Performance Monitoring System (HPMS) data, this study reviewed the types and characteristics of roadways in Alabama. The key characteristics include the number of lanes, presence/width of the shoulder, shoulder type, presence/width of medians, and median type. FIGURE 1 shows the types of roads in the Alabama highway network. TABLE 4 shows the distributions of roadway characteristics. It is clear that most roads are two-lane roadways in Alabama, which account for over 86% of road miles. Four-lane roadways account for 3.4% of miles. Note that about 9.3% of road miles are missing the information for through lane numbers. Regarding the shoulder types, most roads may not have a shoulder or have a missing value in the HPMS data. For roads with information for shoulders, there are a variety of shoulder types, including surfaced shoulder – bituminous concrete, surfaced shoulder – Portland Cement Concrete surface, stabilized shoulder, combination shoulder, earth shoulder, and barrier curb. Regarding median types, again, most roads may not have a median (undivided roads) or it is a missing value in the HPMS data. The median types recorded in the data include unprotected, curbed, positive barrier – flexible, positive barrier – semi-rigid, positive barrier – semi-rigid, and positive barrier – rigid. There are, in total, 872 miles of roads with medians equal to 9 ft or wider, which can also be converted into a temporal travel lane.

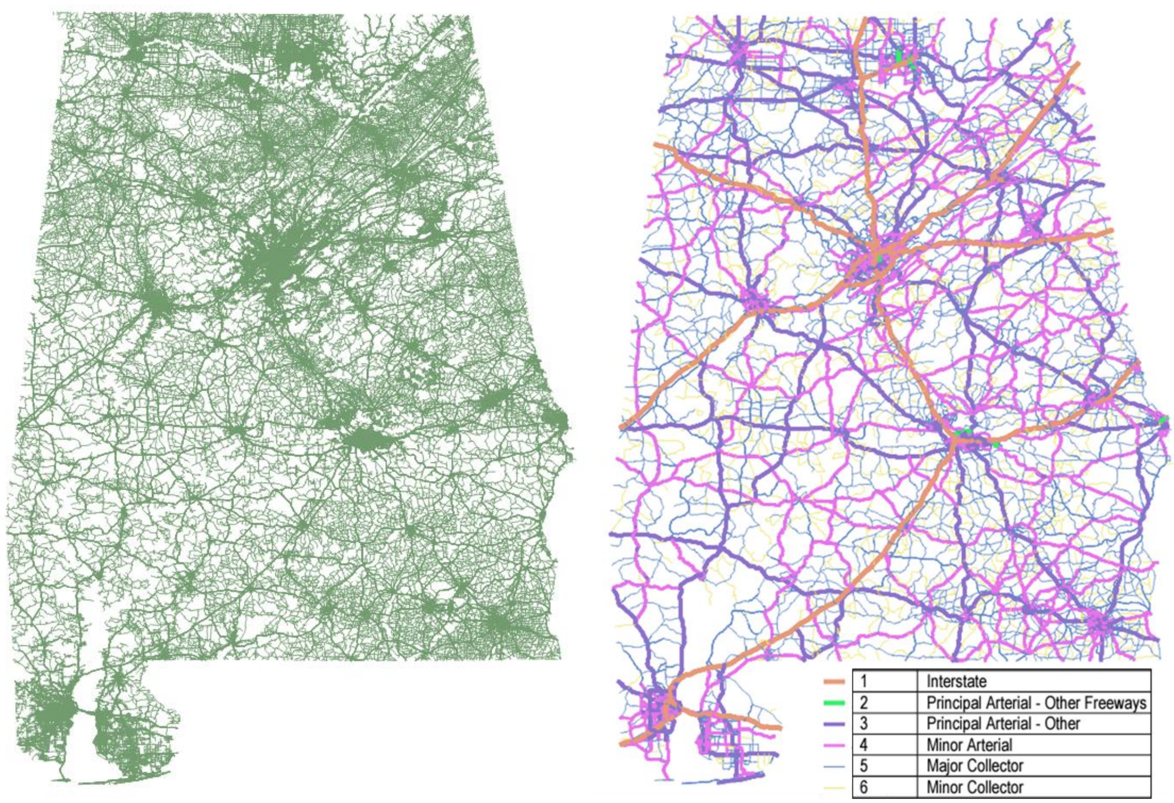


FIGURE 1 Alabama roadway network: (a) all roads in HPMS database; b) roadway functional classes from minor collectors to interstate.

TABLE 4 Feature distributions of Alabama roadways (FHWA, 2022)

Road Features		**Road Miles**	**Percentage**
Functional Class	Interstate	2381.3	2.2%
	Principal Arterial Other Freeways	80.5	0.1%
	Principal Arterial Other	6804.6	6.3%
	Minor Arterial	9489.4	8.7%
	Major Collector	16599.0	15.3%
	Minor Collector	5382.6	5.0%
	Local	65959.4	60.7%
	Unknown	1897.8	1.7%
	Total	108594.7	100.0%
Number of Total Through Lanes	1	345.7	0.3%
	2	93784.7	86.4%
	3	210.7	0.2%
	4	3736.5	3.4%
	5	43.2	0.0%
	6	289.4	0.3%
	7	12.8	0.0%
	8	32.9	0.0%
	9	3.5	0.0%
	10	5.0	0.0%
	Unknown	10130.4	9.3%
	Total	108594.7	100.0%
Median Type	None	1768.0	1.6%
	Unprotected	584.8	0.5%
	Curbed	43.5	0.0%
	Positive Barrier – flexible	60.2	0.1%
	Positive Barrier – semi-rigid	88.6	0.1%
	Positive Barrier – semi-rigid	16.5	0.0%
	Positive Barrier – rigid	89.7	0.1%
	Unknown	105943.4	97.6%
	Total	108594.7	100.0%
Median Width	2 - 8 ft	20.6	0.0%
	9 ft and above	872.0	0.8%
	No median or missing value	107702.1	99.2%
	Total	108594.7	100.0%
Shoulder Type	None	2.6	0.0%
	Surfaced shoulder exists – bituminous concrete	725.7	0.7%

	Surfaced shoulder exists – Portland Cement Concrete surface	233.8	0.2%
	Stabilized shoulder exists	140.8	0.1%
	Combination shoulder exists	763.0	0.7%
	Earth shoulder exists	789.6	0.7%
	Barrier curb exists	57.3	0.1%
	Unknown	105881.9	97.5%
	Total	108594.7	100.0%
Shoulder Width	2 - 8 ft	834.5	0.8%
	9 ft and above	74.7	0.1%
	No shoulder or missing value	107685.5	99.2%
	Total	108594.7	100.0%

With the attributes of Alabama roadways, this study developed construction plans for each hypothetic project by considering the following three factors: number of lanes, shoulder, and median. To better pair various work zone scenarios with their safety, mobility, and sustainability impacts, this study created a coding system, as shown in TABLE 5.

TABLE 5 Coding system used to describe scenarios.

A - Number of lanes			**B – Shoulder**		**C – Median**	
A1 – Two-lane	A2 – Four-lane	A3 – Six-lane or more	B1 - Drivable shoulder	B2 - Undrivable shoulder	C1 - Drivable median	C2 - Undrivable median

The identification of all possible configurations of a work zone is simple in the case of one lane per direction, however when two or more lanes per direction are considered the number of possibilities grows exponentially, which makes the manual identification unfeasible. With the aid of programming software all possible configurations can be derived in a relatively easy manner by applying a set of simple rules that indicate when a lane, median or shoulder are available. In words the rules can be summarized as follows:

- The base condition is when no work zone is placed, all lanes are open and median/shoulder remain on restricted access.
- If any of the lanes in one direction are closed, the rest is going to be affected by work zone conditions. Therefore, a delay will be present on the no-closed lanes.
- All cars travelling on a median/shoulder lane are subject to delay.
- The number of operating lanes (including drivable shoulder or median) is not allowed to exceed the number of operating lanes in normal conditions. With this rule each time a lane is closed only one median/shoulder can be used as a substitute.
- When all lanes are closed in one direction the cars are subject of detour.

FIGURE 2 shows all possible intervention plans for scenario A1B1C1, each row in the image represents a plan. However, some rows are labeled with the same number. See Plan 2, for instance. The characteristics of those plans are equivalent in operational terms for impact evaluation. In other words, the analyst will retrieve the same results with any of the two rows labeled with the number 2.

Plan	D1 Shoulder	D1 lane 1	Median	D2 lane 1	D2 Shoulder
1	Closed	Cons.	Closed	Cons.	Closed
2	Closed	Cons.	Closed	Cons.	↑
2	Closed	Cons.	↓ or ↑	Cons.	Closed
2	↓	Cons.	Closed	Cons.	Closed
3	Closed	Cons.	↓ or ↑	Cons.	↑
3	↓	Cons.	Closed	Cons.	↑
3	↓	Cons.	↓ or ↑	Cons.	Closed
4	Closed	Cons.	Closed	↑	Closed
4	Closed	↓	Closed	Cons.	Closed
5	Closed	Cons.	↓ or ↑	↑	Closed
5	Closed	↓	Closed	Cons.	↑
5	Closed	↓	↓ or ↑	Cons.	Closed
5	↓	Cons.	Closed	↑	Closed
6	Closed	↓	Closed	↑	Closed

Labels	
Closed	Median or Shoulder closed
	Lane under construction
↑	Lane, Median or Shoulder delayed
↑	Lane open

FIGURE 2 Alternative intervention plans for scenario A1B1C1.

Note that plan 6 is the "base plan" with both sides of the road operating under normal conditions. In the case of scenario A2B1C1 there are 17 possible intervention plans with 90 configurations. And for scenario A3B1C1 the number is 28 intervention plans with 434 possible configurations. All plans and configurations are listed in Appendix A.

TABLE 6 Vehicle traveling conditions and phases for each plan on scenario A1B1C1

Plan	Condition 1	Condition 2	Lanes closed	Phases
1	Detour	Detour	2	1
2	Detour	Delay	2	1
3	Delay	Delay	2	1
4	Detour	Open	1	2
5	Delay	Open	1	2
6	Open	Open	0	0

For all intervention plans, the operation conditions are identified as well. As mentioned in previous reports, three possible conditions exist. In normal conditions, vehicles travel without restrictions; in detour conditions, vehicles travel one extra mile and at a lower speed due to closed roads; and in delay conditions, vehicles travel at low speed due to lanes affected by the work zone. In addition, the number of phases needed to complete road maintenance or enhancement. The phases are the number of times that a work unit has to be deployed in order to cover all lanes on the road. It is related to the number of lanes closed, if the plan indicates that only one lane is closed each time on the two-lane road, a work unit will have to work in two phases. TABLE 6 summarizes this information.

5. Methodology

5.1 Mobility Impacts

Work zones refer to areas where road or bridge repairs and reconstruction take place. These zones typically require the closure of shoulders, one or more lanes in one direction, or even the entire road. Different types of work zones—specifically, various lane closure scenarios—can result in different impacts for travelers and construction planners. Most notably, work zones affect roadway mobility, with the primary consequence being increased travel time or delay compared to non-work zone conditions. Various work zone scenarios can impact travelers' travel times. A common example is when travelers must detour due to a full lane closure. Ideally, travelers select the fastest route based on prior experience or external tools like Google Maps. However, in the case of a full closure, travelers must detour and choose an alternative route. This detour may cause additional congestion on the detour route due to the sudden increase in traffic demand. As a result, delays arise from the lane closure and mandatory detour.

In addition to full lane closures, work zones can impact travel time through partial lane closures. These closures temporarily alter the road's geometry (such as the number of available lanes), which in turn affects roadway capacity—the supply of traffic flow available on the road. Delays occur when demand exceeds available capacity or when the road capacity remains sufficient, but increased traffic volume leads to slower travel speeds. The following sections outline the methods used to measure the mobility impact of work zones and the approach to monetizing these mobility impacts.

5.1.1 Delay Estimation

This section introduces work zone capacity, methods for calculating delays, and relevant findings related to speed limits in Alabama work zones. The methods for calculating capacity and free-flow speed are derived from the Highway Capacity Manual (2016), while the delay calculation methods come from the US Department of Transportation (US DOT). Work zone speed limits in Alabama are based on a report by the Alabama Department of Transportation (ALDOT).

Before using the HCM methods, users should be aware of the following limitations. First, the estimates for work zone capacity and free-flow speed should only be used when local data is unavailable. Second, if only a single lane is open, and the road is steep, or if heavy-duty vehicles are present, caution is advised when applying these estimates. Third, this methodology does not account for the impact of law enforcement on capacity and free-flow speed. Fourth, the methodology does not consider the effects of varying pavement conditions. Finally, it is assumed that lane width is 12 feet in this methodology.

Capacity

Work zones can indirectly impact travel time by altering roadway capacity. According to the HCM (2016), capacity is defined as "the maximum sustainable hourly flow rate at which vehicles can reasonably be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions." For the purpose of this study, it is assumed that downstream traffic operations do not affect the specified point used to calculate the highway capacity.

Because there is no existing data to support the work zone capacity modeling, this study employed the work zone capacity calculating method provided by the HCM (2016). The EQUATIONSs are follows:

$$\text{LSCI} = \frac{1}{OR * N_o} \tag{1}$$

where LSCI is the lane closure severity index, OR is the number of open lanes during road work to the total (or normal) number of lanes, and N_o is the number of open lanes in the work zone. The EQUATION (2) shows how to calculate the work zone queue discharge rate QDR_{WZ} (pc/h/ln), which is defined as "*The average flow rate immediately downstream of an active bottleneck (following breakdown) measured over a 15-min sampling interval while there is active queuing upstream of the bottleneck.*"

$$QDR_{WZ} = 2093 - 154 * LCSI - 194 * f_{Br} - 179 * f_{AT} + 9 * f_{LAT} - 59 * f_{DN} \tag{2}$$

The f_{Br} is the indicator variable for barrier type. When the barrier type is concrete and hard barrier separation, the value of f_{Br} is 1; otherwise, the value of f_{Br} is 0. The f_{AT} is the indicator variable for area type. The value 1 represents rural areas, and 0 means urban areas. The f_{LAT} is the lateral distance from the edge of the travel lane adjacent to the work zone to the barrier, barricades, or cones (0-12 ft). The f_{DN} is the indicator variable for daylight or night. The value 1 represents night, and 0 means daylight.

$$c_{WZ} = \frac{QDR_{WZ}}{100 - \alpha_{WZ}} * 100 \tag{3}$$

EQUATION (3) displays the work zone capacity c_{WZ} (pc/h/ln). The α_{WZ} is the percentage drop in prebreakdown capacity at the work zone due to queuing conditions. In general, the average queue discharge drop of 7% in non-work zone conditions, and 13.4% in freeway work zones. Because the value of work zone capacity cannot be greater than the non-work zone capacity, the capacity adjustment factor for a work zone, which is abbreviated as CAF_{WZ}. The value of CAF_{WZ} should be between 0 and 1.

$$CAF_{WZ} = \frac{c_{WZ}}{c} \tag{4}$$

Work Zone Speed Limits in Alabama

In response to federal aid fund requirements, all state transportation departments are required to conduct a biennial work zone process review (ALDOT, 2019). Consequently, ALDOT (2019) provided guidance on establishing work zone speed limits. This guidance is based on the assumption that "road users will only reduce their speeds if they perceive a need to do so." Given this assumption, the guidance outlines how to define work zone speed limits in Alabama, taking into account the type of work zone (as shown in TABLE 7), the posted speed limit, and the road type (e.g., a two-lane highway), with the detailed information provided in TABLE 8. It is important to note that the work zone speed limit can be adjusted. If further speed reduction is necessary, the work zone speed limit may be lowered by an additional 5 MPH beyond what is listed. Generally, the difference between posted speed limits and work zone speed limits should not exceed 15 MPH unless indicated otherwise in TABLE 7.

TABLE 7 Descriptions of different types of work

Type of work	Name	Description
1	Roadside activity	Work performed next to the roadway but does not require the lane closure
2	Lane/paved shoulder closure	Work that needs to require the closure of a travel lane(s) or paved shoulder
3	Temporary roadway diversion	Work that requires rerouting of traffic into a temporary or permanent roadway/alignment around the work zone.

TABLE 8 Work zone speed limits in different conditions (adapted from ALDOT, 2019)

Type of work	Posted speed limit	Work zone speed limit
Two-lane highway		
1	All	No reduction
2	55 MPH 50 MPH ≤ 45MPH	45 MPH 45 MPH No reduction
3	55 MPH 50 MPH ≤ 45MPH	45 MPH (Desirable), 35 MPH (Minimum) 45 MPH (Desirable), 35 MPH (Minimum) 45 MPH (Desirable), 35 MPH (Minimum)
Multilane highway		
1	All	No reduction
2	65 MPH 60 MPH 55 MPH 50 MPH ≤ 45MPH	55 MPH 50 MPH 45 MPH 45 MPH No reduction
3	≥ 55MPH 50 MPH ≤ 45MPH	45 MPH (Desirable), 35 MPH (Minimum) 45 MPH (Desirable), 35 MPH (Minimum) 45 MPH (Desirable), 35 MPH (Minimum)
Multi-lane divided highway (Non-interstate)		
1	All	No reduction
2	65 MPH 60 MPH 55 MPH 50 MPH	55 MPH 55 MPH 50 MPH 50 MPH

	$\leq$ 45MPH	No reduction
3	$\geq$ 55MPH 50 MPH $\leq$ 45MPH	45 MPH (Desirable), 35 MPH (Minimum) 45 MPH (Desirable), 35 MPH (Minimum) 45 MPH (Desirable), 35 MPH (Minimum)
Interstate highway		
1	All	No Reduction
2	70 MPH 65 MPH 60 MPH 55 MPH 50 MPH	55 MPH 55 MPH 50 MPH 50 MPH No reduction
3	70 MPH 65 MPH 60 MPH $\leq$ 55MPH	45 MPH (Desirable), 35 MPH (Minimum) 45 MPH (Desirable), 35 MPH (Minimum) 45 MPH (Desirable), 35 MPH (Minimum) 45 MPH (Desirable), 35 MPH (Minimum)

Delay

This subsection introduces two methods for calculating delay (Elefteriadou, 2016; Ullman et al., 2011). The first method assumes that traffic demand is less than both the work zone capacity and the non-work zone capacity. In other words, the traffic flow will operate at free-flow speed (FFS), regardless of the presence or absence of the work zone. The second method accounts for the queuing condition.

<u>Free-flow speed-based delay estimation.</u> According to the HCM (2016), free-flow speed (FFS) is defined as the average speed of passenger cars measured when traffic flow does not exceed 500 passenger cars per hour per lane (pc/h/ln). In other words, when traffic flow is below this threshold, passenger cars will travel at the free-flow speed (FFS) on both normal roads and work zones, or the work zone free-flow speed (FFS_{WZ}). EQUATION s 5 and 6 illustrate how the HCM (2016) estimates the FFS for basic freeway segments and multilane highway segments:

$$\text{FFS} = \text{BFFS} - f_{LW} - f_{RLC} - 3.22 * TRD^{0.84} \tag{5}$$

$$\text{FFS} = \text{BFSS} - f_{LW} - f_{TLC} - f_M - f_A \tag{6}$$

$$\text{TLC} = LC_R + LC_L \tag{7}$$

where BFFS is the basic free-flow speed, usually the value is 75.4 mi/h. The f_{LW} is the adjustment for lane width. When the lane width is greater than 12 ft, the value is 0 mi/h; when the lane width is located within 11-12 ft, the value is 1.9 mi/h; when the lane width is located within 10-11 ft, the value is 6.6 mi/h. The f_{RLC} is the adjustment for right lateral clearance on freeway segments. The value can be found in Appendix B. The TRD is the total ramp density (ramps/mi). The f_{TLC} is the adjustment for total lateral clearance on freeway segments. The value can be found in Appendix B. The f_M is the adjustment for type of median of multilane highways (mi/h). Undivided median is given a value 1.6, otherwise the value is 0. The f_A is the adjustment for access point density on multilane highway segments. The value can be found in Appendix B.

HCM (2016) also provided the equation of work zone FFS (FFS_{WZ}) calculated in Chapter 10. Same as the work zone capacity, the work zone FFS should not be greater than normal FFS. Therefore, the HCM (2016) used the SAZ_{WZ} to determine whether the calculation is right (i.e., SAZ_{WZ} between 0 and 1). EQUATIONs 8 and 9 show the calculation method of FFS_{WZ} and SAZ_{WZ}:

$$FFS_{WZ} = 9.95 + 33.49 * f_{Sr} + 0.53 * SL_{WZ} - 5.60 * LCSI - 3.84 * f_{Br} - 1.71 * f_{DN} - 8.7 * TRD \quad (8)$$

$$SAZ_{WZ} = \frac{FFS_{WZ}}{FFS} \quad (9)$$

where the f_{Sr} is the speed ratio of non-work zone speed limit to work zone speed limit, SL_{WZ} is the work zone speed limit (mi/h). The delay per vehicle can be calculated by the difference between FFS and FFS_{WZ} times the work zone length (EQUATION 10). The total delay can be calculated by the traffic volumes times the single-vehicle delay (EQUATION 11).

$$\frac{\text{Delay}}{\text{Vehicle}} = L_{WZ} * \left(\frac{1}{FFS_{WZ}} - \frac{1}{FFS}\right) \quad (10)$$

$$\text{Total Delay} = \frac{\text{Delay}}{\text{Vehicle}} * Number\ of\ vehicles \quad (11)$$

Work zone capacity-based delay estimation. The US Department of Transportation (US DOT) provides a delay estimation method for scenarios where queuing is caused by work zones (Ullman et al., 2011). In such cases, traffic speed will be lower than the free-flow speed or the speed limit due to higher traffic volume. The following equations are based on several assumptions: first, the flow rate at the work zone is approaching its capacity; second, the speed-density relationship is linear; and third, the speed within the queue and work zone remains constant until vehicles exit the work zone. EQUATIONs 12 and 13 illustrate the queue speed (u_q) and the work zone speed (u_{WZ}), both measured in miles per hour (MPH).

$$u_q = \left(\frac{FFS}{2}\right)\left(1 - \left(1 - \frac{C_{WZ}}{C}\right)^{0.5}\right) \quad (12)$$

$$u_{WZ} = \frac{FFS}{2} \quad (13)$$

where C is the total capacity of each direction of the road (pc/h), and C_{WZ} is the total work zone capacity of each direction (pc/h).

$$\frac{\text{Delay}}{\text{Vehicle}} = L_q\left(\frac{1}{u_q} - \frac{1}{SL_{WZ}}\right) + L_{WZ}\left(\frac{1}{\frac{FFS}{2}} - \frac{1}{SL_{WZ}}\right) \quad (14)$$

Based on the known speed, work zone speed limit (SL_{WZ}), queue length, and work zone length (L_{WZ}), the delay per vehicle can be calculated. The total delay should be calculated by EQUATION 11.

Detour Delay

This subsection introduces the method for calculating detour delay, which is based on the travel speed difference between using alternative routes and the initial road without a work zone. The method relies on the speed-flow relationship for basic freeway and multilane highway segments (Elefteriadou, 2016) to calculate travel time and changes in travel time. This calculation assumes the existence of only one alternative road (FIGURE 3).

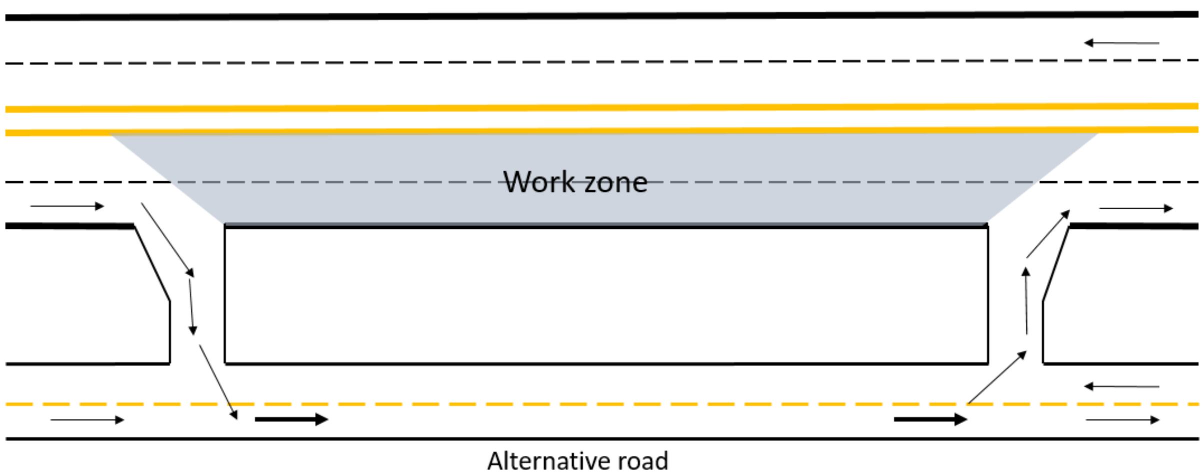


FIGURE 3 An example of a work zone-related detour.

According to the HCM (2016), the formulations to calculate the mean speed (S) of the traffic stream under base conditions (in miles per hour, mi/h) are presented in EQUATIONs 15 through 19:

$$FFS_{adj} = FFS \times SAF \quad (15)$$

$$c = \begin{cases} 2{,}200 + 10(FFS - 50) \;\; c \le 2{,}400 \;\;\; 55 \le FFS \le 75 \;\;\; Basic\ freeway\ segments \\ 1900 + 20(FFS - 45) \;\; c \le 2{,}300 \;\;\; 45 \le FFS \le 70 \;\;\; Multilane\ highwat\ segments \end{cases} \quad (16)$$

$$c_{adj} = c \times CAF \quad (17)$$

$$S = FFS_{adj} \qquad v_p \le BP \quad (18)$$

$$S = FFS_{adj} - \frac{\left(FFS_{adj} - \frac{c_{adj}}{D_C}\right)(v_p - BP)^a}{(c_{adj} - BP)^a} \qquad BP < v_p < c \quad (19)$$

where FFS_{adj} is the adjusted free flow speed (mi/h), SAF is the speed adjustment factor, which is between 0 and 1. c_{adj} is the adjusted segment capacity (pc/h/ln), CAF is the capacity adjustment factor, which is between 0 to 1. D_c is density at capacity (pc/mi/ln), equal to 45 pc/mi/ln. BP is the breakpoint (pc/h/ln). And a is the exponent calibration parameter, which is equal to 2 in basic freeway segments and 1.31 in multilane highway segments.

After calculating the mean speed of the traffic stream under base conditions for two phases of the alternative route (initial and detour) and the initial road without the detour, the detour delay can be determined using EQUATIONs 20 through 23:

$$\frac{\text{Delay}}{\text{Vehicle}_{initial}} = S_{detour} \times L_{alter} - S_{initial} \times L_W \tag{20}$$

$$\frac{\text{Delay}}{\text{Vehicle}_{alter}} = S_{detour} \times L_{alter} - S_{alter} \times L_{alter} \tag{21}$$

$$\text{Total Delay}_{initial} = \frac{\text{Delay}}{\text{Vehicle}_{initial}} * Number\ of\ vehicles_{initial} \tag{22}$$

$$\text{Total Delay}_{alter} = \frac{\text{Delay}}{\text{Vehicle}_{alter}} * Number\ of\ vehicles_{alter} \tag{23}$$

where S_{detour} is the mean speed (mi/h) of the traffic stream (detoured) on the alternative road under base conditions, $S_{initial}$ is the mean speed (mi/h) of the traffic stream on the initial road (without work zone) under base conditions, S_{alter} is the mean speed (mi/h) of the traffic stream (without detour) on the alternative road under base conditions. L_{alter} is the length of the segment (mi), which is used for the detour, L_{alter} is the work zone length (mi). $\frac{\text{Delay}}{\text{Vehicle}_{initial}}$ is the detour delay (h) for vehicles from the initial road,). $\frac{\text{Delay}}{\text{Vehicle}_{alter}}$ is the detour delay (h) for vehicles from the alternative road.

5.1.2 Monetarization

Work zones impact road users in several ways, such as travel time delays, changes in the number of crashes, and increased emissions. However, evaluating work zone impacts across these diverse dimensions is not straightforward. Converting various work zone impacts into dollar values provides a more practical way to assess their overall effect. This section presents a method to convert work zone impacts, specifically travel time delays, into dollar values.

The value of time (VOT) is defined as the amount of money a traveler is willing to pay to reduce their travel time (Burris et al., 2016). Previous study has proposed several methods for calculating VOT (Burris et al., 2016). Two common approaches are the stated preference (SP) method and assuming VOT equals the traveler's wage. The SP method, which requires travelers to participate in an SP survey and answer various questions, can capture more detailed information than the second method. Considering the cost and limitations of the SP method, for this project, the assumption that VOT equals the traveler's wage was adopted as the calculation method. Specifically, to more accurately represent the VOT of all travelers, the median hourly wage of

Alabamians was used as a proxy for their wages. Commercial vehicles were not considered in this calculation. The function used to calculate VOT is shown in EQUATIONs 24 and 25:

$$VOT_{per\ traveler} = median\ hourly\ wage \tag{24}$$

$$VOT_{per\ vehicle} = VOT_{per\ traveler} * the\ average\ occupancy\ rate\ of\ passenger\ car \tag{25}$$

According to the U.S. Bureau of Labor Statistics (n.d.), until May 2021, the median hourly wage of all occupations in Alabama is \$17.91. Thus, the $VOT_{per\ traveler}$ of per traveler is equal to \$17.91 per hour. The average occupancy rate of passenger cars is calculated by the 2017-2021 data from the Alabama Critical Analysis Reporting Environment (CARE) database (The Center for Advanced Public Safety, n.d.). The value is equal to 1.003. Therefore, based on EQUATION 25, the $VOT_{per\ vehicle}$ is \$17.96 per vehicle.

After calculating the $VOT_{per\ vehicle}$, the cost of work zone mobility impact (i.e., delay) can be calculated as follows (EQUATIONS 26-27):

$$Delay\ cost\ per\ vehicle = VOT_{per\ vehicle} * \frac{Delay}{Vehicle} \tag{26}$$

$$Delay\ cost\ per\ vehicle = 17.96 * \frac{Delay}{Vehicle} \tag{27}$$

Note that, as shown in the last section, the delay indicates the delay in hours.

5.2 Safety Impacts

Road construction and maintenance are key responsibilities of state and local governments. During these activities, work zones established by local Departments of Transportation (DOTs) lead to lane closures, shifts, and crossovers (Liu et al., 2016). According to the National Highway Traffic Safety Administration (NHTSA, 2013), active work zones account for nearly twelve billion vehicle miles of travel annually. On average, travelers encounter an active work zone once every 100 miles on the highway system. Existing literature indicates that work zones may contribute to higher crash rates (Yang et al., 2015). The Centers for Disease Control and Prevention (CDC, n.d.) reported that between 1982 and 2019, 28,636 individuals died in work zone crashes, averaging about 774 fatalities per year. Notably, this number has steadily increased from 2015 to 2019. These statistics highlight the significant risks that work zones pose to road users. The following measurement methods will provide a useful framework for analyzing the traffic impact costs of highway infrastructure construction.

5.2.1 Number of Crashes

The safety impact was measured using crash frequency. Specifically, crash frequency can be estimated using Safety Performance Functions (SPFs). According to the Highway Safety Manual (2010), SPFs are used to estimate the average crash frequency for a particular facility type under specified base conditions. For a road with a work zone, the road without a work zone at the same location can serve as the base condition. This allows the SPF to be applied to estimate the average crash frequency for the original road. SPFs are typically determined using the Annual Average

Daily Traffic (AADT) and segment length (L). EQUATION 28 presents an example SPF for rural two-lane, two-way roads, as provided in the Highway Safety Manual (2010).

$$\mathrm{N_{SPF}} = AADT \times L \times 365 \times 10^{-6} \times e^{-0.312} \quad (28)$$

Work Zone without Road Closure

This subsection focuses on the safety impact of work zones without road closures, meaning vehicles continue to travel on the road while the work zone is in place. Various work zone countermeasures are applicable under this condition, such as active work without lane closures, active work with temporary lane closures, and inactive work zones with no lane closures.

To estimate the changes in average crash frequency after implementing a work zone, Crash Modification Factors (CMFs) are needed. CMFs represent the ratio of effectiveness between two conditions (AASHTO, 2010). They are multiplied by the crash frequency predicted by the Safety Performance Function (SPF) to adjust for the differences between the site conditions and the specified base conditions. Several work zone-related CMFs are available in the Crash Modification Factors Clearinghouse (http://www.cmfclearinghouse.org/). EQUATION 29 demonstrates how CMFs are used in crash frequency predictions:

$$N_{predicted} = N_{SPFx} \times \left(CMF_{1x} \times CMF_{2x} \times \ldots \times CMF_{yx}\right) \times C_x \quad (29)$$

where $N_{predicted}$ is the predicted model estimate of crash frequency for a specific year on site type x. The N_{SPFx} represents the predicted average crash frequency determined for base conditions with SPF representing site type x. The CMF_{yx} indicates the CMFs specific to site type x, and the C_x is the Calibration factor to adjust for local conditions for site type x.

The average crash frequency change is represented by EQUATION 30:

$$N_{change} = N_{predicted} - N_{SPFx} \quad (30)$$

where N_{change} is the average crash frequency change.

The CMFs for the aforementioned countermeasures are shown in TABLE 9. It is important to note that all CMFs in TABLE 9 represent values for all crash types and severities. In the Crash Modification Factors Clearinghouse, some countermeasures may have multiple CMFs, each corresponding to different crash types or severities. For this project, the median value of the CMFs is used when multiple values are available.

TABLE 9 CMFs for different work zone countermeasures

Countermeasure	**CMF**	**Reference**
Active work with no lane closure	1.204	Ullman et al. (2008)
Active work with temporary lane closure	1.656	Ullman et al. (2008)
No active with no lane closure	1.145	Ullman et al. (2008)

Additionally, some scenarios may involve closing a lane and using a drivable shoulder or median as a temporary driving lane. Since the width of the shoulder or median may differ from that of regular lanes, CMFs adjusted for changes in AADT and lane width may be required when calculating the average crash frequency. TABLE 10 presents the CMFs for changes in AADT and lane width.

TABLE 10 CMFs with change in AADT and lane width

	AADT		
Lane Width	<400	400-2000	>2000
9 ft or less	1.05	$1.05 + 2.81 \times 10^4 \times (AADT - 400)$	1.05
10 ft	1.02	$1.02 + 1.75 \times 10^4 \times (AADT - 400)$	1.3
11 ft	1.01	$1.01 + 1.05 \times 10^4 \times (AADT - 400)$	1.05
12 ft or more	1	1	1

Road Closure and Detour

This subsection discusses the measurement method for safety impact under detour scenarios. The basic approach involves estimating the average crash frequency and changes in crash frequency. First, the initial average crash frequencies of both the road and alternative roads are estimated. Then, due to the work zone requiring road closure, the sum of the AADT of the initial road and alternative road is used to estimate the average crash frequency for the alternative road. Finally, the change in average crash frequency is calculated by subtracting the sum of the initial average crash frequencies from the newly estimated average crash frequency of the alternative road. This method assumes that only one alternative road exists (FIGURE 3). According to the Highway Safety Manual (2010), the general SPF can be represented by the following equation:

$$N_{SPF} = exp\ [a + b\ ln(AADT) + ln(L)] \tag{31}$$

where a and b are coefficients of SPF. Thus, the SPF of the initial road and alternative road, and the SPF of the alternative road after the initial road closed can be represented by EQUATIONs 32 to 34:

$$N_{SPFini} = exp\ [a_{ini} + b_{ini}\ ln(AADT_{ini}) + ln(L_{ini})] \tag{32}$$

$$N_{SPFalt} = exp\ [a_{alt} + b_{alt}\ ln(AADT_{alt}) + ln(L_{alt})] \tag{33}$$

$$N_{SPFafter} = exp\ [a_{alt} + b_{alt}\ ln(AADT_{alt} + AADT_{ini}) + ln(L_{alt})] \tag{34}$$

Based on EQUATIONs 32 to 34, the average crash frequency change can be calculated by the following equation:

$$N_{SPFchange} = N_{SPFafter} - (N_{SPFini} + N_{SPFalt}) \tag{35}$$

5.2.2 Monetarization

Using the Safety Performance Function (SPF) and the estimated Crash Modification Factors (CMFs), analysts can calculate the changes in crashes for each work zone scenario. However, the change in crash frequency cannot be directly converted to dollar values because different crash severities incur varying costs.

TABLE 11 Comprehensive cost in 2001 dollars value (adapted from AL DOT (2016))

Crash type	Comprehensive crash cost $	Growth rate %
K: Fatal	$4,008,900	3%
A: Disabling injury	$216,000	3%
B: Evident injury	$79,000	3%
C: Possible injury	$44,900	3%
O: PDO	$7,400	3%

To transfer the crash changes to dollar value, it is necessary to calculate the crash cost separately based on the KABCO. Sain Associates Inc. (2016) published a document named "Guidance for Road Safety Assessments & Reviews". This document recorded the table of comprehensive cost in 2001 dollars for each crash severity (i.e., KABCO) and used 3% as the cost growth rate (TABLE 11). Thus, the crash cost for each level of severity C_i ($\mathrm{i} = \mathrm{K, A, B, C, O}$) can be calculated as follows (EQUATION 36):

$$C_i = P_i * (100\% + 3\%)^{Y-2001} \tag{36}$$

where Y is the year of the crash happened. The P_i is the crash cost for crash severity i in 2001. According to Equation 5, the comprehensive crash cost for each crash severity in 2022 can be calculated. The results are shown in TABLE 12.

TABLE 12 Comprehensive cost in 2022 dollars value

Crash type	Comprehensive crash cost $	Growth rate %
K: Fatal	$7,457,735	3%
A: Disabling injury	$401,824	3%
B: Evident injury	$146,963	3%
C: Possible injury	$83,527	3%
O: PDO	$13,766	3%

After calculating the comprehensive crash cost for each crash severity, the total safety cost of the work zone can be estimated by EQUATION 37:

$$Crash\ cost = \sum_{i=i}^{5} CS_i * CC * \ C_i, \qquad i = 1, 2, 3, 4, 5 \tag{37}$$

where CS_i is the percentage of crash severity i in the estimation year. The i is from 1 to 5, representing the KABCO separately. The CC means that the crash changes because of the work zone.

5.3 Environmental Impacts

5.1.1 Fuel Consumptions and CO2 Emissions

Vehicles stuck in congested traffic or detours would consume more fuel and produce more emissions. Work zones affect road capacity and vehicle speeds, resulting in atypical traffic conditions on the network. In this project, we analyze the extra fuel consumption and increased emissions associated with the different options for work zone configurations and road closures. In order to better estimate the environmental impact, this project implements several simulations on the Environmental Protection Agency, MOVES Model, a computer model designed to estimate emissions from cars, trucks, buses, and motorcycles at multiple scales that range from national to county to project-level. For project-level analyses, MOVES allows users to enter specific details of vehicle activity for each link in a highway or transit project.

MOVES is used to develop emission inventories for a variety of regulatory purposes, including the development of state implementation plans (SIPs), transportation conformity determinations, general conformity evaluations, and analyses required under the National Environmental Policy Act (NEPA), among others. It must be noted that California uses the California Air Resources Board EMFAC and nonroad models for regulatory purposes. EPA provides training and technical guidance on using MOVES for SIP and conformity modeling and PM hot-spot analyses, including information on how to choose appropriate model inputs. This document is intended to demonstrate the steps (without being exhaustive) to integrate work zone data in project-level analyses with MOVES, as an optional implementation for the above-mentioned official uses.

Specifically, this study uses MOVES3, the latest official version released in 2021. The geographic scope of this model is the U.S., including Puerto Rico and U.S. Virgin Islands with an option to aggregate to county, state, or nation. The latest MOVES model, User Guide, and supporting documentation are available online at: https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves. Readers should note that this document is heavily based on (USEPA, 2021) and are encouraged to refer to that source for more detailed information on project-level modeling with MOVES.

This project only extracts outputs regarding CO2 and total energy consumption, the latter to calculate the fuel consumption in terms of volume (fuel gallons). There are two types of analyses. On the one hand is the screening analysis that estimates the maximum likely impacts of emissions from a given source (or a mix of sources), based on worst-case traffic. On the other hand, is the refined analysis which uses very detailed local information to provide more specialized and accurate estimates of how sources affect air quality. For this project, we limit the scope to the screening analysis type. In certain situations, practitioners may want or need to complete a refined analysis. At the end of this chapter, some additional guidance will be mentioned on how to use MOVES for refined analyses.

This section describes the steps to run MOVES to estimate CO2 emissions and energy consumption for a project-level analysis. We indicate the inputs related to the influence of a road partially blocked due to work zones. Users reading this guidance should have a basic understanding of how to run MOVES. FIGURE 4 describes the general process for estimating emissions at the project level using MOVES.

As shown in the FIGURE 4, there are two significant components in the process of running MOVES. The first has the label “RunSpec” which stands for run specification. The RunSpec is a computer file in XML format that can be edited and executed directly or with the MOVES Graphical User Interface (GUI). The second significant component is an input database which contains tables that describe the project in detail. EPA specifically developed the Project Data Manager for project analyses and recommended using it to create and specify user-supplied database tables.

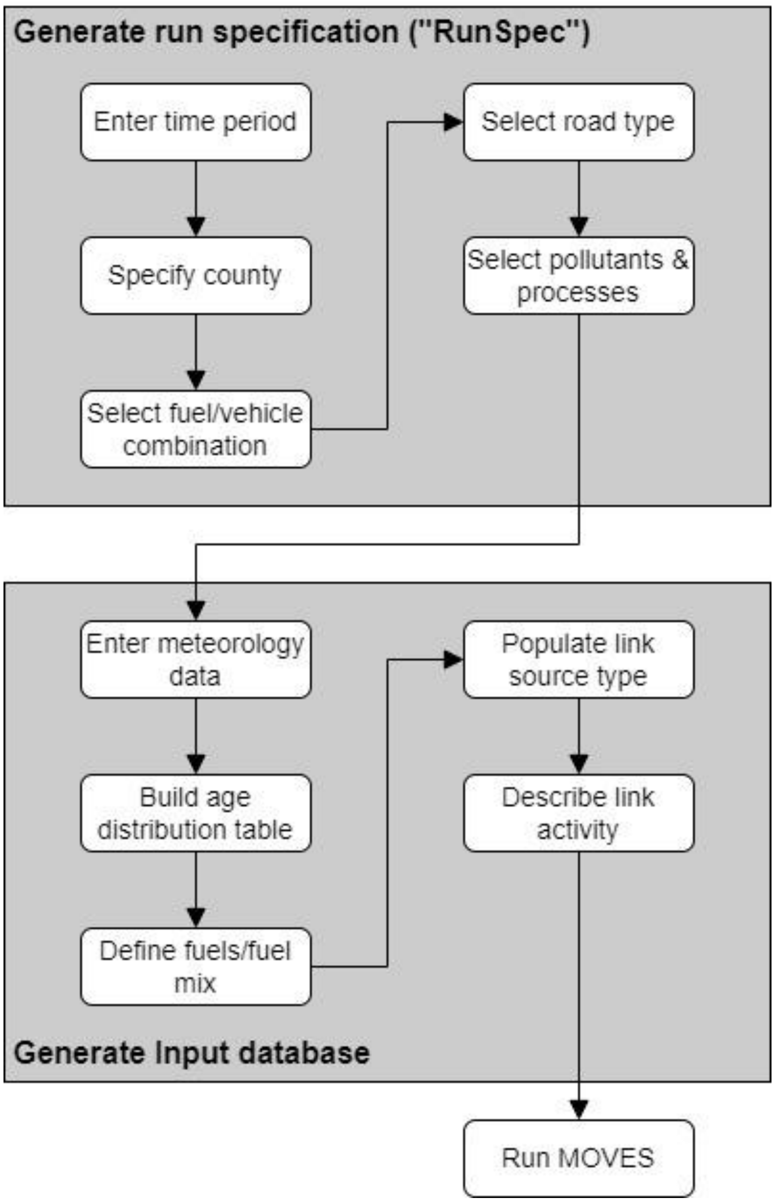


FIGURE 4 Steps for using MOVES in work zone project-level analyses. Adapted from (USEPA, 2021).

RunSpect Creation

MOVES requires the user to set up RunSpec to define the place and time of the analysis as well as the vehicle types, road types, fuel types, and emission-producing processes and pollutants that will be included in the analysis. In order to create a project-level RunSpec, the user must go down the navigation panel filling in the appropriate data for each of the items listed in the Navigation panel of the MOVES GUI (see FIGURE 5).

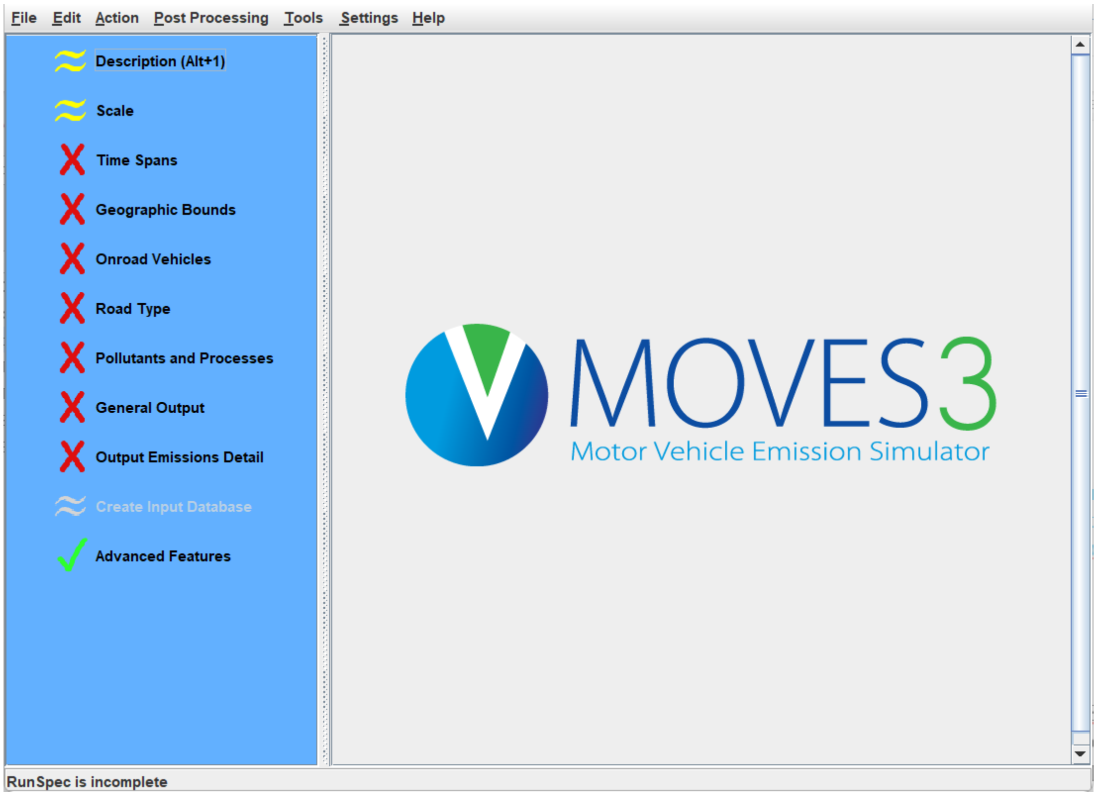


FIGURE 5 Navigation panel of the MOVES GUI.

The subsequent content in this section describes each set of input options needed to create the RunSpec. Additional information on each panel can be found in the MOVES User Guide available on EPA's website (www.epa.gov/otaq/models/moves/index.htm).

Description: This panel allows the user to enter a description of the RunSpec. Entering a complete description of the RunSpec is important for users to keep track of their MOVES runs.

Scale: With this panel, the user can select different scales. All MOVES runs for project-level analyses must be done using the "Project" domain. The Scale panel also requires users to select either "Inventory" or "Emission Rates" which produces output as either grams/hour or grams/vehicle-mile emission rates, respectively. For screening analyses of work zone projects, users should select Inventory as output, which yields results for total emissions on each link. This is equivalent to a grams/hour/link emission factor.

Time Spans: The MOVES model processes one hour, one day, one month, or one year for each run. The user should enter the desired time period in the MOVES Time Spans panel. For a CO2 and energy consumption screening analysis of the work zone, the time aggregation should be set to "hour," which indicates no pre-aggregation. The "day" selection should be set to "weekday".

The year, month, and hour should be set to describe the peak traffic scenario specifically. For example, the run describing a peak traffic scenario might be 2022, April, 8:00 to 8:59 a.m.

Geographic Bounds: MOVES includes county codes and descriptive information for all 3,222 counties in the United States. Specifying a county in MOVES determines certain default information for the analysis. For this project, we use Alabama data.

Onroad vehicles: MOVES allows the user to select from among 13 “source use types” (the terminology that MOVES uses to describe vehicle types), and several different fuels. Some fuel/source type combinations do not exist (e.g., diesel motorcycles) and therefore are not included in the MOVES database. Users should always select Gasoline, CNG, Diesel, and Ethanol (E-85) and all valid vehicle type combinations in the Vehicle/Equipment panel to reflect the full range of vehicles that will operate in the project area. For now, only passenger cars are considered in the simulation. The next step will include more vehicle types.

Road Type: This panel is used to define the types of roads that are included in the project. MOVES defines five different Road Types:

- Rural Restricted Access – a rural highway that can be accessed only by an on-ramp;
- Rural Unrestricted Access – all other rural roads (arterials, connectors, and local streets);
- Urban Restricted Access – an urban highway that can be accessed only by an on-ramp;
- Urban Unrestricted Access – all other urban roads (arterials, connectors, and local streets);
- Off-Network – any location where the predominant activity is vehicle starts and hotelling (parking lots, truck stops, rest areas, freight or bus terminals).

MOVES uses these road types to determine the default drive cycle on a particular link. For example, MOVES uses drive cycles for unrestricted access road types that assume stop-and-go driving, including multiple accelerations, decelerations, and short periods of idling. For restricted access road types, MOVES uses drive cycles that include a higher fraction of cruise activity with much less time spent accelerating and idling.

Road Type is a necessary input into the RunSpec and users should select one or more of the five road types that correspond to the road types of the project. The determination of rural or urban road types should be based on the Highway Performance Monitoring System (HPMS) functional classification of the road type. For now, only rural roads are considered in the simulation. The next step will include more road types.

Pollutants and Processes: In this panel, the user must select both the types of pollutants and the emission processes that produce them. For CO2 emissions and energy consumption analysis, we select in the column “Running Exhaust” the checkboxes “Total Energy Consumption”, “Atmospheric CO2” and “CO2 Equivalent”.

General Output: Users should make sure to choose “grams” and “miles” for the output units if it is intended to provide results for air quality modeling. Also, “Distance Traveled” and “Population” should be selected under the “Activity” heading to obtain vehicle volume information for each link in the output.

Output Emissions Detail: This panel is used to specify the level of detail desired in the output data. Emissions by the hour and link are the default selections and cannot be changed. EPA recommends that users select the box labeled "Emission Process." No other boxes should be selected in order to produce fleet aggregate emission rates for each link.

Advanced Features: Most project-level analyses will not use the Advanced Performance Features panel. This panel can be skipped.

Input Database Creation Using Project Data Manager
After creating the RunSpec, MOVES requires the user to create an input database containing the tables describing the project in detail. Only one set of input tables will need to be created using the Project Data Manager, which can be accessed from the MOVES GUI by selecting Enter/Edit Data in the domain Create Input Database. FIGURE 6 shows the MOVES Project data manager

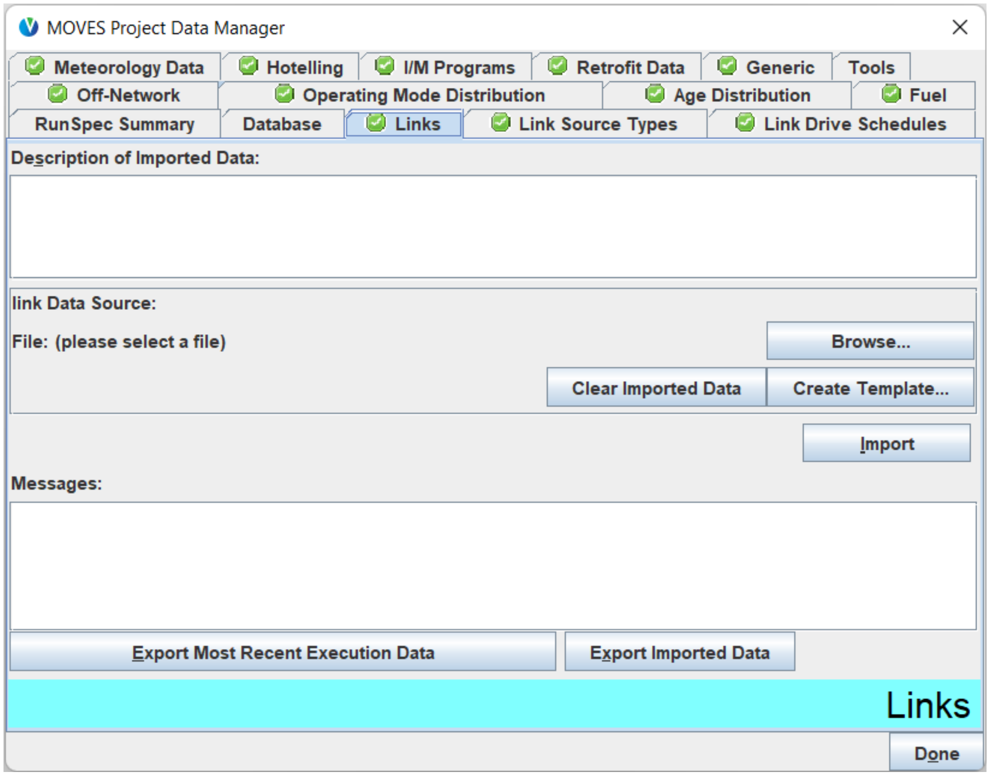


FIGURE 6 MOVES Project data manager once all input data is correct.

The Project Data Manager includes multiple tabs that open importers, which are used to enter project-specific data. Each of the importers allows the user to create a template file with the required data field names. The user then edits this template to add project-specific local data with a spreadsheet application and imports that data into MOVES.

In some importers, there is also the option to export default data from the MOVES database in order to review it. MOVES includes a default database of meteorology, fleet, activity, fuel, and control program data for the entire United States. The data included in this database come from a variety of sources and are not necessarily the most accurate or up-to-date information available at the local level for a particular project. The user determines that the default data are accurate and applicable to the particular project or determines that the default data need to be changed and makes those changes. The MOVES User Guide provides details on the mechanics of using the data importers. Specific comments on the importers related to project-level work zone analyses are described below.

It is important to clarify that not all importers are necessary to see all “green checks” and to run MOVES. For instance, a project with no off-network links will not use the Off-Network, Operating Mode Distribution, or Hoteling importers when activity is defined through the average speed function of the Links importer. These tabs will remain “red X’s” but do not indicate a problem with a run.

Meteorology: This panel is used to import temperature and humidity data for the month and hour that are defined in the MOVES run specification. Default temperature and humidity values are available in MOVES, but are not recommended for use in a project-level analysis as some emissions are found to vary significantly depending on temperature.

Although it is out of the scope of this project for refined analyses, users should enter data specific to the project’s location and time period modeled, as well as run MOVES for multiple time periods. For example, for January AM peak periods corresponding to 6 a.m. to 9 a.m., the average January temperature based on the meteorological record for those hours should be used in estimating the average January AM peak period temperature for MOVES runs. For this project, default values were used.

Meteorological data may be obtained either from the National Weather Service (NWS) or as part of a site-specific measurement program. Local universities, the Federal Aviation Administration (FAA), military stations, and state and local air agencies may also be sources of such data. A data source should be selected that is representative of local meteorological conditions.

Age Distribution: The user provides in this panel the distribution of vehicle fractions by age for each calendar year (yearID) and vehicle type (sourceTypeID). The distribution of ageID (the variable for age) fractions must sum to one for each vehicle type and year. If no state or local age distribution is available, the MOVES default age distribution should be used. This can be obtained from the tables available on the EPA website: www.epa.gov/otaq/models/moves/tools.htm. The user can select the analysis year(s) and find the corresponding age distribution. These fractions are national defaults and could be significantly different from the local project age distribution. Age distribution can have a considerable impact on emission estimates, so the default data should be used only if an alternative state or local dataset cannot be obtained. For this project, the default values were used.

Fuel: The Fuel panel contains four required tables: Fuel Supply, Fuel Formulation, Fuel Usage, and AVFT (Alternative Vehicle and Fuel Technology). The Fuel Supply table defines the fuels present in the project area. The Fuel Formulation table defines the properties of those fuels. The Fuel Usage table defines the fraction of Ethanol (E-85) capable vehicles that are using E-85 vs. conventional gasoline. Finally, the AVFT table defines the prevalence of each vehicle/fuel type combination for the project area.

Users should review the default fuel data in MOVES by exporting it through the Fuel tab, and make changes only if local volumetric fuel property information is available. Otherwise, EPA strongly recommends that the MOVES default fuel information be used for project-level analyses unless a full local fuel property study exists.

Inspection and Maintenance (I/M): Projects within areas covered by an I/M program should define the program in the MOVES Inspection and Maintenance Importer. For this project, the I/M program was excluded.

Link Source Type: This panel allows users to enter the fraction of the link traffic volume, which is represented by each vehicle type (source type). For each LinkID, the "SourceTypeHourFractions" must sum to one across all source types. Additionally, the user must ensure that the source types selected in the MOVES Vehicles/Equipment panel match the source types defined through the Link Source Type Importer. No defaults can be exported from the Link Source Type Importer. For any analysis at the project level, the user must provide source type fractions for all vehicles being modeled.

Links: The Links panel provides the interface to enter the characteristics of all links being modeled. Therefore is the most important for our project. All links should have unique IDs. The Links Importer requires information on each link's length (in miles), traffic volume (units of vehicles per hour), average speed (miles per hour), and road grade (percent).

Within MOVES, a link represents a segment of the road where a certain type of vehicle activity occurs. Generally, the links specified for a project should include segments with similar traffic/activity conditions and characteristics. For example, a free-flow highway segment with a relatively stable average speed might be modeled as a single link, whereas an intersection will involve several types of links. From the link-specific activity and other inputs, MOVES calculates emissions from every link of a project for a given time period (or run). There are no limits in MOVES as to how many links can be defined; however, model run times increase as the user defines more links.

Users should dedicate enough time to conceptualize the project before entering any data on the MOVES RunSpec or in the Input database. FIGURE 7 is an example of a simple signalized intersection showing the links developed to represent the two general categories of vehicle activity expected to take place at this intersection (approaching the intersection and departing the intersection). This project limits the analysis, assuming that work zones can be modeled as one single link with reduced conditions on capacity and speed. Nonetheless, MOVES has several options to describe vehicle activity. The users are encouraged to take advantage of those capabilities.

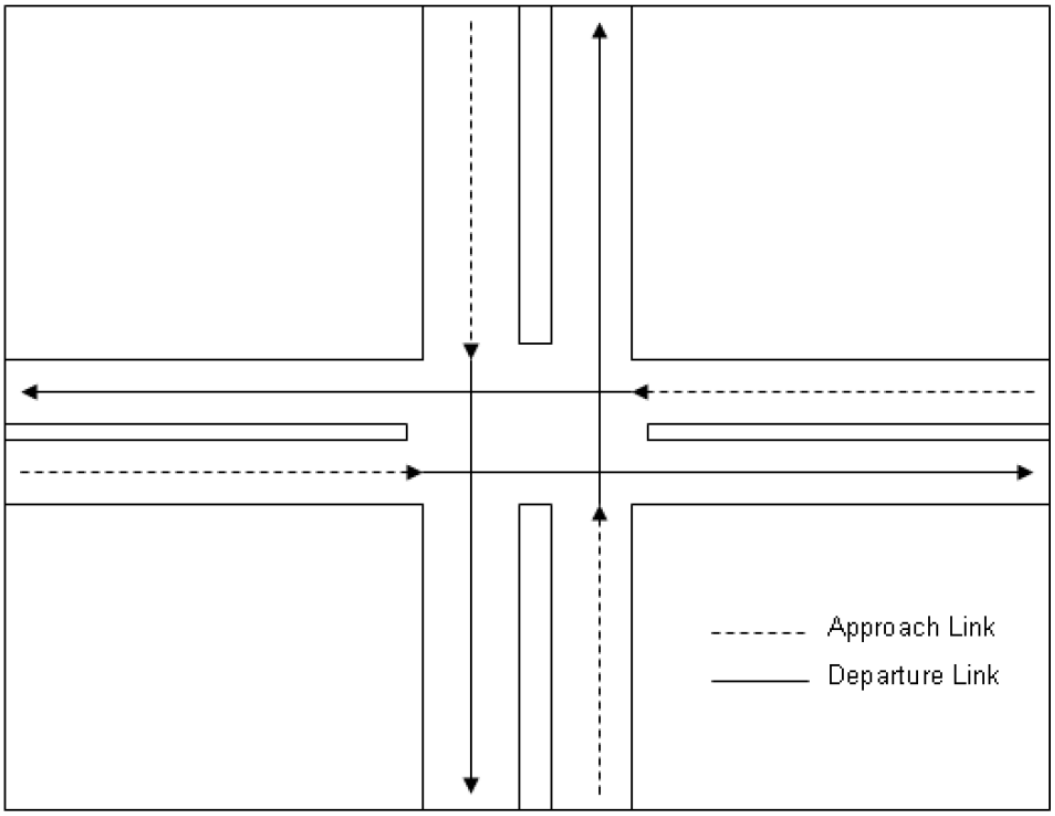


FIGURE 7 Example of Approach and Departure Links for a Simple Intersection, source: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1009HZG.TXT.

When modeling an intersection, each link can be modeled as one or more links in MOVES depending on the option chosen to enter traffic activity. This document suggests three possible options for characterizing activity. Option 1: The user estimates the average speeds for each link in the intersection based on travel time and distance. Travel time should account for the total delay attributable to traffic signal operation, including the portion of travel when the light is green and the portion of travel when the light is red.

Option 2: The user enters vehicle activity into MOVES as a series of link drive schedules to represent individual segments of cruise, deceleration, idle, and acceleration of a congested intersection. A link drive schedule defines a speed trajectory to represent the entire vehicle fleet via second-by-second changes in speed and highway grade. Unique link drive schedules can be defined to describe types of vehicle activity that have distinct emission rates, including cruise, deceleration, idle, and acceleration.

FIGURE 8 illustrates why using this more refined approach can result in a more detailed emissions analysis. This figure shows the simple trajectory of a single vehicle approaching an intersection during the red signal phase of a traffic light cycle. This trajectory is characterized by several distinct phases (a steady cruise speed, decelerating to a stop for the red light, idling during the red signal phase, and accelerating when the light turns green). In contrast, the trajectory of a single vehicle approaching an intersection during the green signal phase of a traffic light cycle is characterized by a more or less steady cruise speed through the intersection.

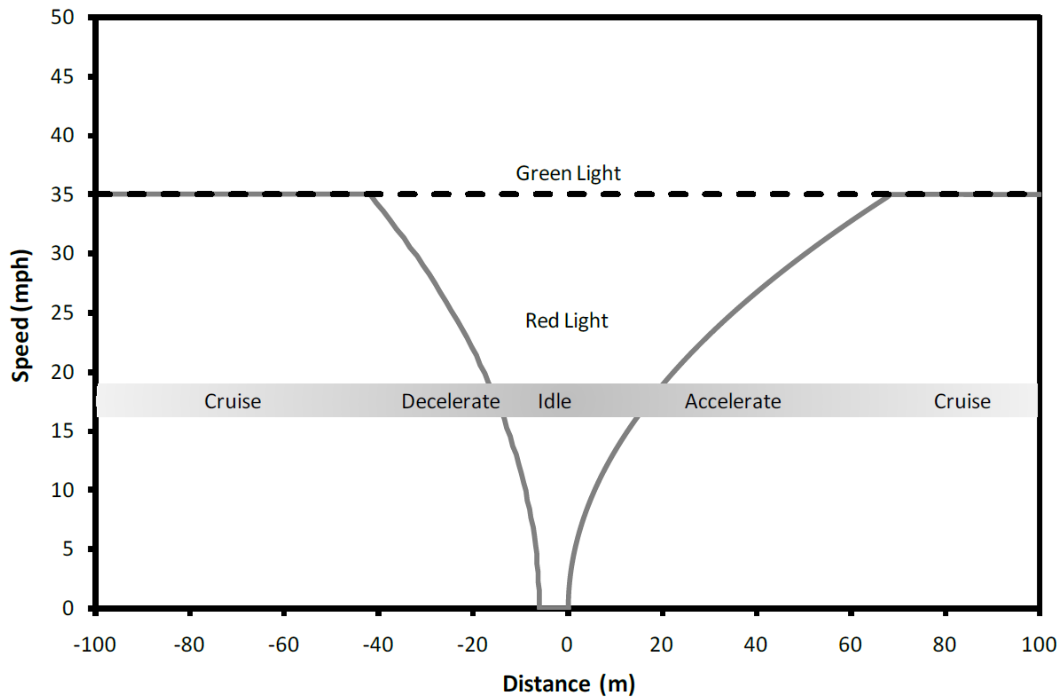


FIGURE 8 Example Single Vehicle Speed Trajectory through a Signalized Intersection, source: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1009HZG.TXT.

CO2 Equivalent to Fuel Consumption

Results from MOVES reflect the CO2 Equivalent and Total energy consumption (in Joules) for each link, source type and fuel type. The MOVES model stores and accesses data for its calculations in a series of MariaDB databases. Specifically, the output database stores tables that describe each run in the output, activity data, information on errors during the run and other tables used for diagnostics and troubleshooting. The name of the output database is specified by the user in the RunSpec. The emission inventory is contained inside the output database in the "movesOutput" table (USEPA, 2021). The process to convert units is extracted from (USEPA, 2020). It applies the following EQUATION 38:

$$Fuel\ (gallons) = Energy(KJ) \times \left(\frac{1}{energyContent}\right)\left(\frac{g}{KJ}\right) \times \left(\frac{1}{fuelDensity}\right)\left(\frac{gallons}{g}\right) \tag{38}$$

The fuel density and the energy content values are stored in the fuelType and fuelSubType tables in MariaDB.

5.1.2 Monetarization

The implementation of work zones increases CO2 (or equivalent) emissions and fuel consumption from vehicles, which not only affects the environment but also imposes additional costs on road users and taxpayers. Specifically, the rise in fuel consumption leads to higher fuel costs for road users. In addition, to counteract the increased CO2 emissions, more urban trees must be planted. This section proposes formulas for translating these environmental impacts into dollar values. The aim is to present the cost of environmental impacts in a more straightforward manner. First, this section will address the cost of increased fuel consumption, followed by the cost of planting urban trees to offset the rise in CO2 emissions.

Before calculating the cost of extra fuel consumption, some assumptions are made to simplify the calculation. First, the fuel type of passenger cars is regular gas. All short-haul trucks use diesel. This study adopts 2022 Alabama average gas prices to calculate the cost of fuel consumption. Specifically, the average regular gas price ($\mathrm{GP}_{\mathrm{regular}}$) and the average diesel price (GP_{diesel}) are used to calculate the cost of extra fuel consumption (EQUATION 39).

$$C_F = \mathrm{GP}_{\mathrm{regular}} \times FC_{pc} + GP_{diesel} \times (FC_{sust} + FC_{cst}) \tag{39}$$

where C_F is the cost of fuel consumption (dollar). The FC_{pc}, FC_{sust}, and FC_{cst} are the extra fuel consumptions under the work zone condition of passenger cars, single unit short-haul trucks, and combination short-haul trucks compared with the normal condition of the road, the unit is a gallon.

To calculate the cost of planting urban trees, some assumptions are made as follows (USEPA, 2024):

- urban trees are allowed to grow for 10 years;
- the urban trees are raised in a nursery for one year at first, after their diameter and height are greater than 1 inch and 4.5 ft, they will be planted in a suburban/urban setting;

the survival rate of urban trees in the first ten years is 68%.

Based on these assumptions, the U.S. Environmental Protection Agency (USEPA, 2024) calculated that each urban tree planted can sequester 0.060 metric tons of CO2. Thus, the cost of eliminating extra CO2 or equivalent emissions can be calculated by the following equation:

$$C_T = (CE\ /0.060)\ \times\ P_T \tag{40}$$

where C_T is the cost of eliminating extra CO_2 or equivalent emissions (dollar), and CE is the CO_2 equivalent (metric ton). The P_T represents the price of planting an urban tree (dollar).

The total cost of environmental impact (C) is the sum of the cost of fuel consumption (dollar) and the cost of eliminating extra CO_2 or equivalent emissions (dollar), which is shown as follows (EQUATION 41):

$$\mathrm{C} = C_F + C_T \tag{41}$$

6. Calculator Design

6.1 Workflow

The goals of the calculator (spreadsheets) are to ensure clarity, accuracy, and ease of use. FIGURE 9 outlines the spreadsheet workflow. It is important to note that the factors listed in FIGURE 9 represent only a subset of the considerations required for calculating traffic impact costs. The evaluation of construction zone traffic impacts focuses on three key aspects: mobility, safety, and environmental effects.

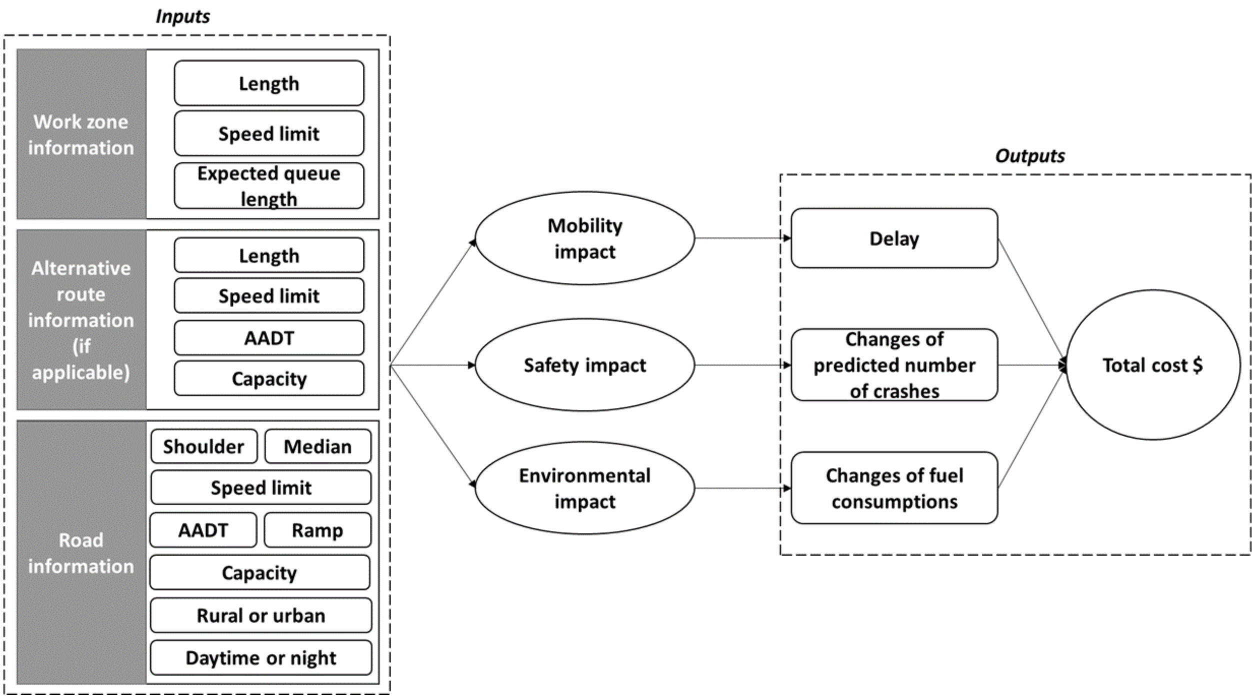


FIGURE 9 Workflow of spreadsheets.

To assess these three dimensions of traffic impacts, users must input specific types of information into the spreadsheets. This includes basic data about the road segment(s) affected by the construction zone. Additionally, detailed work zone information—such as the length and duration of the work zone—is crucial for accurate calculations. If users indicate the presence of a detour plan for the work zone, information on alternative routes must also be provided. Using this data across the three categories, the spreadsheet calculates and monetizes various metrics, including work zone traffic delays, the predicted changes in crash frequency, fuel consumption, and CO2 equivalent emissions.

6.2 Spreadsheets

Because of the complexity and flexibility of a construction plan, the spreadsheet cannot accommodate all possible scenarios (e.g., fully closing one direction, closing the same number of lanes in both directions, or closing different numbers of lanes in each direction). Thus, the results calculated by the spreadsheet are not for the entire construction plan. Instead, the results are for a specific stage and direction of the construction plan. For example, if users plan to create a construction zone on a section of a three-lane highway, they might choose to close one lane in one direction and two lanes in the other. In this case, users can input the information for closing one lane and then input the information for closing two lanes. They would receive results for both scenarios and can add them together to calculate the final impacts.

Five spreadsheets, in total, are integrated into one Excel file for calculating the traffic impact costs of work zones. Three input spreadsheets, titled Road Information, Work Zone Information, and Alternative Route Information, are provided separately to ensure clarity and ease of use. FIGURE 10 shows a screenshot of the Road Information spreadsheet.

	A	B	C
1		**Road Information**	
2	**Items**	**Inputs**	**Notes**
3	AADT	22000	
4	Shoulder Width	11	0-12 ft
5	Median Width	100	ft
6	Median Type	Divided	
7	Location	Rural	Please answer "Urban" or "Rural"
8	# of Ramp	0	Answer it if road segment is on freeway
9	# of Access Points	0	Answer it if road segment is not on freeway
10	Speed Limit	70	Mile per hour
11	Lateral Distance	6	0-12 ft
12	Barriers	0	If the barrier type is "Concrete" or "Hard Barrier", f_Br = 1; Otherwise, f_Br = 0
13	# of Lanes	2	For each direction of the road segment
14	Capacity	2400	Veh/hour/lane
15	Lane Width	12	0-12 ft
16	Adjustment for Right Lateral Clearance on Freeway Segments	0	Appendix A
17	f_TLC	0	Appendix B
18	f_A	0	Appendix C
19	Road Type	Freeway	Please indicate "Freeway" or "Highway"
20	Free Flow Speed (FFS)	73.5	Mile per hour
21	Average regular gas price in Alabama	2.803	dollar/gallon
22	Average diesel price in Alabama	2.775	dollar/gallon
23	**General Notes:**	**1. Only "Yellow" items need to be input.**	
24		**2. Please follow the instruction or "Notes" to input.**	
25			
26			

Road Information | Work Zone Information | Alternative Route Information | Output | Appendix

FIGURE 10 "Road Information" spreadsheet.

Three key elements are included in this spreadsheet: Items, Inputs, and Notes. The Items column lists the road segment information required for traffic impact cost calculations. Users are not required to modify this column, as it only serves as a label. The Inputs column is where users input the required data, with items highlighted in yellow indicating where user input is necessary. Grey-highlighted items are calculated automatically based on other inputs. The Notes column provides helpful hints, instructions, or units for specific items to assist users. Below the table, General Notes are displayed to provide users with brief guidance on how to use the spreadsheet effectively.

Condition #1

Work Zone Information		
Items	**Inputs**	**Notes**
Lane Closure	Yes	Please indicate "Yes" or "No"
# of Open Lane	1	Note: If one direction is fully closed but lanes from another direction is used for the closed direction, the number of open lane is 1.
Work Zone Length	4	Miles
Detour	No	Please indicate "Yes" or "No". If "Yes", please fill next sheet: "Alternative route information"
Work Zone Speed Limit	60	Miles per hour
Expected Queue Length	1	Miles
Work Zone Duration	100	Hours. For each stage.
Lane Width	11	Feets
Day or Night	Day	Please indicate "Day" or "Night". If "Day", f_DN = 0. Otherwise, f_DN = 1
Lateral distance from the edge of the travel lane adjacent to the work zone to the barrier, barricades, or cones	0	0-12 ft

General Notes: **1. Only "Yellow" items need to be input.**
2. Please follow the instruction or "Notes" to input.

Condition #2

Work Zone Information		
Items	**Inputs**	**Notes**
Lane Closure	Yes	Please indicate "Yes" or "No"
# of Open Lane	1	Note: If one direction is fully closed but lanes from another direction is used for the closed direction, the number of open lane is 1.

FIGURE 11 "Work Zone Information" spreadsheet.

FIGURE 11 illustrates a screenshot of the Work Zone Information spreadsheet. Like the Road Information spreadsheet, it contains the same three basic elements and a General Notes section. Users must provide the required data in the Inputs column, with all items highlighted in yellow signifying mandatory input fields. In this spreadsheet, users can input up to three different work zone plan conditions for the same road segment(s). Providing all three plans is optional; if users wish to compare multiple conditions, they can scroll down to find the corresponding tables for Conditions #2 and #3. The methods for inputting information remain the same across all condition tables.

Alternative Route Plan #1 (If Applicable)			Alternative Route Plan #2 (If Applicable)			Alternative Route Plan #3 (If Applicable)		
Items	**Values**	**Notes**	**Items**	**Values**	**Notes**	**Items**	**Values**	**Notes**
AADT			AADT			AADT		
Shoulder Width		0-12 ft	Shoulder Width		0-12 ft	Shoulder Width		0-12 ft
Median Width		ft	Median Width		ft	Median Width		ft
Median Type	Undivided		Median Type	Undivided		Median Type	Undivided	
Location		Please answer "Urban" or "Rural"	Location		Please answer "Urban" or "Rural"	Location		Please answer "Urban" or "Rural"
# of Ramp		Answer it if road segment is on freeway	# of Ramp		Answer it if road segment is on freeway	# of Ramp		Answer it if road segment is on freeway
# of Access Points		Answer it if road segment is not on freeway	# of Access Points		Answer it if road segment is not on freeway	# of Access Points		Answer it if road segment is not on freeway
Speed Limit		Mile per hour	Speed Limit		Mile per hour	Speed Limit		Mile per hour
Lateral Distance		0-12 ft	Lateral Distance		0-12 ft	Lateral Distance		0-12 ft
Barriers		If the barrier type is "Concrete" or "Hard Barrier", f_Br = 1; Otherwise, f_Br = 0	Barriers		If the barrier type is "Concrete" or "Hard Barrier", f_Br = 1; Otherwise, f_Br = 0	Barriers		If the barrier type is "Concrete" or "Hard Barrier", f_Br = 1; Otherwise, f_Br = 0
# of Lanes		For each direction of the road segment	# of Lanes		For each direction of the road segment	# of Lanes		For each direction of the road segment
Capacity	2300	Veh/hour/lane	Capacity	2300	Veh/hour/lane	Capacity	2300	Veh/hour/lane
Lane Width		0-12 ft	Lane Width		0-12 ft	Lane Width		0-12 ft
Adjustment for Right Lateral Clearance on Freeway Segments		Appendix A	Adjustment for Right Lateral Clearance on Freeway Segments		Appendix A	Adjustment for Right Lateral Clearance on Freeway Segments		Appendix A
f_TLC		Appendix B	f_TLC		Appendix B	f_TLC		Appendix B
f_A		Appendix C	f_A		Appendix C	f_A		Appendix C
Road Type		Please indicate "Freeway" or "Highway"	Road Type		Please indicate "Freeway" or "Highway"	Road Type		Please indicate "Freeway" or "Highway"
Detour Length			Detour Length			Detour Length		
Free Flow Speed (FFS)	#DIV/0!	Mile per hour	Free Flow Speed (FFS)	#DIV/0!	Mile per hour	Free Flow Speed (FFS)	#DIV/0!	Mile per hour
Plan #	1		Plan #	2		Plan #	3	

General Notes: **1. Please input when detour is applicable for the targeted plan.**
2. Only "Yellow" items need to be input.
3. Please follow the instruction or "Notes" to input.

Road Information | Work Zone Information | Alternative Route Information | Output | Appendix

FIGURE 12 "Alternative Route Information" spreadsheet.

FIGURE 12 shows a screenshot of the Alternative Route Information spreadsheet. Its structure and functionality are identical to the Road Information spreadsheet. However, this spreadsheet is only used when a detour is necessary for a given work zone plan. For example, if users select "Yes" for the “Detour” item in the table for Work Zone Condition #2, they must fill in the corresponding “Alternative Route Plan #2 (If Applicable)” table.

Appendix A. Adjustment for Right Lateral Clearance on Freeway Segments (Adapted from HCM 2016)

Right-side lateral clearance (ft)	2 lane per direction	3 lane per direction	4 lane per direction	5 or more lane per direction
≥ 6	0	0	0	0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3	2	1	0.5
0	3.6	2.4	1.2	0.6

Note: Interpolate for non-integer values of right-side lateral clearance.

Appendix B-1. Adjustment for Total Lateral Clearance on Four-lane Highway Segments (Adapted from HCM 2016)

TLC (ft)	Reduction in FFS, f_TLC (mi/h)
12	0
10	0.4
8	0.9
6	1.3
4	1.8
2	3.6
0	5.4

Note: Interpolation to the nearest 0.1 is recommended.

Appendix B-2. Adjustment for Total Lateral Clearance on Six-lane Highway Segments (Adapted from HCM 2016)

TLC (ft)	Reduction in FFS, f_TLC (mi/h)
12	0
10	0.4
8	0.9
6	1.3
4	1.7
2	2.8
0	3.9

Note: Interpolation to the nearest 0.1 is recommended.

Appendix C. Adjustment for Access Point Density on Multilane Highway Segments (Adapted from HCM 2016)

Access point density (access point/mi)	f_A (mi/h)
0	0
10	2.5
20	5
30	7.5
≥ 40	10

Note: Interpolation to the nearest 0.1 is recommended.

Note: **TLC is sum of right and left lateral clearance on freeway segments.**

Road Information | Work Zone Information | Alternative Route Information | Output | Appendix

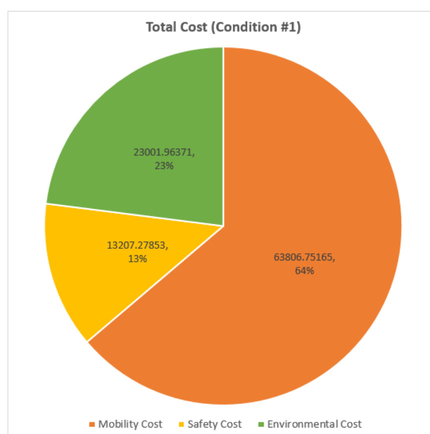
FIGURE 13 "Appendix" spreadsheet.

For some input items in the Road Information and Alternative Route Information spreadsheets (e.g., "f_TLC" and "f_A"), users cannot directly provide the needed values. Instead, the notes for these items direct users to the Appendix spreadsheet (FIGURE 13). Users can open the Appendix spreadsheet, locate the relevant table (e.g., "Appendix A"), and find the value by referencing the corresponding row and column. For instance, if the road segment has two lanes per direction and a right-side lateral clearance of 1 ft, the adjustment factor for right lateral clearance on freeway segments is 3 (as shown in FIGURE 13).

Condition #1

Items	Output	Unit	Note
Mobility Impact			
Delay Per Vehicle (Work Zone)	0.077514	Hour	
Total Delay (Hour)	3552.714	Hour	
Mobility Cost	63806.75	Dollar	Using 2021 median hourly wage of all occupations in Alabama, which is $17.91
Safety Impact			
Number of Crashes (Initial)	0.197356	Crash	
Number of Crashes (Work Zone)	0.343162	Crash	
Number of Crashes (Alternative Initial)	0	Crash	If applicable
Number of Crashes (Alternative Detour)	0	Crash	If applicable
Change of Number of Crashes	0.145806	Crash	
Safety Cost	13207.28	Hour	
Environmental Impact			
Initial Fuel Consumptions (Per Vehicle)	0.204031	Gallon	
Work Zone Fuel Consumptions (Per Vehicle)	0.259426	Gallon	
Detour Alternative Road Fuel Consumptions (Per Vehicle)	0	Gallon	If applicable
Change of Fuel Consumptions (Gas)	2194.413	Gallon	
Change of Fuel Consumptions (Diesel)	344.5352	Gallon	
Cost of Fuel Consumptions	7107.024	Dollar	Using Alabama average regular gas and diesel price $2.803 per gallon and $2.775 per gallon (September 2024)
Initial CO2 Equivalent Emission (Per Vehicle)	0.001915	Metric Gram	
Work Zone CO2 Equivalent Emission (Per Vehicle)	0.00245	Metric Gram	
Detour Alternative Road CO2 Equivalent Emission (Per Vehicle)	0	Metric Gram	If applicable
Change of CO2 Equivalent	24.49458	Metric Gram	
Cost of CO2 Equivalent	15894.94	Dollar	Using the average price of planting an urban tree ($38.938)
Environmental Cost	23001.96	Dollar	
Total Cost (Plan #1)	43316.27	Dollar	

Condition #2



Road Information | Work Zone Information | Alternative Route Information | Output | Appendix

FIGURE 14 "Output" spreadsheet.

The last spreadsheet provided by this calculator is the “Output” spreadsheet (FIGURE 14). In this spreadsheet, the users do not need to provide any information. The delay, changed number of crashes, changed fuel consumptions (gas and diesel), and CO2 equivalent emission caused by the planned work zone(s) will be output based on the input of road, work zone, and alternative route (if applicable) information. Also, this spreadsheet provides the monetarized cost ($) of the aforementioned impacts. For each work zone plan (up to three), a table and pie chart are provided in this spreadsheet. The table will show all the impacts, and the pie chart will show the percentage of each kind of impact on the total cost.

7. Case Study

7.1 Scenario Description

Case studies are conducted to test the developed calculator. Specifically, this report selects real-world work zones to conduct the case studies. According to records from AlgoTraffic (https://algotraffic.com/map), two ongoing work zones in the State of Alabama were chosen. Note that the case studies only use real-world work zone locations, while other information, such as work zone duration, work zone time (i.e., daytime or nighttime), and work zone plans, are designed and set by the research team. Roadway information is estimated by measuring the roads using the satellite map feature in Google Maps. The AADTs are estimated based on information provided by the Alabama Traffic Data website (https://aldotgis.dot.state.al.us/TDMPublic/). Since 2-lane and 3-lane highways/freeways are two of the most common road segments in Alabama, this study selects one 2-lane highway/freeway-based work zone and one 3-lane highway/freeway-based work zone for the case study. The average regular gas price in Alabama is assumed to be $2.803 per gallon, and the average diesel price is $2.775 per gallon. The following sections illustrate the descriptions and detailed settings of the proposed work zone scenarios.

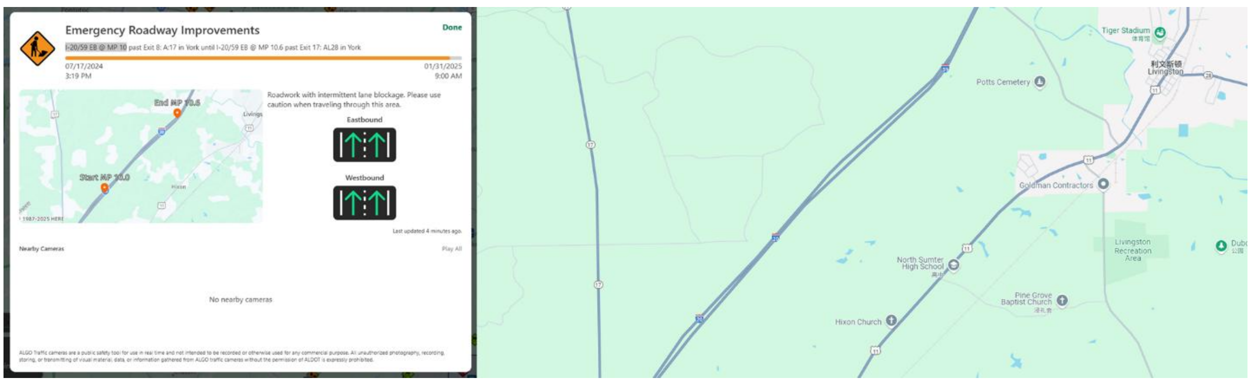
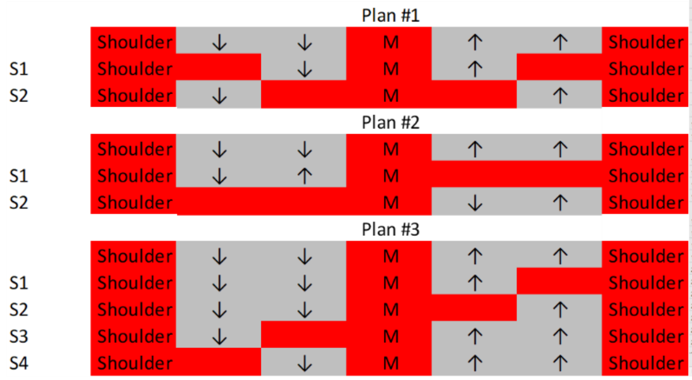
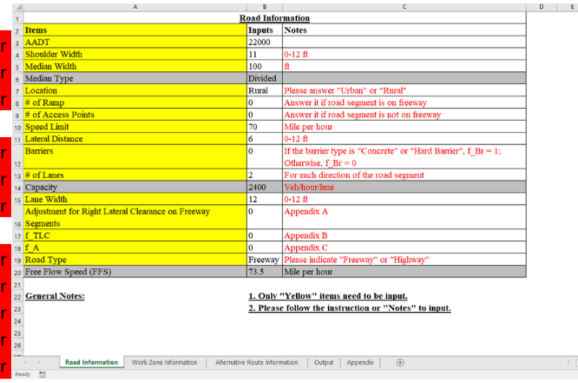


FIGURE 15 Location of case study #1.

FIGURE 15 shows the location of case study #1, which is a work zone on a 2-lane freeway. It is located on Interstate 59/Interstate 20 (I-59/I-20), between York and Livingston. The estimated work zone length is approximately 4 miles. This study proposes three different work zone plans (FIGURE 16). Note that the red-highlighted areas indicate that a lane, median, or shoulder is closed due to the work zone plan. Plan #1 has two stages. In each stage, one lane in each direction will be closed. Plan #2 also has two stages; however, unlike Plan #1, in each stage, one entire direction will be closed. The open direction will provide one lane for traffic traveling from the opposite direction. Plan #3 includes four stages, where only one lane is closed for maintenance or improvement during each stage.

FIGURE 16 also illustrates the roadway information for the proposed work zone. Specifically, it is a section of a rural 2-lane freeway with an AADT of 22,000 vehicles, 11-ft-wide shoulders, a 100-ft-wide median, a 70 MPH speed limit, and no ramp access.





Road Information

Items	Inputs	Notes
AADT	22000	
Shoulder Width	11	0-12 ft
Median Width	100	ft
Median Type	Divided	
Location	Rural	Please answer "Urban" or "Rural"
# of Ramp	0	Answer it if road segment is on freeway
# of Access Points	0	Answer it if road segment is not on freeway
Speed Limit	70	Mile per hour
Lateral Distance	6	0-12 ft
Barriers	0	If the barrier type is "Concrete" or "Hard Barrier", f_Br = 1; Otherwise, f_Br = 0
# of Lanes	2	For each direction of the road segment
Capacity	2400	Veh/hour/lane
Lane Width	12	0-12 ft
Adjustment for Right Lateral Clearance on Freeway Segments	0	Appendix A
f_TLC	0	Appendix B
f_A	0	Appendix C
Road Type	Freeway	Please indicate "Freeway" or "Highway"
Free Flow Speed (FFS)	73.5	Mile per hour

General Notes:

1. Only "Yellow" items need to be input.

2. Please follow the instruction or "Notes" to input.

Road Information | Work Zone Information | Alternative Route Information | Output | Appendix

FIGURE 16 Work zone plans and roadway information of case study #1.

TABLE 13 presents the detailed settings of the different work zone plans. Since there are no differences among the stages within each plan, the settings for one stage are used to represent each plan for estimation purposes.

TABLE 13 shows that all proposed plans involve lane closures, with at least one lane remaining open in each direction. The work zone is 4 miles long, with a speed limit of 60 MPH. The expected queue length is 1 mile, and the lane width is 11 feet. The work zone operates during the day. After setting up the work zones, the lane width remains 11 feet for Plans #1 and #3, while it is reduced to 10 feet for Plan #2. For Plans #1 and #2, the work zone duration for each stage is 120 hours. In contrast, the duration for Plan #3 is 100 hours, accounting for the workload and the fixed number of workers and equipment.

TABLE 13 Inputs of case study #1

	Plan #1	**Plan #2**	**Plan #3**	
Items	**Inputs**	**Inputs**	**Inputs**	**Notes**
Lane Closure	Yes	Yes	Yes	Please indicate "Yes" or "No"
# of Open Lane	1	1	1	Note: If one direction is fully closed but lanes from another direction is used for the closed direction, the number of open lane is 1.
Work Zone Length	4	4	4	Miles
Detour	No	No	No	Please indicate "Yes" or "No". If "Yes", please fill next sheet: "Alternative route information"
Work Zone Speed Limit	60	60	60	Miles per hour
Expected Queue Length	1	1	1	Miles
Work Zone Duration	100	120	100	Hours. For each stage.
Lane Width	11	11	11	Feets
Day or Night	Day	Day	Day	Please indicate "Day" or "Night". If "Day", f_DN = 0. Otherwise, f_DN = 1
Lateral distance from the edge of the travel lane adjacent to the work zone to the barrier, barricades, or cones	0	0	0	0-12 ft

The second case study is also located on I-59/I-20 in Tuscaloosa (FIGURE 17). This segment is a 3-lane freeway approximately 16 miles long with five ramps. The speed limit on I-59/I-20 at this location is 70 MPH. The shoulder width is 10 feet, and the median is at least 30 feet wide. However, a concrete barrier separates the two directions of traffic for most of this segment. Additionally, the AADT for this road segment is approximately 65,000. The detailed roadway information is illustrated in FIGURE 18.

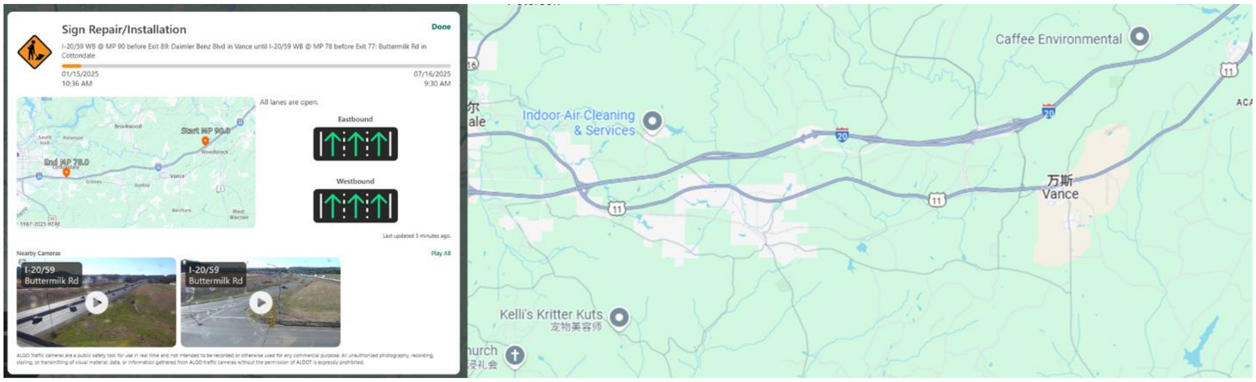
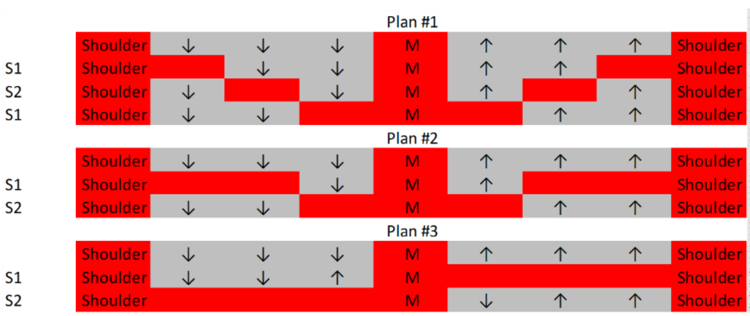


FIGURE 17 Location of case study #2.

Similar to the first case study, the research team proposed three work zone plans for the second case study (FIGURE 18). Unlike the first case study, this case includes two different conditions for both directions: closing one lane or closing two lanes.

In detail, Plan #1 has three stages. In each stage, one lane from each direction will be closed for construction works. Plan #2 consists of two stages. In the first stage, two lanes in each direction will be closed. In the second stage, the remaining lane will be closed. The condition in the second stage of Plan #2 is identical to each stage of Plan #1. Plan #3 also consists of two stages. In each stage, one direction will be fully closed. To accommodate traffic from the closed direction, one lane from the opposite direction will be made available for this purpose.



	A	B	C
1	**Road Information**		
2	**Items**	**Inputs**	**Notes**
3	AADT	65000	
4	Shoulder Width	10	0-12 ft
5	Median Width	30	ft
6	Median Type	Divided	
7	Location	Urban	Please answer "Urban" or "Rural"
8	# of Ramp	5	Answer it if road segment is on freeway
9	# of Access Points	0	Answer it if road segment is not on freeway
10	Speed Limit	70	Mile per hour
11	Lateral Distance	6	0-12 ft
12	Barriers	1	If the barrier type is "Concrete" or "Hard Barrier", f_Br = 1; Otherwise, f_Br = 0
13	# of Lanes	3	For each direction of the road segment
14	Capacity	2396.16	Veh/hour/lane
15	Lane Width	12	0-12 ft
16	Adjustment for Right Lateral Clearance on Freeway Segments	0	Appendix A
17	f_TLC	0	Appendix B
18	f_A	0	Appendix C
19	Road Type	Freeway	Please indicate "Freeway" or "Highway"
20	Free Flow Speed (FFS)	72.2938	Mile per hour
21			
22	**General Notes:**	**1. Only "Yellow" items need to be input.**	
23		**2. Please follow the instruction or "Notes" to input.**	

FIGURE 18 Work zone plans and roadway information of case study #2.

TABLE 14 presents the detailed settings for each plan. Except for Plan #1, each plan includes two conditions: closing one lane and closing two lanes. Similar to the first case study, all proposed work zones operate during the daytime, with a work zone length of 16 miles. In each stage of Plan #1, two lanes remain open for passing traffic. The speed limit is 60 MPH, the lane width is 11 ft, the expected queue length is 2.5 miles, and the operation time is 200 hours. For Condition #1 of Plan #2, one lane is open, and the expected queue length is 3.5 miles. Due to limitations in workers, equipment, and workload, the work zone duration increases to 240 hours. The settings for Condition #2 of Plan #2 are identical to those of Plan #1. In Plan #3, for Condition #1, one lane remains open. The work zone duration is 260 hours, the expected queue length is 3.5 miles, and the lane width is 10 ft. For Condition #2 of Plan #3, two lanes remain open, which reduces the expected queue length to 2.5 miles compared to Condition #1.

TABLE 14 Inputs of case study #2

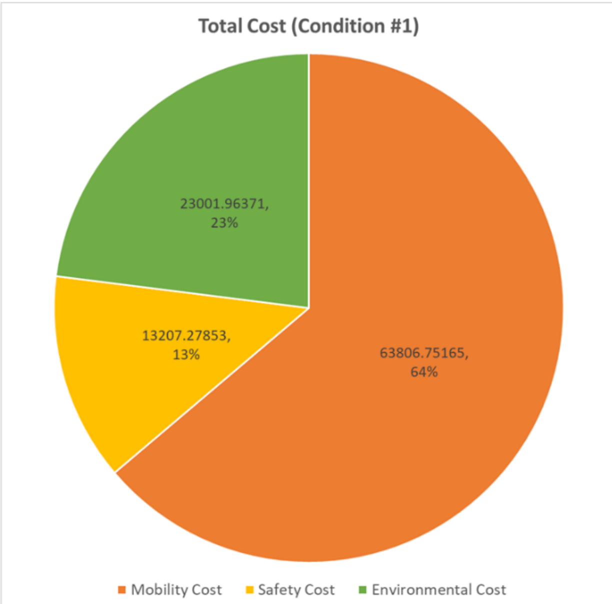
Work Zone Information						
	Plan #1	Plan #2	Plan #2	Plan #3	Plan #3	
		Condition #1	Condition #2	Condition #1	Condition #2	
Items	**Inputs**	**Inputs**	**Inputs**	**Inputs**	**Inputs**	**Notes**
Lane Closure	Yes	Yes	Yes	Yes	Yes	Please indicate "Yes" or "No"
# of Open Lane	2	1	2	1	2	Note: If one direction is fully closed but lanes from another direction is used for the closed direction, the number of open lane is 1.
Work Zone Length	16	16	16	16	16	Miles
Detour	No	No	No	No	No	Please indicate "Yes" or "No". If "Yes", please fill next sheet: "Alternative route information"
Work Zone Speed Limit	60	60	60	60	60	Miles per hour
Expected Queue Length	2.5	3.5	2.5	3.5	2.5	Miles
Work Zone Duration	200	240	200	260	260	Hours. For each stage.
Lane Width	11	11	11	10	10	Feets
Day or Night	Day	Day	Day	Day	Day	Please indicate "Day" or "Night". If "Day", f_DN = 0. Otherwise, f_DN = 1
Lateral distance from the edge of the travel lane adjacent to the work zone to the barrier, barricades, or cones	0	0	0	0	0	0-12 ft

7.2 Results of Case Studies

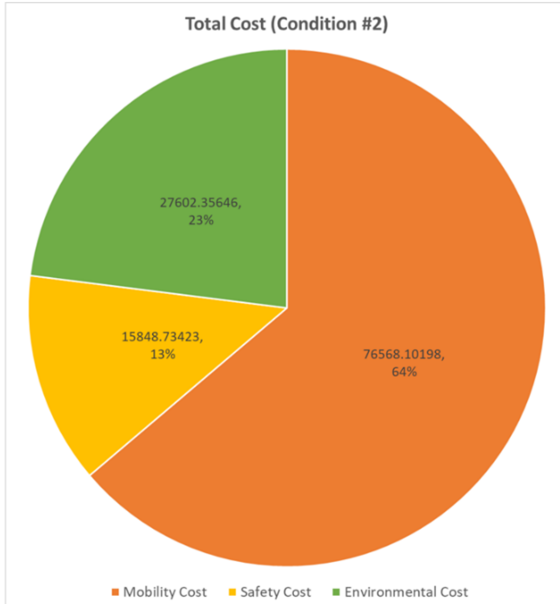
7.2.1 Case Study #1

This section presents the results of the first case study (i.e., 2-lane freeway work zones). Based on the settings of the proposed work zone plans, Plans #1 and #3 have similar conditions. Also, this condition is a part of plan #2. As shown in FIGURE 19, the cost for these conditions is \$100,015.99, which includes \$63,806.75 for mobility impact, \$13,207.28 for safety impact, and \$23,001.96 for environmental impact. Given the number of stages in each direction for Plans #1 and #3, the estimated total cost for each plan is \$370,064. The condition in Plan #2 costs \$120,019.19. The majority of this cost is associated with mobility impact, which totals \$76,568.10.

The safety and environmental impacts are $15,848.73 and $27,602.36, respectively. Considering the number of stages in each direction, the estimated total cost for Plan #2 is $440,070. The comparison results for each plan is shown in TABLE 15.



(a) Cost of a single condition of plans #1 and 3



(b) Cost of a single condition of plan #2

FIGURE 19 Results of case study #1.

TABLE 15 Comparison of the results of case study #1

	Plan #1	**Plan #2**	**Plan #2**
Mobility cost	$225,227	$280,749.7	$225,227
Safety cost	$52,829.12	$58,112.02	$52,829.12
Environmental cost	$92,007.84	$101,208.64	$92,007.84
Total cost	$370,064	$440,070	$370,064

7.2.2 Case Study #2

This section presents the results of the second case study (i.e., 3-lane freeway work zones). As described in Section 7.1, the work zone plans for 3-lane freeways are more complex than those for 2-lane freeways, with some plans featuring multiple conditions within the same stage for different directions. The cost for all conditions in this case study is shown in FIGURE 20. The comparison results for each plan is shown in

TABLE 16.

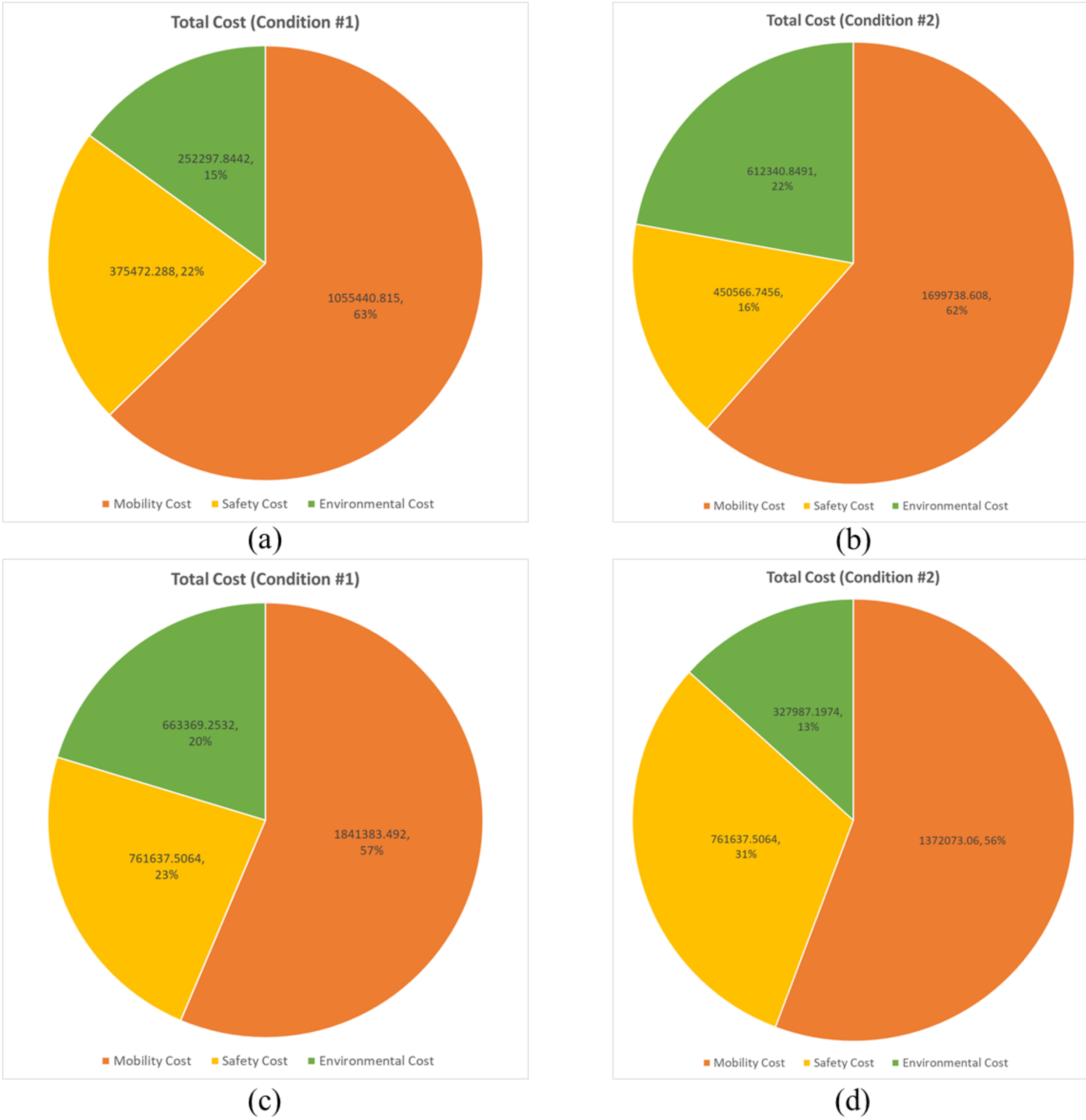


FIGURE 20 Results of case study #2. (a) Plan #1 and plan #2 condition #2; (b) plan #2 condition #1; (c) plan #3 condition #1; (d) plan #3 condition #2.

Plan #1 has only one condition and a total cost of $1,683,210.95. This includes $1,055,440.82 for mobility impact, $375,472.29 for safety impact, and $252,297.84 for environmental impact. Given the three stages and the work in both directions, in total will occur six times, the total cost for Plan #1 is $10,099,265.82.

TABLE 16 Comparison of the results of case study #2

	Plan #1	**Plan #2**	**Plan #2**
Mobility cost	$6,332,645.04	$5,510,358.86	$6,426,913.1
Safety cost	$2,252,833.74	$1,652,078.08	$3,046,550.04
Environmental cost	$1,513,787.04	$1,729,277.38	$1,982,712.9
Total cost	$10,099,265.82	$8,891,714.32	$11,456,176.04

Plan #2 has two conditions. Condition #2 is identical to Plan #1. Condition #1 of Plan #2 has a cost of $2,338,608, which includes $1,699,738.61 for mobility impact, $450,566.75 for safety impact, and $612,340.85 for environmental impact. Considering each direction and stage, each condition will occur two times, the total cost for Plan #2 is $8,891,714.32.

Plan #3 also includes two conditions. Compared to the conditions of the previous plans, the work zone duration is longer (260 hours), and the lane width is 1 ft shorter. The cost of Condition #1 for Plan #3 is $3,266,390.25, which breaks down as follows: $1,841,383.49 for mobility impact, $761,637.51 for safety impact, and $663,369.25 for environmental impact. The cost of Condition #2 for Plan #3 is $2,461,697.77, with costs of $1,372,073.06 for mobility impact, $761,637.51 for safety impact, and $327,987.20 for environmental impact. Considering the three stages and both directions, each condition will occur two times, the total cost for Plan #3 is $11,456,176.04.

8. Summary

This report documents the work of developing a framework and tool for construction planning, considering the impacts of work zones on road users. Utilizing the formulations and data provided by different sources, such as HCM 2016, HSM 2010, and MOVES, the research team built the spreadsheets for calculating the monetarization mobility, safety, and environmental impacts of given work zone conditions on road users. The major tasks completed in this project are as follows: 1) review of related work of work zone impact evaluation from research and state practical perspectives, 2) illustration of all possible work zone plans for different types of roads in Alabama, 3) development and summary of the estimation methods for mobility (delay), safety (change of number of crashes), and environmental (change of fuel consumption and CO2 equivalent emissions) impacts, 4) development of monetization methods for work zone impacts, and 5) development and testing of work zone impact calculator (spreadsheets).

Specifically, the team considered different numbers of lanes, median types, and shoulder types to generate combinations of potential road and work zone scenarios. Regarding the median and shoulder types, the team mainly focused on whether the median or shoulder is drivable. This consideration is to check whether the median or shoulder can be used as a temporary traffic lane during the work zone operation.

After scanning all possible scenarios, the team summarized and developed the estimation methods for mobility, safety, and environmental impacts. Regarding the mobility impact, the direct impact caused by the work zone is decreasing the travel speed because of the requirement, the change of roadway geometry, and the potential increasing volume. Therefore, delay per vehicle is selected as the measurement of work zone mobility impact. According to the work zone capacity and speed estimation methods on HCM and other materials, the team restructured the estimation flow for Alabama work zones. The most direct safety impact of the work zone is the change in the number of crashes. The research team employed SPF and CMF to estimate the safety impact. In terms of the environmental impact, the team adopted the state-of-science emission modeling system MOVES to simulate the differences in fuel consumption and CO2 equivalent emissions under various travel speeds. The changes in fuel consumption and CO2 equivalent emissions are seen as the direct environmental impact caused by work zones.

However, delays, changes in the number of crashes, and changes in fuel consumption and CO2 equivalent emissions cannot directly reflect the cost of the work zone. Monetarizing these impacts is required to evaluate the cost and calculate the total cost. In this project, the team utilized the average value of time (VOT) for travelers, the cost of crashes for different severity levels, the cost of planting trees, and the average gas price to transfer the impacts with different unit-to-dollar values. For estimation purposes, the team developed a spreadsheet that integrated all impacts to output the dollar value of mobility, safety, environmental, and total costs for the potential user's reference.

Note that the developed measurement methods and tools have several limitations because the methods may not be suitable for every potential work zone condition. The calculation results can only be used as a reference for planning a new work zone in Alabama. In the future, considering the changing traffic components, such as more electrical vehicles and more connected and automated vehicles on the road, the impacts caused by the work zone may change. For instance, more electric vehicles will eliminate the potential environmental impact caused by the work zone. The up-to-date impact estimation methods may be required at that time.

Appendix A

Appendix A-1 Legend for scenarios.

Labels

Closed	Median or Shoulder closed
	Lane under construction
↑	Lane, Median or Shoulder delaye
↑	Lane open

Appendix A-2 One-lane scenarios.

Plan	D1 Shoulder	D1 Lane 1	Median	D2 Lane 1	D2 Shoulder
1	Closed	Const.	Closed	Const.	Closed
2	Closed	Const.	Closed	Const.	↑
2	Closed	Const.	↓ or ↑	Const.	Closed
2	↓	Const.	Closed	Const.	Closed
3	Closed	Const.	↓ or ↑	Const.	↑
3	↓	Const.	Closed	Const.	↑
3	↓	Const.	↓ or ↑	Const.	Closed
4	Closed	Const.	Closed	↑	Closed
4	Closed	↓	Closed	Const.	Closed
5	Closed	Const.	↓ or ↑	↑	Closed
5	Closed	↓	Closed	Const.	↑
5	Closed	↓	↓ or ↑	Const.	Closed
5	↓	Const.	Closed	↑	Closed
6	Closed	↓	Closed	↑	Closed

Appendix A-3 Two-lane scenarios (part 1).

Plan	D1 Shoulder	D1 Lane 1	D1 Lane 2	Median	D2 Lane 1	D2 Lane 2	D2 Shoulder
1	Closed	Const.	Const.	Closed	Const.	Const.	Closed
2	Closed	Const.	Const.	Closed	Const.	↑	Closed
2	Closed	Const.	Const.	Closed	↑	Const.	Closed
2	Closed	Const.	↓	Closed	Const.	Const.	Closed
2	Closed	↓	Const.	Closed	Const.	Const.	Closed
3	Closed	Const.	Const.	Closed	Const.	Const.	↑
3	Closed	Const.	Const.	↓ or ↑	Const.	Const.	Closed
3	↓	Const.	Const.	Closed	Const.	Const.	Closed
4	Closed	Const.	↓	Closed	Const.	↑	Closed
4	Closed	Const.	↓	Closed	↑	Const.	Closed
4	Closed	↓	Const.	Closed	Const.	↑	Closed
4	Closed	↓	Const.	Closed	↑	Const.	Closed
5	Closed	Const.	Const.	Closed	Const.	↑	↑
5	Closed	Const.	Const.	Closed	↑	Const.	↑
5	Closed	Const.	Const.	↓ or ↑	Const.	↑	Closed
5	Closed	Const.	Const.	↓ or ↑	↑	Const.	Closed
5	Closed	Const.	↓	Closed	Const.	Const.	↑
5	Closed	Const.	↓	↓ or ↑	Const.	Const.	Closed
5	Closed	↓	Const.	Closed	Const.	Const.	↑
5	Closed	↓	Const.	↓ or ↑	Const.	Const.	Closed
5	↓	Const.	Const.	Closed	Const.	↑	Closed
5	↓	Const.	Const.	Closed	↑	Const.	Closed
5	↓	Const.	↓	Closed	Const.	Const.	Closed
5	↓	↓	Const.	Closed	Const.	Const.	Closed
6	Closed	Const.	Const.	↓ or ↑	Const.	Const.	↑
6	↓	Const.	Const.	Closed	Const.	Const.	↑
6	↓	Const.	Const.	↓ or ↑	Const.	Const.	Closed
7	Closed	Const.	↓	Closed	Const.	↑	↑
7	Closed	Const.	↓	Closed	↑	Const.	↑
7	Closed	Const.	↓	↓ or ↑	Const.	↑	Closed
7	Closed	Const.	↓	↓ or ↑	↑	Const.	Closed
7	Closed	↓	Const.	Closed	Const.	↑	↑
7	Closed	↓	Const.	Closed	↑	Const.	↑
7	Closed	↓	Const.	↓ or ↑	Const.	↑	Closed
7	Closed	↓	Const.	↓ or ↑	↑	Const.	Closed
7	↓	Const.	↓	Closed	Const.	↑	Closed
7	↓	Const.	↓	Closed	↑	Const.	Closed
7	↓	↓	Const.	Closed	Const.	↑	Closed
7	↓	↓	Const.	Closed	↑	Const.	Closed

Appendix A-4 Two-lane scenarios (part 2).

8	Closed	Const.	Const.	↓ or ↑	Const.	↑	↑
8	Closed	Const.	Const.	↓ or ↑	↑	Const.	↑
8	Closed	Const.	↓	↓ or ↑	Const.	Const.	↑
8	Closed	↓	Const.	↓ or ↑	Const.	Const.	↑
8	↓	Const.	Const.	Closed	Const.	↑	↑
8	↓	Const.	Const.	Closed	↑	Const.	↑
8	↓	Const.	Const.	↓ or ↑	Const.	↑	Closed
8	↓	Const.	Const.	↓ or ↑	↑	Const.	Closed
8	↓	Const.	↓	Closed	Const.	Const.	↑
8	↓	Const.	↓	↓ or ↑	Const.	Const.	Closed
8	↓	↓	Const.	Closed	Const.	Const.	↑
8	↓	↓	Const.	↓ or ↑	Const.	Const.	Closed
9	↓	Const.	Const.	↓ or ↑	Const.	Const.	↑
10	Closed	Const.	↓	↓ or ↑	Const.	↑	↑
10	Closed	Const.	↓	↓ or ↑	↑	Const.	↑
10	Closed	↓	Const.	↓ or ↑	Const.	↑	↑
10	Closed	↓	Const.	↓ or ↑	↑	Const.	↑
10	↓	Const.	↓	Closed	Const.	↑	↑
10	↓	Const.	↓	Closed	↑	Const.	↑
10	↓	Const.	↓	↓ or ↑	Const.	↑	Closed
10	↓	Const.	↓	↓ or ↑	↑	Const.	Closed
10	↓	↓	Const.	Closed	Const.	↑	↑
10	↓	↓	Const.	Closed	↑	Const.	↑
10	↓	↓	Const.	↓ or ↑	Const.	↑	Closed
10	↓	↓	Const.	↓ or ↑	↑	Const.	Closed
11	↓	Const.	Const.	↓ or ↑	Const.	↑	↑
11	↓	Const.	Const.	↓ or ↑	↑	Const.	↑
11	↓	Const.	↓	↓ or ↑	Const.	Const.	↑
11	↓	↓	Const.	↓ or ↑	Const.	Const.	↑
12	Closed	Const.	Const.	Closed	↑	↑	Closed
12	Closed	↓	↓	Closed	Const.	Const.	Closed
13	Closed	Const.	↓	Closed	↑	↑	Closed
13	Closed	↓	Const.	Closed	↑	↑	Closed
13	Closed	↓	↓	Closed	Const.	↑	Closed
13	Closed	↓	↓	Closed	↑	Const.	Closed
14	Closed	Const.	Const.	↓ or ↑	↑	↑	Closed
14	Closed	↓	↓	Closed	Const.	Const.	↑
14	Closed	↓	↓	↓ or ↑	Const.	Const.	Closed
14	↓	Const.	Const.	Closed	↑	↑	Closed
15	Closed	Const.	↓	↓ or ↑	↑	↑	Closed
15	Closed	↓	Const.	↓ or ↑	↑	↑	Closed
15	Closed	↓	↓	Closed	Const.	↑	↑
15	Closed	↓	↓	Closed	↑	Const.	↑
15	Closed	↓	↓	↓ or ↑	Const.	↑	Closed
15	Closed	↓	↓	↓ or ↑	↑	Const.	Closed
15	↓	Const.	↓	Closed	↑	↑	Closed
15	↓	↓	Const.	Closed	↑	↑	Closed
16	Closed	↓	↓	↓ or ↑	Const.	Const.	↑
16	↓	Const.	Const.	↓ or ↑	↑	↑	Closed
17	Closed	↓	↓	Closed	↑	↑	Closed

Appendix A-5 Three-lane scenarios (part 1).

Plan	D1 Shoulder	D1 Lane 1	D1 Lane 2	D1 Lane 3	Median	D2 Lane 1	D2 Lane 2	D2 Lane 3	D2 Shoulder
1	Closed	Const.	Const.	Const.	Closed	Const.	Const.	Const.	Closed
2	Closed	Const.	Const.	Const.	Closed	Const.	Const.	↑	Closed
2	Closed	Const.	Const.	Const.	Closed	Const.	↑	Const.	Closed
2	Closed	Const.	Const.	Const.	Closed	↑	Const.	Const.	Closed
2	Closed	Const.	Const.	↓	Closed	Const.	Const.	Const.	Closed
2	Closed	Const.	↓	Const.	Closed	Const.	Const.	Const.	Closed
2	Closed	↓	Const.	Const.	Closed	Const.	Const.	Const.	Closed
3	Closed	Const.	Const.	Const.	Closed	Const.	Const.	Const.	↑
3	Closed	Const.	Const.	Const.	↓ or ↑	Const.	Const.	Const.	Closed
3	↓	Const.	Const.	Const.	Closed	Const.	Const.	Const.	Closed
4	Closed	Const.	Const.	Const.	Closed	Const.	↑	↑	Closed
4	Closed	Const.	Const.	Const.	Closed	↑	Const.	↑	Closed
4	Closed	Const.	Const.	Const.	Closed	↑	↑	Const.	Closed
4	Closed	Const.	Const.	↓	Closed	Const.	Const.	↑	Closed
4	Closed	Const.	Const.	↓	Closed	Const.	↑	Const.	Closed
4	Closed	Const.	Const.	↓	Closed	↑	Const.	Const.	Closed
4	Closed	Const.	↓	Const.	Closed	Const.	Const.	↑	Closed
4	Closed	Const.	↓	Const.	Closed	Const.	↑	Const.	Closed
4	Closed	Const.	↓	Const.	Closed	↑	Const.	Const.	Closed
4	Closed	Const.	↓	↓	Closed	Const.	Const.	Const.	Closed
4	Closed	↓	Const.	Const.	Closed	Const.	Const.	↑	Closed
4	Closed	↓	Const.	Const.	Closed	Const.	↑	Const.	Closed
4	Closed	↓	Const.	Const.	Closed	↑	Const.	Const.	Closed
4	Closed	↓	Const.	↓	Closed	Const.	Const.	Const.	Closed
4	Closed	↓	↓	Const.	Closed	Const.	Const.	Const.	Closed
5	Closed	Const.	Const.	Const.	Closed	Const.	Const.	↑	↑
5	Closed	Const.	Const.	Const.	Closed	Const.	↑	Const.	↑
5	Closed	Const.	Const.	Const.	Closed	↑	Const.	Const.	↑
5	Closed	Const.	Const.	Const.	↓ or ↑	Const.	Const.	↑	Closed
5	Closed	Const.	Const.	Const.	↓ or ↑	Const.	↑	Const.	Closed
5	Closed	Const.	Const.	Const.	↓ or ↑	↑	Const.	Const.	Closed
5	Closed	Const.	Const.	↓	Closed	Const.	Const.	Const.	↑
5	Closed	Const.	Const.	↓	↓ or ↑	Const.	Const.	Const.	Closed
5	Closed	Const.	↓	Const.	Closed	Const.	Const.	Const.	↑
5	Closed	Const.	↓	Const.	↓ or ↑	Const.	Const.	Const.	Closed
5	Closed	↓	Const.	Const.	Closed	Const.	Const.	Const.	↑
5	Closed	↓	Const.	Const.	↓ or ↑	Const.	Const.	Const.	Closed
5	↓	Const.	Const.	Const.	Closed	Const.	Const.	↑	Closed
5	↓	Const.	Const.	Const.	Closed	Const.	↑	Const.	Closed
5	↓	Const.	Const.	Const.	Closed	↑	Const.	Const.	Closed
5	↓	Const.	Const.	↓	Closed	Const.	Const.	Const.	Closed
5	↓	Const.	↓	Const.	Closed	Const.	Const.	Const.	Closed
5	↓	↓	Const.	Const.	Closed	Const.	Const.	Const.	Closed
6	Closed	Const.	Const.	Const.	↓ or ↑	Const.	Const.	Const.	↑
6	↓	Const.	Const.	Const.	Closed	Const.	Const.	Const.	↑
6	↓	Const.	Const.	Const.	↓ or ↑	Const.	Const.	Const.	Closed

Appendix A-6 Three-lane scenarios (part 2).

7	Closed	Const.	Const.	↓	Closed	Const.	↑	↑	Closed
7	Closed	Const.	Const.	↓	Closed	↑	Const.	↑	Closed
7	Closed	Const.	Const.	↓	Closed	↑	↑	Const.	Closed
7	Closed	Const.	↓	Const.	Closed	Const.	↑	↑	Closed
7	Closed	Const.	↓	Const.	Closed	↑	Const.	↑	Closed
7	Closed	Const.	↓	Const.	Closed	↑	↑	Const.	Closed
7	Closed	Const.	↓	↓	Closed	Const.	Const.	↑	Closed
7	Closed	Const.	↓	↓	Closed	Const.	↑	Const.	Closed
7	Closed	Const.	↓	↓	Closed	↑	Const.	Const.	Closed
7	Closed	↓	Const.	Const.	Closed	Const.	↑	↑	Closed
7	Closed	↓	Const.	Const.	Closed	↑	Const.	↑	Closed
7	Closed	↓	Const.	Const.	Closed	↑	↑	Const.	Closed
7	Closed	↓	Const.	↓	Closed	Const.	Const.	↑	Closed
7	Closed	↓	Const.	↓	Closed	Const.	↑	Const.	Closed
7	Closed	↓	Const.	↓	Closed	↑	Const.	Const.	Closed
7	Closed	↓	↓	Const.	Closed	Const.	Const.	↑	Closed
7	Closed	↓	↓	Const.	Closed	Const.	↑	Const.	Closed
7	Closed	↓	↓	Const.	Closed	↑	Const.	Const.	Closed
8	Closed	Const.	Const.	Const.	Closed	Const.	↑	↑	↑
8	Closed	Const.	Const.	Const.	Closed	↑	Const.	↑	↑
8	Closed	Const.	Const.	Const.	Closed	↑	↑	Const.	↑
8	Closed	Const.	Const.	Const.	↓ or ↑	Const.	↑	↑	Closed
8	Closed	Const.	Const.	Const.	↓ or ↑	↑	Const.	↑	Closed
8	Closed	Const.	Const.	Const.	↓ or ↑	↑	↑	Const.	Closed
8	Closed	Const.	Const.	↓	Closed	Const.	Const.	↑	↑
8	Closed	Const.	Const.	↓	Closed	Const.	↑	Const.	↑
8	Closed	Const.	Const.	↓	Closed	↑	Const.	Const.	↑
8	Closed	Const.	Const.	↓	↓ or ↑	Const.	Const.	↑	Closed
8	Closed	Const.	Const.	↓	↓ or ↑	Const.	↑	Const.	Closed
8	Closed	Const.	Const.	↓	↓ or ↑	↑	Const.	Const.	Closed
8	Closed	Const.	↓	Const.	Closed	Const.	Const.	↑	↑
8	Closed	Const.	↓	Const.	Closed	Const.	↑	Const.	↑
8	Closed	Const.	↓	Const.	Closed	↑	Const.	Const.	↑
8	Closed	Const.	↓	Const.	↓ or ↑	Const.	Const.	↑	Closed
8	Closed	Const.	↓	Const.	↓ or ↑	Const.	↑	Const.	Closed
8	Closed	Const.	↓	Const.	↓ or ↑	↑	Const.	Const.	Closed
8	Closed	Const.	↓	↓	Closed	Const.	Const.	Const.	↑
8	Closed	Const.	↓	↓	↓ or ↑	Const.	Const.	Const.	Closed
8	Closed	↓	Const.	Const.	Closed	Const.	Const.	↑	↑
8	Closed	↓	Const.	Const.	Closed	Const.	↑	Const.	↑
8	Closed	↓	Const.	Const.	Closed	↑	Const.	Const.	↑
8	Closed	↓	Const.	Const.	↓ or ↑	Const.	Const.	↑	Closed
8	Closed	↓	Const.	Const.	↓ or ↑	Const.	↑	Const.	Closed
8	Closed	↓	Const.	Const.	↓ or ↑	↑	Const.	Const.	Closed
8	Closed	↓	Const.	↓	Closed	Const.	Const.	Const.	↑
8	Closed	↓	Const.	↓	↓ or ↑	Const.	Const.	Const.	Closed
8	Closed	↓	↓	Const.	Closed	Const.	Const.	Const.	↑
8	Closed	↓	↓	Const.	↓ or ↑	Const.	Const.	Const.	Closed
8	↓	Const.	Const.	Const.	Closed	Const.	↑	↑	Closed
8	↓	Const.	Const.	Const.	Closed	↑	Const.	↑	Closed
8	↓	Const.	Const.	Const.	Closed	↑	↑	Const.	Closed
8	↓	Const.	Const.	↓	Closed	Const.	Const.	↑	Closed
8	↓	Const.	Const.	↓	Closed	Const.	↑	Const.	Closed
8	↓	Const.	Const.	↓	Closed	↑	Const.	Const.	Closed
8	↓	Const.	↓	Const.	Closed	Const.	Const.	↑	Closed
8	↓	Const.	↓	Const.	Closed	Const.	↑	Const.	Closed
8	↓	Const.	↓	Const.	Closed	↑	Const.	Const.	Closed
8	↓	Const.	↓	↓	Closed	Const.	Const.	Const.	Closed
8	↓	↓	Const.	Const.	Closed	Const.	Const.	↑	Closed
8	↓	↓	Const.	Const.	Closed	Const.	↑	Const.	Closed
8	↓	↓	Const.	Const.	Closed	↑	Const.	Const.	Closed
8	↓	↓	Const.	↓	Closed	Const.	Const.	Const.	Closed
8	↓	↓	↓	Const.	Closed	Const.	Const.	Const.	Closed

Appendix A-7 Three-lane scenarios (part 3).

9	Closed	Const.	Const.	Const.	↓ or ↑	Const.	Const.	↑	↑
9	Closed	Const.	Const.	Const.	↓ or ↑	Const.	↑	Const.	↑
9	Closed	Const.	Const.	Const.	↓ or ↑	↑	Const.	Const.	↑
9	Closed	Const.	Const.	↓	↓ or ↑	Const.	Const.	Const.	↑
9	Closed	Const.	↓	Const.	↓ or ↑	Const.	Const.	Const.	↑
9	Closed	↓	Const.	Const.	↓ or ↑	Const.	Const.	Const.	↑
9	↓	Const.	Const.	Const.	Closed	Const.	Const.	↑	↑
9	↓	Const.	Const.	Const.	Closed	Const.	↑	Const.	↑
9	↓	Const.	Const.	Const.	Closed	↑	Const.	Const.	↑
9	↓	Const.	Const.	Const.	↓ or ↑	Const.	Const.	↑	Closed
9	↓	Const.	Const.	Const.	↓ or ↑	Const.	↑	Const.	Closed
9	↓	Const.	Const.	Const.	↓ or ↑	↑	Const.	Const.	Closed
9	↓	Const.	Const.	↓	Closed	Const.	Const.	Const.	↑
9	↓	Const.	Const.	↓	↓ or ↑	Const.	Const.	Const.	Closed
9	↓	Const.	↓	Const.	Closed	Const.	Const.	Const.	↑
9	↓	Const.	↓	Const.	↓ or ↑	Const.	Const.	Const.	Closed
9	↓	↓	Const.	Const.	Closed	Const.	Const.	Const.	↑
9	↓	↓	Const.	Const.	↓ or ↑	Const.	Const.	Const.	Closed
10	↓	Const.	Const.	Const.	↓ or ↑	Const.	Const.	Const.	↑
11	Closed	Const.	↓	↓	Closed	Const.	↑	↑	Closed
11	Closed	Const.	↓	↓	Closed	↑	Const.	↑	Closed
11	Closed	Const.	↓	↓	Closed	↑	↑	Const.	Closed
11	Closed	↓	Const.	↓	Closed	Const.	↑	↑	Closed
11	Closed	↓	Const.	↓	Closed	↑	Const.	↑	Closed
11	Closed	↓	Const.	↓	Closed	↑	↑	Const.	Closed
11	Closed	↓	↓	Const.	Closed	Const.	↑	↑	Closed
11	Closed	↓	↓	Const.	Closed	↑	Const.	↑	Closed
11	Closed	↓	↓	Const.	Closed	↑	↑	Const.	Closed

Appendix A-8 Three-lane scenarios (part 4).

12	Closed	Const.	Const.	↓	Closed	Const.	↑	↑	↑
12	Closed	Const.	Const.	↓	Closed	↑	Const.	↑	↑
12	Closed	Const.	Const.	↓	Closed	↑	↑	Const.	↑
12	Closed	Const.	Const.	↓	↓ or ↑	Const.	↑	↑	Closed
12	Closed	Const.	Const.	↓	↓ or ↑	↑	Const.	↑	Closed
12	Closed	Const.	Const.	↓	↓ or ↑	↑	↑	Const.	Closed
12	Closed	Const.	↓	Const.	Closed	Const.	↑	↑	↑
12	Closed	Const.	↓	Const.	Closed	↑	Const.	↑	↑
12	Closed	Const.	↓	Const.	Closed	↑	↑	Const.	↑
12	Closed	Const.	↓	Const.	↓ or ↑	Const.	↑	↑	Closed
12	Closed	Const.	↓	Const.	↓ or ↑	↑	Const.	↑	Closed
12	Closed	Const.	↓	Const.	↓ or ↑	↑	↑	Const.	Closed
12	Closed	Const.	↓	↓	Closed	Const.	Const.	↑	↑
12	Closed	Const.	↓	↓	Closed	Const.	↑	Const.	↑
12	Closed	Const.	↓	↓	Closed	↑	Const.	Const.	↑
12	Closed	Const.	↓	↓	↓ or ↑	Const.	Const.	↑	Closed
12	Closed	Const.	↓	↓	↓ or ↑	Const.	↑	Const.	Closed
12	Closed	Const.	↓	↓	↓ or ↑	↑	Const.	Const.	Closed
12	Closed	↓	Const.	Const.	Closed	Const.	↑	↑	↑
12	Closed	↓	Const.	Const.	Closed	↑	Const.	↑	↑
12	Closed	↓	Const.	Const.	Closed	↑	↑	Const.	↑
12	Closed	↓	Const.	Const.	↓ or ↑	Const.	↑	↑	Closed
12	Closed	↓	Const.	Const.	↓ or ↑	↑	Const.	↑	Closed
12	Closed	↓	Const.	Const.	↓ or ↑	↑	↑	Const.	Closed
12	Closed	↓	Const.	↓	Closed	Const.	Const.	↑	↑
12	Closed	↓	Const.	↓	Closed	Const.	↑	Const.	↑
12	Closed	↓	Const.	↓	Closed	↑	Const.	Const.	↑
12	Closed	↓	Const.	↓	↓ or ↑	Const.	Const.	↑	Closed
12	Closed	↓	Const.	↓	↓ or ↑	Const.	↑	Const.	Closed
12	Closed	↓	Const.	↓	↓ or ↑	↑	Const.	Const.	Closed
12	Closed	↓	↓	Const.	Closed	Const.	Const.	↑	↑
12	Closed	↓	↓	Const.	Closed	Const.	↑	Const.	↑
12	Closed	↓	↓	Const.	Closed	↑	Const.	Const.	↑
12	Closed	↓	↓	Const.	↓ or ↑	Const.	Const.	↑	Closed
12	Closed	↓	↓	Const.	↓ or ↑	Const.	↑	Const.	Closed
12	Closed	↓	↓	Const.	↓ or ↑	↑	Const.	Const.	Closed
12	↓	Const.	Const.	↓	Closed	Const.	↑	↑	Closed
12	↓	Const.	Const.	↓	Closed	↑	Const.	↑	Closed
12	↓	Const.	Const.	↓	Closed	↑	↑	Const.	Closed
12	↓	Const.	↓	Const.	Closed	Const.	↑	↑	Closed
12	↓	Const.	↓	Const.	Closed	↑	Const.	↑	Closed
12	↓	Const.	↓	Const.	Closed	↑	↑	Const.	Closed
12	↓	Const.	↓	↓	Closed	Const.	Const.	↑	Closed
12	↓	Const.	↓	↓	Closed	Const.	↑	Const.	Closed
12	↓	Const.	↓	↓	Closed	↑	Const.	Const.	Closed
12	↓	↓	Const.	Const.	Closed	Const.	↑	↑	Closed
12	↓	↓	Const.	Const.	Closed	↑	Const.	↑	Closed
12	↓	↓	Const.	Const.	Closed	↑	↑	Const.	Closed
12	↓	↓	Const.	↓	Closed	Const.	Const.	↑	Closed
12	↓	↓	Const.	↓	Closed	Const.	↑	Const.	Closed
12	↓	↓	Const.	↓	Closed	↑	Const.	Const.	Closed
12	↓	↓	↓	Const.	Closed	Const.	Const.	↑	Closed
12	↓	↓	↓	Const.	Closed	Const.	↑	Const.	Closed
12	↓	↓	↓	Const.	Closed	↑	Const.	Const.	Closed

Appendix A-9 Three-lane scenarios (part 5).

13	Closed	Const.	Const.	Const.	↓ or ↑	Const.	↑	↑	↑
13	Closed	Const.	Const.	Const.	↓ or ↑	↑	Const.	↑	↑
13	Closed	Const.	Const.	Const.	↓ or ↑	↑	↑	Const.	↑
13	Closed	Const.	Const.	↓	↓ or ↑	Const.	Const.	↑	↑
13	Closed	Const.	Const.	↓	↓ or ↑	Const.	↑	Const.	↑
13	Closed	Const.	Const.	↓	↓ or ↑	↑	Const.	Const.	↑
13	Closed	Const.	↓	Const.	↓ or ↑	Const.	Const.	↑	↑
13	Closed	Const.	↓	Const.	↓ or ↑	Const.	↑	Const.	↑
13	Closed	Const.	↓	Const.	↓ or ↑	↑	Const.	Const.	↑
13	Closed	Const.	↓	↓	↓ or ↑	Const.	Const.	Const.	↑
13	Closed	↓	Const.	Const.	↓ or ↑	Const.	Const.	↑	↑
13	Closed	↓	Const.	Const.	↓ or ↑	Const.	↑	Const.	↑
13	Closed	↓	Const.	Const.	↓ or ↑	↑	Const.	Const.	↑
13	Closed	↓	Const.	↓	↓ or ↑	Const.	Const.	Const.	↑
13	Closed	↓	↓	Const.	↓ or ↑	Const.	Const.	Const.	↑
13	↓	Const.	Const.	Const.	Closed	Const.	↑	↑	↑
13	↓	Const.	Const.	Const.	Closed	↑	Const.	↑	↑
13	↓	Const.	Const.	Const.	Closed	↑	↑	Const.	↑
13	↓	Const.	Const.	Const.	↓ or ↑	Const.	↑	↑	Closed
13	↓	Const.	Const.	Const.	↓ or ↑	↑	Const.	↑	Closed
13	↓	Const.	Const.	Const.	↓ or ↑	↑	↑	Const.	Closed
13	↓	Const.	Const.	↓	Closed	Const.	Const.	↑	↑
13	↓	Const.	Const.	↓	Closed	Const.	↑	Const.	↑
13	↓	Const.	Const.	↓	Closed	↑	Const.	Const.	↑
13	↓	Const.	Const.	↓	↓ or ↑	Const.	Const.	↑	Closed
13	↓	Const.	Const.	↓	↓ or ↑	Const.	↑	Const.	Closed
13	↓	Const.	Const.	↓	↓ or ↑	↑	Const.	Const.	Closed
13	↓	Const.	↓	Const.	Closed	Const.	Const.	↑	↑
13	↓	Const.	↓	Const.	Closed	Const.	↑	Const.	↑
13	↓	Const.	↓	Const.	Closed	↑	Const.	Const.	↑
13	↓	Const.	↓	Const.	↓ or ↑	Const.	Const.	↑	Closed
13	↓	Const.	↓	Const.	↓ or ↑	Const.	↑	Const.	Closed
13	↓	Const.	↓	Const.	↓ or ↑	↑	Const.	Const.	Closed
13	↓	Const.	↓	↓	Closed	Const.	Const.	Const.	↑
13	↓	Const.	↓	↓	↓ or ↑	Const.	Const.	Const.	Closed
13	↓	↓	Const.	Const.	Closed	Const.	Const.	↑	↑
13	↓	↓	Const.	Const.	Closed	Const.	↑	Const.	↑
13	↓	↓	Const.	Const.	Closed	↑	Const.	Const.	↑
13	↓	↓	Const.	Const.	↓ or ↑	Const.	Const.	↑	Closed
13	↓	↓	Const.	Const.	↓ or ↑	Const.	↑	Const.	Closed
13	↓	↓	Const.	Const.	↓ or ↑	↑	Const.	Const.	Closed
13	↓	↓	Const.	↓	Closed	Const.	Const.	Const.	↑
13	↓	↓	Const.	↓	↓ or ↑	Const.	Const.	Const.	Closed
13	↓	↓	↓	Const.	Closed	Const.	Const.	Const.	↑
13	↓	↓	↓	Const.	↓ or ↑	Const.	Const.	Const.	Closed

Appendix A-10 Three-lane scenarios (part 6).

14	↓	Const.	Const.	Const.	↓ or ↑	Const.	Const.	↑	↑
14	↓	Const.	Const.	Const.	↓ or ↑	Const.	↑	Const.	↑
14	↓	Const.	Const.	Const.	↓ or ↑	↑	Const.	Const.	↑
14	↓	Const.	Const.	↓	↓ or ↑	Const.	Const.	Const.	↑
14	↓	Const.	↓	Const.	↓ or ↑	Const.	Const.	Const.	↑
14	↓	↓	Const.	Const.	↓ or ↑	Const.	Const.	Const.	↑
15	Closed	Const.	↓	↓	Closed	Const.	↑	↑	↑
15	Closed	Const.	↓	↓	Closed	↑	Const.	↑	↑
15	Closed	Const.	↓	↓	Closed	↑	↑	Const.	↑
15	Closed	Const.	↓	↓	↓ or ↑	Const.	↑	↑	Closed
15	Closed	Const.	↓	↓	↓ or ↑	↑	Const.	↑	Closed
15	Closed	Const.	↓	↓	↓ or ↑	↑	↑	Const.	Closed
15	Closed	↓	Const.	↓	Closed	Const.	↑	↑	↑
15	Closed	↓	Const.	↓	Closed	↑	Const.	↑	↑
15	Closed	↓	Const.	↓	Closed	↑	↑	Const.	↑
15	Closed	↓	Const.	↓	↓ or ↑	Const.	↑	↑	Closed
15	Closed	↓	Const.	↓	↓ or ↑	↑	Const.	↑	Closed
15	Closed	↓	Const.	↓	↓ or ↑	↑	↑	Const.	Closed
15	Closed	↓	↓	Const.	Closed	Const.	↑	↑	↑
15	Closed	↓	↓	Const.	Closed	↑	Const.	↑	↑
15	Closed	↓	↓	Const.	Closed	↑	↑	Const.	↑
15	Closed	↓	↓	Const.	↓ or ↑	Const.	↑	↑	Closed
15	Closed	↓	↓	Const.	↓ or ↑	↑	Const.	↑	Closed
15	Closed	↓	↓	Const.	↓ or ↑	↑	↑	Const.	Closed
15	↓	Const.	↓	↓	Closed	Const.	↑	↑	Closed
15	↓	Const.	↓	↓	Closed	↑	Const.	↑	Closed
15	↓	Const.	↓	↓	Closed	↑	↑	Const.	Closed
15	↓	↓	Const.	↓	Closed	Const.	↑	↑	Closed
15	↓	↓	Const.	↓	Closed	↑	Const.	↑	Closed
15	↓	↓	Const.	↓	Closed	↑	↑	Const.	Closed
15	↓	↓	↓	Const.	Closed	Const.	↑	↑	Closed
15	↓	↓	↓	Const.	Closed	↑	Const.	↑	Closed
15	↓	↓	↓	Const.	Closed	↑	↑	Const.	Closed

Appendix A-11 Three-lane scenarios (part 7).

16	Closed	Const.	Const.	↓	↓ or ↑	Const.	↑	↑	↑
16	Closed	Const.	Const.	↓	↓ or ↑	↑	Const.	↑	↑
16	Closed	Const.	Const.	↓	↓ or ↑	↑	↑	Const.	↑
16	Closed	Const.	↓	Const.	↓ or ↑	Const.	↑	↑	↑
16	Closed	Const.	↓	Const.	↓ or ↑	↑	Const.	↑	↑
16	Closed	Const.	↓	Const.	↓ or ↑	↑	↑	Const.	↑
16	Closed	Const.	↓	↓	↓ or ↑	Const.	Const.	↑	↑
16	Closed	Const.	↓	↓	↓ or ↑	Const.	↑	Const.	↑
16	Closed	Const.	↓	↓	↓ or ↑	↑	Const.	Const.	↑
16	Closed	↓	Const.	Const.	↓ or ↑	Const.	↑	↑	↑
16	Closed	↓	Const.	Const.	↓ or ↑	↑	Const.	↑	↑
16	Closed	↓	Const.	Const.	↓ or ↑	↑	↑	Const.	↑
16	Closed	↓	Const.	↓	↓ or ↑	Const.	Const.	↑	↑
16	Closed	↓	Const.	↓	↓ or ↑	Const.	↑	Const.	↑
16	Closed	↓	Const.	↓	↓ or ↑	↑	Const.	Const.	↑
16	Closed	↓	↓	Const.	↓ or ↑	Const.	Const.	↑	↑
16	Closed	↓	↓	Const.	↓ or ↑	Const.	↑	Const.	↑
16	Closed	↓	↓	Const.	↓ or ↑	↑	Const.	Const.	↑
16	↓	Const.	Const.	↓	Closed	Const.	↑	↑	↑
16	↓	Const.	Const.	↓	Closed	↑	Const.	↑	↑
16	↓	Const.	Const.	↓	Closed	↑	↑	Const.	↑
16	↓	Const.	Const.	↓	↓ or ↑	Const.	↑	↑	Closed
16	↓	Const.	Const.	↓	↓ or ↑	↑	Const.	↑	Closed
16	↓	Const.	Const.	↓	↓ or ↑	↑	↑	Const.	Closed
16	↓	Const.	↓	Const.	Closed	Const.	↑	↑	↑
16	↓	Const.	↓	Const.	Closed	↑	Const.	↑	↑
16	↓	Const.	↓	Const.	Closed	↑	↑	Const.	↑
16	↓	Const.	↓	Const.	↓ or ↑	Const.	↑	↑	Closed
16	↓	Const.	↓	Const.	↓ or ↑	↑	Const.	↑	Closed
16	↓	Const.	↓	Const.	↓ or ↑	↑	↑	Const.	Closed
16	↓	Const.	↓	↓	Closed	Const.	Const.	↑	↑
16	↓	Const.	↓	↓	Closed	Const.	↑	Const.	↑
16	↓	Const.	↓	↓	Closed	↑	Const.	Const.	↑
16	↓	Const.	↓	↓	↓ or ↑	Const.	Const.	↑	Closed
16	↓	Const.	↓	↓	↓ or ↑	Const.	↑	Const.	Closed
16	↓	Const.	↓	↓	↓ or ↑	↑	Const.	Const.	Closed
16	↓	↓	Const.	Const.	Closed	Const.	↑	↑	↑
16	↓	↓	Const.	Const.	Closed	↑	Const.	↑	↑
16	↓	↓	Const.	Const.	Closed	↑	↑	Const.	↑
16	↓	↓	Const.	Const.	↓ or ↑	Const.	↑	↑	Closed
16	↓	↓	Const.	Const.	↓ or ↑	↑	Const.	↑	Closed
16	↓	↓	Const.	Const.	↓ or ↑	↑	↑	Const.	Closed
16	↓	↓	Const.	↓	Closed	Const.	Const.	↑	↑
16	↓	↓	Const.	↓	Closed	Const.	↑	Const.	↑
16	↓	↓	Const.	↓	Closed	↑	Const.	Const.	↑
16	↓	↓	Const.	↓	↓ or ↑	Const.	Const.	↑	Closed
16	↓	↓	Const.	↓	↓ or ↑	Const.	↑	Const.	Closed
16	↓	↓	Const.	↓	↓ or ↑	↑	Const.	Const.	Closed
16	↓	↓	↓	Const.	Closed	Const.	Const.	↑	↑
16	↓	↓	↓	Const.	Closed	Const.	↑	Const.	↑
16	↓	↓	↓	Const.	Closed	↑	Const.	Const.	↑
16	↓	↓	↓	Const.	↓ or ↑	Const.	Const.	↑	Closed
16	↓	↓	↓	Const.	↓ or ↑	Const.	↑	Const.	Closed
16	↓	↓	↓	Const.	↓ or ↑	↑	Const.	Const.	Closed

Appendix A-12 Three-lane scenarios (part 8).

17	↓	Const.	Const.	Const.	↓ or ↑	Const.	↑	↑	↑
17	↓	Const.	Const.	Const.	↓ or ↑	↑	Const.	↑	↑
17	↓	Const.	Const.	Const.	↓ or ↑	↑	↑	Const.	↑
17	↓	Const.	Const.	↓	↓ or ↑	Const.	Const.	↑	↑
17	↓	Const.	Const.	↓	↓ or ↑	Const.	↑	Const.	↑
17	↓	Const.	Const.	↓	↓ or ↑	↑	Const.	Const.	↑
17	↓	Const.	↓	Const.	↓ or ↑	Const.	Const.	↑	↑
17	↓	Const.	↓	Const.	↓ or ↑	Const.	↑	Const.	↑
17	↓	Const.	↓	Const.	↓ or ↑	↑	Const.	Const.	↑
17	↓	Const.	↓	↓	↓ or ↑	Const.	Const.	Const.	↑
17	↓	↓	Const.	Const.	↓ or ↑	Const.	Const.	↑	↑
17	↓	↓	Const.	Const.	↓ or ↑	Const.	↑	Const.	↑
17	↓	↓	Const.	Const.	↓ or ↑	↑	Const.	Const.	↑
17	↓	↓	Const.	↓	↓ or ↑	Const.	Const.	Const.	↑
17	↓	↓	↓	Const.	↓ or ↑	Const.	Const.	Const.	↑
18	Closed	Const.	↓	↓	↓ or ↑	Const.	↑	↑	↑
18	Closed	Const.	↓	↓	↓ or ↑	↑	Const.	↑	↑
18	Closed	Const.	↓	↓	↓ or ↑	↑	↑	Const.	↑
18	Closed	↓	Const.	↓	↓ or ↑	Const.	↑	↑	↑
18	Closed	↓	Const.	↓	↓ or ↑	↑	Const.	↑	↑
18	Closed	↓	Const.	↓	↓ or ↑	↑	↑	Const.	↑
18	Closed	↓	↓	Const.	↓ or ↑	Const.	↑	↑	↑
18	Closed	↓	↓	Const.	↓ or ↑	↑	Const.	↑	↑
18	Closed	↓	↓	Const.	↓ or ↑	↑	↑	Const.	↑
18	↓	Const.	↓	↓	Closed	Const.	↑	↑	↑
18	↓	Const.	↓	↓	Closed	↑	Const.	↑	↑
18	↓	Const.	↓	↓	Closed	↑	↑	Const.	↑
18	↓	Const.	↓	↓	↓ or ↑	Const.	↑	↑	Closed
18	↓	Const.	↓	↓	↓ or ↑	↑	Const.	↑	Closed
18	↓	Const.	↓	↓	↓ or ↑	↑	↑	Const.	Closed
18	↓	↓	Const.	↓	Closed	Const.	↑	↑	↑
18	↓	↓	Const.	↓	Closed	↑	Const.	↑	↑
18	↓	↓	Const.	↓	Closed	↑	↑	Const.	↑
18	↓	↓	Const.	↓	↓ or ↑	Const.	↑	↑	Closed
18	↓	↓	Const.	↓	↓ or ↑	↑	Const.	↑	Closed
18	↓	↓	Const.	↓	↓ or ↑	↑	↑	Const.	Closed
18	↓	↓	↓	Const.	Closed	Const.	↑	↑	↑
18	↓	↓	↓	Const.	Closed	↑	Const.	↑	↑
18	↓	↓	↓	Const.	Closed	↑	↑	Const.	↑
18	↓	↓	↓	Const.	↓ or ↑	Const.	↑	↑	Closed
18	↓	↓	↓	Const.	↓ or ↑	↑	Const.	↑	Closed
18	↓	↓	↓	Const.	↓ or ↑	↑	↑	Const.	Closed

Appendix A-13 Three-lane scenarios (part 9).

19	↓	Const.	Const.	↓	↓ or ↑	Const.	↑	↑	↑
19	↓	Const.	Const.	↓	↓ or ↑	↑	Const.	↑	↑
19	↓	Const.	Const.	↓	↓ or ↑	↑	↑	Const.	↑
19	↓	Const.	↓	Const.	↓ or ↑	Const.	↑	↑	↑
19	↓	Const.	↓	Const.	↓ or ↑	↑	Const.	↑	↑
19	↓	Const.	↓	Const.	↓ or ↑	↑	↑	Const.	↑
19	↓	Const.	↓	↓	↓ or ↑	Const.	Const.	↑	↑
19	↓	Const.	↓	↓	↓ or ↑	Const.	↑	Const.	↑
19	↓	Const.	↓	↓	↓ or ↑	↑	Const.	Const.	↑
19	↓	↓	Const.	Const.	↓ or ↑	Const.	↑	↑	↑
19	↓	↓	Const.	Const.	↓ or ↑	↑	Const.	↑	↑
19	↓	↓	Const.	Const.	↓ or ↑	↑	↑	Const.	↑
19	↓	↓	Const.	↓	↓ or ↑	Const.	Const.	↑	↑
19	↓	↓	Const.	↓	↓ or ↑	Const.	↑	Const.	↑
19	↓	↓	Const.	↓	↓ or ↑	↑	Const.	Const.	↑
19	↓	↓	↓	Const.	↓ or ↑	Const.	Const.	↑	↑
19	↓	↓	↓	Const.	↓ or ↑	Const.	↑	Const.	↑
19	↓	↓	↓	Const.	↓ or ↑	↑	Const.	Const.	↑
20	Closed	Const.	Const.	Const.	Closed	↑	↑	↑	Closed
20	Closed	↓	↓	↓	Closed	Const.	Const.	Const.	Closed
21	Closed	Const.	Const.	↓	Closed	↑	↑	↑	Closed
21	Closed	Const.	↓	Const.	Closed	↑	↑	↑	Closed
21	Closed	↓	Const.	Const.	Closed	↑	↑	↑	Closed
21	Closed	↓	↓	↓	Closed	Const.	Const.	↑	Closed
21	Closed	↓	↓	↓	Closed	Const.	↑	Const.	Closed
21	Closed	↓	↓	↓	Closed	↑	Const.	Const.	Closed
22	Closed	Const.	Const.	Const.	↓ or ↑	↑	↑	↑	Closed
22	Closed	↓	↓	↓	Closed	Const.	Const.	Const.	↑
22	Closed	↓	↓	↓	↓ or ↑	Const.	Const.	Const.	Closed
22	↓	Const.	Const.	Const.	Closed	↑	↑	↑	Closed

Appendix A-14 Three-lane scenarios (part 10).

23	Closed	Const.	↓	↓	Closed	↑	↑	↑	Closed
23	Closed	↓	Const.	↓	Closed	↑	↑	↑	Closed
23	Closed	↓	↓	Const.	Closed	↑	↑	↑	Closed
23	Closed	↓	↓	↓	Closed	Const.	↑	↑	Closed
23	Closed	↓	↓	↓	Closed	↑	Const.	↑	Closed
23	Closed	↓	↓	↓	Closed	↑	↑	Const.	Closed
24	Closed	Const.	Const.	↓	↓ or ↑	↑	↑	↑	Closed
24	Closed	Const.	↓	Const.	↓ or ↑	↑	↑	↑	Closed
24	Closed	↓	Const.	Const.	↓ or ↑	↑	↑	↑	Closed
24	Closed	↓	↓	↓	Closed	Const.	Const.	↑	↑
24	Closed	↓	↓	↓	Closed	Const.	↑	Const.	↑
24	Closed	↓	↓	↓	Closed	↑	Const.	Const.	↑
24	Closed	↓	↓	↓	↓ or ↑	Const.	Const.	↑	Closed
24	Closed	↓	↓	↓	↓ or ↑	Const.	↑	Const.	Closed
24	Closed	↓	↓	↓	↓ or ↑	↑	Const.	Const.	Closed
24	↓	Const.	Const.	↓	Closed	↑	↑	↑	Closed
24	↓	Const.	↓	Const.	Closed	↑	↑	↑	Closed
24	↓	↓	Const.	Const.	Closed	↑	↑	↑	Closed
25	Closed	↓	↓	↓	↓ or ↑	Const.	Const.	Const.	↑
25	↓	Const.	Const.	Const.	↓ or ↑	↑	↑	↑	Closed
26	Closed	Const.	↓	↓	↓ or ↑	↑	↑	↑	Closed
26	Closed	↓	Const.	↓	↓ or ↑	↑	↑	↑	Closed
26	Closed	↓	↓	Const.	↓ or ↑	↑	↑	↑	Closed
26	Closed	↓	↓	↓	Closed	Const.	↑	↑	↑
26	Closed	↓	↓	↓	Closed	↑	Const.	↑	↑
26	Closed	↓	↓	↓	Closed	↑	↑	Const.	↑
26	Closed	↓	↓	↓	↓ or ↑	Const.	↑	↑	Closed
26	Closed	↓	↓	↓	↓ or ↑	↑	Const.	↑	Closed
26	Closed	↓	↓	↓	↓ or ↑	↑	↑	Const.	Closed
26	↓	Const.	↓	↓	Closed	↑	↑	↑	Closed
26	↓	↓	Const.	↓	Closed	↑	↑	↑	Closed
26	↓	↓	↓	Const.	Closed	↑	↑	↑	Closed
27	Closed	↓	↓	↓	↓ or ↑	Const.	Const.	↑	↑
27	Closed	↓	↓	↓	↓ or ↑	Const.	↑	Const.	↑
27	Closed	↓	↓	↓	↓ or ↑	↑	Const.	Const.	↑
27	↓	Const.	Const.	↓	↓ or ↑	↑	↑	↑	Closed
27	↓	Const.	↓	Const.	↓ or ↑	↑	↑	↑	Closed
27	↓	↓	Const.	Const.	↓ or ↑	↑	↑	↑	Closed
28	Closed	↓	↓	↓	Closed	↑	↑	↑	Closed

Appendix B

Appendix B-1 Adjustment for right lateral clearance on freeway segments (Adapted from HCM 2016)

Right-side lateral clearance (ft)	2 lane per direction	3 lane per direction	4 lane per direction	5 or more lane per direction
≥6	0.0	0.0	0.0	0.0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.6

Note: Interpolate for non-integer values of right-side lateral clearance.

Appendix B-2 Adjustment for total lateral clearance on four-lane highway segments (Adapted from HCM 2016)

TLC (ft)	Reduction in FFS, f_{TLC} (mi/h)
12	0.0
10	0.4
8	0.9
6	1.3
4	1.8
2	3.6
0	5.4

Note: Interpolation to the nearest 0.1 is recommended.

Appendix B-3 Adjustment for total lateral clearance on six-lane highway segments (Adapted from HCM 2016)

TLC (ft)	f_{TLC} (mi/h)
12	0.0
10	0.4
8	0.9
6	1.3
4	1.7
2	2.8
0	3.9

Note: Interpolation to the nearest 0.1 is recommended.

Appendix B-4 Adjustment for access point density on multilane highway segments (Adapted from HCM 2016)

Access point density (access point/mi)	**f_A (mi/h)**
0	0.0
10	2.5
20	5.0
30	7.5
≥ 40	10.0

Note: Interpolation to the nearest 0.1 is recommended.

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