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An Enhanced Framework to Compute Road User Costs Associated with Construction Zones

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An Enhanced Framework to Compute Road User Costs Associated with Construction Zones

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by

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ABSTRACT

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The monetary quantification of inconveniences caused to the road users by ongoing construction activities is known as the Road Users Costs (RUCs). While the importance of RUCs is widely known, some highway agencies lack an appropriate methodology to compute RUCs. Thus, there is a need to develop a framework to compute RUCs that can be adopted quickly by highway agencies. This study reviewed existing literature and conducted a nationwide survey to identify and summarize the current practices of computing RUCs. It developed an enhanced framework and tool to compute RUCs that balances the effort required to calculate RUCs and the accuracy of the results. This enhanced framework accounts for the spatiotemporal variation of RUCs. The results of the study are expected to enable highway agencies to quickly and accurately compute RUCs to make better project management decisions, such as selecting the best contractor that minimizes the agency costs and RUCs.

DEDICATION

This thesis is dedicated to God's glory and to all those who have stood by me through the process of completing this project.

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I want to express my gratitude to God for being intentional about me and making this project a success. I am incredibly grateful to my devoted parents. I appreciate your love, support, and sacrifices. To my twin sister, thank you for being my biggest support.

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Chapter 1. Introduction

State Departments of Transportation (DOTs) in the United States are obligated to ensure a safe, convenient, and high-level transportation service to the public they serve by constructing, maintaining, and rehabilitating roadways for ease of movement. While this road construction is ongoing, road users find it difficult to travel around the construction zone, thereby posing inconveniencies on the road users and reversing the ease of service guaranteed by the DOT.

These inconveniences incurred by road users were traditionally not considered by state DOTs when contracting construction projects to contractors, as contractors are awarded such project is using the traditional concept of contracting. The traditional concept stated as the "Apparent Lowest Bidder Selection" considers only the lowest construction price among bidders as the basis to award project contracts to contactors. DOTs are now including inconveniences incurred by road users during the construction projects to the contract award consideration process by introducing the concept of Road User Cost (RUC). Therefore, the concept of RUC quantifies the inconveniences faced in the construction environment into monetary values, which helps DOTs effectively identify the impact of these inconveniencies and assist DOTs in evaluating a way to reduce these impacts on road users.

In the Work Zone Safety and Mobility rules and regulation, the Federal Highway Administration (FHWA) stated the need to implement policies that consider and effectively manage work zone operation impacts for federal-aid highway projects and non-federal aid projects (FHWA,2004). Furthermore, Flannery et al. (2016) and Lee et al. (2018) expressed the importance of road user cost inclusion in comparing alternative projects and as an essential factor for life cycle cost analysis. The RUC were traditionally used for new projects to conduct benefit-cost analysis and life cycle cost analysis. But with the introduction of innovative contracting methods such as A+B bidding and other accelerated construction techniques, its application in bid evaluation has increased recently.

As early as 1965, studies were conducted to quantify RUC (Chui & McFarland, 1986; Mallela & Sadasivam, 2011; Qin & Cutler, 2013; Sun et al., 2013). The earliest study on RUC by Haney (1967) only considered the Value of Time, or travel time delay, as the only component of the RUC. Chui and McFarland (1986) further categorized the RUC into time costs, vehicle operating costs, accident cost, traffic violation cost, and non-monetary values such as comfort and convenience. Recent studies and methodologies for RUC are developed based on these prior studies and additional impacts, such as accounting for excess pollution and the local business impacts (Fisher, 2018; Mallela & Sadavisam, 2011). However, the methodology used in estimating the RUC for bid evaluation varies. Different DOTs have developed their own method or used standard methods provided by the FHWA and American Association of State Highway and Transportation officials (AASTHO) (Mallela & Sadavisam, 2011; AASTHO, 2010). This has, however, caused a lack of consistency in the methodology to compute the RUC among state DOTs.

Research Objective

This study aims to develop a streamlined and simplified framework methodology to estimate RUC based on ease of deriving data attributes in the work zone. The framework consists of the main components required by DOTs to be considered in the RUC methodologies. Objectives of this research involves:

- Reviewing existing methodology to compute RUC.
- Conducting a nationwide survey to identify the best practices of calculating and utilizing RUC.

- Developing a framework methodology to calculate road user cost based on work zone characteristics.
- Developing an excel tool to implement the framework methodology.

The research methodology follows the study's objective and is completed in the steps highlighted above. Furthermore, four case studies were conducted using the enhanced framework.

Organization of Report

This thesis is organized and divided into seven chapters for better understanding. Chapter 1 presents the introduction to the study. Chapter 2 presents the literature reviews, which give an extensive review of the RUC components, history, and application. Chapter 3 presents the thesis methodology, which gives an overview of how the research activities are to be completed. Chapter 4 presents the nationwide survey showing the findings and summary of the survey questionnaire sent to all 50 states DOT in the US. Chapter 5, framework methodology, describes the simplified methodology to calculate RUC. Chapter 6 presents the case studies conducted with the framework methodology developed. Chapter 7 gives the conclusion and recommendation for future projects and studies.

Chapter 2. Literature Review

History of Road User Cost (RUC)

The concept of Road User Cost (RUC) was established way before 1965 and primarily involved estimating the value of time for road users based on perception, with no theoretical model to match (Chui & McFarland, 1986; Haney, 1967). Advancing through the years, many researchers and agencies have continued studies to develop a theoretical model to improve and update the RUC for more precise estimation involving other inconveniences (Chui & McFarland, 1986).

RUC traditionally involves projects to ascertain Cost-Benefit Analysis (COBA) and Life Cycle Cost Analysis (LCCA). A survey conducted by the National Cooperative Highway Research Program (NCHRP) in 1984 discovered the early consideration of RUC in the LCCA of pavement construction (Peterson, 1985). An LCCA evaluates the economic worth of a dedicated project, studying the project's initial cost and future costs such as maintenance and rehabilitation. Similarly, RUC was applied in COBA as early as 1972, whereby agencies used the COBA program to compare interurban road improvement by integrating RUC elements such as cost of travel time, change in vehicle operating cost, and incurred accident cost (Simpson, 1992). Furthermore, it compared the construction and maintenance costs against the benefits included after project completion. The benefit includes reducing time loss, excess vehicle operating, accident occurrence, saving energy and fuel consumption (Willis et al., 1998).

Overview of RUC

RUC is generally defined as the total cost attributed to road users traveling along a work zone. LaMondia et al. (2018) describe RUC in relation to road rehabilitation and maintenance as the total and temporary estimated cost a road user experiences personally in terms of time loss and excess vehicle operating due to roadway undergoing maintenance. Jia (2008) describes RUC as an increase in cost incurred by road users when traversing a road work zone, and it is determined by the input of the work zone and capacity. Cutler (2013) further describes RUC as a concept used to quantify the impact road construction, maintenance, and rehabilitation causes on road users' mobility, considering the safety, economic effect, and other forms of impact on the environment.

Ellis and Herbsman (1997) categorize the RUC into Quantifiable and Unquantifiable effects. Further review and study by Mallela and Sadavisam (2011) organize the RUC into Monetary and Non-monetary impacts. The Monetary impacts include the impacts incurred in the construction works zones that can be converted into monetary terms. The Monetary impacts are functions of the Delay Cost (DC) associated with loss of time when traveling through a work zone, further estimated and expressed in terms of the Value of Time (VOT) of road users. The Vehicle Operating Cost (VOC) related to vehicles' performance efficiency in the road work zone, Accident (AC) pertaining to crash and fatality in the work zone area, and Emission Cost (EC) relating to fuel and energy combustion causing pollution in the work zone area.

The Non-monetary impacts are a function of the costs that cannot be quantified. Examples are the impacts on local and businesses around work one area, noise pollution, and other environmental effects due to construction activities. Though studies have tried to quantify the impacts to loca business around work zone locations (Buddemeyer et al., 2008; Fisher, 2018; LaMondia et al., 2018). Still, there has not been a consensus or adequate methodology on how to effectively quantify the impacts on local businesses. Typically, RUC is calculated depending on the various impacts' information available and the purpose to which the RUC estimation is needed (Zhu & Ahmad, 2008).

Components of RUC

The component for RUC consists of the impact incurred during the construction of the work zone. These components, as stated earlier, are a list of quantifiable and non-quantifiable impacts on road users expressed as monetary and non-monetary value. Because the RUC is estimated based on the monetary impact, this section will review the monetary components of the RUC, including the factors considered in calculating each component, data requirements and data requirements.

Value of Time (VOT)

Für and Gmbh (2009) describe the value of time as the time estimate in terms of monetary value road user spends traveling through a work zone and experiencing delay, whereas the delay experienced could be used for other activities. This delay occurs due to reduced speed, the passing of alternative routes or detours, and vehicles idling through the work zone. Für and Gmbh further expresses that the VOT makes up the DC, which quantifies the delay experienced due to various construction activities and work-zone traffic control procedures such as diversion and traffic control signaling. Therefore, the DC is expressed as the excess cost incurred by a motorist expressed due to time loss when passing road work zones.

The VOT is an essential component to consider in the planning stage when comparing alternatives to make a decision (Daniels et al., 1999). Mallela and Sadavisam (2011) describe the various factors considered in estimating the VOT, which are the primary data sets composed of traffic data set. These factors include:

- Travel delay time
- Unit cost data for vehicle traffic composition
- Number and type of input for work zone capacity

- Average vehicle occupancy factor
- The unit cost of time-related vehicle depreciation.

Travel Delay Time

The travel delay time is expressed as the delay time experienced by a motorist during the construction activity. It is calculated based on various functions and construction activities employed in the construction work zone. Daniels et al. (1999) state some of the functions of the time delay as:

- Time delays due to Detours and Rerouting,
- Reduction of roadway capacity whereby traffic capacity reduces, and travel time increases due to speed reduction.
- Delay in opening a new facility or improved facility, minimizing the access to free traffic flow.

The AASTHO report' *User and Non-User Benefit Analysis for Highways'* (2010), further includes the time delay due to an intersection powered by a traffic control device. Generally, the travel delay time is estimated based on traffic activities and functions employed during the construction period.

Traffic Data and Type of Input for Work Zone Capacity

The traffic data used in evaluating the VOT depends on the agency's goal in estimating DC. Traffic data often used are the average daily travel (ADT), average annual daily travel (ADDT), and hourly or peak hour traffic data, while the traffic input capacity includes the vehicles per hour and passenger cars per hour. The type of traffic data and input for the work zone depends on the agency's choice in evaluation. Therefore, the number and type of transportation modes based on the selection of traffic data and the type of input for work zone capacity are used to compute the DC.

Unit Cost Data for Vehicle Traffic Composition

The traffic composition is made up of the various vehicle classes travel through the work zone. Typical traffic composition in the work zones include motorcycle, passenger car, passenger truck, buses, light commercial trucks, single-unit trucks, and combination trucks. Unit cost for each vehicle class depends on the wages and compensation of drivers for each traffic and estimating for dollar value for the passengers (Mallela & Sadavisam, 2011).

The unit cost considers the road users' trip purpose and trip mode for precise estimation of the travel time value (Mallela & Sadavisam, 2011). Examples of trip purposes include personal and business travel for passenger cars and in-vehicle business and excess (waiting time) business for a truck. At the same time, the trip mode includes the local and intercity travel mode. AASTHO (2010) provides a recommended guideline based on the distributed percentages for evaluating the VOT as an hourly dollar value for road users or passengers based on transportation mode and trip purposes shown in appendix (see Appendix A, Table A.2). Therefore, the unit cost combined with the delay time will estimate the road user's DC.

Average Vehicle Occupancy Factor (AVO)

Mallela and Sadavisam (2011) describe the Average Vehicle Occupancy Factor (AVO) as the ratio of person to vehicle mile traveled, considering the purpose and type of trip and the mode of the transportation. The AVO converts personal hourly dollar value to account for all passengers' dollar value based on the mode of transportation. This is achieved by factoring in the estimated AVO for different vehicle types. FHWA recommends AVO factors published by the National Household Travel Survey (NTHS) shown in appendix (see Appendix A, Table A.3).

The AVO's addition into the DC depends on the agency's choice to either consider it or not. Qin and Cutler (2013) state in their study that the AVO's consideration when evaluating the DC could increase VOT estimate precision.

In general, the VOT is derived by monetizing travel time based on the context of travel (business trip and personal trip), mode of travel (intercity and local), by estimating time-related depreciation of the vehicle, and by considering the value of freight inventory transported. All these are estimated based on different classes of vehicles that represent the traffic composition. Therefore, the delay in the work zone is multiplied by the value of travel time for trip purposes and mode, considering the AVO and the Average Annual Daily Travel (AADT) of vehicles.

Vehicle Operating Cost (VOC)

Vehicle Operating Cost (VOC) is the additional cost associated with excess operating and ownership of the vehicle along a work zone over its analysis period (Mallela & Sadavisam, 2011). *AASTHO* (2010) defines VOC as the cost incurred by vehicles' operation whereby running costs vary with vehicles' usage the mileage. The operating cost is associated with the vehicle's mechanical components and operation while in motion. Ellis and Herbsman (1997) describe a vehicle's operating cost, involves fuel, lubricating oil, tire wear, vehicle maintenance, and repair cost. In addition, Qin and Cutler (2013) describe that the operating cost is also related to the cost of owning the vehicle, including the insurance, registration fees and taxes, economic depreciation over time, and finance charges. However, in computing road user cost, fixed costs such as time-dependent deprecation and financing are not considered, as they are not affected by vehicle movement (Sinha & Labi, 2011).

However, VOC still occurs in the absence of a work zone, as the vehicle's mechanical operation will still increase because the vehicle is in transition. Therefore, in estimating the

RUC, the vehicle's operating cost is based on the speed changes through the work zone, and the vehicle's excess operating cost due to the longer distance traveled when there is a detour for the work zone. (Mallela & Sadavisam, 2011; *RUCM, 2015*; Zhu & Ahmad, 2008). Sinha and Labi (2011), in their study, describe the various components of VOC. They express the components as the vehicle features in which the consumption rate increases due to vehicle utilization and operations. The vehicle components considered as the consumption cost are:

- Fuel consumption
- Tire wear
- Engine Oil consumption
- Maintenance and repair
- Depreciation related to mileage.

Sinha and Labi (2011) further express Shipping inventory cost for commercial vehicles as one of the components incurring a fee for vehicle utilization and can be factored into the VOC estimation. The components or features are further described below.

Fuel Consumption

According to Sinha and Labi (2011), fuel is an essential component of vehicle operation, as it takes up 50% to 70% of utilization in the vehicle relating to the cost of operation. The fuel consumption rate depends on the distance traveled and road surface features such as steep uphill grades and curves contributing to high fuel consumption. Furthermore, Sinha and Labi state that the fuel consumption rate also depends on the fuel efficiency needed to power the vehicle. Fuel efficiency is associated with the type, class, speed, and age of the vehicle. In general, total fuel consumption cost will be affected by the amount of fuel used, the fuel efficiency, and the fuel price per gallon.

The unit price for fuel with fuel efficiency is used in estimating the fuel consumption cost. Unit cost for fuel is derived from various agencies' publications such as state gas price averages, the American Petroleum Institute (API), the American Automobile Association (AAA), the American Transportation Research Institute (ATRI), and government energy agencies' data which are published periodically. The unit cost is derived based on dollars and cents per gallon, including mileage from the AAA and other Environment and Energy publications. The HERS-ST model also provides equations to estimate the fuel consumption rate based on the roadway's grade and pavement conditions (Sinha & Labi, 2011).

Engine/ Lubricating Oil

The lubrication oil consists of the vehicle's brake fluid, engine oil, engine coolant, power steering fluid, and transmission fluid (*AAA, 2019*). Studies express that it contributes to less than 2% of the vehicle's operating cost because the consumption is more related to the engine wear than to the vehicle operating condition ("Chapter 3 RUC Surveys", n.d.). Sinha (2011) further describes that the oil consumption rate is subjected to traffic characteristics, e.g., vehicle speed, idling and delay, and roadway characteristics involving the road's grades and curves.

The oil consumption rate is estimated from the unit cost of the oil consumed and the consumption rate. The unit price ($/ quart) and consumption rates (quarts/miles) for the oil type are derived from the FHWA reports or prominent government agencies regulating the oil price and consumption. AAA also reports the operating cost of lubricating oil but populated with the maintenance cost because it involves changing and refilling lubricating and engine oil (*AAA, 2019*).

Tire Wear

Tire wear is associated with the vehicle tire component's degradation when in contact with the road surface during operation. Roadway surface attributes such as pavement roughness and smoothness directly affect tire wear. According to “Chapter 3 RUC Surveys” (n.d.) roadway geometry with speed and direction causes scraping or wearing the tire surface. The report further discusses that load weight on the tire axle could affect the tire wear due to compression on the tire axle carrying the most load weight.

Estimating tire wear cost requires the unit price and the wear rate of the tire. The tire's unit price and wear rate are derived from prominent sources such as the FHWA reports (Work zone road user costs: Concepts and Applications) and the Highway Economic Requirement System software (HERS-ST) technical reports FHWA.

Maintenance and Repair

Maintenance and repair are costs incurred based on repairing and replacing vehicle parts after a certain age of use. Sinha and Labi (2011) state that the vehicle's repair and maintenance occur due to prolonged usage, mishandling, and vehicle crashes. The maintenance and repair are also attributed to the work zone conditions, causing excess use of vehicle parts in work zone. factors such as speed change, pavement condition of the road surface, and road curvature based on the work zone’s configuration influence the vehicle's maintenance and repair. This, therefore, contributes to the operating cost of the vehicle.

Components that can be repaired and replaced in the vehicle include major and minor electric parts, body parts, and mechanical parts. “Chapter 3 Road User Cost (RUC) Surveys” (n.d.) further expresses that maintenance and repair also include labor costs to repair and maintain vehicle parts purchased. The unit cost for labor and the vehicle part are both considered to estimate the maintenance and repair.

Estimating the repair and maintenance cost can be difficult as there is no consumption rate and unit to identify with the maintenance and repair of vehicles. Some parts have to become damaged or worn out before a consumption value can be estimated. This can occur at different times for different vehicle classes and in various conditions. Also, regarding estimation based on the labor and damaged part, there is no consensus attached to the cost as the unit cost for the labor and parts varies based on geographical location.

The maintenance and repair are generally estimated alongside non-fuel costs to streamline the maintenance and repair component estimation. *AAA (2019*) reports unit price for the maintenance and repairs, including tire cost, as a combination for non-fuel cost in cents per vehicle miles traveled for various vehicle classes. This cost is reported and published yearly. The FHWA HERS-ST technical report also has an equation to estimate the consumption and unit cost value for the maintenance and repairs.

Depreciation Related to Mileage

Depreciation is considered as the devaluation of the vehicle due to usage and lifecycle operations. It is a function of the miles traveled and the duration from the inception of manufacture and purchase to present use (Sinha & Labi, 2011). Sinha and Labi further state that the depreciation cost is the most significant cost component in estimating the operating cost. The depreciation of the vehicle in terms of mileage corresponds with how effective the vehicle will function. This means the vehicle operation effectiveness will reduce as the mileage increases.

Factors that affect the depreciation rate are a large component of the road condition. Other factors that can influence the depreciation are speed, weather conditions, geometrics involving curves and grade of the road, etc. In some cases, the depreciation rate is calculated as a non-fuel cost due to the ease of deriving an adequate rate with other non-fuel components. In contrast, other prominent sources such as the FHWA report and the HERS-ST Technical reports provide a cost rate to calculate the mileage depreciation cost. *AAA (2019*) also offers the depreciation cost rate, indicated under the vehicle's ownership cost.

Factors and Conditions Affecting Vehicle Operating Cost

The operating cost for a vehicle is estimated based on the unit cost for vehicle operating components and the consumption rate of each component in terms of vehicle miles traveled. The unit cost and consumption rate are affected by various factors, while Sinha and Labi (2011) describe the various factors affecting the unit cost, and it is categorized into:

Vehicle/Operator Characteristic –This represents the vehicle's attributes involving the class and type of vehicle, fuel type, and the vehicle’s age. It is understood that the bigger the size of a vehicle, the more fuel the vehicle will consume, bringing about an increase in the VOC. Modern vehicles have improved with technology adoption to lower fuel consumption, allowing for high fuel efficiency, reducing the VOC rate. Furthermore, the operator or driver has a role in maintaining the vehicle. In terms of vehicle operation, the driver's behavior can affect the VOC in the aspect of maintenance and repair.

Economic Factors – This involves the price rate attributed to the various operating components. The different components involving the price for fuel, tire, lubricating oil, and repair and maintenance will affect the unit cost of VOC as most of the components vary with price at different locations.

Fixed Asset Characteristics- This involves the resources available for roadway operation. It is categorized as physical and operational characteristics. The physical represents the roadway features, such as the highway's types, grades, and pavement surface. The road's physical features will heavily affect the tire component with the vehicle's repair and maintenance. The operational characteristics involve the operation conditions of vehicles transitioning through the specific roadway. This includes the average speed, delay, and speed cycle change resulting from roadway traffic conditions and geometrics.

Policy and Institutional Factors- These represent the various rules and regulations set by federal agencies or state agencies to regulate traffic control and movement. An example is a design for the roadway's posted speed limit and a particular lane's uses. Furthermore, sales tax added to the non-fuel component affects the unit cost rate for VOC.

Crash Cost (CC)

Für and Gmbh (2009) define CC as estimating crashes associated with fatality and injuries into deriving a physical measurement value. CC is associated with the financial consequences of a crash incurred by a road user in the work zone.

Work zones on the highway bring about the interruption of traffic flow and low safety conditions for motorists traveling through the work zone. Huebschman et al. (2003) report high risks and reports of accidents at the work zone due to the motorists' effort to save traveling time through the work zone. This explains that even though road improvement and rehabilitation are being made to reduce vehicle operation and reduce traveling time, it could also increase the crash rate.

Batista dos Santos et al. (2014) express that CC is evaluated based on the information and attributed values from the work zone being analyzed. This is because work zone safety can be affected by various risk factors and effects that might not be fully recognized during work zone design. Therefore, CC should be considered for evaluation at the planning stage when evaluating highway design to influence choices regarding safety to be implemented for construction (Ellis & Herbsman, 1997). Für and Gmbh (2009) also recommend evaluating crash rates and cost be included in project evaluation to reduce incidents about the loss of life and property. Therefore, there is a need to estimate the cost associated with the accident at the work zone to compute the total road user cost.

Mallela and Sadavisam (2011) state various components to consider in the work zone to estimate the CC in evaluating the RUC. These components add up to calculate the total accident or crash rate in a work zone. They are categorized as:

- Crash rates and the frequency at work zones
- Crash severity rate at work zones
- The unit cost of the crashes at the work zone

Crash Rate and Frequency

The crash rate is the number or estimated frequency of crashes observed at a roadway over time. It considers the road length, segment, and traffic volume at the period of study. The crash rate is expressed in terms of crashes per vehicle miles traveled (VMT), crashes per miles per year for roadway section, and crashes per million entering vehicles (MEV) in scenarios whereby there is an intersection (Mallela & Sadavisam, 2011).

According to the *Highway Work Zone Safety Survey* by Associated General Contractors of America (2019), the crash rate in terms of work zones shows that there has been an increase in work zone crashes over the years. Mallela and Sadavisam (2011) expresses concern about the increase in work zone crash rates. They state a probability of 20 to 70% of a crash rate increase in a work zone, and this is based on location, traffic volume, time, and duration of the construction period. Therefore, to evaluate the RUC and mitigate crashes in the work zone, a need exists to predict the crash rate in the planning stage of construction to assess safety measures. To derive this, Für and Gmbh (2009) state that the crash rate over time can be used as a factor to estimate safety in a work zone, making use of the observed rate of crashes to modify future estimates in terms of safety and crash mitigation.

Therefore, a Crash Modification Factor (CMF) is adopted by highway safety officials to predict crashes in the work zone. Gross et al. (2010) state that CMF is mostly used in a project's planning and design stage to reduce the crash rate and predict safety performance over time. The CMF is developed based on historic crash studies. Mallela and Sadavisam (2011) expressed that pre-crash records for the prior three years of operation or more, if available, are collected, studied, and reviewed to forecast crash rates, as this guides analysts with previous knowledge to predict crash rate for estimation purposes.

In developing CMF, it is observed from Ullman et al. (2008) that the increase or decrease in crash risk varies significantly based on operation time and condition of the work zone. Operating time involves the time of the day, i.e., daytime or nighttime, when construction might occur. Work operating conditions applies to work zone configuration such as lane closure, active work without the lane closure, and no active work in the construction zone.

Crash Severity Rate at Work Zones

Crash severity categorizes the injury level incurred by a road user in a crash in a work zone environment. The severity is categorized into a fatal crash involving loss of life, injury crash whereby the motorist sustains injuries, and property damages. A crash severity rating identifies the severity of crashes in the work zone and assists safety personnel in reporting crash incidents in a summarized and precise form. A summarized description of crash rates is shown in the tables below.

In evaluating the severity of crashes in work zones, the KABCO injury and Abbreviated Injury Scales (AIS) are recommended by the National Highway Traffic Safety Administration (NHTSA) for reporting accident severity (Burch et al., 2014). The KABCO injury scale, as described in Table 1, is initiated by the American National Standards Institute (Sinha & Labi, 2011). Sinha and Labi further describe that KABCO is exclusively designed for the police to record crash information at an accident scene in the form of a coding system depending on the severity. Similarly, the AIS scale used for crash severity s shown in Table 2 below as established by the Associated for the Advancement of Automotive Medicine. It helps emergency medical responders to record crash information, ranking the injuries based on the threat to life relating to the injuries (Blincoe et al., 2002). Sinha and Labi recommend simultaneous use of the KABO and the AIS in reporting crash rate statistics to various transportation agencies (Sinha & Labi, 2011).

Table 1

KABO Scale used for Crash Severity

Code	**Severity**	**Description**
K	Fatal	An injury that results in death within 30 days of crash occurrence
A	Incapacitating	Any injury other than a fatal injury that prevents the injured person from walking, driving, or normally continuing the activities the person could perform before the injury occurred (e.g., severe lacerations, broken limbs, damaged skull)
B	Injury Evident	Any injury other than a fatal injury or an incapacitating injury that is evident to observers at the scene of the crash in which the injury occurred (e.g., abrasions, bruises, minor cuts)

C	Injury Possible	Any injury reported that is not a fatal, incapacitating, or non-incapacitating evident injury (e.g., pain, nausea, hysteria)
O	Property Damage Only (PDO)	Property damage to property that reduces the monetary value of that property

Note. Reprinted T*ransportation Decision Making: Principles of Project Evaluation and Programming* (p.129) by Sinha and Labi, 2011 John Wiley & Sons, Inc. Copyright, 2007 by Kumares Sinha

Table 2

Abbreviated Injury Scale (AIS) Used for Crash Severity

Code	**Severity**	**Description**
AIS 6	Fatal	Loss of life due to description, torso transaction massively crushed chest etc.
AIS 5	Critical	Spinal cord injury, excessive second- or third-degree burns, cerebral concussion (unconscious more than 24 hours).
AIS 4	Severe	Partial spinal cord severance, spleen rupture, leg crush, chest wall perforation, cerebral concussion (unconscious less than 24 hours)
AIS 3	serious	Major nerve laceration, multiple rib fracture, abdominal organ contusion; hand, foot, or arm crush/amputation
AIS 2	Moderate	Major abrasion or laceration of skin, cerebral concussion finger or toe crush/amputation, close pelvic fracture.

Code	Severity	Description
AIS 1	Minor	Superficial abrasion or laceration of skin, digit sprain, first-degree burn, head trauma with headache or dizziness.
AIS 0	Uninjured	No injury

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Factors Affecting Crash Rate and Severity

Various studies have been conducted to identify the factors affecting crash rates and severity in the work zone. Khattak et al. (2002) showed a high occurrence of injury in the work zone. They further estimated 17.5% of injury cases and 23.5% of non-injury crashes at the work zone. At the same time, Jin et al. (2008) compared crash rate and severity during construction time and non-construction time and recorded an increase in crash rate during the construction period. This increase results from various construction operations and environments (Akepati & Dissanayake, 2011; Ozturk, 2014). Examples of the factors affecting the crash rate and severity stated by Ahmed (2018) include weather conditions, road surface conditions, light conditions, and the time of day when construction operation occurs. Some of the factors are further explained below.

Environmental and Location Factor

Ozturk (2014) expresses the various environmental factors relating to work zone environment as the weather conditions, the lighting of the work zone, road geometry, and pavement condition. He described a significant crash rate in cloudy and snowy weather conditions as the road surface gets wet and icy, causing the road surface to be slippery with low visibility. Qi et al. (2005) also discovers a high relationship between the weather condition and crash occurring involving an accident of a rear-end collision between vehicles, as cases with rear-end crashes increase during the work zone constriction period. In terms of location, Chambless et al. (2002) state in their study that crashes are more likely to occur in the work zone located on highways and interstate. This could be explained by the high traffic volume traveling through the work zone.

Time of Day

Time of the day for work zone operation has always been a concern in the construction planning stage. Most agencies try to operate when the work zone activities do not incur inconvenience on road users. However, the day for work zone operations affects the crash rate in a work zone as many researchers have worked on time occurrence factors and analyses for work zone crashes. Arditi et al. (2007) investigate crashes based on “Day and Not daytime” working conditions in the work zone. It was observed that the crash rate is five times more dangerous in the Not daytime than in the Day time. Ullman et al. (2008), however, in their report, observe no significant difference in the comparison between “day and night” time work zone operation. However, they reported a 66% daytime and 61% nighttime increase in the crash rate at the work zone with the introduction of a temporary lane closure.

At the same time, Dissanayake and Akepati (2009) studied work zone crashes for five states, including Iowa, Kansas, Missouri, Nebraska, and Wisconsin. The study found that crashes predominantly occur in the daytime with the clear weather condition. Supportive research based on this observation is that of Garber and Woo's (1990) study on “*Work zone crash characteristics analysis*.” They observe that poor weather conditions slightly affect the work zone crash rate, as the work zone operated in daylight and with dry road conditions experience over 50% crash rate. Furthermore, Li and Bai (2006) discovered that the work operating during the peak hour illustrated as (10:00 a.m.–4:00 p.m.) would encounter more crashes in injuries and fatalities and serve as the most crucial time for risk of crash rate.

Speed Limit and Traffic Control Operation

An increase above the speed limit will always be a significant factor for an increase in crash rate both in a free roadway and in a work zone environment (Aarts & van Schagen, 2006). Several studies and research have analyzed the relationship between speed and crash in a work zone. In Dissanayake and Akepati (2009), work zone crashes for five states. The observation from the five states' comparison showed that the crash rate occurs and increases at a posted speed interval of 51-60 mph. Work zone speed limit of 45-55 mph is observed to have a high crash rate, stating that a lot of the crash rate occurs on a work zone at a speed limit of 55 mph (Chambless et al., 2002b; Daniel et al., 2000).

Traffic operating devices and control in traffic operation such as the signal signs, lane marks, and flaggers for the work zone environment could increase crash rate while decreasing the risk of crash rates. Ozturk (2014) concludes that traffic control involving signal signs and lane marks affects reducing crash rates in the work zone to 4.7 percent and 55 percent rate reduction, respectively. In the advent of control devices, temporary devices created in the work zone to control traffic flow are stated to contribute to one-third of the work zone's injuries due to the impact with the control device.

Nevertheless, when utilized in work zones, Traffic control helps to mitigate crash rates as most crashes in the work zone occur due to the absence of traffic control devices to direct and coordinate traffic flow (Dissanayake & Akepati, 2009; Li & Bai, 2006).

Unit Cost of Crashes at Work Zone

The unit cost for crashes in the work zone is categorized based on market economic cost and non-market economic cost (Sinha & Labi, 2011). The market economic cost is the direct and indirect cost incurred due to a crash on the roadway (Islam, 2002). Direct cost includes administrative costs such as police and fire departments, material costs, and direct medical costs. The indirect cost includes costs related to loss of productivity and rehabilitating costs in terms of an operational environment (Tervonen, 1999). The non-market economic cost, according to Haight (1994), is described as the cost incurred and measured based on emotional fatalities, pains, hurts, and loss of victim health due to crash occurrence. The market economic cost is also referred to as the Human Capital Cost (Blincoe et al., 2002).

Human capital cost is used to estimate the value cost for fatal and non-fatal injuries. The human capital cost calculates the saving cost from reducing injuries and crashes while revealing and signifying crash complications in locations. The non-market economic cost is referred to as the comprehensive cost, which can be presented as the willingness to pay. Comprehensive cost is used to estimate intangible costs related to pain, loss of life, and property damage, which cannot be assessed based on market economic data. Comprehensive cost is understood as the cost that society will be willing to pay to mitigate risk and crash probability (Wang et al., 1996). The human capital cost and the comprehensive cost are both used to estimate the crash unit cost. However, it is observed from Islam (2002) and other concluded research cited by Sinha and Labi (2011) that the comprehensive or non-market economic cost has higher cost values than the human capital cost making it the dominating cost value. Islam (2002) explains this as the comprehensive cost includes evaluating loss of life and property value, which is essential in estimating unit cost directed to vehicle crashes and not to underestimate the actual value of the impact that took place in the crash incident (Wang et al., 1996).

Estimating Crash Cost (CC)

To estimate CC, the crash rate of the vehicle in the work zone and the unit cost for crashes is determined based on the severity of crashes at the work zone. This cost is calculated based on the crash rate assumption using a factor to predict future rates and perceived values regarding the unit cost consisting of the human capital and comprehensive cost. Crash rates or frequency are predominately derived from historical data, particularly to analyze the work zone area. The FHWA and AASTHO methods recommends this as the right step to predict future crash rates based on occurring rate trends (Mallela & Sadavisam, 2011; AASTHO, 2010). The crash rate can be retrieved from the safety agencies of the state and locations where there is a work zone. This will help provide detailed data considering the specified work zone geometry and the characteristics of the driver's behavior (AASTH0, 2010). In cases whereby, the crash records are not available for the specified work zone segment to be analyzed, a comprehensive data set can be retrieved from the National Highway Traffic Safety Administration published yearly. It provides the accident rate data for both the national and state-level in terms of the vehicle type and severity of the crash involved (NHTSA, 2020). However, since it is not observed for a specific location, the data will consist of data rate based on different driving periods, characteristics, and conditions which might not be streamlined to the specified work zone condition (AASTH0, 2010).

Crash Modification Factor (CMF)

The Crash Modification Factor (CMF) is used to predict the rate of crashes in the specified work zone. Future work zone crash data is established using the CMF and previous crash rate records of analyzed work zone routes (Mallela & Sadavisam, 2011). Furthermore, Qin and Cutler (2013) state that CMF is used to improve traffic safety and implementation for the work zone. CMF can be derived from the FHWA office of safety, and the CMF clearinghouse website based on work zone features (Mallela & Sadavisam, 2011; Ullman et al., 2008). Qin and Cutler (2013) suggest that CMF can also be derived from an agency's internally developed values. This is recommended because the CMF will be developed based on crash rate trends in the specified work zone segment while considering segment features and characteristics. They further state that this self-developed CMF will increase the precision of the factor to be used in the analyzed work zone. Qin and Cutler (2013) further describe that CMF is developed based on various scenarios and can be classified based on crash type and severity, countermeasures, and roadway features. The CMF provided by the FHWA for work zone where there is temporary lane closure for a freeway is shown in Table 3 below.

Table 3

FHWA CMF for a Temporary Lane Closure on Freeway

Crash Types	**Crash severity**	**CMF**
All	All	1.77
All	Property damage only (PDO)	1.9
All	Serious injury, Minor injury	1.6
Nighttime	All	1.57
Nighttime	Property damage only (PDO)	1.63
Nighttime	Serious injury, Minor injury	1.4

Note. Reprinted from "*Review of Road User Costs and Methods*." by Qin, X., and Cutler, C. 2013, (p.25). copyright 2013 by Xiao Qin

Highway agencies like the South Dakota Department of Transportation (DOT) have developed CMF for various scenarios in planning and project development of highway improvement projects, work zone with project management and construction options, and safety improvement (Qin & Cutler, 2013).

Unit Cost

Unit cost for crash rate is based on the human capital and comprehensive cost described in the unit cost section above. Data for unit cost can be found in the FHWA report (Council et al., 2005). Mallela and Sadavisam (2011) describe that the report includes the human capital and comprehensive cost. It collates 22 scenarios for crash geometries, six levels of KABCO severity rating, and two conventional vehicle speeds ≤ 45 mph and ≥ 50 mph, as shown in Table 4. Qin and Cutler (2013) further recommend unit costs from the FHWA Highway Safety Manual (HSM) show in appendix (see Appendix A, Table A.8). The comprehensive societal crash cost is tabulated against crash and recorded injury severity.

Table 4

FHWA Report Sample of Crash Cost Estimate from 2001 Dollar Value

Crash Geometry	**Speed Limit(mph)**	**Max. Injury severity in crash**	**Max. injury severity code**	**Human capital cost per cash**		**Comprehension cost per cash**	
				Mean	**Std. Err**	**Mean**	**Std. Err**
	<=45	No injury	0	$8,512	997	$10,249	1,408
	<=45	B or C	1.5	$33,369	4,561	$60,333	9,021
	<=45	A	3	$163,157	15,153	$316,380	33,532
	<=45	K	4	$975,643	30,468	$3,234,016	114,015

	<=45	Injured, severity unknown	5	$67,342	22,127	$129,418	42,249
	<=45	Unknown	9	$14,386	-	$22,841	-
	>=50	No injury	0	$3,672	-	$4,015	-
	>=50	B or C	1.5	$54,605	32,590	$101,712	61,756
	>=50	A	3	$116,545	26,407	$189,805	36,182
	>=50	K	4	$1,022,983	1,695	$3,404,944	2,819
	>=50	Injured, severity unknown	5	$61,573	-	$146,281	-
	>=50	Unknown	N.A.	N.A.	N.A.	N.A.	N.A.

Source: (Mallela & Sadavisam, 2011)

Emission Cost (EC)

Vehicle emission is described as the release of gases into the air due to the vehicle's mechanical operation combustion process. These gases can be harmful to the environment and road users. Mallela and Sadavisam (2011), Tan (2014), and Sinha and Labi (2011) describe emissions as categorized into Air pollutants and Greenhouse gases. Air pollutant emission is described as gases such as Carbon monoxide (CO), Nitrogen oxides (NOx), Sulfur oxides (Sox), Particulate Matter (PM10), and Volatile Organic Compounds that are released directly into the atmosphere. These gases also cause acidic decomposition and ozone depletion when formed in the atmosphere through physical and chemical processes. Greenhouse’s gases such as Carbon dioxide (Co_2), Nitrous oxide (N_2o) and Methane (CH_4) give rise to increasing heat and temperature. Various air emissions produced by vehicles in work zone environment are summarized into description, source, harmful effect, and scale in Table 5 below.

Table 5

Description of Various Pollutants in Work Zone Environment

Emission	**Description**	**Sources**	**Harmful Effects**	**Scale**
Carbon dioxide (CO_2)	A product combustion	Fuel production and tailpipes	Climate Change	Global
Carbon monoxide (CO)	A toxic gas caused by incomplete combustion	Tailpipes	Human health, climate change	Very local
Fine particulates ($PM_{10;}$ PM_{25})	Inhalable particles	Tailpipes, brake linings, tire wear.	Human health aesthetics.	Local and regional
Road dust (non-tailpipe particulates)	Dust particles created by vehicle movement.	Vehicle use, brake linings, tire wear.	Human health aesthetics.	local
Methane (CH_4)	A flammable gas	Fuel production and tailpipes	Climate change	global
Nitrogen oxides (NO_X) and nitrous oxide (N_2O).	Various compounds, some are toxic,	Tailpipes	Human health, ozone precursor, ecological damage.	Local and regional.

	all contribute to ozone.			
Sulfur oxides (SOx)	Lung irritant and acid rain.	Diesel vehicle tailpipes.	Human health and ecological damage.	Local and regional.
VOC (volatile organic hydrocarbons)	Various hydrocarbon (HC) gasses.	Fuel production storage & tailpipes.	Human health, ozone precursor.	Local and regional.
Toxics (e.g., benzene)	Toxic and carcinogenic VOCs	Fuel production and tailpipes	Human health risks	Very Local

Emission in the work zone is generated from the composition of several vehicle emissions generated from impacts and delays such as stopping, and queuing encountered during work zone activities (Oduyemi & Davidson, 1998). Sinha and Labi (2011) state that vehicles are the local contributors of air pollutants such as CO, NOx, Sox, and PM to the environment, causing excess concentration of photochemical oxidants. Smit et al. (2008) and Tsanakas et al. (2020) discuss how congestion in the traffic stream would cause an increase in emission rate as congestion causes a change in the vehicle mechanical operation causing fuel combustion. Abdel-Rehim (2012) explained in his study how the reduction of emission rate could also occur due to traffic signals and traffic control that modifies vehicle speed in the traffic stream. Generally, the emission rate will depend on the traffic characteristics and composition in the work zone. Other studies conducted to examine the emission effect further discovered that vehicle weight and an increase in the road grade contribute to CO_2 and NOx emission on the highway (Alwakiel, 2011).

Factors Affecting Emission Rate in Work Zone

Various factors affecting vehicle emission ranges from roadway characteristics, traffic characteristics, driver characteristics, vehicle characteristics, and weather characteristics (Alwakiel, 2011; Litman, 2002; Mallela & Sadavisam, 2011; Sinha & Labi, 2011). The various factors are summarized by Mallela and Sadavisam (2011) in Table 6. However, not all factors could significantly affect the emission rate in the work zone environment. The factors that would affect emission rates are mainly attributed to traffic flow and operation condition, operating speed, vehicle class, and type with the fuel type (Franco et al., 2013).

Table 6

Factors Affecting the Emission Rate in Vehicles

Roadway Characteristics	**Traffic Characteristics**	**Driver Characteristics**	**Vehicle Characteristics**	**Weather Characteristics**
Number of lanes Lane width Sight distance Horizontal curves Vertical curves Grades Roadway type	Volume Capacity Volume/capacity ratio. Vehicle composition Vehicle speed.	Attitude Experience Gender Age Aggressiveness Driving modes Driving Modes	Age Milage Weight Fuel type Engine size Engine type and cycle characteristics Air to fuel mass ratio.	Temperature Humidity Visibility

Speed limits Pavement quality Signal coordination Other traffic control measures			Catalyst Maintenance Aerodynamics Emission control devices. Acceleration and deceleration characteristics.	

Note. Reprinted from *Work zone road user costs: Concepts and Applications* by Mallela & Sadavisam, 2011, (No. FHWA-HOP-12-005). Copyright 2011, The United States. Federal Highway Administration

Vehicle Class and Type

The work zones consist of various commuting vehicle classes grouped into light and heavyweight vehicle classes. Moreover, it is observed that the emission rate in a work zone environment is dependent on the vehicle class and weight (Clark et al., 2002; Feng et al., 2005). Pollutants such as CO, NOx, SO_2 and PM are the significant emissions released in the environment based on the vehicle class and weight. Gajendran and Clark (2003) observe the emission rate of two classes of trucks (7 and 8). They documented the increased carbon monoxide (CO) emission and particulate matter (PM) in heavyweight truck types. These emissions occur based on the weight during operation, and there is a reduction, or no emission released when the truck is not in operation. Generally, these emissions will increase in heavyweight vehicles due to the fuel type used. The heavyweight truck uses the diesel type of fuel and will experience an increase in PM and carbon dioxide CO_2 emissions in relation to the vehicle weight (Durbin et al., 2000). Furthermore, according to Alwakiel (2011), NOx emission also increases in the vehicle when observed against vehicle speed and road grade.

Operating Speed

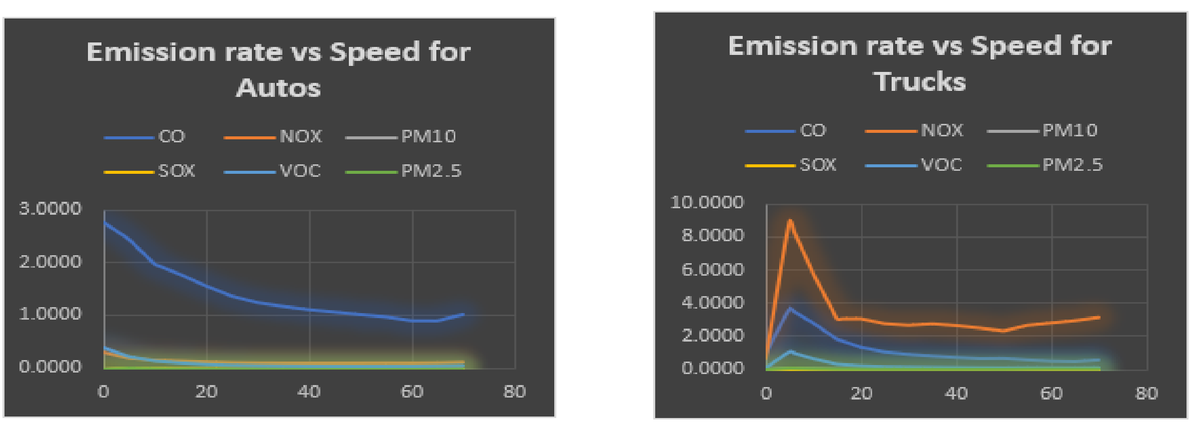
Operating speed in the work zone environment impacts the vehicle's emission rate (Zhang et al., 2011). Carbon monoxide (CO), particulate matter (PM), nitrogen oxides (NOx), and unburned hydrocarbons (HC) are significant gases that are emitted based on vehicle operating speed (Alwakiel, 2011; Clark et al., 2002; Frey et al., 2001). However, more studies describe that emission could either increase or decrease with relation to speed.

Clark et al. (2002) infers in their research that the emission rate of carbon monoxide (CO) and particulate matter (PM) increases as vehicle speed increases. They explained that these emissions increase as the engine produces more power to generate speed. Simultaneously, driving with increased and steady acceleration will increase the vehicle's emissions rate (Bigazzi & Bertini, 2009). Also, it is observed that the emission of Nitrogen oxide and Nitric oxide gases are predominately released as speed increases. At the same time, carbon monoxide (CO), particulate matter (PM), and unburned hydrocarbons (HC) are not sensitive to increasing speed change (Clark et al., 2002; Frey et al., 2001). Brodrick et al. (2004) observe that NOx and CO_2 gas emission is also released during the idling of a vehicle and not only when the vehicle is in operation. This is to attest that many studies have described the occurrence and increase in vehicles' emissions rates even in a freeway and work zone environment.

Other studies show that the emission rate decreases with an increase in vehicle speed. According to Pandian et al. (2009), fuel consumption and emission are likely to reduce as the speed increases. This can be explained by rapid fuel combustion that occurs significantly at a lower speed rate consuming more fuel at a lower gear. Therefore, there is not much fuel combustion when the vehicle operates at a higher speed. In contribution to this, Hao et al. (2010), in their study, observe that emissions do not occur significantly on the expressway where there is no interference as compared to a minor arterial having a similar operation process with a work zone. Brodrick et al. (2004) explain this by a frequent 'stop and go' flow and utterly stop traffic flow situation identical in the work zone environment due to the operation process, causing the frequent deacceleration and acceleration of vehicles, whereby it causes an increase in emission compared to a non-interference speed on the highway. A graph illustrating the emission rate based on the operating speed for both auto and truck vehicles derived from the Emission factor model developed by the California Air Resource Board (CARB) is shown in Figure 1 below, and data in gram per miles shown in the appendix (see Appendix A, Table A.13)

Figure 1

EMFAC Emission Factor Based on Speed for Auto and Truck Vehicle Type



Note. The graph shows the trend of emission based on operating speed using the emission rate from the EMFAC model 2020.

Estimating and Deriving Emission Cost (EC)

The quantification of the EC is somewhat challenging as the derivation of EC involves extensive data and software models to derive the emission pollutant and rates. Moreover, there is no consensus about each pollutant's dollar value rate (Mallela & Sadavisam, 2011). Data variation for estimating EC occurs as several agencies compute emission rates and factors based on their geographical location and population density. In terms of monetizing emission, Qin and Cutler (2013) report that the economic analysis of the medical and societal impact of the emission on road users is being used to derive unit cost. This also varies based on the location of the work zone and population density. However, this has made the derivation of EC more challenging to attain. Nevertheless, the FHWA recommends that the derivation of emission rate and unit cost associated with different pollutants in the work zone environment is to be used to estimate the EC (Mallela & Sadavisam, 2011).

Emission Rate/Factor

The emission rate is derived by using various models developed by government agencies such as the Environmental Protection Agency (EPA), California Air Resource Board (CARB), and Georgia Institute of Technology (Mallela & Sadavisam, 2011; Sinha & Labi, 2011). With the development of many models, Mallela and Sadavisam (2011) categorize them based on estimation with different operating conditions. The emission rate derivation is classified into two models: The Static Emission and the Dynamic Emission model. The Static Emission model calculates emission by considering the vehicle's operating condition and multiplying it with the emission factor, while the Dynamic Emission model calculates EC by considering the emission rate based on the change in the vehicle's operating condition in estimating emission in the analysis environment.

The FHWA report further explains the limitation and extensions of the two models. The Static model calculation based on the emission factor only accounts for vehicle speed and types but cannot capture the emission based on the change in driving operations such as acceleration, deacceleration, cruise, and idling. These are likely driving operations that will occur in a work zone environment. Therefore, the FHWA report suggested the model could be used on a wide range of planning analyses to derive emission rates and cost on a larger scale. Examples of the static models are Mobile 6.2 and the EMFAC model (Mallela & Sadavisam, 2011; Sinha & Labi, 2011). An example for EMFAC model emission factor rate in gram per mile is shown in the appendix (see Appendix A, Table A.13).

The Dynamic Emission model, on the other hand, does require a lot of extensive data estimation to calculate emissions based on the work zone driving condition, as mentioned earlier. The model accounts for emission factors based on the driving conditions at different time intervals, speed changes, and cycles (Kalandiyur, 2007). Therefore, the model is integrated with the traffic simulation model to better estimate emissions at traffic management planning (Thompson et al., 2010). Examples of the Dynamic emission models are the Motor Vehicle Emission Simulator (MOVES), Comprehensive Model Emission Model (CMEM), and the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURES) (Mallela & Sadavisam, 2011). A sample of MOVES model emission factor for auto and truck for Sullivan County in Tennessee is shown in the appendix (see Appendix A, Table A.14).

In recent years, emission factors of various pollutants have continued to reduce. This can be attributed to the technological based on induced travel demands and vehicles' efficiency over the years (Bigazzi & Figliozzi, 2012; Pradenas et al., 2013). The FHWA report prepared by ICF Consulting (2005) in *Assessing the Effect of Freight Assessing the Effects of Freight Movement on Air Quality at the National and Regional Level* recorded a reduction in emission factors from the previous year shown in Table 7 below. This proves the reduction of emission rate for different types of vehicles with prior knowledge that the truck type of vehicle produces the highest emission rate based on fuel type, fuel efficiency, payload, and engine load (Durbin et al., 2000; Feng et al., 2005; Zhang et al., 2011)

Table 7

Emission Factors (g/miles) for Arterial Trucks for Different Years

Truck Class	**Year**	**VOC**	**CO**	**NOX**	**PM-10 Total**	**PM-10 Exhaust Only**
Single-unit Truck-Gasoline	2002	2.29	59.87	7.18	0.13	0.11
	2010	0.61	14.24	4.95	0.09	0.07
	2020	0.21	9.00	1.92	0.05	0.03
Single-Unit Truck- Diesel	2002	0.59	2.86	15.34	0.42	0.38
	2010	0.37	1.41	6.18	0.17	0.13
	2020	0.26	0.30	1.01	0.07	0.03
Combination Truck- Diesel	2002	0.61	3.18	17.02	0.41	0.37
	2010	0.39	1.47	6.38	0.17	0.13
	2020	0.28	0.33	1.03	0.07	0.03

Note. Reprinted "*Transportation Cost and Benefit Analysis: Techniques, Estimates and Implications 2nd Edition"* (p 5.10-12) by Litman and Doherty, 2016, Victoria Transport Policy Institute. Copyright 2016 by Todd Alexander Litman.

Unit Cost

According to the FHWA report, there has not been any consensus to attribute a monetary cost to various pollutants (Mallela & Sadavisam, 2011). The unit cost for the emission type is computed based on society's health impact around the work zone. Mallela and Sadavisam further describe variations in deriving the dollar value to estimate the EC. This is because the cost will largely depend on the population density in the work zone, i.e., a work zone with a larger population will incur more health effects than a location with a smaller population and result in a higher portion of dollar value in the high populated area.

The FHWA report covers some of the computed dollar value derived by the California Department of Transportation and the computed estimate of air pollutant damage cost by the Highway Economic Requirements System Model (HERS-ST) developed in 2000 shown in appendix (see Appendix A, Table A.12). These dollar values are not of current values, and there is a need to update to recent year's value. The FHWA report states that there has not been a consensus guideline to adjust to the present value. Still, a common procedure used for adjustment is the Implicit Price Deflator for Gross Domestic Product Goods to change to the current year (Mallela & Sadavisam, 2011). Table 8 shows the compilated dollar value for each pollutant type for California DOT and the HERS-ST model based on a low and high-density populated environment.

Table 8

California DOT Estimate of Health Cost of Transportation Emission ($/ U.S ton) in 2010-Dollar Values

Pollutant	**L.A./South Coast**	**CA Urban Area**	**CA Rural Area**
Carbon Monoxide	$135	$70	$65
Nitrogen Oxide (NOx)	$55,700	$16,300	$12,100
Particular Matter (PM10)	$456,500	$131,800	$94,000
Sulfur Oxide (SOx)	$171,500	$65,800	$47,500
Volatile organic compounds	$3,465	$1,140	$895
Greenhouse Gases (CO_2)		$37	

Note. Reprinted from *Work zone road user costs: Concepts and Applications* by Mallela & Sadavisam, 2011, (No. FHWA-HOP-12-005). Copyright 2011, The United States. Federal Highway Administration

Local and Business Impact Cost (LBIC)

The local and business impact accounts for the loss of revenue of surrounding businesses in the work zone as this construction blocks and hinders access to business around the construction area while businesses suffer the loss of revenue. Mallela and Sadavisam (2011) stated various impacts that could affect business and the local environment, such as temporary loss of customers and impact and decrease in property and land values. These impacts are not easily quantified. It requires allocating and deriving data such as understanding the business's revenue in the nearby areas, predicting customers' travel behavioral patterns and expenses. However, few studies such as Buddemeyer et al. (2008) and Wolffing et al. (2004) have conducted case studies to quantify the local and business impact in rural areas. So also, Fisher (2018) quantified the LBIC using a nationally representative survey of road user travel and behavioral response to business when there is a work zone and using a developed ordered probit model to predict behavioral travel patterns.

In conclusion, the various impacts that can be quantified, depending on the datasets and information available, are computed to account for the road user cost and further applied to project decision-making and implementation.

Application of RUC

RUC is a type of cost estimating procedure for construction projects. It can be applied to different construction projects before the start and within the stages of such projects to quantify the cost incurred. Qin and Cutler (2013), in their study, describe that agencies and analyst apply

RUC to compare construction projects' economic benefits over a long period. They further illustrated stages in construction where RUC is can be applied. They expressed that RUC can be applied in the project planning, design and development, and project construction stages, which are all generally categorized into the project planning and construction stage of projects.

In terms of the project planning stage, the application of RUC can help prevent inconveniences that might occur and offer alternatives that would reduce mobility impact, thus guiding decisions of the project to be executed. In this stage, the RUC is applied in estimating COBA and LCCA to compare various project alternatives, using projected cost with the RUC estimate to evaluate the project alternatives' economic benefit in the long term. In addition, the RUC applied in the planning stage helps evaluate contract strategies and techniques for project initiation.

Vadakpat et al. (2000) acknowledge the importance of RUC being an essential model for project contracting strategies. Mallela and Sadavisam (2011) further state that RUC has been used among DOTs and Highway agencies as a necessary factor in determining innovative and alternative contracting procedures. The RUC is applied to innovative and alternative contracting procedures such as Incentives/Disincentives (I/D), Lane rental, Liquidated damages, and A+B bidding to identify the best delivery methods in saving cost and shortening the duration of construction time. RUC is applied early in the planning stages involving the preliminary, conceptual, and development stages of projects when plans are still flexible to mitigate errors and changes before the final designs are drafted. Also, as much to analyze the construction project alternatives related to choosing the best options with less risk and high safety components (NJDOT, 2015).

Furthermore, the RUC is applied during the construction stages to evaluate inconveniences in the work zone. It can be applied to different ongoing construction activities in the work zone, such as detours, partial lane closure, and new facility openings. Qin and Cutler (2013) further state that RUC is applied in the construction stage to provide daily user costs based on short-term analysis and analysis of work zone to derive alternatives to use in the work zone configuration.

Chapter 3. Methodology

This section presents the organization of this study. The study was conducted and completed in four phases which are:

- Review of existing studies on RUC.
- Conduct a nationwide survey.
- Develop a framework methodology to compute the RUC.
- Develop case studies using the developed framework.

Reviewed Existing Studies

This study conducted an extensive review of studies related to the RUC. The review includes the history, applications, components, and methodologies of the RUC. Further reviews included that of studies and reports published by highway agencies such as the FHWA, AASTHO, and state DOTs with additional pieces of literature from academic papers and studies.

Conducting a Nationwide Survey

A nationwide survey was conducted based on the review of existing studies. The nationwide survey aimed to better understand the RUC methodologies used by various DOTs in the U.S. The survey question was developed using a web-based surveying tool called REDCap. The survey questionnaire was sent to highway and transportation engineers and staff involved in transportation planning, design, and operations in all state's DOT in the U.S. The email contacts of the engineers were obtained by visiting state DOTs' websites and pertinent websites and reports. The result was compiled and analyzed with the REDCap tool, and findings were expressed in the bar diagrams to aid visual observation and assessment.

Developed a Framework Compute the RUC

Based on the findings from reviewing existing literature and results from nationwide surveys, a framework was developed to calculate RUC for the Tennessee Department of Transportation (TDOT). In addition, the framework was developed to enhance previous methodologies and accommodate the ease of deriving data attributes for calculation. Furthermore, an Excel spread sheet was created to implement the framework developed.

Case Studies to Implement the Framework

Sample construction projects were derived from the TDOT website, and data attributes needed based on the framework methodology were derived from construction documents on the TDOT website. The data and information derived from the construction document were used to implement and show the effectiveness of the framework developed.

Chapter 4. Nationwide Survey

This chapter presents the findings from the nationwide survey questionnaire. The survey aimed to review various procedures used in estimating RUC in different state DOTs and to identify the best practices used. Afterwards, an enhanced methodology will be developed for the Tennessee Department of Transportation (TDOT) through feedbacks received from the survey. A short sample questionnaire was developed and divided into three question segments: Applications of road user cost, RUC calculation methodologies, and Data requirement for RUC. The sample questionnaire can be found in the Nationwide survey section in appendix b.

Survey Methodology

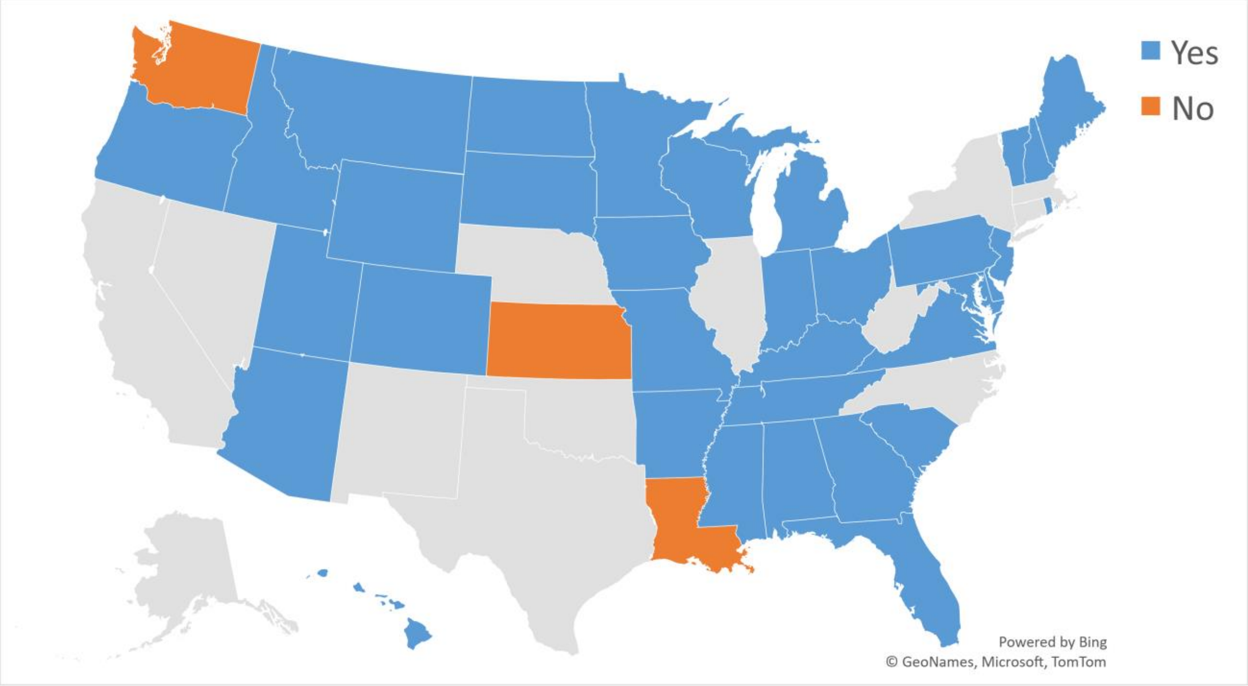
In creating the questionnaire for the survey, a total of twenty-two questions were created. The survey included questions about the application of road user costs and methodology in calculating road user costs. Simultaneously, there was a request to provide more information such as a user manual, document, weblink, and RUC calculation spreadsheet about the RUC method of the state DOTs if available. The survey questions were organized in a Likert scale and multiple-choice format to ease the respondent's responses to the survey. The respondent could also list other information not provided in the multiple-choice, which the respondent would like to state. The survey did not collect any of the respondents' personal data but only the information needed about calculating their state's DOT RUC. The East Tennessee State University (ETSU) Institutional Review Board (IRB) determined that the study did not meet the definition of human subject research. Hence, it did not require IRB approval. The survey was emailed to all intended states' DOT in the United States using Redcap, a web-based surveying tool.

Survey Results

A total of 37 state departments of transportation responded to the survey. The departments of transportation that responded are Alabama (ALDOT), Arizona (ADOT), Arkansas (ARDOT), Colorado (CDOT), Delaware (DelDOT), Florida (FDOT), Georgia (GDOT), Hawaii (HDOT), Idaho (ITD), Iowa (Iowa DOT), Indiana (INDOT), Kansas (KDOT), Kentucky (KYTC), Louisiana (La DOTD), Maine (Maine DOT), Maryland (MDOT), Michigan (MDOT), Minnesota (MnDOT), Mississippi (MDOT), Missouri (Mo DOT), Montana (MDT), New Hampshire (NHDOT), New Jersey (NJDOT), North Dakota (NDDOT), Ohio (ODOT), Oregon (ODOT), Pennsylvania (PennDOT), Rhode Island (RIDOT), South Carolina (SCDOT), South Dakota (SDDOT), Tennessee (TDOT), Utah (UDOT), Vermont (V Trans), Virginia (VDOT), Washington (WSDOT), Wisconsin (Wis DOT) and Wyoming (WYDOT). Furthermore, a virtual representation of states DOT that responded to the questionnaire, including the states DOT that calculate and do not calculate RUC, is shown in Figure 2 below.

Figure 2

State DOTs that Responded to the Survey and Calculate RUC for Roadway Projects



The survey results were summarized into three sections to determine the application of road user cost, the state's RUC calculation methodologies, and the various data requirement and attribute considered by each DOT to calculate the RUC.

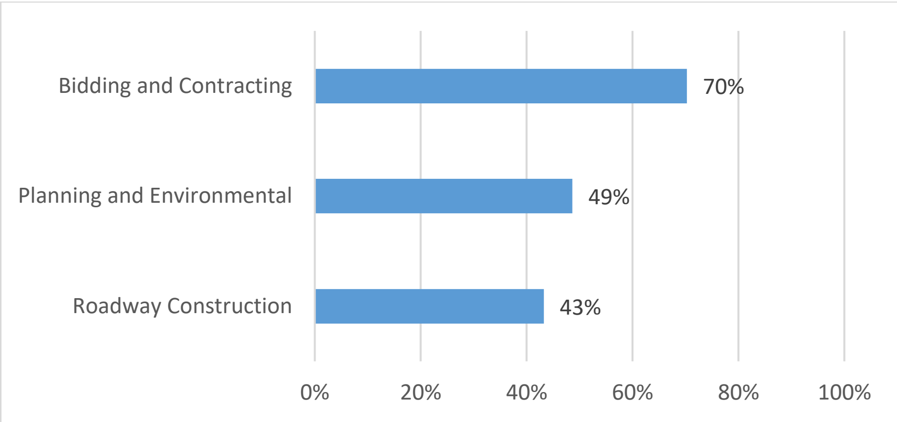
Application of Road User Cost

34 state DOTs out of the 37 responding states calculate road user cost for a construction project shown in Figure 2**.** Kansas DOT, Louisiana DOT, and Washington DOT do not calculate the RUC for a construction roadway project. Though they did not state why they do not calculate the RUC in a construction project, Washington state DOT noted that the RUC is evaluated during the planning stage before construction, whereas they use the RUC for other purposes but not for construction roadway projects. About three-quarters (70%) of the responding DOT indicated the use of RUC in the contracting and bidding stages for a construction project. Approximately half of the responding DOT indicated the use of RUC in the planning and

environmental stage. Less than half of the DOT also indicates the use of RUC in the roadway construction stage, as shown in Figure 3.

Figure 3

Stages Where RUC is Utilized

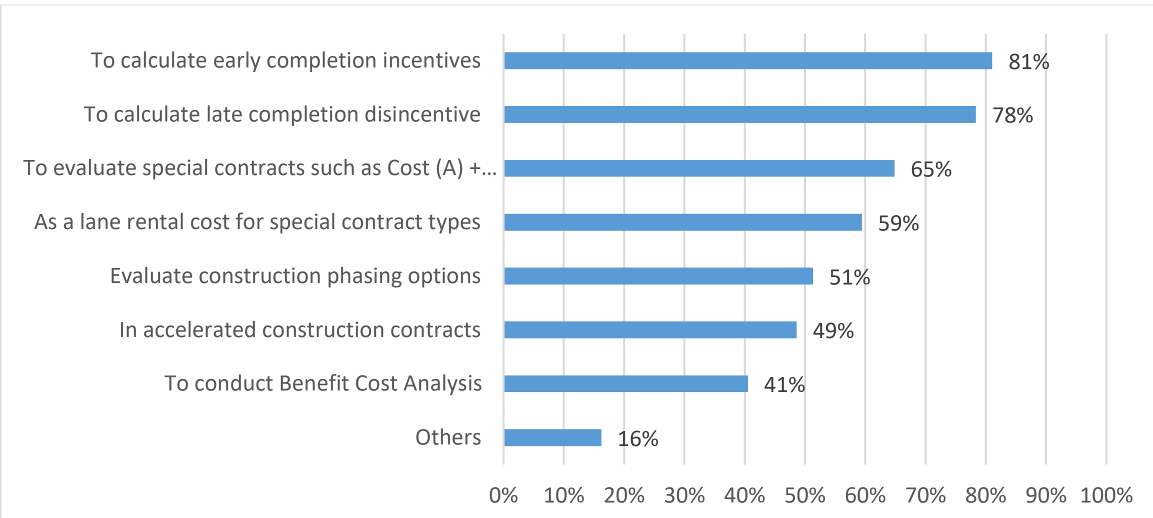


The significant use of RUC in the bidding and contracting stage of a construction project is explained in the application of the RUC section in chapter two, where Benekohal et al. (2003) express the use of RUC in deriving incentive/disincentives (I/D) and proposed liquidated damage for a project during the contracting phase. Furthermore, there has been the recent application of RUC in applying innovative contracting methods such as the A+B bidding method of awarding projects based on cost and time. Agencies such as Arkansas DOT, Michigan DOT, Mississippi DOT, New Jersey DOT, North Dakota DOT, Oregon DOT, and South Carolina DOT indicated the use of RUC in all three stages.

The survey inquired current application of the RUC in each state DOT. From the response, Figure 4, more than three-quarters of the DOT use the RUC to calculate early and late completion incentives and disincentives, such as liquidated savings for early completion and liquidated damages for late completion. This indicates the effective use of RUC as the basis of estimating incentive and disincentive in the contract bidding. The result shows that 81% of DOT use RUC when calculating early completion incentives. Furthermore, more than half of the DOT uses the RUC to evaluate and select special contracts such as cost (A) + time (B), lane rental cost, and construction phasing options. Simultaneously, less than half of the respondents use the RUC in accelerated construction contracts, such as no excuse bonus or locked incentives, and to conduct a cost-benefit analysis.

Figure 4

Current Application of RUC



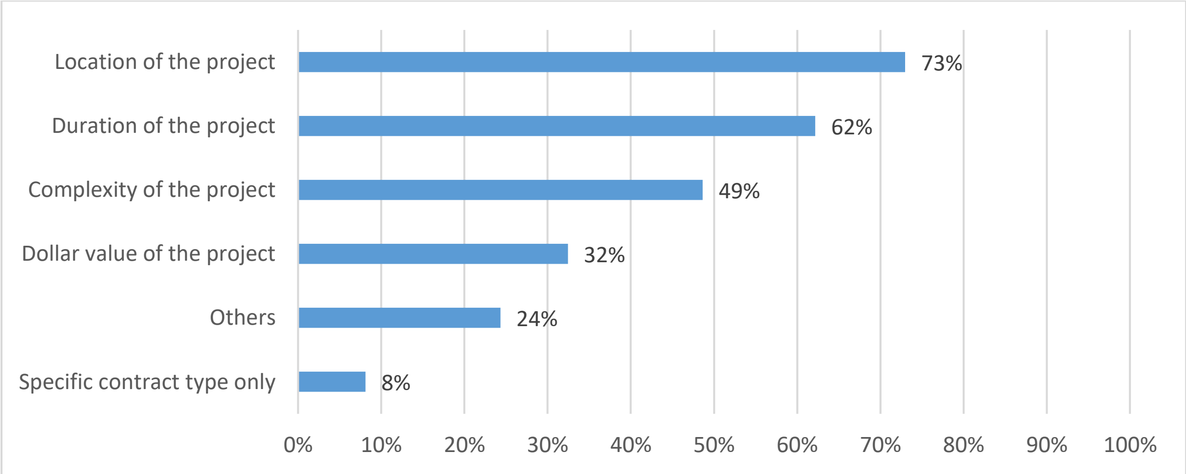
Arkansas DOT, Colorado DOT, New Jersey DOT, Oregon DOT, Virginia DOT, and Wisconsin DOT currently use the RUC in calculating all the options stated in the questionnaire. Oregon DOT further declares that their current use of RUC also varies by project.

Florida DOT, Indiana DOT, Maine DOT, Michigan DOT, and Washington DOT states other current use of road user costs in the department. For example, Florida DOT states that they currently use the RUC to calculate Damage Recovery- like the lane rental. Indiana DOT currently uses the RUC for Maintenance of Traffic (MOT) strategy selection if multiple strategies are viable and traffic is not to be fully detoured, crossed over, or diverted through a runaround. Maine DOT states that they currently use RUC to evaluate alternatives analysis, feasibility alternatives, and project prioritization, which is done in the planning stage. Michigan DOT further states that the RUC is used in the pavement type selection process, evaluating time to construct asphalt pavement versus a concrete pavement. Lastly, Wisconsin DOT states that they only use RUC to calculate life cycle cost analysis.

To conclude this section, the criteria used in determining the implementation of RUC were queried. More than half the respondents indicated that the project's location and duration are the criteria consider when considering the inclusion of RUC in the contract. The project's complexity also stands out as criteria compared to the dollar value of the project and the specific contract type, as shown in Figure 5. Seventy-three percent of the respondents indicated the project's location as the criteria considered for the inclusion of RUC. The location can be an essential criterion because state DOTs will likely consider evaluating the RUC in a contract bidding for an urban area or location with high traffic volume. This type of project will need to be completed on time to reduce the impact on road users.

Figure 5

Criteria used in determining the implementation of RUC



Michigan DOT, Minnesota DOT, and Washington DOT do not consider any of the options as criteria for the inclusion of RUC in a contract. However, Minnesota DOT and

Washington DOT indicate that there are other criteria they do consider. Minnesota DOT states that decisions about the criteria to be considered are often made on an ad-hoc basis but are applied to many projects as part of the contract development process. They further included that this criterion is determined and handled by the district project engineers. Alabama DOT, Iowa DOT, Maine DOT, Montana DOT, New Jersey DOT, South Carolina DOT, Utah DOT, and Washington DOT documented other criteria considered in implementing RUC for a project. Alabama DOT states that the DOT does not actively establish criteria to calculate RUC; however, they mainly calculate the RUC based on request and need. Maine DOT states that RUC is considered in the planning and programming phase, safety, and mobility projects. However, Michigan DOT and New Jersey DOT assert that the criteria to include RUC will always be based on any project that will impact road users. New Jersey DOT further states a reason for that criterion: the RUC will be included in all construction projects as part of liquidated damages. SCDOT notes that a primary criterion is for areas where construction could create a significant queue, particularly related to the nighttime work requirement. UDOT also notes that the lane restriction projects based on user cost are a criterion for the inclusion of RUC.

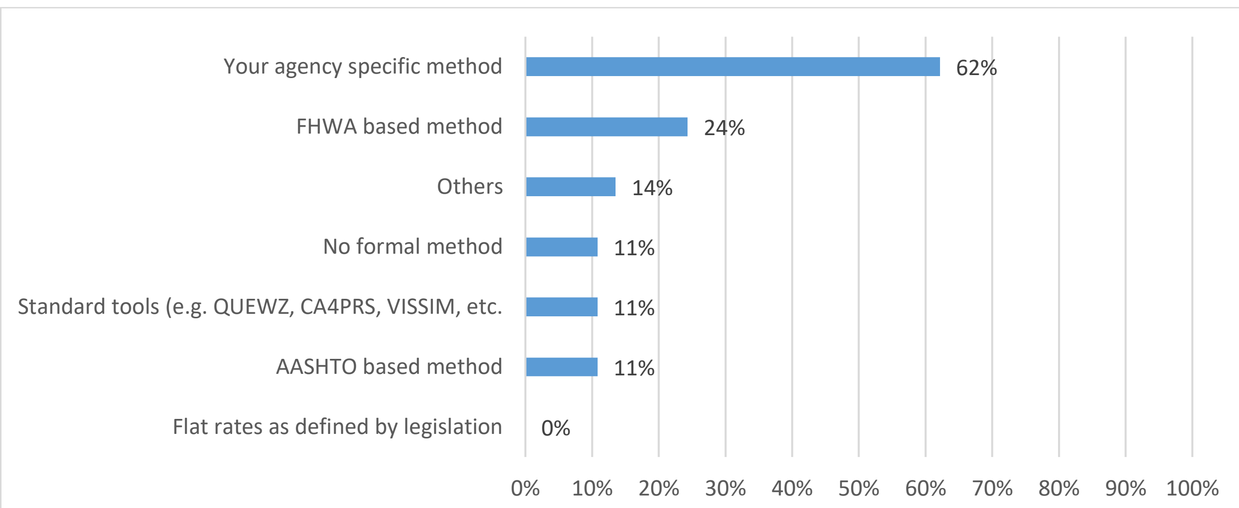
RUC Calculation Methodology

ASSTHO and FHWA, as highway agencies, have a base method for calculating RUC as many DOTs use these agencies' methodology to develop a framework methodology for their state or agency. However, since various state road user inconveniences will vary based on the different construction activities and measures during construction, state RUC calculation methodology would differ. Therefore, there is a need to investigate the different RUC methodology utilized. In Figure 6, a significant percentage, 62%, of the respondent indicates using their agency-specific methodology to calculate RUC, while the FHWA based method is used by 24% of the respondent to calculate the RUC. Furthermore, fewer respondents use the AASTHO and standards tools such as QUEWZ, CA4PRS, and VISSIM.

The agency-specific method's significant use can be explained based on the data variation for evaluation in various state geographical locations. As stated earlier, state DOTs and agencies would prefer to develop their specific methodology based on the data available in their location. Similarly, an explanation for why more state DOTs uses the FHWA based methods than the ASSTHO and other methods can be explained based on the comprehensive, updated, and ease of obtaining data methodology developed by the FHWA. However, some of the methods used are also obtained from the standard methods such as the Highway Capacity Manual and Highway Safety Manual and recommended for use by the FHWA.

Figure 6

Methodology Used to Calculate RUC

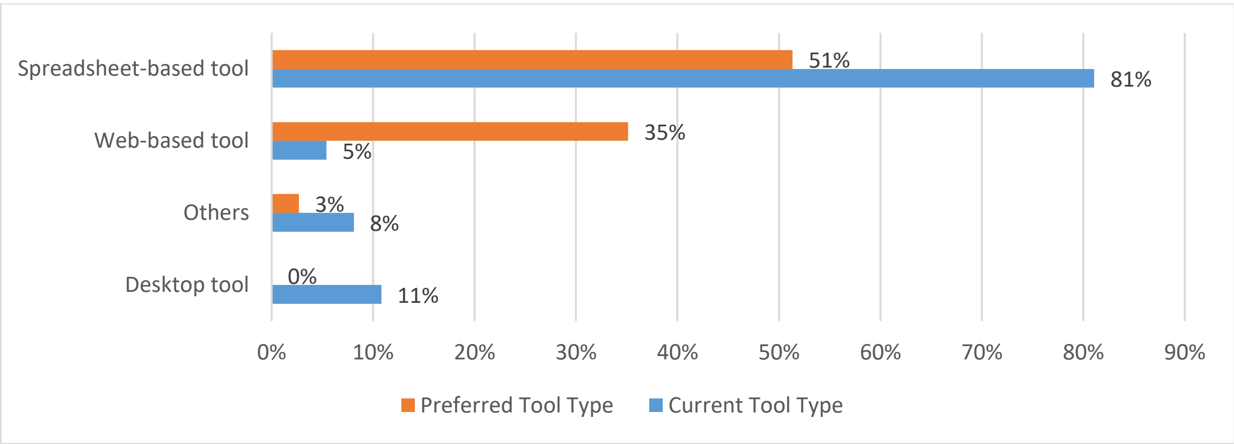


Alabama DOT, Maryland DOT, Michigan DOT, Minnesota DOT, Idaho DOT, and Ohio DOT provided more information on the RUC methodology used. Alabama DOT further clarifies that they use many of the given options, but the methodology is usually project-specific, based on physical constraints and public perception. Maryland DOT also explains that they use guidelines from the AASHTO Red Book for "value of time" calculations related to delay costs and FHWA guideline values for stopping and idling costs. Furthermore, they use the standard Internal Revenue Service (IRS) reimbursement rate to determine the cost per mile in terms of operating cost, whereas the IRS reimbursement rate is a government standard rate generated yearly for business, charity, and medical trips cost of automobile operation. Michigan DOT also notes the use of an Excel-based sheet and further describes the tool as a Construction Congestion Cost (CO^3) which measures the impact of congestion and compares to construction cost (Robert, 1998). Idaho DOT state the use of Work zone (WZQ) pro-Excel, which computes work zone capacity, speed, queue length, delay, and users cost as a basis to develop RUC calculation. Ohio DOT also states the use of an Excel spreadsheet based on matching Permitted Lane Closure Segment (PLCS) for calculating the user cost.

In terms of the various tools used in various DOTs, 81% of the responding state DOTs currently use a spreadsheet-based tool (Excel-based) for their RUC calculation, while less than two-fifths of the state DOTs use a web-based method and a desktop tool, as shown in Figure 7. The extensive use of a spreadsheet-based tool can be understood because of the ease of updating data attribute in the work zone. Figure 7 also compares the current use tool against the preferred tool type by the state DOTs. From the response, over half of the responding DOTs prefer the spreadsheet-based tool, whereas one-third of the DOTs prefer the web-based tool, and none of the DOTs prefer the Desktop tool. Most DOTs are moving from desktop-based tools to web and spreadsheet-based tools, as seen in other construction tools such as the AASHTOWare. This is because the desktop-based tools used are fixed to only a user with the desktop installation, whereby the tool cannot be accessed from multiple computers unless installed. Most desktop tools also require an extensive cost when undergoing an update, and the analyst will always need to install updated versions to derive accurate estimation, unlike the web-based and spreadsheet that can be updated without a new installation. From the response, states DOTs that indicated the current use of a web-based tool include Colorado DOT, Indiana DOT, and Virginia DOT. Florida DOT, Maryland DOT, Rhode Island DOT, and Virginia DOT indicated the current use of a desktop tool, while Alabama DOT, Hawaii DOT, Oregon DOT are the only states that indicated the "others" option because they do not have a systematically developed tool for now.

Figure 7

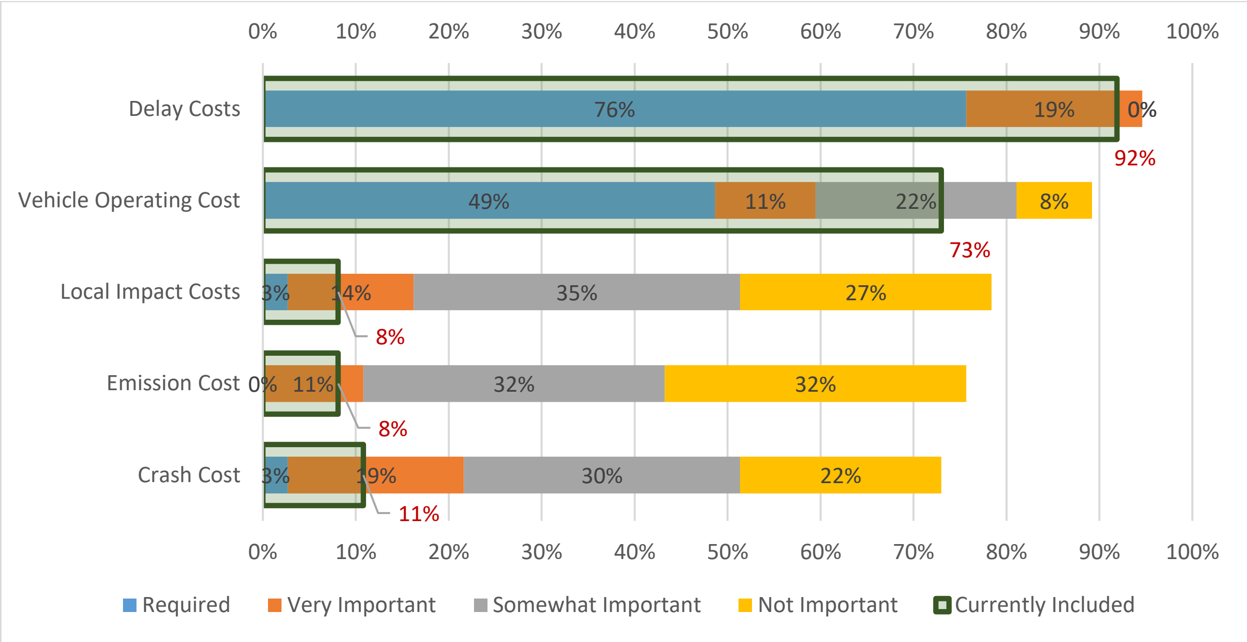
Current RUC Method/Tool



As discussed in the literature review section, the road user cost is calculated based on five components: Delay cost (DC) involving the road users' value of time, Vehicle Operating Cost (VOC), Crash Cost (CC), Emission Cost (EC), and Local and Business Impact Cost (LBIC). From the survey response shown in Figure 8, more than half of the respondent indicates that the DC and the VOC are a required component to consider when calculating the RUC. More than two-thirds of the state DOTs currently include them in their RUC calculation. The respondent further indicates that the crash, emission, and local impact costs are not necessarily required. No respondent indicates the EC as a required component to consider when calculating the RUC. However, 11% of the respondents currently include the CC, while 8% include the local impact and EC when calculating the RUC. The chart showing the various state DOTs and the components included in their methodologies are shown in the appendix (see Appendix A, Table A.15).

Figure 8

Component Included in RUC Calculations

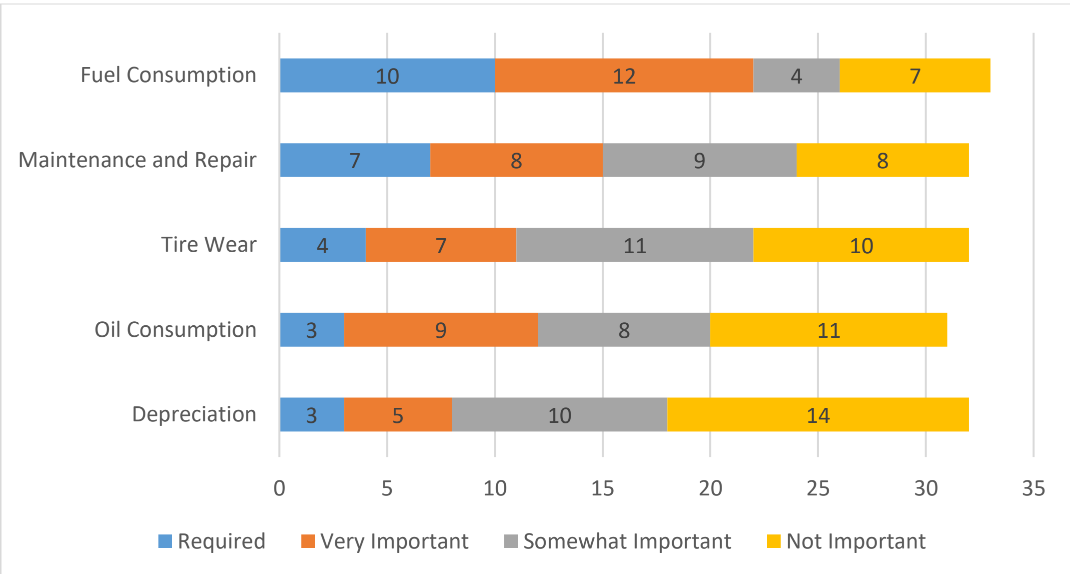


The DC is the most significant component required and included in the RUC calculation by nearly all the state DOTs. This can be understood because the DC accounts for the delay incurred by road users based on the construction operation and duration. The RUC is developed to be used in alternative contracting bidding as an incentive/disincentive for early and late time completion to reduce construction time and save cost. Therefore, the DC accounts for all delays incurred by road users involving stopping, queueing, and detouring caused by construction activities. Simultaneously, the vehicle's operating cost is significant as it also accounts for the cost of vehicle operation during delays in the work zone. The cost is associated with the VOC incurred during delays includes stopping and idling costs and excess operating costs when taking a detour.

The VOC is divided into the fuel component and the non-component, including the maintenance and repair, tire wear, oil consumption, and depreciation, as discussed in the literature review section. However, when considering the VOC in calculating the RUC, most of the responding DOTs, as shown in Figure 9, indicate that the fuel component is the most required component to estimate the VOC. This is because the fuel component accounts for a more significant percentage of the VOC (Sinha & Labi 2011).

Figure 9

Vehicle Operating Component

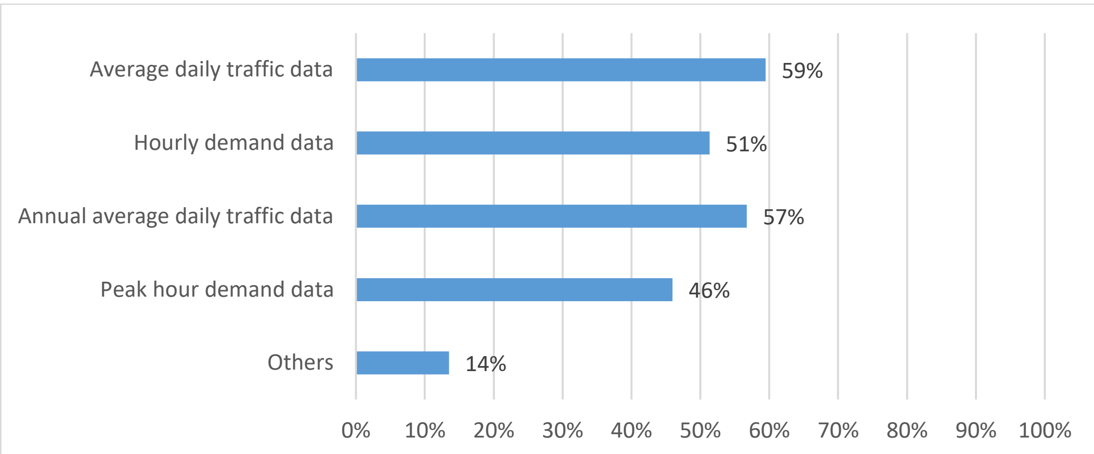


Data Requirements for Road User Costs

This session intends to gather the types of traffic composition and work zone configuration used and observed by the state DOTs in developing their methodology to calculate the road user cost. This intends to assist readers and analysts with knowledge of basic data input that can be used to create an RUC methodology and help other state DOTs improve on their present methods. The questions were based on the FHWA's data requirements for work zone RUC mobility analysis (Mallela & Sadavisam, 2011). In terms of traffic data used by state DOTs for RUC, traffic volume data used by most state DOTs include the Average daily traffic (ADT), the Annual average daily traffic (AADT), and Hourly demand data. They are indicated by more than half of the state DOTs, with the ADT and AADT having a significant percentage, as shown in Figure 10 below.

Figure 10

Traffic Data used for RUC Calculation



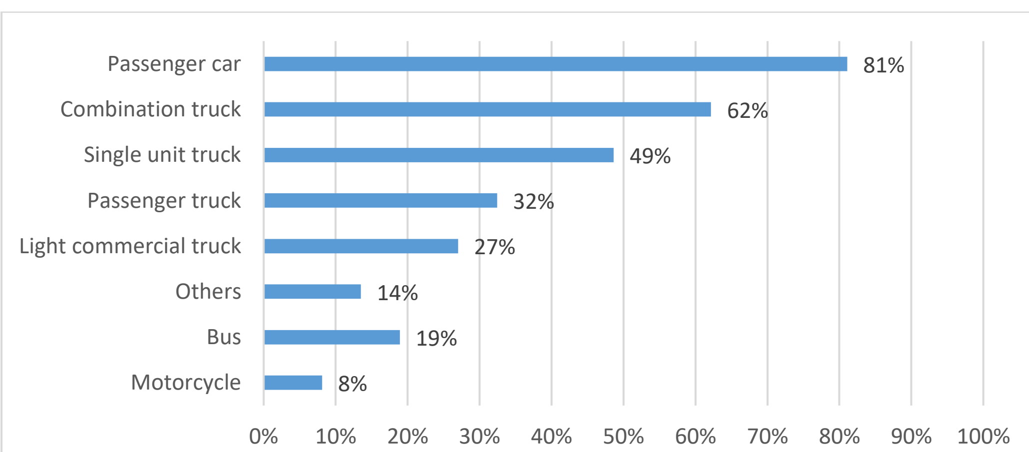
According to Carter et al. (2017), The ADT is the traffic volume count to reflect the daily traffic volume for the day it is collected. It is further expressed as the daily traffic volume counted for 24 hours in a day. In contrast, the AADT is the average number of traffic passing a roadway in either a single or both directions for all the days in a year. The AADT accounts for a particular year of traffic data. Mallela and Sadavisam (2011) describe the hourly demand data as the hourly distribution of traffic through a road segment in a single direction under a normal free flow condition in 24 hours. The hourly demand data can be derived from the ADT of the road segment. The Peak hour demand derives the highest traffic volume in a particular hour distribution through the hourly distribution or demand data. The hourly distribution and the peak hour demands are used in the DC to estimate delay accounting for queue delay, stopping, and idling delay based on detailed traffic analysis. The ADT and the ADDT traffic volume data are easy to derive and integrate with the RUC calculation to develop a simple methodology. This could be the reason why the state DOTs mostly use the ADT and the AADT.

Maine DOT further states that they do add the Vehicle miles travel (VMT) and the Vehicle hour traveled (VHT) in their RUC calculation. Minnesota DOT explains that most analyses that the DOT conducts rely on average daily traffic data, typically adjusted for seasonality as hourly or peak-hour demand data are used infrequently but may be employed where an additional level of detail is required. Maryland MDOT explains that daily traffic data is mostly considered, as the goal is to calculate a dollar amount per day. They also consider the hourly demand when evaluating lane closure and peak hour demand data when evaluating congestion-related delay. Oregon DOT also describes that the traffic data used depends on the project scenario.

The vehicle composition is an integral part of the traffic data. The vehicle composition describes the various vehicle type in the traffic stream. As seen in Figure 11 below, the passenger car and trucks are mostly considered by the state DOTs. However, most DOT would consider the vehicle composition based on the traffic count or data available.

Figure 11

Vehicle Traffic Composition Considered in Calculating RUC

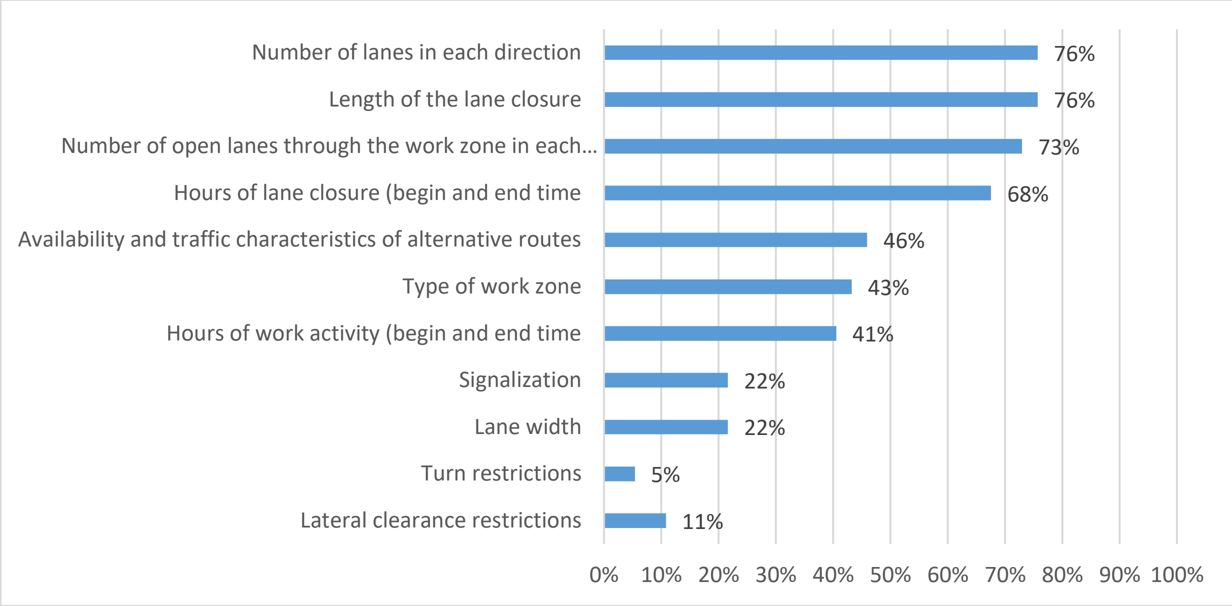


FHWA reports categorized the traffic composition into different classes ranging from passenger cars to combination trucks (Mallela & Sadavisam 2011). Maryland DOT states that they consider two vehicle types - automobiles (including FHWA classes 1-3) and trucks (including FHWA classes 4-13) for their calculation. Mississippi DOT also considered the passenger vehicle and truck data based on the FHWA classification scheme. Maine DOT and New Jersey DOT noted that they group all the 13 classifications into "cars" and "trucks." South Carolina DOT, Missouri DOT, and Michigan DOT consider the “motorcycle” traffic in their RUC calculation.

The work zone configuration inputs to calculate the RUC estimation were inquired. More than three-fourths of the responding states indicated the number of lanes in each direction, and work zone lane length is required as an input to calculate RUC. Most states' DOT also chooses the number of the opened lane through the work zone in each direction as an input, as shown in Figure 12. This is to acknowledge that the number and length of the lanes in the work zone are required input for work zone calculation.

Figure 12

Work Zone Configuration Inputs to Calculate RUC



More state DOTs consider lane closure (begin and end time) for time input consideration than work activity hours (begin and end time). This could be explained as hours of lane closure accounts for the hourly distribution of vehicles and will generate traffic delays such as queuing and stopping. The hours of work activity are considered as the construction duration. However, most state DOTs aim at calculating a dollar amount per day to be used as a value for incentives and disincentives. The type of work zone is considered an input when the DOT considers the various work zone conditions such as a temporary lane closure, flagging operation, and temporary signal. However, RUC can be calculated separately for this work zone condition as DOTs will identify the work zone types in the module for calculation but not necessarily an input.

FHWA defines the work zone capacity as the maximum flow volume whereby a vehicle can transverse through a work zone segment at a particular time under the work zone condition type (Mallela & Sadavisam, 2011). They further expressed that it can be categorized as passenger cars per hour per lane (pcphpl) or vehicles per hour per lane (vphpl). Twenty-five respondents indicated the vehicles per hour per lane (vphpl) as input for work zone capacity, while five state DOTs indicate passenger cars per hour per lane (pcphpl), as shown in Figure 13 below. In investigating the methods to estimate work zone capacity, as shown in Figure 14, over one-third of the respondents indicated using their agency-specific estimating method to evaluate work zone capacity. 27% of the respondent indicates the use of Highway Capacity Manual (HCM) which provides a guideline to evaluate the reduction capacity and traffic behavior in the work zone area. While 11% of the responding state DOTs indicated, they prefer to use the work zone capacity model, which provides a methodology based on various previous work zones studied from the same or different states.

Figure 13

Input for Work Zone Capacity

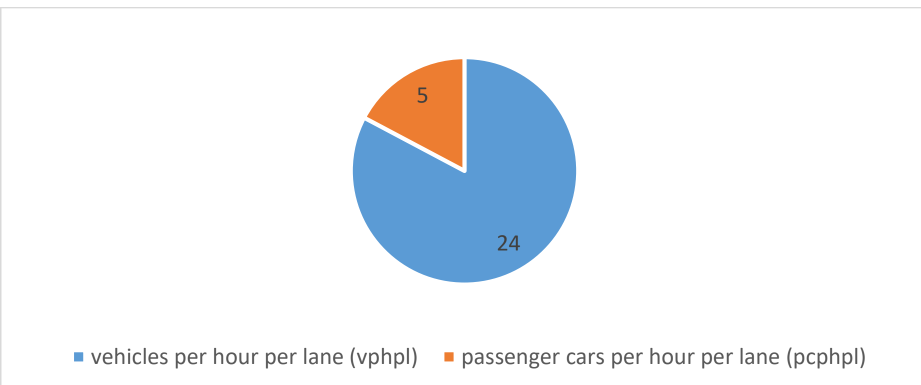
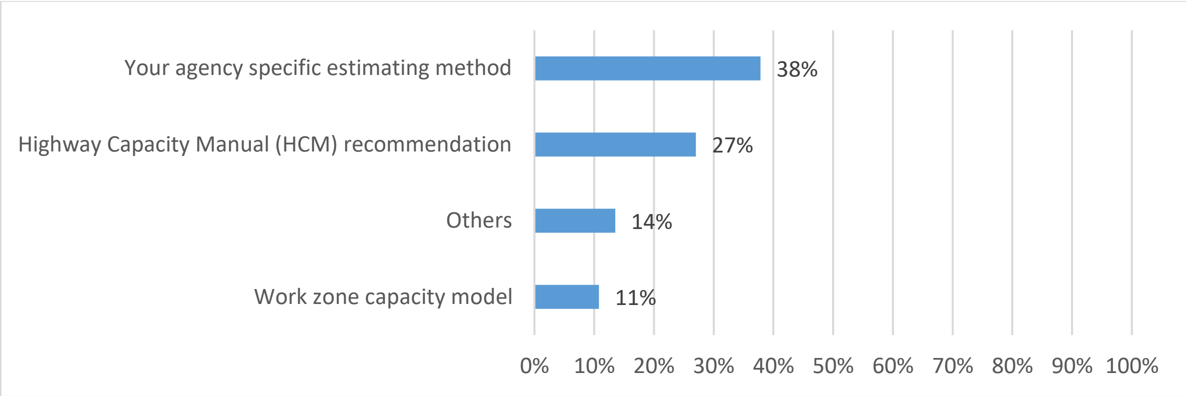


Figure 14

Methods to Estimate Work Zone Capacity



Additionally, some state DOTs noted other methodology used to estimate work zone capacity. For example, Maine DOT reported that they use a spreadsheet model and sim traffic. The sim traffic is a microscopic model used to simulate traffic operations and behavior in the work zone environment. Mississippi DOT also noted that they use a microsimulation model to estimate work zone capacity. However, FHWA states that the microsimulation model provides a more precise estimate than the spreadsheet model (Mallela & Sadavisam, 2011). Virginia DOT noted that they use the combination of HCM, statewide research studies, and Metropolitan Washington Council of Governments (MWCOG) Regional Travel Demand Forecasting Model inputs classified by Route Type, Area Type, and District. Finally, Washington DOT noted that they use the FHWA real cost to estimate work zone capacity to account for components such as stopping delay and queue delay even though they do not estimate to consider the road user cost.

Further Discussions

Further discussion and recommendations were stated and expressed in the survey response and are discussed and summarized in this section.

From the response, most state DOTs assert a need to improve the current practice of calculating and utilizing RUC in their state. They suggested that a way to improve the current practice is to have a more consistent methodology with corresponding and liable value around the state's transportation departments, which can be achieved by updating the standard dataset while making use of reliable transportation and highway publications such as the FHWA, ASSTHO, AAA, and ATRI to derive updated dataset for various RUC components to be considered in the calculation.

Furthermore, other state DOTs expressed that they would like to improve the RUC calculation practice by accounting for various scenarios such as full lane closure, partial lane closure, detour, flagging, idling, stopping, and reduced speed. However, extensive data are needed to consider such multiple scenarios, and most DOTs do not have access to relevant data for estimating RUC based on those scenarios as some DOTs argue that they would only like to estimate the RUC based on the dataset easily available; further expressing that most of the method to calculate RUC is based and tailored to the needs of the department which is based on the scenario at work zone and availability of time to compute and estimate RUC for each study. In other recommendations, some DOT recommended integrating real-time data in the work zone into the RUC calculation. For example, Oregon DOT expressed that they are working on integrating observed speed data, such as the Regional Integrated Transportation Information System (RITIS), an automated data sharing system that shares situational alertness, performance measure, and real-time data feeds to estimate their RUC calculation. In addition, state DOT such as Maryland DOT would like to consider estimating work zone capacity to integrate with their RUC methodology to enhance effective results. However, most state DOTs are in the interest of making efforts to have a streamlined, clean, and more standard RUC calculation tool.

In terms of RUC tools, most state DOTs expressed that despite the satisfaction with their spreadsheet, it can be buggy and extensive sometimes. Therefore, they expressed that they would like to correct this by having an updated and easy-to-use program or spreadsheet with a user manual and training to be provided for their engineers. South Carolina DOT, Delaware DOT, Kentucky TC, and Arkansas DOT stated they are currently updating their RUC program or spreadsheet for better and effective results.

Chapter 5. Development of RUC Framework

This section presents an improved methodology to compute RUC. The methodology is developed based on previous studies discussed in the literature review section and feedback from the nationwide survey. This methodology proposes changes to resources and data to estimate the various costs and is intended to improve the current methodology used by many states. The framework is developed based on the ease of assessing data attributes around the work zones.

The framework accounts for four components of the RUC, namely a.) Delay cost (DC) b.) Vehicle operating cost (VOC), c.) Crash cost (CC) and d.) Emission cost (EC). Furthermore, the framework estimates the RUC considering the additional costs experienced in the work zone environment compared to the base condition when there is no work zone based on the four components.

Delay Cost (DC)

The DC is expressed as the excess cost incurred by motorists and road users due to time loss when passing through work zones or an alternative route. The DC is estimated by considering the travel delay time or excess delay time, the value of time of road users, traffic data and type of input for work zone capacity, and the average vehicle occupancy factor. The total DC is therefore estimated by accounting for the sum of DC experienced by different vehicle types driving through the work zone environment expressed in Equation ***5-1*** below:

$$Delay\ Cost = \sum(D_{per\ vehicle} \times VOT_{per\ vehicle} \times AADT) \qquad \textbf{5-1}$$

Where:

VOT = hourly value of time per vehicle

$D_{per\ vehicle}$ = Delay per vehicle

AADT = Annual Average Daily Travel

Value of Time (VOT)

The VOT is an essential component to estimate the DC. It is attributed to the hourly dollar value of road users based on the median annual income, wage rate, compensation, and benefit. It further considers the road users' trip modes and travel purposes to accurately estimate the dollar value of each road user. Therefore, in estimating the DC, the value of time is to be derived first.

Estimating Value of Time (VOT)

The estimation of the VOT is based on the FHWA recommend procedures and values. Estimation of the VOT for road users first considers the road user's transportation mode in terms of vehicle types by deriving the traffic composition in the work zone. Next, the hourly dollar values of the passengers based on the wages, benefits, and compensation are considered in terms of trip mode and travel purpose, in addition to the average vehicle occupancy to account for each vehicle's time value. Estimation of the VOT for auto and truck vehicle types is further illustrated in the chart below (see Figure 15 and Figure 16)

Figure 15

Framework to Estimate Auto Vehicle Type VOT

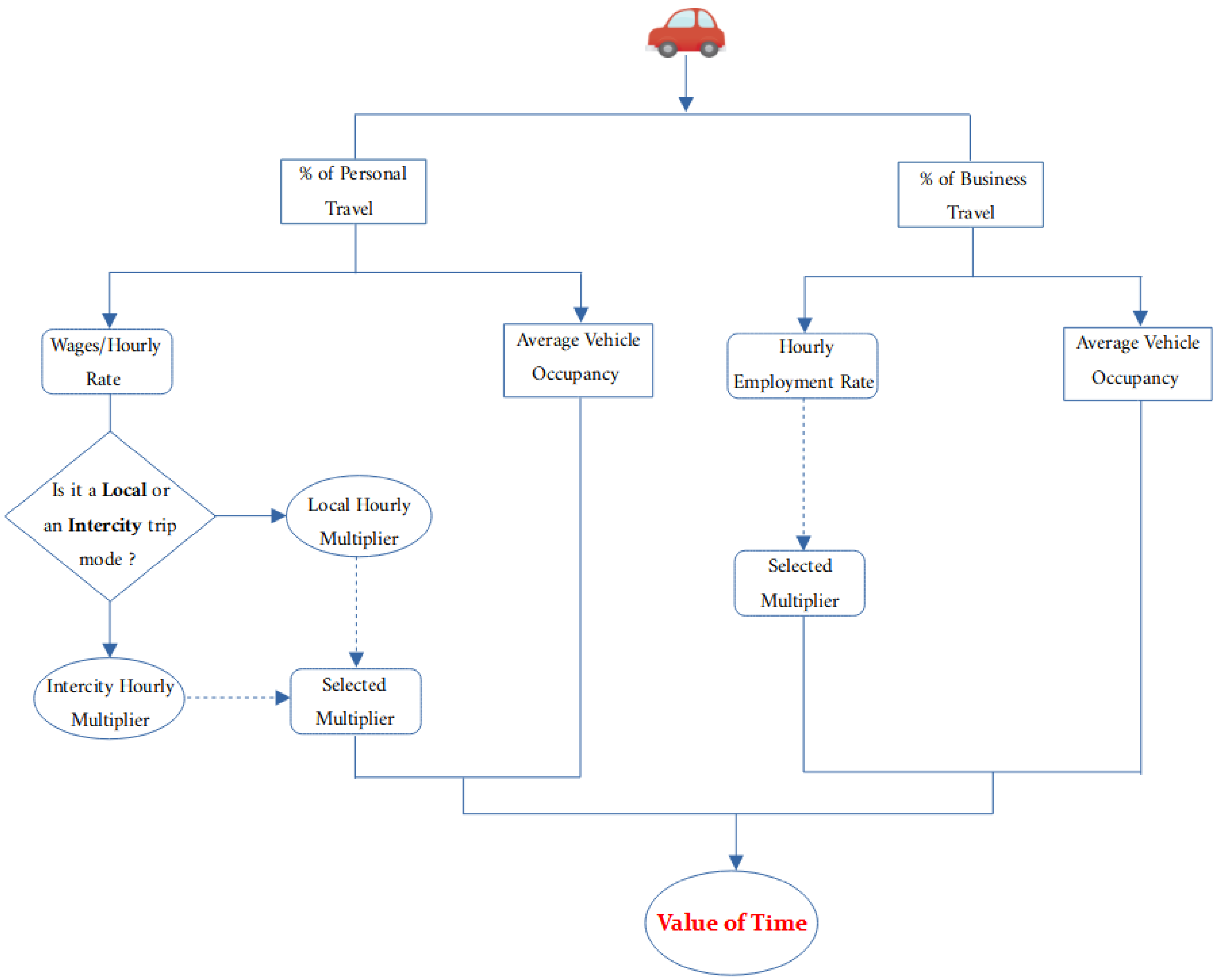
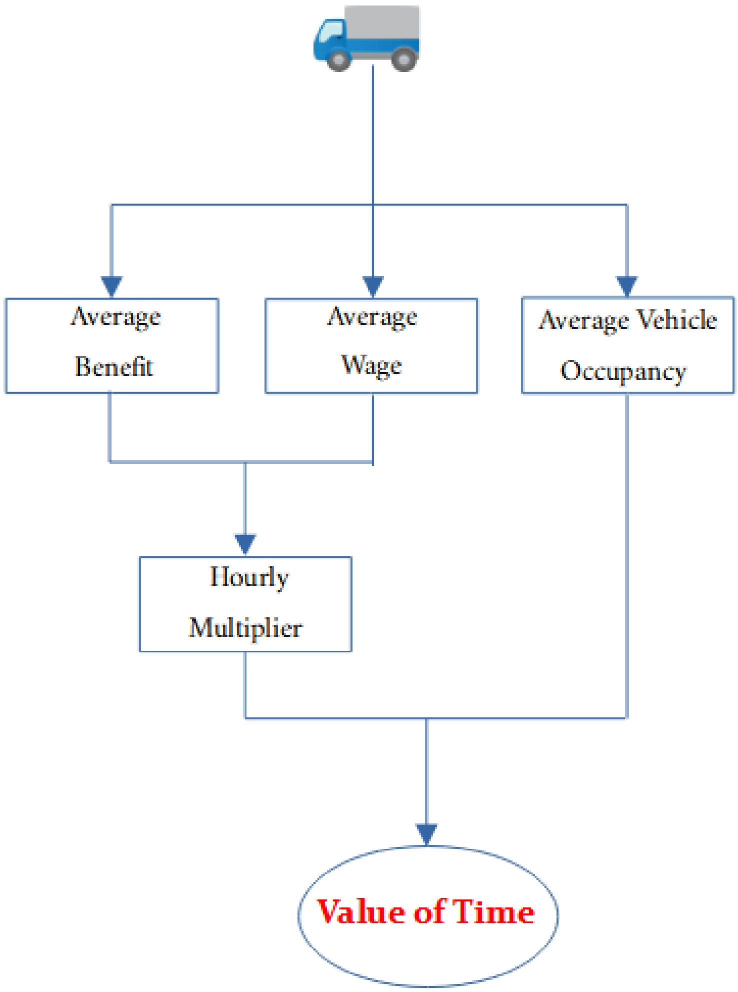


Figure 16

Framework to Estimate Truck Vehicle Type VOT



Auto Vehicle Type

For a passenger car or auto vehicle, the VOT is estimated by accounting for the percentage of AADT of cars on two different trip types or purposes, expressed as personal travel trips and business travel trips.

Estimating Personal Trip Purpose

The VOT for the percentage of AADT on a personal travel trip is estimated by deriving the average annual median household income based on the location specification of the work zone and converted to an equivalent hourly income. It is further estimated to an hourly rate per person by multiplying equivalent hourly income with the percentage of wages for the value of time based on the trip mode (Intercity or local trip) expressed as the hourly multiplier as shown in Figure 15. The hourly rate per person is further estimated to account for the passenger in the vehicle by multiplying the hourly rate per person with the average vehicle occupancy factor to derive the hourly time value of a passenger car type. It is further expressed in Equations ***5-2*** to ***5-4*** below.

$$HEI = \frac{Median\ Household\ Income}{2080} \quad \textbf{5-2}$$

$$HR_{Per\ person} = HEI \times Wm_{Local\ or\ Intercity} \quad \textbf{5-3}$$

$$HTV_{for\ all\ passengers} = HR_{Per\ person} \times AVO \quad \textbf{5-4}$$

Where:

HEI = Hourly Equivalent Income

$HR_{Per\ person}$ = Hourly rate per person

$Wm_{Local\ or\ Intercity}$ = Wage multiplier based on either local or intercity trip mode

AVO = Average vehicle occupancy factor

$HTV_{for\ all\ passengers}$ = Hourly time Value for car accounting for all passengers in the vehicle

Estimating Business Trip Purpose

The business travel trip estimation uses the hourly employment cost based on location dollar value or a national value, further estimated to the hourly rate per person based on the wages, compensation, and benefits by multiplying with the percentage of wages for the value of time based on the trip mode (Intercity or local trip), also expressed as the hourly multiplier shown in Figure 15 to estimate the hourly rate per person. The hourly rate per person is further multiplied with the average vehicle occupancy factor to account for the hourly time value of the passenger car type based on a business trip. It is further expressed in Equations ***5-5*** and ***5-6*** below.

$$HR_{Per\ person} = HEC \times Wm_{Local\ or\ Intercity} \quad \textbf{5-5}$$

$$HTV_{for\ all\ passengers} = HR_{Per\ person} \times AVO \quad \textbf{5-6}$$

Where:

$HR_{Per\ person}$ = Hourly rate per person

HEC = Hourly employment cost

$Wm_{Local\ or\ Intercity}$ = Wage multiplier based on either local or intercity trip mode

AVO = Average vehicle occupancy factor

$HTV_{for\ all\ passengers}$ = Hourly time Value for auto accounting for all passengers in the vehicle

Note, For Auto vehicles, the wage rate and hourly employment rates are estimated based on the Trip mode (local and intercity) and the Trip purpose (personal travel and business travel) to effectively allocate the value of time.

Truck Vehicle Type

For the Truck vehicle type, the VOT is estimated by considering the average wages and benefits of the truck drivers based on the truck type, either light or heavy truck and tractor. The truck vehicle estimation accounts for trip mode and purpose based on only in-vehicle business and excess (waiting time) in business, having the hourly percentage value of time of 100% as the recommended percentage value of time as the hourly multiplier based on the trip mode and purpose table shown in appendix (see Appendix A, Table A.12). The truck driver's average wages and benefits based on the selected multiplier are multiplied with the average vehicle occupancy factor to account for the hourly time value of the truck vehicle. The value of time calculation for **TRUCK** vehicle type is therefore expressed in Equations ***5-7*** and 5-***8***:

$$HR_{Per\ person} = (AW + AB) \times Wm_{Local\ or\ Intercity} \quad \textbf{5-7}$$

$$HTV_{for\ all\ passengers} = HR_{Per\ person} \times AVO \quad \textbf{5-8}$$

Where:

$HR_{Per\ person}$ = Hourly rate per person

$Wm_{Local\ \&\ Intercity}$ = Wages multiplier for local and intercity trip mode

AW = Average wage

AB = Average Benefit

AVO = Average vehicle occupancy factor

$HTV_{for\ all\ passengers}$ = Hourly time Value for auto accounting for all passengers in the vehicle

Estimating VOT Based on an All-Trip Mode

In developing the methodology, consideration was put in place to account for the difficulty of an analyst allocating the AADT into the different trip modes to account for the different trip mode VOT (i.e., to determine if the road users are traveling through a local or and intercity mode). Considering this type of scenario, an option to calculate the hourly VOT based on "All trip modes" was created. Therefore, All-trip mode value is derived by taking the average of trip mode based on the trip purposes as expressed in Equations ***5-9*** and ***5-10*** below.

Hourly Value of Time for All Trip Mode:

$$For\ Personal\ Trip\ Purpose = \frac{HTV_{Intercity} + HTV_{Local}}{2} \quad \textbf{5-9}$$

$$For\ Business\ Trip\ Purpose = \frac{HTV_{Intercity} + HTV_{Local}}{2} \quad \textbf{5-10}$$

Where:

$HTV_{Intercity}$ = Hourly VOT based on intercity travel mode

HTV_{Local} = Hourly VOT based on local travel mode

Estimating the Delay Time

In estimating the delay time, this methodology considers two scenarios of travel in the work zone to estimate the DC. The DC involves the delay caused by an additional time of vehicles passing through the work zone in comparison to the absence of a work zone and the delay caused by the vehicles taking a detour.

Delay Time Based on Vehicles not Taking a Detour

In estimating the delay time for this scenario, the time taken to travel the original route without the work zone and the time taken to travel through the work zone based on the distance and posted speed limits for the work zone is derived and differentiated. The difference in the estimation is the excess additional travel time or delay time. It is further expressed in Equations ***5-11*** to ***5-13***

$$T_{without\ work\ zone} = \frac{L_{work\ zone}}{S_{pre-work\ zone}} \times 60\ (mins) \qquad \textbf{5-11}$$

$$T_{with\ work\ zone} = \frac{L_{work\ zone}}{S_{work\ zone}} \times 60\ (mins) \qquad \textbf{5-12}$$

$$D_{per\ vehicle} = T_{without\ work\ zone} - T_{with\ work\ zone} \qquad \textbf{5-13}$$

Where:

C	= Classes of vehicle (Auto and Truck)
$L_{work\ zone}$	= Length of work zone
$S_{pre-work\ zone}$	= Posted speed limit for original roadway when there is no work zone
$S_{work\ zone}$	= Work zone speed limit
$T_{without\ work\ zone}$	= Time taken to travel without the work zone
$T_{with\ work\ zone}$	= Time taken to travel along the work zone
$D_{\text{per vehicle}}$	= Delay time for vehicles

Delay Time Based on Vehicles Taking a Detour

In estimating the delay time based on the vehicles taking a detour, the time taken to travel the original route without the presence of a work zone based on the distance and the posted speed limit is derived and differentiated from the time taken to travel along the detour based on the distance and the posted speed limit of the detour route. The difference in the estimation is the additional travel time or delay time. This is further expressed from Equations ***5-14*** to ***5-16*** below.

$$T_{without\ work\ zone} = \frac{L_{route\ pre-work\ zone}}{S_{pre-work\ zone}} \times 60\ (mins) \qquad \textbf{5-14}$$

$$T_{through\ detour\ route} = \frac{L_{detour\ route}}{S_{detour\ route}} \times 60\ (mins) \qquad \textbf{5-15}$$

$$D_{per\ vehicle} = T_{without\ work\ zone} - T_{through\ detour\ route} \qquad \textbf{5-16}$$

Where:

$L_{route\ pre-work\ zone}$ = Length of the original route without the presence of work zone

$S_{pre-work\ zone}$ = Posted speed limit for original roadway when there is no work zone

$L_{detour\ route}$ = Length of the detour route

$S_{detour\ route}$ = Speed limit at detour route

$T_{without\ work\ zone}$ = Time taken to travel without the work zone

$T_{through\ detour\ route}$ = Time taken to travel through the detour route

$D_{\text{per vehicle}}$ = Delay time for vehicles

Therefore, the delay time based on vehicle taking a detour when there is a work zone and not taking a detour (i.e., vehicles passing through the work zone) is multiplied by the hourly time value of money to derive the DC based on vehicle taking a detour.

Estimating the Delay Cost Based on the Delay Time

The DC is estimated using the hourly time value expressed as the VOT of each vehicle type to quantify the delay time experienced into a dollar value. Therefore, the additional delay time based on the two scenarios described above (see. Equation ***5-13*** and ***5-16***) is multiplied by the hourly time value of money for each vehicle type (see. Equation ***5-6*** and ***5-8***) to derive the DC. This is further expressed below in Equations ***5-17*** to ***5-19***:

Based on the Vehicles Taking a Detour and not Taking a Detour

$$DC_{per\ vehicle} = \sum_{C_1}^{n} \frac{D_{per\ vehicle} \times HTV_{for\ all\ passengers}}{60} (hrs) \quad \textbf{5-17}$$

$$DC_{per\ day} = DC_{per\ vehicle} \times \sum_{C_1}^{n} AADT_{taking\ detours\ /\ not\ taking\ detour} \quad \textbf{5-18}$$

$$DC_{per\ construction\ day} = DC_{per\ day} \times construction\ duration \quad \textbf{5-19}$$

Where:

C	= Classes of vehicle (Auto and Truck)
$HTV_{for\ all\ passengers}$	= Hourly time value for auto accounting for all passengers in the vehicle
$DC_{\mathrm{per\ vehicle}}$	= Delay cost per vehicle
$AADT_{taking\ detours}$	= Percentage vehicles taking detours
$DC_{per\ construction\ days}$	= Delay cost per work zone duration

Therefore, the DC based on the two scenarios is added together to account for the total delay cost as expressed below Equation ***5-20***.

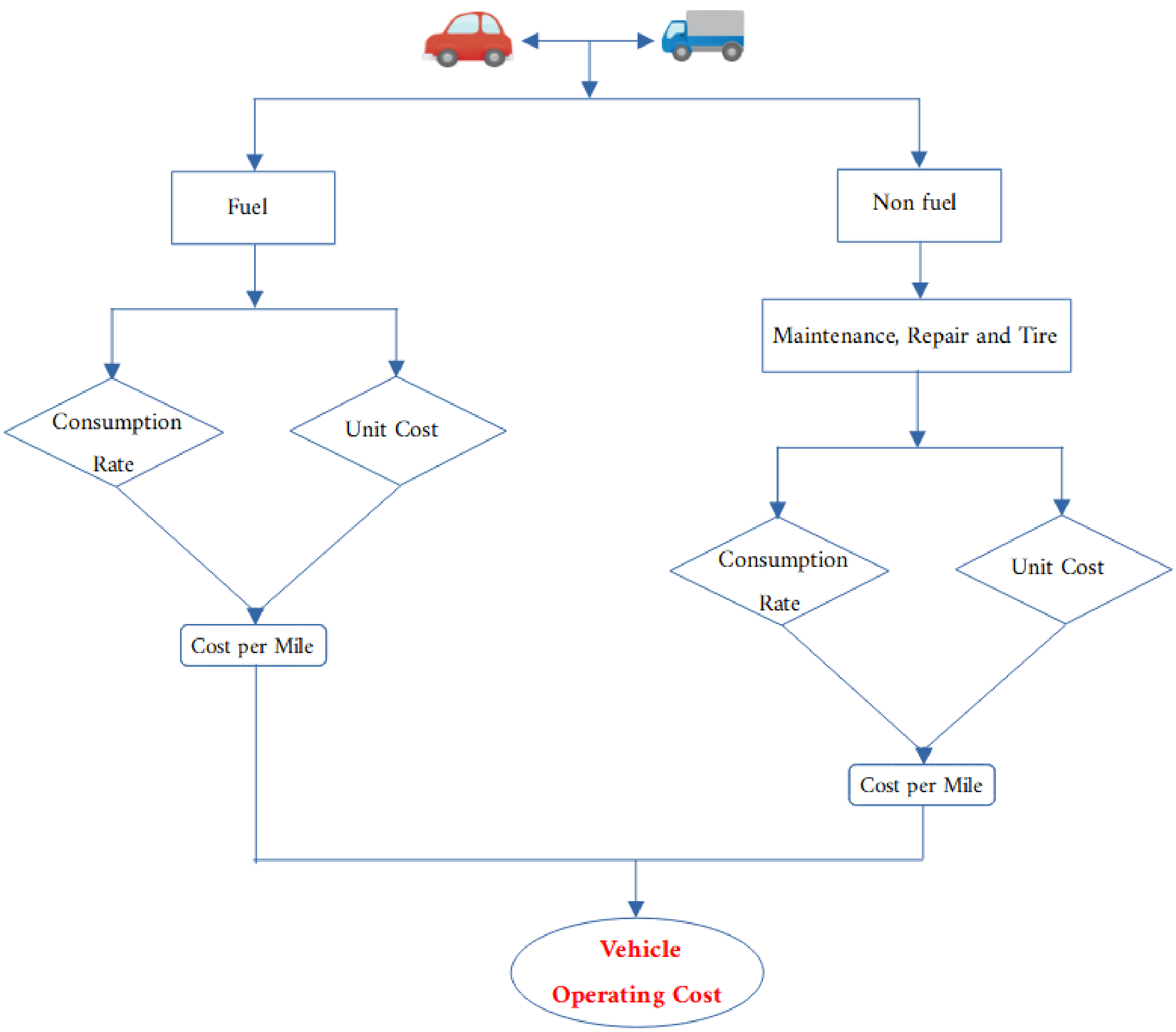
$$Total\ delay\ cost = Delay\ cost_{\ vehicles\ not\ taking\ a\ detour} + Delay\ cost_{\ vehicles\ taking\ a\ detour} \quad \textbf{5-20}$$

Vehicle Operating Cost (VOC)

The VOC is the additional cost associated with vehicles' use for more extended periods when driving through the work zone, based on vehicle idling, slowing movement, and halting due to the work zone configuration. In addition, the operating cost considers the fuel and the non-fuel component of vehicles travelling through the work zone. The fuel component considers the fuel unit price for different vehicle types and the fuel consumption rate. While the non-fuel component consists of the consumption rate in terms of tire wear, engine oil consumption, and repair and maintenance with the derivation of each component's unit cost. Therefore, each category's consumption rate and unit cost are derived to estimate the operating cost per mile for each vehicle type. The framework to estimate the VOC is further illustrated in Figure 17 below.

Figure 17

Framework to Estimate VOC



The estimation of the operating cost is based on two procedures. The operating cost for the vehicle types can either be derived using the AASHTO or the American Automobile Association (AAA) and The American Transportation Research Institute (ATRI) procedures, depending on the user's preference. Using the AASTHO methodology only estimates the operating cost based on the fuel component. In contrast, the AAA-ATRI methodology estimates the operating cost based on the fuel component and non-fuel component.

The AAA-ATRI methodology uses the data provided by the AAA and ATRI publications. The AAA is an organization that publishes the actual cost of owning and driving a vehicle in the United States, and it is updated yearly *(AAA, 2019*). The publication records the operating cost in terms of fuel cost and non-fuel cost. The fuel cost comprises various fuel types based on multiple vehicle auto classes, while the non-fuel cost comprises the maintenance, repair, and tire cost. It is also based on the different vehicle auto classes. ATRI also publishes a survey of various analyses of operational costs for the trucking industry to provide accurate data for their members. The research and surveys are continuously published and updated yearly (Murray & Glidewell, 2019). The survey publishes the estimated operating cost for mileages and hourly bases and records unit values for fuel cost and non-fuel cost, adding drivers' wages and benefit estimated cost per miles.

The AASTHO methodology uses the AASTHO provided data set for fuel consumption based on the gallon per mile with vehicle's operating speed, which is the latest data set published by AASTHO. Using the AASTHO methodology, the average fuel price per gallon in the work zone environment is used to convert the gallon per mile to a dollar value cost per mile. Based on the AASTHO and AAA-ATRI procedures, a hybrid methodology is developed. This hybrid methodology accounts for the vehicle's fuel component and non-fuel component by using the AASTHO procedure to estimate fuel cost and the AAA and ATRI procedure to estimate for non-fuel cost only. Therefore, these two components derived from the using AASTHO and AAA-ATRI procedures are computed together to determine the vehicles operating cost.

The operating cost is further estimated for road users based on two scenarios expressed as accounting for the operating cost of vehicles not taking detours and vehicles taking detours.

Furthermore, the additional operating cost for each vehicle involved in the two scenarios is being determined.

Estimating Vehicle Operating Cost (VOC)

Estimating the VOC, as discussed earlier, uses the AAA-ATRI procedure and the hybrid procedure, which estimates the operating cost using AAA-ATRI non-fuel component value only and AASTHO to account for the fuel component values. This methodology uses both the AASTHO and the AAA-ATRI data sources.

AAA and ATRI Method

Using the AAA and ATRI method is a simplified method that accounts for the vehicle's fuel and non-fuel components. This method uses the cost per mile value of different vehicle classes derived from the AAA and the ATRI publications shown in the appendix (see Appendix A, Table A.5 and Table A.6). The data set is published and updated annually. However, if the cost value cannot be retrieved, the CPI can be used to adjust the cost per mile value to the recent year. Therefore, the cost per mile values estimates the additional consumption and operating cost of the fuel and non-fuel components for vehicles taking detours only. This is because the AAA and ATRI estimate and account for differences in operating cost based on the miles traveled (Equation ***5-21*** to ***5-24***). For the AAA published data value, the cost element used for estimating the total operating cost includes:

a) Fuel

b) Maintenance, Repair, and Tire

c) Depreciation

d) Finances charges

While from the ATRI published estimated cost per mile, the element considered to estimate the total operating cost includes:

a) Fuel
b) Truck/Trailer Lease or Purchase Payment
c) Repair and Maintenance
d) Tires

Additional operating cost for vehicles taking a detour.

$$\text{Operating cost along original route} = OCPS_{\$/mile} \times L_{original\ route} \quad \textbf{5-21}$$

$$\text{Operating cost detour route} = OCDS_{\$/mile} \times L_{detour\ route} \quad \textbf{5-22}$$

Additional consumption cost of vehicle operating component per vehicle = **5-23**

$$\sum_{c_1}^{n} operating\ cost\ \ along\ detour\ route\ - operating\ cost\ along\ original\ route$$

Additional vehicle operating component consumption for all vehicle =

$$Additional\ consumption\ cost\ of\ vehicle\ operating\ component\ per\ vehicle \times \quad \textbf{5-24}$$

$$\sum_{c_1}^{n} AADT_{taking\ detours}$$

Where:

$OCPS_{\$/mile}$ = Vehicle operating components cost at operating speed based on posted speed limit ($/miles)

$OCDS_{\$/mile}$ = Vehicle operating components cost at operating speed based on detour speed limit ($/miles)

$L_{original\ route}$ = length of original route

$L_{detour\ route}$ = length of detour route

$\% \, AADT_{taking\ detours}$ = Average number of vehicles taking a detour

Hybrid Method

In estimating the VOC using the hybrid method, the AASTHO procedure of estimating the operating cost is first derived. This is done by estimating the fuel consumption rate for posted speed at the work zone route and detour route derived from the AASTHO gallon per mile table shown in the appendix (see Appendix A, Table A.4). The fuel consumption rate in gallon per mile is further converted to cost per mile($/mile) by multiplying the fuel consumption rate in gallon per mile(g/miles) by the average fuel price per gallon ($/gal). The average fuel price per gallon can be derived from gas station prices around the work zone location. This is expressed below in Equation ***5-25***.

$$\sum_{s}^{n} FCPS_{\$/mile} = \sum_{c=1}^{n} OPS_{gallon\ per\ miles} \times AFC_{price\ per\ gallon} \qquad \textbf{5-25}$$

Where:

C = Classes of the vehicle involving auto and truck

S = Operating speed based on a scenario involving posted speed limit, work zone speed limit, and detour speed limit

$OPS_{gallon\ per\ miles}$ = Fuel consumption rate at posted or operating speed in (gallon per miles)

$AFC_{price\ per\ Gallon}$ = Average fuel price (dollar per gallon)

$FCPS_{\$/mile}$ = Fuel cost based on operating speed in (dollar per miles)

As stated earlier, the AASTHO procedure only accounts for the fuel component of the vehicle. To account for the non-fuel components, the AAA and the ATRI cost per mile values are introduced. These data sets from AAA and ATRI include both the fuel component and the non-fuel component cost per mile value. Therefore, a total cost to fuel ratio of the AAA and the ATRI cost per mile values is derived and used as the non-fuel component value. The total cost to fuel ratio for both AAA and ATRI is derived by dividing the total VOC per mile of relevant components based on the AAA and the ATRI data set by the fuel cost component only. This is expressed below in Equation ***5-26***.

$$Total\ cost\ to\ fuel\ ratio = \frac{relevant\ vehicle\ components}{fuel\ component} \qquad \textbf{5-26}$$

Based on the derivation of the total cost to fuel ratio, the non-fuel component in dollar per mile ($/mile) is established. Furthermore, to account for the total operating component of the vehicle, the fuel cost derived from the AASTHO procedure (Equation ***5-25***), and the non-fuel component derived from the AAA and the ATRI procedure (Equation ***5-26***) are multiplied. It is therefore expressed below in Equation ***5-27***.

$$Total\ operating\ cost = \ Fuel\ cost\ \times\ Non\ fuel\ cost \qquad \textbf{5-27}$$

Where:

$Fuel\ cost$ $=estimated\ based\ on\ ASSTHO\ procedure$

$Non\ fuel\ cost$ $=estimated\ based\ on\ AAA.ATRI\ PROCEDURE$

In conclusion, to estimating the VOC using the hybrid method, the additional total operating cost (based on the estimate of the AASTHO and the AAA-ATRI (Equation ***5-27***) and the operating cost based on the estimate of the AAA and the ATRI (cost per mile) is averaged to derive an effective operation cost estimate to account for the fuel and non-fuel cost component. Furthermore, the total operating cost is therefore used in estimating the additional operating cost for vehicles taking a detour and not taking a detour which is expressed below from Equation ***5-28*** to ***5-35***.

Additional Total Operating Cost for Vehicles Not Taking a Detour.

$$Operating\ cost\ without\ work\ zone = OCPS_{\$/mile} \times\ L_{work\ zone} \qquad \textbf{5-28}$$

Operating cost of with work zone = $OCWS_{\$/mile} \times\ L_{work\ zone}$ **5-29**

Additional consumption cost of vehicle operating component per vehicle=

$$\sum_{c_1}^{n} Operating\ cost\ without\ work\ zone\ -\ Operating\ cost\ \ with\ work\ zone$$ **5-30**

Additional vehicle operating component consumption for all vehicle = **5-31**

$$Additional\ consumption\ cost\ of\ vehicle\ operating\ component\ per\ vehicle\ \times \sum_{c_1}^{n} AADT_{not\ taking\ detours}$$

Where:

$OCPS_{\$/mile}$	= Vehicle operating components cost at operating speed based on posted speed limit ($/miles)
$OCWS_{\$/mile}$	= Vehicle operating components cost at operating speed based on work zone speed limit ($/miles)
$L_{work\ zone}$	= length of work zone (reduced speed limit)
$AADT_{taking\ detours}$	= Average number of vehicles not taking a detour

Additional Total Operating Cost for Vehicles Taking a Detour.

Operating cost along original route = $OCPS_{\$/mile} \times\ L_{original\ route}$ **5-32**

Operating cost detour route = $OCDS_{\$/mile} \times\ L_{detour\ route}$ **5-33**

Additional consumption cost of vehicle operating component per vehicle = **5-34**

$$\sum_{c_1}^{n} operating\ cost\ \ along\ detour\ route\ -operating\ cost\ along\ original\ route$$

$$Additional\ vehicle\ operating\ component\ consumption\ for\ all\ vehicle = Additional\ consumption\ cost\ of\ vehicle\ operating\ component\ per\ vehicle \times \sum_{c_1}^{n} AADT_{taking\ detours} \quad \textbf{5-35}$$

Where:

$OCPS_{\$/mile}$ = Vehicle operating components cost at operating speed based on posted speed limit ($/miles)

$OCDS_{\$/mile}$ = Vehicle operating components cost at operating speed based on detour speed limit ($/miles)

$L_{original\ route}$ = length of original route

$L_{detour\ route}$ = length of detour route

$AADT_{taking\ detours}$ = Average number of vehicles taking a detour

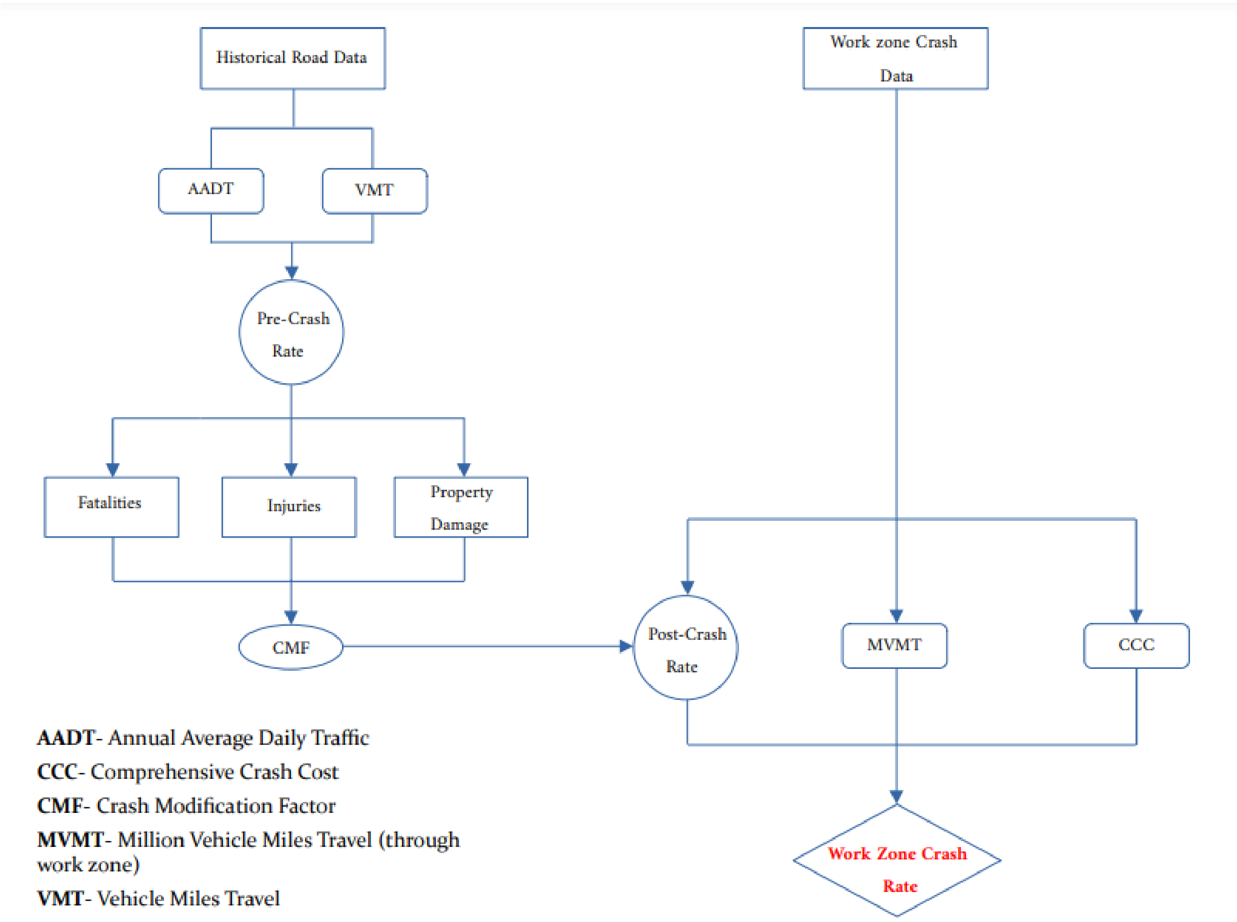
In summary the hybrid method uses the AASTHO, AAA, and ATRI procedures. In addition, the average of the AASTHO and AAA and ATRI procedures is estimated to derive an effective operating cost value which accounts for the fuel and non-fuel components of the vehicles.

Crash Cost (CC)

The CC accounts for the likelihood of crashes occurring in the work zone, and it is associated with the financial significance of crashes occurring in the work zone that affect the road user. In estimating the CC, historical crash data are considered for computing the previous crash rate along the work zone area. The crash rates, categorized by severities, uses the crash modification factor to predict the likelihood of increased or reduced crash rates in the work zone area and further multiplied with the comprehensive cost attributed to each crash severity to account for the CC. A chart illustrating the estimation of the CC is shown in Figure 18.

Figure 18

Framework to Estimate CC



The framework to estimate the CC is developed in two methods. The first method involves using the FHWA recommended procedures, accounting for the CC based on the KABCO crash severity reporting and uses the FHWA Comprehensive Societal Crash Costs to derive the CC based on the various severity updated to the recent year values using the CPI, also updated to the Tennessee value (see Appendix A, Table A.8 and Table A.10). The second methodology involves using the Highway safety manual recommended procedure, which involves converting the comprehensive societal crash costs to the corresponding equivalent property damage (EPDO) account for CC (see Appendix A, Table A.9).

Furthermore, the methodologies use a crash modification factor (CMF) to adjust and convert historical crash rate data to predict the likelihood of crash rates in the work zone. The CMF is also derived from the FHWA recommended methodology values for work zone involving a temporary lane closure. The CMF is therefore distributed into crash type based on the stated work zone configuration (see Appendix A, Table A.11)

Estimating Crash Cost (CC)

Using the FHWA methodology

To calculate the CC, the historical base condition of crash rate along the work zone area is computed to account for the preconstruction crash rate. The historical data for crash rate along the work zone area is to be derived from the safety department or crash-related department in the DOT and used to compute the total number of crashes based on the type of severity along the work zone area for previous years (i.e., in the space of 4 to 5 years). To further compute the CC, the crash rate is estimated to the total vehicle miles traveled in millions by multiplying the number of years of crash data by the length of road section corresponding to the crash data and the average AADT from the historical data as expressed below in Equation ***5-36***:

Historical Base condition (Preconstruction)

$$T.MVMT = \frac{N \times AADT \times L \times 365}{10^6} \quad \textbf{5-36}$$

Where:

$T.MVMT$	= Total millions of vehicle miles traveled in historical data
10^6	= to get value in millions
N	= number of years of crash data
AADT	= average AADT from the historical data
L	= length of section corresponding to crash data

Total million vehicle miles traveled in historical data is further categorized into the crash severity to be expressed in crash rate per million expressed below in Equation ***5-37***:

$$Cr_{historical\ data} = \sum_{s}^{n} \frac{T\ of\ crashes}{T.MVMT_{historical\ data}} \qquad \textbf{5-37}$$

Where:

s	= severity level
$Cr_{historical\ data}$	= historical crash rate data in terms of severity (per MVMT)
$T\ of\ crashes$	= total number of crashes from historical data in terms of severity
$T.MVMT_{historical\ data}$	= total millions of vehicle miles traveled in historical data

The CMF is then used to adjust the crash rate based on severity to the predicted crash rate in the present construction work zone. This is done to estimate the expected increase in crash rate based on the presence of the work zone construction whereby the CMF adjusted crash rate and the previous historical crash rate data are used to derive the expected increase in the crash rate. This is expressed below in Equation ***5-38*** to ***5-39***.

$$Cr_{Adjusted\ \ data} = \sum_{s}^{n} CMF \times Cr_{historical\ data} \qquad \textbf{5-38}$$

$$Cr_{Expected\ increase} = Cr_{Adjusted\ \ data} - Cr_{historical\ data} \qquad \textbf{5-39}$$

Where:

CMF	= Crash modification factor
$Cr_{Adjusted\ \ data}$	= CMF adjusted crash rate per MVMT
$Cr_{historical\ data}$	= Historical crash rate data in terms of severity (per MVMT)
$Cr_{Expected\ increase}$	= Expected increase in crash rate because of work zone per MVMT

Therefore, the expected increase in crash rate because of the work zone is multiplied with the comprehensive societal crash costs to account for the CC associated with increased crashes in the work zone, as expressed below in Equation ***5-40***:

$$Crash\ Cost\ =\ \sum_{S}^{n} Cr_{Expected\ increase} \times T.MVMT_{work\ zone}\ \times\ Unit\ crash\ cost \quad \textbf{5-40}$$

Where:

Unit crash cost = FHWA comprehensive societal crash costs

$T.MVMT_{work\ zone}$ = the total million vehicle miles traveled in the work zone

Where the total million vehicle miles traveled in the work zone is expressed as

$$T.MVMT_{work\ zone} = \frac{Total\ vehicle\ not\ taking\ detour \times Length\ of\ work\ zone(\ reduced\ speed)}{10^6} \quad \textbf{5-41}$$

Using the Equivalent property damage (EPDO)

The EPDO also uses the same procedure as the FHWA methodology. However, this methodology uses the weighted Property Damage Only (PDO) values to account for the number of crashes per million vehicle miles traveled. This is done by converting all severity crash types to EPDO as the only type. Estimating the CC using the EPDO method is expressed below:

The weighted factored compared to the PDO is first derived, and it is expressed in Equation ***5-42***:

$$W_s = \frac{CC_S}{CC_{PDO}} \quad \textbf{5-42}$$

Where:

W_s = Weighted factor compared to PDO based on the various severity (KABCO)

CC_S = FHWA comprehensive societal crash costs

CC_{PDO} = FHWA comprehensive societal crash costs for PDO crash severity

The weighted factor for each severity corresponding to PDO is then summed up to derive the total EPDO score, as shown below in Equation ***5-43***:

$$Total\ EPDO\ score = \sum_{s}^{n} W_s \times T\ of\ crashes \qquad \textbf{5-43}$$

Where:

W_s = Weighted factor compared to PDO based on the various severity (KABCO)

$T\ of\ crashes$ = total number of crashes from historical data in terms of severity

Therefore, use the total EPDO score to derive the crash rate per million based on the historical data as expressed below:

$$Cr_{historical\ data} = \frac{T.MVMT_{historical\ data}}{Total\ EPDO\ score} \qquad \textbf{5-44}$$

Where:

$Cr_{historical\ data}$ = Historical crash rate data corresponding to EPDO

$T.MVMT_{historical\ data}$ = Total millions of vehicle miles traveled in historical data

The CMF is then used to adjust the historical crash rate data corresponding to EPDO to the likelihood of crash rate because of the work zone. After that, the CMF adjusted crash rate and the historical crash rate data are used to derive the expected increase in the crash rate. This is expressed below in Equation ***5-45*** and ***5-46***:

$$Cr_{Adjusted\ \ data} = CMF \times Cr_{historical\ data} \qquad \textbf{5-45}$$

$$Cr_{Expected\ increase} = Cr_{Adjusted\ \ data} - Cr_{historical\ data} \qquad \textbf{5-46}$$

Where:

CMF = Crash modification factor

$Cr_{Adjusted\ \ data}$ = CMF adjusted crash rate per MVMT

$Cr_{historical\ data}$ = Historical crash rate data corresponding to EPDO (Per MVMT)

$Cr_{Expected\ increase}$ =Expected increase in crash rate because of work zone per MVMT

Therefore, the CC associated with increase crashes is derived by multiplying the expected increase in crash rate because of work zone per MVMT by EPDO unit CC and the total million vehicle miles traveled in the work zone as shown below in Equation ***5-47***:

$$Crash\ Cost\ Associated\ with\ Increased\ Crash = Cr_{Expected\ increase} \times CC_{PDO} \times T.MVMT_{work\ zone} \quad \textbf{5-47}$$

Where:

$Cr_{Expected\ increase}$ = Expected increase in crash rate because of work zone per MVMT

CC_{PDO} = FHWA comprehensive societal crash costs for PDO crash severity

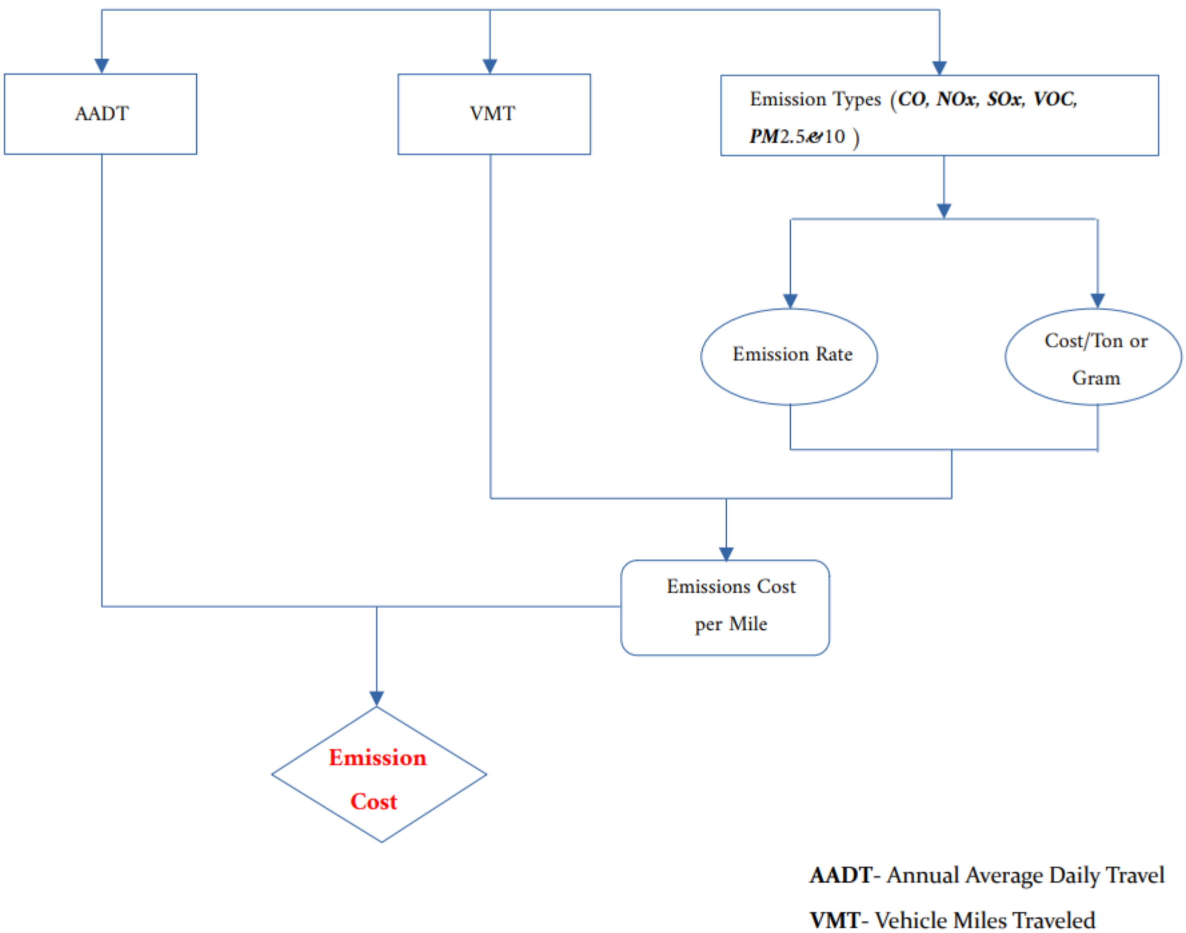
$T.MVMT_{work\ zone}$ = the total million vehicle miles traveled in the work zone expressed as in Equation ***5-43***

Emission Cost (EC)

EC account for the cost of pollutants and emissions in the construction zone. The EC has the lowest percentage in terms of the total road user cost. The EC considers the types of pollutants present in the construction work zone and the emission rate of the pollutant. It considers the cost of the pollutants as it indirectly affects road users, but the cost is expressed as the comprehensive cost impacting the environment. Figure 5.5 below illustrates the estimation of the EC.

Figure 19

Framework to Estimate EC



The Pollutants estimated in this methodology are Carbon monoxide (CO), Nitrogen oxides (NOx), Sulfur oxides (SOx), Volatile organic compounds, Particulate Matter (PM 2.5), as these are significant pollutant in work zone areas. The emission rate is generated using the MOVES software model developed by the Environmental Protection Agency (EPA) (Mallela & Sadavisam, 2011). It accounts for emission rates based on extensive operating conditions such as idling, starting, and running of the vehicles. The emission rates for each of the pollutant are derived for each county in Tennessee. The is then computed using the unit cost of the pollutants provided by the FHWA, which were derived from the HERS-ST Technical Report as shown in the appendix (see Appendix A, Table A.12). The HERS-ST dollar value for each pollution is estimated per vehicle mile as a function of vehicle speed, vehicle type, and roadway functional class. Since the HERST-ST cost are in 2000-dollar value, they are adjusted to the current dollar value by using CPI.

Estimating the Emission cost (EC)

As described in Figure 5.5, the EC is estimated by deriving the emission rates of each pollutant from the MOVES software. The emission rates are expressed in gram per mile, which are then converted to tons per mile by using the short ton conversion factor as recommended by the USDOT 2020 BCA guideline. It is therefore expressed below in Equation ***5-50***:

$$Emission\ rate_{\ tons/mile} = \sum_p^n EF_{g/miles} \times 0.00000\,11023 \qquad \textbf{5-48}$$

Where:

P = pollutants

$EF_{g/miles}$ = Emission factor in grams per mile based on operating speed

Lastly, the EC is estimated by multiplying the emission rate (ton/mile) to the unit cost of the pollutants. It is, therefore, expressed below in Equation ***5-51***:

$$Emission\ Cost_{\ \$/ton} = \sum_p^n Emission\ rate_{\ tons/mile} \times Unit\ cost_{\ \$/ton} \qquad \textbf{5-49}$$

Where:

$Emission\ rate_{\ tons/mile}$ = emission rate converted to tons/mile for various pollutant

$Unit\ cost_{\ \$/ton}$ = Unit cost of emission for various pollutant

The EC calculation for this methodology is based on pre-construction speed, work zone speed accounting for vehicles not taking detour, and for vehicles taking a detour. The EC for each vehicle operating speed is multiplied by the length of the roadway section and the number of vehicles in each section to account for the EC in the different roadway sections. It is, therefore, expressed in Equatio***5-50***.

$$Emission\ cost = Emission\ Cost_{\$/ton} \times D.of\ road\ section \times AADT \qquad \textbf{5-50}$$

Where:

Emission cost = based on posted speed, work zone speed, and detour speed limit

D. of road section = Distance of posted speed, work zone speed, and detour speed limit roadway section

AADT = Average annual daily travel of vehicles in each roadway section

Therefore, the emission cost is estimated by subtracting the emission cost of all the posted speeds from the emission cost of the work zone operating speed limit and the detour speed limit. It is, therefore, expressed as in Equation ***5-51***

$$Additional\ Emission\ cost = (Detour\ speed\ limit + work\ zone\ speed\ limit) - Original\ route\ posted\ speed \qquad \textbf{5-51}$$

Consumer Price Index (CPI)

The framework applied the CPI adjustment factor to the developed methodology. The CPI adjustment factor is used to convert dollar values of previous years to the present year of calculation. The adjustment factor is estimated using the geometric average based on previous years and the present year of estimation. The geometric average adjustment factor estimation is further expressed below in Equations ***5-52*** to ***5-53***.

$$Net\ Adjustment\ factor = \frac{PY}{CY} \qquad \textbf{5-52}$$

$$Geomertic\ Average\ \ adjustment\ factor\ = Net\ Adjustment\ factor^{\frac{1}{(CY-PY)}} \quad \textbf{5-53}$$

Where:

PY= Previous year

CY= Current year

The geometric average CPI adjustment factor is used to adjust dollar values used in various components to estimate the cost. These dollar's values adjusted with the CPI adjustment factor in the RUC components to estimate costs is stated below.

- Used in VOT estimate to adjust the median household income, wages rate for auto and truck vehicle drivers based on work zone location.
- Used in VOC estimate to adjust the AAA and ATRI cost per mile values.
- Used in CC estimate to adjust unit crash cost by severity.
- Used in EC estimate to adjust HERS-ST emission cost.

Therefore, the dollar values in each component are adjusted to recent values by multiplying the precious year dollar values by the geometric average CPI adjustment factor. It is further expressed below in Equation ***5-54***.

$$\text{Present}\ year\ dollar\ value\ =\ PY\ dollar\ value \times\ \text{G.A CPI}^{(\text{CY}-\text{PY})} \quad \textbf{5-54}$$

Where:

$PY\ dollar\ value$	= Previous year dollar value
G.A CPI	= Geometric average CPI adjustment factor
PY	= Previous year
CY	= Current year

Note: The dollar values used to calculate the cost for each component might not be converted using this methodology if an updated dollar value is available, if this is not available the dollar value will be needed to convert to the recent year.

Development of an Excel-based RUC Calculation Tool

An Excel-based spreadsheet tool was created to implement the developed methodology and designed to ease the calculation of the RUC. The Excel tool requires the analyst to enter project data information about the general traffic, work zone configuration, and crash data and generate the RUC result automatically. The Excel spreadsheet consists of 13 tabs involving the Instruction tab, Main sheet, VOT calculation, VOT data compilation, DC calculation, VOC calculation, VOC data compilation tab, CC calculation tab, CC data compilation tab, EC calculation, EC data compilation, other options tab, and the inflation index tab as shown in Figure 20 and 21.

The Instruction tab presents the important points to consider when navigating the spread tools and the overview of the various tabs, briefly describing each tab section as shown in Figure 20. The main sheet tab shows the input and the output sections. The input section is where the data information is entered manually by the analyst, while the calculation of the RUC based on the dataset's information provided runs in the background and is outlined in the output section. The components calculation tab shows how each component is estimated and presents the dataset used to compute those components in the data compilation tab. The Options tab stores various options that are shown as a drop-down list in the main sheet. It also provides brief descriptions of those options. The Inflation Indexes tab stores historical CPI data and computes the annual CPI used in the spreadsheet to adjust various costs to the current dollar values. Analyst, therefore, saves the automatically generated total road user cost for the duration of construction based on the data attribute inputted for the work zone location to be used as the estimate for the project management decision or application intended.

Figure 20

Overview of Instruction Tab in Excel Tool

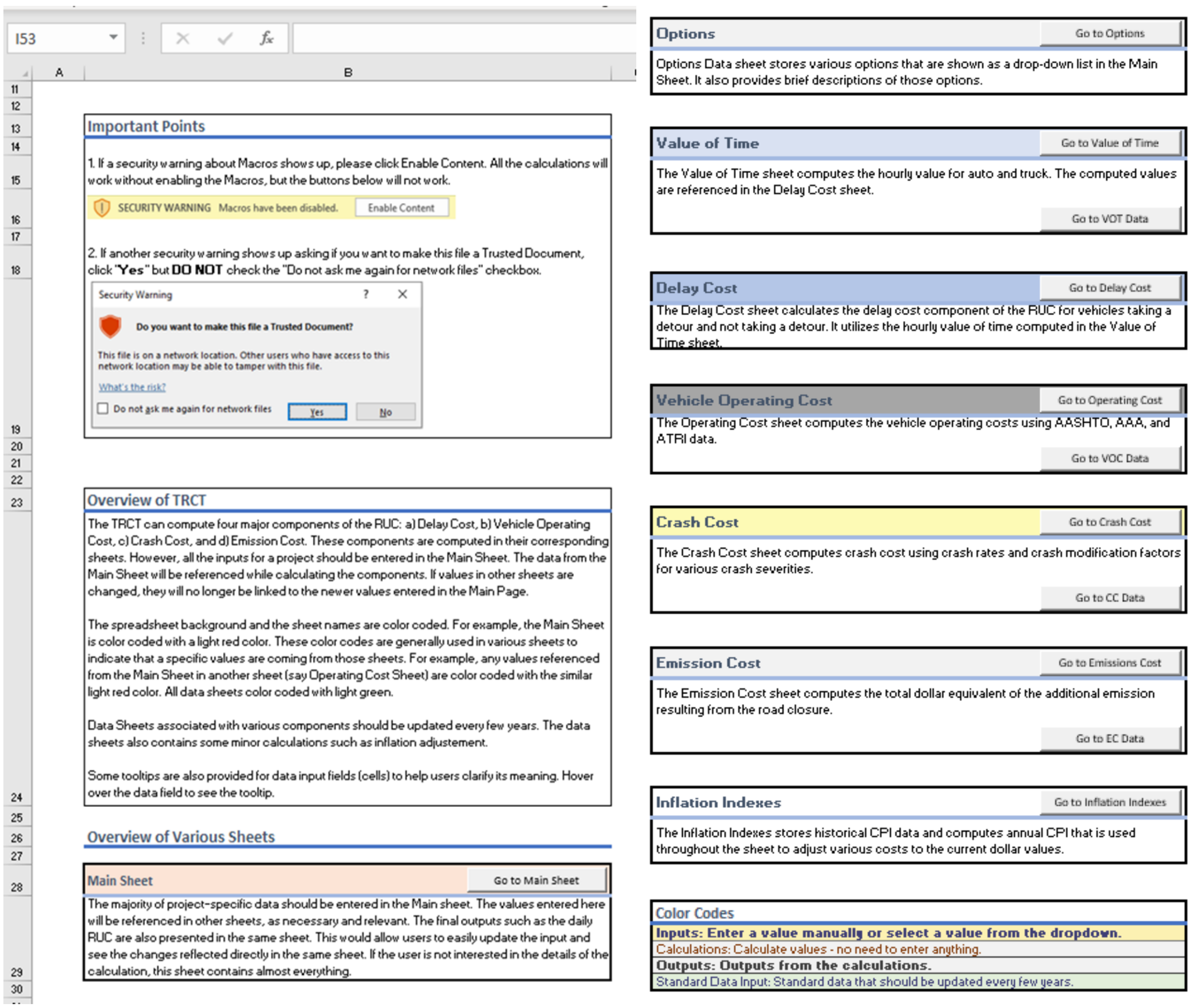
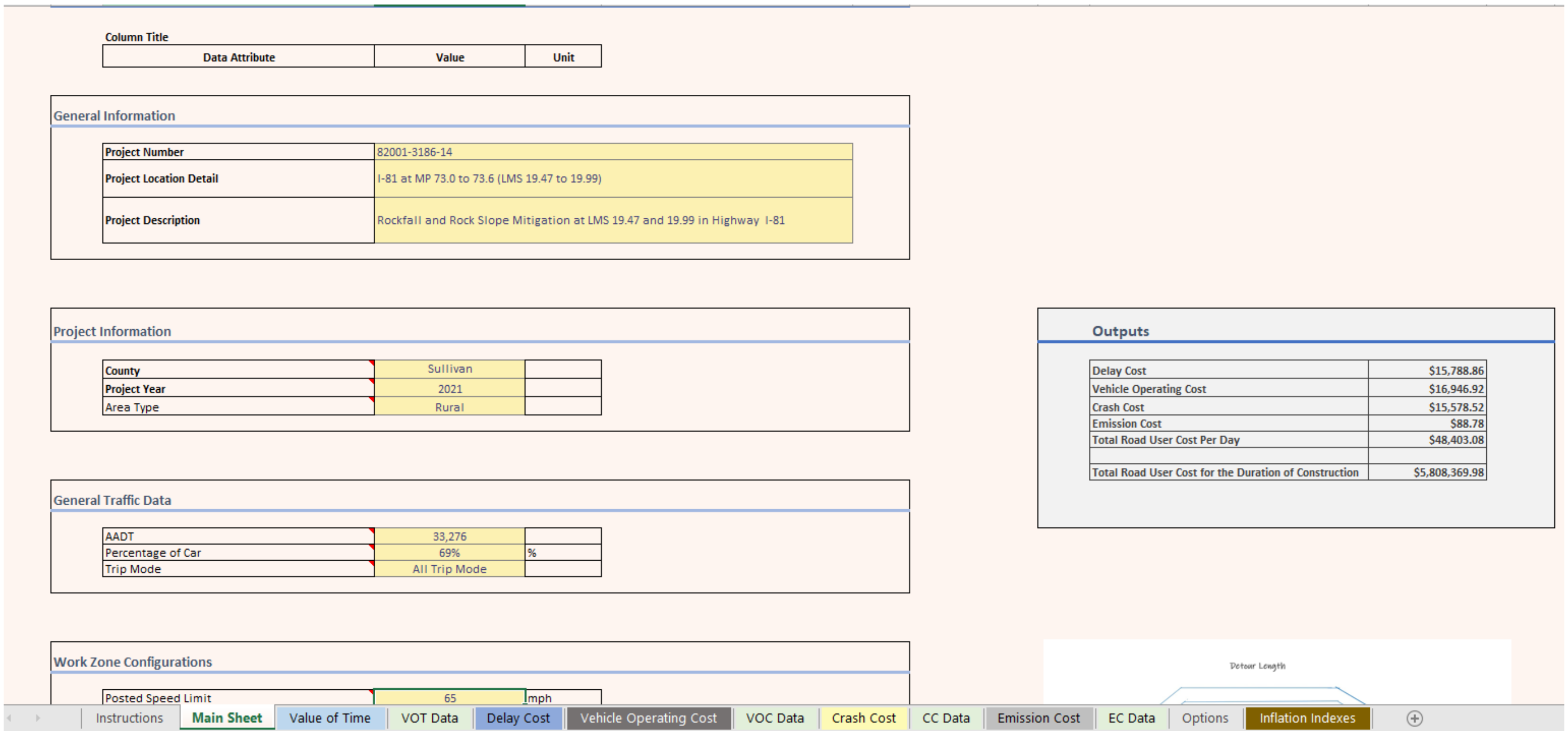


Figure 21

Overview of Mainsheet in Excel Tool



Column Title

Data Attribute	Value	Unit

General Information

Project Number	82001-3186-14
Project Location Detail	I-81 at MP 73.0 to 73.6 (LMS 19.47 to 19.99)
Project Description	Rockfall and Rock Slope Mitigation at LMS 19.47 and 19.99 in Highway I-81

Project Information

County	Sullivan	
Project Year	2021	
Area Type	Rural	

General Traffic Data

AADT	33,276	
Percentage of Car	69%	%
Trip Mode	All Trip Mode	

Work Zone Configurations

Posted Speed Limit	65	mph

Outputs

Delay Cost	$15,788.86
Vehicle Operating Cost	$16,946.92
Crash Cost	$15,578.52
Emission Cost	$88.78
Total Road User Cost Per Day	$48,403.08
Total Road User Cost for the Duration of Construction	$5,808,369.98

Detour Length

Instructions | Main Sheet | Value of Time | VOT Data | Delay Cost | Vehicle Operating Cost | VOC Data | Crash Cost | CC Data | Emission Cost | EC Data | Options | Inflation Indexes

Chapter 6. Case Study

This section presents case studies to implement the framework developed. Information and data about these projects are derived from TDOT websites. The data attribute for these projects are categorized into five input sections a) General traffic data b) Roadway characteristics c) Work zone configuration d) Crash Data e) Miscellaneous. Data sets for each category are derived from the information in and around the work zone area, while data sets pertaining to crashes are derived from historical data of crashes in the work zone environment. Furthermore, the historical crash rate based on the severity was populated from the Enhanced Tennessee Roadway Information Management System (E-TRIM).

Therefore, the data input and attributes based on the work zone environment for the various construction projects is shown Table 9 below.

Table 9

Case Studies Data Input and Attributes

	1	**2**	**3**	**4**
Project Information				
Project Year	2021	2017	2021	2021
Project County	Sullivan	Williamson	Carroll	Robertson
General Traffic				
AADT	33,276	20630	511	53,810
Percentage of Car	69%	95.50%	95%	70%
Roadway Characteristics				
Area Type	Rural	Urban	Rural	Rural
Work Zone Configurations				

Posted Speed Limit	65 mph	45 mph	55 mph	70 mph
Work Zone Speed Limit	55 mph	35 mph	45 mph	55 mph
Detour Speed Limit	55 mph	60 mph	0	0
Construction Duration	120 days	60 days	26 days	1460 days
Length of Work Zone (Reduced Speed Limit)	0.75 miles	2.63 miles	5.6 miles	10 miles
Length of Original Route	5.37 miles	2.63miles	5.6 miles	10 miles
Length of Detour Route	8.45 miles	6.9 miles	0	0
Crash Data				
Number of Years of Crash Data	4	4	4	4
Length of Section Corresponding to Crash Data	0.6 miles	2.575 miles	5.6 miles	10 miles
Average AADT from the Historical Data	36,296	23691	579	0
Total Number of Crashes from the Historical Data				
K - Fatal Injury	1	0	0	0
A - Incapacitating Injury	0	0	0	0
B - Non-Incapacitating	5	0	2	0
C - Possible Injury	0	0	4	0
O - Property damages only	16	7	6	0
Miscellaneous				
Average Gasoline Price	$2.26/gal	$2.26/gal	$2.26/gal	$2.89/gal
Average Diesel Price	$2.30/gal	$2.30/gal	$2.30/gal	$3.08/gal

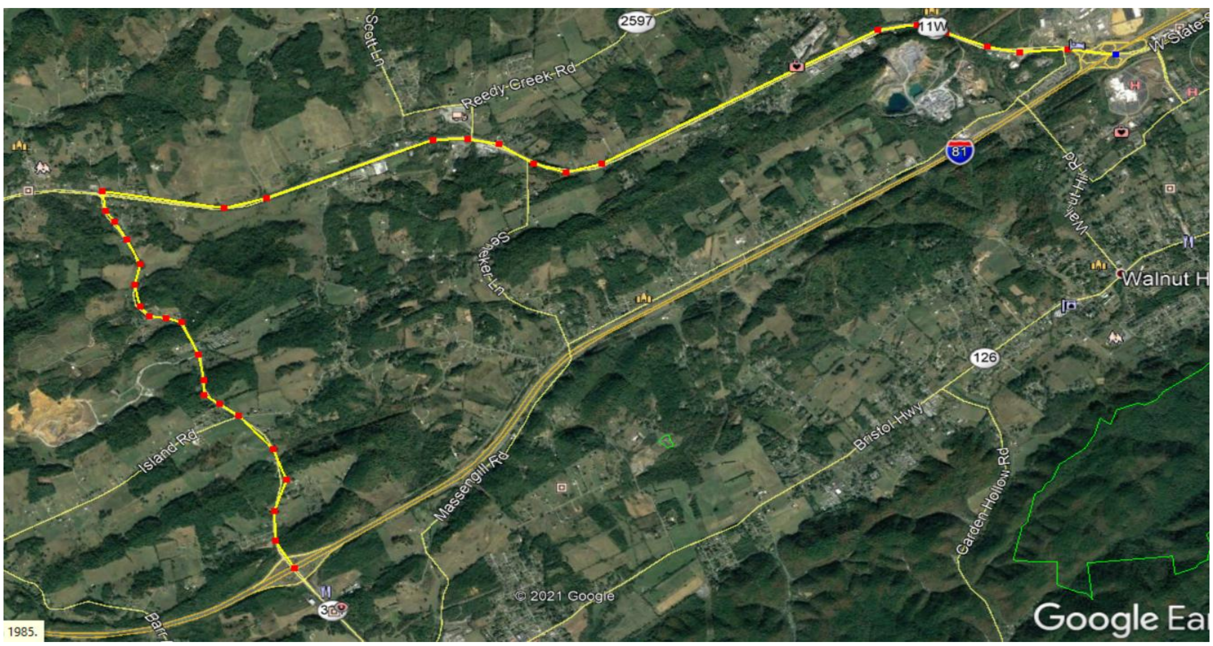
Case study one RUC estimation based on the four components accounted for, is expressed and calculation steps are shown, while case study two and three RUC estimate calculation steps are not shown but the RUC estimates is summarized.

Case Study One

The first case study involves a construction project in Sullivan County in Tennessee with a rockfall and rock slope mitigation project description. Figure 22 below shows the work zone environment and the roadway sections of the construction project.

Figure 22

Work Zone Environment Showing Detour Route and Original Route in Sullivan County



The work zone environment above shows the original route which starts from the red dot to the blue dot through the I-81 route having a length of 5.37 miles. The detour route can be seen from the red dots connecting through US 11W route to the blue dot having a length of 8.45miles. The work zone is located between the original route and having a length of 0.75miles.

The total RUC per day would account for four components of RUC, involving the DC, VOC, CC, and EC. Furthermore, the total road user cost per day was estimated using two-variable data input involving:

1. The assumption that 25% of the AADT will take a detour.
2. Assuming an All-trip mode, which involves using an all-trip mode multiplier.

Delay Cost (DC)

Estimating the VOT for Auto Vehicles

The VOT is calculated based on two travel purposes a) Personal trip and b) Business trip. This travel mode is thereby distributed into weighted percentages based on the travel mode, and it is shown in the Table 10 below.

Table 10

Weighted Distributed Percentage to Allocate AADT Based on Trip Purpose and Mode

	Percentage AADT	
	Local	**Intercity**
Personal	95.5%	78.6%
Business	4.6%	21.4%

Estimating VOT for Personal Trip

The VOT for personal trip is estimated using the median annual income for Sullivan County, TN derived from the Bureau of Labor Statistics (BLS) website and is converted to an hourly rate and estimated based on the trip mode. The average occupancy factor is therefore used to account for the VOT of all passengers in the vehicle travelling through the work zone. It is further expressed in the Table 11.

Table 11

Calculation Steps to Estimate VOT for Personal Trip Mode

Estimate Hourly Equivalent Income	$\frac{MHI}{2080}$	$22.17
Project year (2021) median household income value for Sullivan County, TN= $46,124		
Hourly Equivalent Income	$\frac{46,124}{2080}$	$22.17
The next steps calculate the hourly rate per person using the selected multiplier based on trip mode and purpose, as shown in the appendix.		
Local trip mode multiplier estimate	$\$22.17 \times 50\%$	$11.085
Intercity trip mode multiplier estimate	$\$22.17 \times 70\%$	$15.519
Estimate the hourly dollar value to account for the whole vehicle by multiplying the value of time based on the trip mode with the average vehicle occupancy factor.		
Hourly time value for Local trip mode accounting for whole vehicle	$\$11.085 \times 1.7$	$18.85
Hourly time value for intercity trip mode accounting for whole vehicle	$\$15.519 \times 1.7$	$26.39

Estimating VOT for Business Trip

The hourly employment cost based on a business trip is derived from Employer Costs for Employee Compensation for private industry workers by census region and division table from the BLS website and converted to an hourly rate per person using the wages multiplier based on trip mode. The average occupancy factor is therefore used to account for the VOT of all passengers in the vehicle travelling through the work zone. it is further expressed in Table 12 below.

Table 12

Calculation Steps to Estimate VOT for Business Trip Mode

The hourly employment cost based on a business trip for Sullivan County= $30.15		
The hourly rate per person is derived by multiplying the hourly employment cost by the percentage wage multiplier based on trip mode expressed as:		
Local trip mode multiplier estimate	$\$30.15 \times 100\%$	$30.15
Intercity trip mode multiplier estimate	$\$30.15 \times 100\%$	$30.15
Therefore, the hourly time value accounting for all passengers for both the intercity and local trip mode in the auto vehicle is estimated as	$\$30.15 \times 1.67$	$ 50.34

Therefore, the value of time for auto vehicle road users on a personal and business trip based on the different trip modes is expressed in Table 13 below.

Table 13

Summarized VOT Based on Trip Purpose and Mode

Auto	**Local**	**Intercity**
Personal Trip	$18.85	$26.39
Business Trip	$50.34	$50.34

However, this project assumes an "All Trip" mode. Therefore, the hourly value to be used for this project would be based on an All-Trip mode, and this is derived by estimating the weighted hourly cost average of local and intercity hourly value trip modes. However, this estimation factors in the distributed percentage of AADT based on trip mode and purpose shown in Table 10 above. Estimating the All-Trip mode is therefore expressed in Table 14.

Table 14

Calculation Steps to Estimate VOT for All- Trip Mode

Weighted hourly cost value for Local trip mode	$\frac{(18.85 \times 95.4\%) + (50.34 \times 4.6\%)}{(95.4\% \ + \ 4.6\%)}$	\$20.3
Weighted hourly cost value for Intercity trip mode	$\frac{(26.39 \times 78.6\%) + (50.34 \times 21.4\%)}{(78\% \ + \ 21.4 \ \%)}$	\$31.51
All-Trip mode weighted hourly cost value	$\frac{\$20.3 + \$31.51}{2}$	\$25.91

Therefore, the hourly cost values expressed as the VOT for auto vehicles are shown in the Table 15 below.

Table 15

Summarized Hourly Cost for Auto Vehicles Based on Trip Purpose and Mode

Auto	**Local**	**Intercity**	**All Trip mode**
Personal trip	18.85	26.39	22.62
Business trip	50.34	50.34	50.34
Weighted hourly cost	20.30	31.51	25.91

Estimating VOT for Truck Vehicles

The hourly time value of the truck vehicle type is estimated using the average wage derived from annual mean wages of light truck drivers for TN state, selected multiplier based on trip mode expressed as 100%, and the average vehicle occupancy factor. It is further expressed in Table 16 below.

Table 16

Calculation Steps to Estimate the VOT for Truck Vehicle

The wage rate for truck drivers in Sullivan County = $21.53.		
The hourly rate per person is estimated as	$\$21.53 \times 100\%$	$21.53
The hourly travel time value of truck vehicle accounting for all passengers	$\$21.53 \times 1.0$	$21.53
Therefore, the VOT for truck vehicle = $21.53.		

Estimating Delay Time and Cost

The delay time is estimated to account for the additional DC based on vehicles taking the detour and not taking a detour compared to the base scenario of the absence of work zone. Furthermore, the delay time is accounted using the speed and distance of the original route, work zone route and the detour route. Table 17 shows data information needed to estimate the additional travel time.

Table 17

Data Attributes to Estimate Delay Cost

Data Attributes	**Values**
AADT	33,276
Percentage of Car	69%
Percentage of Vehicles Taking Detour	25%
Percentage of vehicles not taking detour	75%

Posted Speed Limit	65 mph
Work Zone Speed Limit	55 mph
Detour Speed Limit	55 mph
Construction Duration	1 day
Length of Work Zone (Reduced Speed Limit)	0.75 mile
Length of Original Route	5.37 miles
Length of Detour Route	8.45 miles

Estimating Delay Time for Vehicles not Taking Detour

The delay time is estimated using the distance of the work zone route and different speeds based on work zone posted speed and original route posted speed in the absence of a work zone. The estimated delay for a vehicle is therefore derived based on the difference in time taken to travel without the work zone and time taken to travel with the work zone. It is therefore expressed in Table 18 below.

Table 18

Calculation Steps to Estimate the Delay Time for Vehicles Not Taking Detour

Time taken to travel without the work zone (mins)	$\frac{0.75\ miles}{65\ mph} \times 60\ mins$	$0.69\ minutes$
Time taken to travel with the presence of work zone (mins)	$\frac{0.75\ miles}{55\ mph} \times 60\ mins$	$0.82\ minutes$
Delay per vehicle	$0.82 - 0.69$	$0.13\ minutes$

The estimated delay time for vehicles not taking the detour is computed with the hourly value of time (see Table 13) to estimate the DC for vehicles not taking detour. The DC based on this scenario is therefore estimated for the auto and truck vehicles shown in *Table 19* and *Table 20.*

Estimating Delay Cost for Auto Vehicle

Table 19

Calculation Steps to Estimate the Delay Cost for Auto Vehicles Not Taking a Detour

Percentage of car	69%	
Number of auto not taking detour	$69\% \times 75\% \times 33{,}276$	17220
Delay cost per auto	$\frac{0.13 \times \$25.91}{60}$	\$ 0.05
Delay cost for all autos not taking detour per day	$\$\,0.05 \times 17220$	\$935.90

Estimating Delay Cost for Truck Vehicle

Table 20

Calculation Steps to Estimate the Delay Cost for Truck Vehicles Not Taking a Detour

Percentage of truck	31%	
Number of trucks not taking detour	$31\% \times 75\% \times 33{,}276$	7,737
Delay cost per truck	$\frac{0.13 \times \$21.53}{60}$	\$ 0.05
Delay cost for all truck not taking detour per day	$\$\,0.05 \times 7{,}737$	\$349.38

Estimating Delay Time for Vehicles Taking Detour.

The delay time is estimated using the distance of the original route and the detour route with different speeds based on original posted speed and detour route posted speed. The estimated delay for vehicles is therefore derived based on the difference in time taken to travel without the work zone and time taken to travel along the detour. It is therefore expressed in Table 21 below.

Table 21

Calculation Steps to Estimate the Delay Time for Vehicles Not Taking Detour

Time taken to travel without the work zone	$\frac{5.37\ miles}{65\ mph} \times 60\ mins$	$4.96\ minutes$
Time taken to travel along the detour	$\frac{8.45\ miles}{55\ mph} \times 60\ mins$	$9.22\ minutes$
Delay per vehicle	$9.22\ -\ 4.96$	$4.26\ minutes$

The estimated delay time for vehicles taking a detour is therefore computed with the hourly value of time (see Table 13) to estimate the DC for vehicles taking detour. The DC based on this scenario is therefore estimated for the auto and truck vehicles shown in Table 22 and 23.

Estimating Delay Cost for Auto Vehicle

Table 22

Calculation Steps to Estimate the Delay Cost for Auto Vehicles Taking a Detour

Percentage of car	69%	
Number of autos taking detour	$69\%\ \times 25\% \times\ 33{,}276$	5,740
Delay cost per auto	$\frac{4.26\ \times\ \$25.91}{60}$	$ 1.84
Delay cost for all autos not taking detour per day	$\$\ 1.84 \times 5740$	$10,5671.07

Estimating Delay Cost for Truck Vehicle

Table 23

Calculation Steps to Estimate the Delay Cost for Truck Vehicles Taking a Detour

Percentage of truck	31%	
Number of trucks taking detour	$31\% \times 25\% \times 33{,}276$	2,579
Delay cost per truck	$\frac{4.26 \times \$21.53}{60}$	\$ 1.53
Delay cost for all truck not taking detour per day	$\$\,1.53 \times 2579$	\$3492.38

The delay time delay per vehicle (minutes), cost per vehicle and total DC are thereby summarized in Table 24 below.

Table 24

Summary of the Delay Time and the Delay Cost per Vehicle

	Auto		**Truck**		**Total**
	Original Route	**Detour Route**	**Original Route**	**Detour Route**	
Delay Per Vehicle (min)	0.13	4.26	0.13	4.26	
Cost Per Vehicle	\$0.05	\$1.84	\$0.05	\$1.53	
Total Cost	\$935.90	\$10,561.07	\$349.38	\$3,942.52	**\$15,788.86**

Vehicle Operating Cost (VOC)

In estimating the VOC, the methodology uses the AAA and ATRI, AASTHO, and the hybrid methodology discussed in the framework chapter.

Using AAA and ATRI

Using the AAA and the ATRI method involves using the operating cost per mile published by AAA for auto vehicles and ATRI for truck vehicles, as seen in the appendix. For the AAA published data value, the cost element used for estimating the total operating cost includes:

- Fuel
- Maintenance, Repair, and Tire
- Depreciation
- Finances charges

While from the ATRI published estimated cost per mile, the elements considered to estimate the total operating cost includes:

- Fuel
- Truck/Trailer Lease or Purchase Payment
- Repair and Maintenance
- Tire

The total VOC per mile to be used from the ATRI and the AAA published in 2019 is in the table below and further converted to the project year using the CPI of *1.0202*. Furthermore, the Table 25 below shows the total cost to fuel cost ratio based on the AAA and ATRI cost.

Table 25

Total Cost to Fuel Cost Ratio

Vehicle Type	Total cost (2019-Data year)	Project year (2021)	Total Cost to Fuel Cost Ratio
Auto	$\$0.58$	$\$0.58 \times 1.02^{(2021-2019)} = \$0.60$	$\$0.58/\$0.12 = \$4.80$
Truck	$\$0.88$	$\$0.88 \times 1.02^{(2021-2019)} = \$0.92$	$\$0.88/\$0.39 = \$2.24$

The AAA and the ATRI method accounts for only vehicles taking detours. This is because the calculation is based on the miles traveled by vehicles and accounts for differences in operating cost based on the miles traveled. Therefore, estimating the VOC for vehicles taking a detour is estimated below in Table 27 and Table 28. In addition, data information needed to estimate the additional operating cost for vehicles in the work zone environment is shown below in Table 26**.**

Table 26

Data Attributes to Estimate the VOC

Data Attribute	Values
AADT	33,276
Percentage of Car	69%
Percentage of Vehicles Taking Detour	25%
Posted Speed Limit	65mph
Work Zone Speed Limit	55mph

Detour Speed Limit	55mph
Length of Work Zone (Reduced Speed Limit)	0.75mile
Length of Original Route	5.37mile
Length of Detour Route	8.45mile
Percentage of Vehicles Taking Detour	25%
Average Gasoline Price per Gallon	$2.26
Average Diesel Price per Gallon	$2.30

Estimating VOC for Vehicle Taking detour

The cost per mile value of the vehicle is computed with the detour route mile to estimate the additional operating cost based on the vehicle taking a detour route compared to the original route without the presence of work zone. The operating cost estimation for both auto and truck vehicles is expressed in Table 27 and Table 28.

For Auto Vehicles

Table 27

Calculation Steps to Estimate the VOC for Auto Vehicles Taking a Detour

Number of autos taking a detour	$33276 \times 69\% \times 25\%$	$ 5,740
Unit vehicle operating cost per mile $0.60\ \$/mile$		
Vehicle operating cost along the original route	$0.60\ \$/mile \times 5.37mile$	$ 3.2191
Unit vehicle operating cost per mile $0.60\ \$/mile$		

Vehicle operating cost along the detour route	$0.60\ \$/mile \times 8.45\ miles$	\$ 5.07
Additional vehicle operating cost per auto	$\$\ 5.07 - \$\ 3.2191$	\$ 1.85
Additional vehicle operating cost for all autos not taking detour	$\$1.85 \times 5740$	\$10,598.32

For Truck Vehicles

Table 28

Calculation Steps to Estimate the VOC for Truck Vehicles Taking a Detour

Number of trucks taking a detour	$33276 \times (100\% - 69\%) \times 25\%$	2,579
Unit vehicle operating cost per mile $0.92\ \$/mile$		
Vehicle operating cost along the original route	$0.92\ \$/mile \times 5.37\ mile$	\$ 4.9181
Unit vehicle operating cost per mile $0.92\ \$/mile$		
Vehicle operating cost along the detour route	$0.92 \times 8.45\ miles$	\$ 7.74
Additional vehicle operating cost per truck	$\$\ 7.74 - \$\ 4.9181$	\$ 2.84
Additional vehicle operating cost for all trucks not taking detour	$\$2.82 \times 2{,}579$	\$ 7,274.61

The total operating cost for vehicle taking detour based on AAA and ATRI values is expressed Table 29 below.

Table 29

Total Operating Cost for Vehicle Taking Detour Based on AAA and ATRI Values

Taking Detour	
Auto	$10,598.32
Truck	$7,274.61
Total	$ 17,872.93

Using the Hybrid Method

The hybrid method involves using the ASSTHO and the AAA and AATRI data values to estimate the VOC. The ASSTHO methodology only accounts for only the fuel component of the vehicle and provides a fuel consumption rate based on operating speed. The AAA and ATRI, as discussed above, estimated both for the fuel and non-fuel components.

To estimate using the hybrid methodology, the fuel consumption rate based on the different operating speeds in the work zone, using the AASTHO fuel consumption rates in gallon per mile, is first derived in Table 30 Then, it is further converted to a dollar value by multiplying the consumption rate with the average fuel price per gallon for both auto and truck vehicles shown in the calculation step in Table 30.

Table 30

Calculation Steps to Estimate Fuel Consumption Rate Based on Operating Speed

<table>
<tr><td colspan="4">Derive the fuel consumption rate based on the fuel operating speed from the AASTHO fuel consumption rate in gallon per miles.</td></tr>
<tr><th>Speed Type</th><th>Speed</th><th>Auto (gal/mile)</th><th>Truck (gal/mile)</th></tr>
<tr><td>Posted speed limit</td><td>65mph</td><td>0.039</td><td>0.158</td></tr>
<tr><td>Work zone</td><td>55mph</td><td>0.041</td><td>0.163</td></tr>
<tr><td>Detour speed limit</td><td>55mph</td><td>0.041</td><td>0.163</td></tr>
<tr><td colspan="4">Convert the fuel consumption rate to a dollar per mile by multiplying with the cost of fuel around the work zone environment</td></tr>
<tr><th>Speed Type</th><th>Auto (gal/mile)</th><th colspan="2">Unit cost ($/mile)</th></tr>
<tr><td>Posted speed limit</td><td>0.039</td><td colspan="2">$0.039 \times 2.26 = \$0.882$</td></tr>
<tr><td>Work zone</td><td>0.041</td><td colspan="2">$0.041 \times 2.26 = \$0.093$</td></tr>
<tr><td>Detour speed limit</td><td>0.041</td><td colspan="2">$0.041 \times 2.26 = \$0.093$</td></tr>
<tr><td></td><td></td><td colspan="2"></td></tr>
<tr><th>Speed Type</th><th>Truck (gal/mile)</th><th colspan="2">Unit cost ($/mile)</th></tr>
<tr><td>Posted speed limit</td><td>0.158</td><td colspan="2">$0.158 \times 2.30 = \$0.363$</td></tr>
<tr><td>Work zone</td><td>0.163</td><td colspan="2">$0.163 \times 2.30 = \$0.375$</td></tr>
<tr><td>Detour speed limit</td><td>0.163</td><td colspan="2">$0.163 \times 2.30 = \$0.375$</td></tr>
</table>

Therefore, the total fuel to cost ratio derived from the AAA and ATRI estimate from the value is multiplied with the fuel unit cost in dollars per mile to derive a complete operating cost unit, accounting for the fuel and non-fuel component. This is further expressed in Table 31.

Table 31

Calculation Steps to Estimate Non-Fuel Cost Based on AAA and ATRI Value

	Auto ($/mile)
Posted speed limit	$0.882 \times 4.80 = 0.42$
Work zone	$0.093 \times 4.80 = 0.44$
Detour speed limit	$0.093 \times 4.80 = 0.44$
	Truck ($/mile)
Posted speed limit	$0.363 \times 2.24 = 0.82$
Work zone	$0.375 \times 2.24 = 0.84$
Detour speed limit	$0.375 \times 2.24 = 0.84$

Therefore, the VOC is further estimated to account for the additional vehicle operating cost expressed below Table 32 and Table 33.

Estimating VOC for Vehicle not Taking a detour

Table 32

Calculation Steps to Estimate the VOC for Auto and Truck Not Taking a Detour Based on the Hybrid Method

For Auto vehicles		
Number of auto not taking a detour	$33{,}276 \times 69\% \times (100\% - 25\%)$	17220
Unit Vehicle operating cost at posted speed limit $0.42\ \$/mile$.		
Vehicle operating cost without work zone	$0.42\ \$/mile \times 0.75$	$ 0.32

Unit Vehicle operating cost at work zone speed limit $0.44\ \$/mile$.		
Vehicle operating cost without work zone	$0.44\ \$/mile\ \times 0.75$	$\$\ 0.33$
Additional vehicle operating cost per auto	$\$\ 0.33 - \$\ 0.32$	$\$0.02$
Additional vehicle operating cost for all autos not taking detour	$0.02 \times 17{,}220$	$\$\ 280.33$
For Truck Vehicles		
Number of trucks not taking a detour	$33{,}276 \times (100\% - 69\% \times (100\% - 25\%)$	$7{,}737$
Unit Vehicle operating cost at posted speed limit $0.82\ \$/mile$.		
Vehicle operating cost without work zone	$0.82\ \$/mile\ \times 0.75 miles$	$\$\ 0.61$
Unit Vehicle operating cost at work zone speed limit $0.84\$/mile$.		
Vehicle operating cost without work zone	$0.84\$/mile \times 0.75$	$\$\ 0.63$
Additional vehicle operating cost per truck	$\$\ 0.63 - \$\ 0.61$	$\$0.02$
Additional vehicle operating cost for all Trucks not taking detour	$0.02\ \times 7{,}737$	$\$\ 150.06$

Estimating VOC for Vehicle Taking detour

Table 33

Calculation Steps to Estimate the VOC for Auto and Truck Taking a Detour Based on the Hybrid Method

For Auto Vehicles

Number of autos taking a detour	$33276 \times 69\% \times 25\%$	$= \$ 5,740$
Unit vehicle operating cost at the posted speed limit $0.42\ \$/mile$		
Vehicle operating cost along the original route	$0.42\ \$/mile \times 5.37 mile$	$\$ 2.2729$
Unit vehicle operating cost at the detour speed limit $0.44\ \$/mile$		
Vehicle operating cost along the detour route	$0.44\ \$/mile \times 8.45\ miles$	$\$ 3.76$
Additional vehicle operating cost per auto	$\$3.76 - \$2.27$	$\$ 1.49$
Additional vehicle operating cost for all autos not taking detour	$\$1.49 \times 5740$	$8535.83

For Truck Vehicles

Number of trucks taking a detour	$33276 \times (100\% - 69\%) \times 25\%$	$2,579$
Unit vehicle operating cost at the posted speed limit $0.82\ \$/mile$		
Vehicle operating cost along the original route	$0.82\ \$/mile \times 5.37\ mile$	$\$ 4.3884$
Unit vehicle operating cost at the detour speed limit $0.84\ \$/mile$		
Vehicle operating cost along the detour route	$0.84\ \$/mile \times 8.45\ miles$	$\$ 7.12$

Additional vehicle operating cost per truck	$\$ 7.12 - \$ 4.3884$	$\$ 2.74$
Additional vehicle operating cost for all trucks not taking detour	$\$2.74 \times 2{,}579$	$\$ 7{,}054.68$

Therefore, the VOC unit cost based on the vehicle taking detour and not taking detour is summarized below.

Table 34

Summarized VOC for Vehicle Taking Detour and Not Taking Detour

Not Taking Detour	
Auto	$280.33
Truck	$150.06
Taking Detour	
Auto	$8,535.83
Truck	$7,054.68
Grand Total	**$16,020.91**

Crash Cost

The CC is estimated using the FHWA method and the Equivalent Property Damage Only method. The CC estimates the cost incurred by the likelihood of increased crashes in the work zone. The CC make use of the historical crash rates to estimate the increase in crashes. Therefore, data attributes needed to calculate the CC are shown in Table 35.

Table 35

Data Attributes to Estimate Crash Cost

Data Attributes	**Values**
AADT	33,276
Percentage of Vehicles Taking Detour	25%
Number of Years of Crash Data	4 years
Length of Section Corresponding to Crash Data	0.6 mile
Length of Work Zone (Reduced Speed Limit)	0.75 mile
Length of Original Route	5.37 miles
Length of Detour Route	8.45 miles
Average AADT from the Historical Data	36,296
Total Number of Crashes from the Historical Data	
K - Fatal Injury	1
A - Incapacitating Injury	0
B - Non-Incapacitating	5
C - Possible Injury	0
O - Property damages only	16

The first step to estimating the CC involves deriving the total million vehicle miles traveled based on the historical conditions and current work zone conditions. The current work zone conditions involve estimating the total million vehicle miles traveled in the work zone and the additional million vehicle miles traveled by vehicles taking a detour. It is thereby expressed in Table 36 below.

Table 36

Steps to Calculating Million Vehicles Miles Travelled

Historical base condition		
Total Million Vehicle Miles Travelled in Historical Data	$\frac{0.6 miles \times 36{,}296 \times 4\ yrs \times 365}{10^6}$	31.7949 $MVMT$
Current work zone condition (During Construction) ***Vehicles Not Taking Detour***		
Total Vehicles not taking detour	$33{,}276 \times (100\% - 25\%)$	24,957
Total million vehicle miles travelled in work zone	$\frac{24{,}957 * 0.75}{10^6}$	0.0187 $MVMT$
Vehicles Taking Detour		
Total vehicles taking detour	$33276 \times 25\%$	8,319
Additional Distance Travelled Per Vehicle Taking Detour	$8.45 miles - 5.37 miles$	$3.08 miles$
Additional Million Vehicle Miles Traveled by Vehicles Taking Detour	$\frac{3.08\text{miles} \times 8{,}319}{10^6}$	0.0256 $MVMT$

The next step involves the calculation of the CC using the desired methodology (i.e., either the FHWA or the EPDO method). However, the comprehensive CC based on the FHWA values is adjusted to present year and to state value.

Adjusting Unit cost to Tennessee value

The comprehensive crash cost is converted to the current year value using the CPI value of ***1.0202*** and converted to Tennessee state value using the location adjustment factor derived using the Nationwide Per Capita Income and Per Capita Income for Tennessee state. It is therefore expressed in Table 37.

Table 37

Calculation Steps to Adjust Crash Cost to Work Zone Location Value

Crash Cost Data Year		2016
Project Year		2021
CPI Per Year		1.0202
Nationwide Per Capita Income		$34,103
Per Capita Income for Tennessee		$29,859
Location Adjustment Factor		$29,859/$34,103 = 0.88
Adjustment factor		$0.88 \times 1.0202^{(2021-2016)} = 0.973$
The adjustment factor is therefore multiplied with the crash cost form Comprehensive Crash Cost derived from the FHWA recommended values		
Crash Type	**Comprehensive Crash Cost**	**Adjusted for Tennessee for Current Dollar Value**
K - Fatal Injury	$11,295,400.00	0.973 × $11,295,400 = $10,928,065.28
A - Incapacitating Injury	$655,000.00	0.973 × $655,000 = $633,698.92
B - Non-Incapacitating	$198,500.00	0.973 × $198,500 = $192,044.63
C - Possible Injury	$125,600.00	0.973 × $125,600 = $121,515.40
O - Property damages only	$11,900.00	0.973 × $$11,900 = $11,513

Estimating the Crash Cost using the FHWA method

The CC is estimated by accounting for:

- the historical crash rate per million vehicle miles traveled,
- the adjusted crash rate per million vehicle miles traveled using an all-crash severity CMF,
- expected increase in crash rate because of the work zone,
- and increased crashes for vehicles taking a detour and not taking detour based on the different crash types (i.e., based on the KABCO severity rating).

It is therefore expressed in Table 38.

Table 38

Steps to Estimate the Crash Cost Associated with Increased Crashes

Crash Type	**Total Number of Crashes from the Historical Data**	**Crash Rate (Per MVMT) in Historical Data**
K - Fatal Injury	1	$\frac{1}{31.7949\ MVMT} = 0.0315$
A - Incapacitating Injury	0	$\frac{0}{31.7949\ MVMT} = 0$
B - Non-Incapacitating	5	$\frac{1}{31.7949\ MVMT} = 0.1573$
C - Possible Injury	0	$\frac{0}{31.7949\ MVMT} = 0$
O - Property damages only	16	$\frac{0}{31.7949\ MVMT} = 0.5032$
The Crash rate (Per MVMT) based on historical data is further adjusted to the likelihood of increased crashes of vehicle taking detour and not taking detour using the CMF based on the severity level.		

CMF	CMF Adjusted Crash Rate (Per MVMT)	Expected Increase in Crash Rate Because of Work Zone Per MVMT	Increased Crash for Vehicles Not Taking Detour	Increased Crash for Vehicles Taking Detour
1.77	$1.77 \times 0.0315 = 0.0598$	$0.0598 - 0.0315 = 0.0283$	0.00053	0.00081
1.77	0.0000	0.0000	0.00000	0.00000
1.77	$1.77 \times 0.1573 = 0.2516$	$0.2516 - 0.1573 = 0.0944$	0.00177	0.00403
1.77	0.0000	0.0000	0.00000	0.00000
1.77	$1.77 \times 0.5032 = 0.9561$	$0.9561 - 0.5032 = 0.4529$	0.00848	0.01289

The total increased crashes in the work zone environment are therefore computed by multiplying the increased crashes for vehicles not taking detour and increased crash for vehicles taking detour by the expected increase in crash rate because of work zone per MVMT and the crash rate (Per MVMT) in historical data respectively.

Increased Crash for Vehicles Not Taking Detour	Increased Crash for Vehicles Taking Detour	Total Increased Crashes

$0.0187 \times 0.0283 = 0.00053$	$0.0256 \times 0.0315 = 0.00081$	$0.00053 + 0.00081 = 0.00134$
0.00000	0.00000	0.00000
$0.0187 \times 0.0944 = 0.00177$	$0.0256 \times 0.1573 = 0.00403$	$0.00177 + 0.00403 = 0.0058$
0.00000	0.00000	0.00000
$0.0187 \times 0.4529 = 0.00848$	$0.0256 \times 0.5032 = 0.01289$	$0.00848 + 0.01289 = 0.02137$

Thereafter, the crash cost associated with the increased crashes based on the different crash types is expressed by multiplying the increased crashes by the unit crash cost of the current year.

Table 39

Calculation Steps to Estimate Crash Cost Associated with Increased Crashes

Crash type	**Unit Crash Cost in Current Year**	**Total increased crashes**	**Crash Cost Associated with Increased Crashes**
K - Fatal Injury	$10,928,065	0.00134	$0.00134 \times \$10,928,065 = \$14,596.65$
A - Incapacitating Injury	$633,699	0.00000	$0.00
B - Non-Incapacitating	$192,045	0.0058	$0.0058 \times \$192,045 = \$\ 1112.99$
C - Possible Injury	$121,515	0.00000	$0.00

O - Property damages only	$\$11{,}513$	0.02137	$0.02137 \times \$11{,}513 = \$246.05$

Therefore, the total crash cost associated with increased crashes accounting for vehicles not taking a detour and for vehicles taking the detour =$\$15{,}955.69$

Estimating the CC using the EPDO method

The CC is estimated using the weighted equivalent property damage only cost to estimate the increase in the crash rate for vehicles taking a detour and not taking a detour, and it is expressed below.

Table 40

Calculation Steps to Derive EPDO Values

Crash Type	**Unit Crash Cost**	**Weight Compared to PDO**
K - Fatal Injury	$\$10{,}928{,}065$	$\frac{\$10{,}928{,}065.28}{\$11{,}513} = 949.19$
A - Incapacitating Injury	$\$633{,}699$	$\frac{\$633{,}698.92}{\$11{,}513} = 55.04$
B - Non-Incapacitating	$\$192{,}045$	$\frac{\$192{,}044.63}{\$11{,}513} = 16.68$
C - Possible Injury	$\$121{,}515$	$\frac{\$121{,}515.40}{\$11{,}513} = 10.55$
O - Property damages only	$\$11{,}513$	$\frac{\$11{,}513}{\$11{,}513} = 1.00$

The unit cost equated to PDO for each severity is therefore used to account for the CC associated with increased crashes accounting for vehicles not taking a detour and for vehicle taking detours. The estimation is further shown in the Table 41 below.

Table 41

Calculation Steps to Estimate Crash Cost Associated with Increased Crashes Accounting for Vehicles not Taking a Detour and for Vehicle Taking Detour

Crash Type	Total Number of Crashes from the Historical Data	Weight Compared to PDO	Equivalent Property Damage Only (EPDO) Crashes
K - Fatal Injury	1	\$949	$\$949 \times 1 = \$949$
A - Incapacitating Injury	0	\$55	0
B - Non-Incapacitating	5	\$17	$\$17 \times 5 = \$83$
C - Possible Injury	0	\$11	0
O - Property damages only	16	\$1	$\$16 \times 1 = \$16$
Therefore, the total equivalent EPDO is divided by the total million vehicle miles travelled in historical data estimated in ***Table 6-28***			
Number of Equivalent Property Damage Only (EPDO) Crashes	$\$949 + \$83 + \$16$	$\$1049$	
Unit Crash Cost for PDO Crashes in Current Year $\$11{,}513$			
EPDO Crashes Per MVMT in Historical Data	$\frac{\$1049}{31.7949}$	32.9801	

Estimating Crash Cost for Vehicle Not Taking Detour		
CMF for All Crashes (Per MVMT) = 1.77		
CMF Adjusted Crash Rate (Per MVMT)	32.9801×1.77	58.3747
Expected Increase in Crash Rate Because of Work Zone (Per MVMT)	$58.3747 - 32.9801$	25.3947
Therefore, the crash associated with increased crashes for vehicles not taking detour is derived by multiplying the expected increase in crash rate because of work zone (Per MVMT) by the total million vehicle miles travelled in work zone and the unit crash cost for PDO crashes		
Crash Cost Associated with Increased Crashes for Vehicles Not Taking Detour	$25.3947 \times 0.0187 MVMT \times \$11{,}513$	\$5,472.48
Estimating Crash Cost for Vehicle Taking Detour.		
The crash cost associated with increased crashes for vehicles taking detour is estimated by multiplying the additional million vehicle miles traveled by vehicles taking detour, by the unit crash cost for EPDO crashes in current year and the EPDO crashes per MVMT in historical data		
Crash Cost Associated with Increased Crashes for Vehicles Taking Detour	$0.0256\ MVMT \times \$11{,}513 \times 32.9801$	\$9,728.86
Therefore, the total crash cost associated with increased crashes accounting for vehicles not taking a detour and for vehicle taking detour =\$15,201.35		

Emission Cost (EC)

In estimating the major pollutants emission rate in gram per miles observed in the work zone environment involving CO, NOX, SO_2, VOC, P.M 2.5 were derived from the MOVES software. These datasets were based on Sullivan County work zone environment considering the rural area environment condition. The emission rates data are then derived for the three speed types involving the posted speed, work zone speed, and the detour speed limit. The emission factor rates for each pollutant based on the different posted speed for both auto and trucks are shown in Table 42 below.

Table 42

Emission Factor for Pollutants Derived from MOVE Software

AUTO						
Speed type	**Speed (mph)**	**CO (g/mile)**	**NOX (g/mile)**	**SO2 (g/mile)**	**VOC (g/mile)**	**PM 2.5 (g/mile)**
Posted speed limit	65	1.142434	0.066599	0.001711	0.007120	0.000848
Work zone speed limit	55	1.096303	0.063436	0.001716	0.007765	0.000826
Detour speed limit	55	1.096303	0.063436	0.001716	0.007765	0.000826
TRUCK						
Speed type	**Speed (mph)**	**CO (g/mile)**	**NOX (g/mile)**	**SO2 (g/mile)**	**VOC (g/mile)**	**PM 2.5 (g/mile)**

Posted speed limit	65	0.872218	1.942973	0.005432	0.044619	0.040905
Work zone speed limit	55	0.891539	1.835460	0.005100	0.045812	0.042133
Detour speed limit	55	0.891539	1.835460	0.005100	0.045812	0.042133

The emission factor rate shown above is therefore converted to tons per mile by multiplying each emission factor rate for different speed types by the short ton conversion factor of ***0.00000110231*** as shown in Table 43.

Table 43

Emission Factor in Converted to Tons Per Mile

AUTO						
Speed type	**Speed (mph)**	**CO (tons/mile)**	**NOX (tons/mile)**	**SO2 (tons/mile)**	**VOC (tons/mile)**	**PM 2.5 (tons/mile)**
Posted speed limit	65	0.000001259	0.000000073	0.000000002	0.000000008	0.000000001
Work zone speed limit	55	0.000001208	0.000000070	0.000000002	0.000000009	0.000000001

Detour speed limit	55	0.000001208	0.000000070	0.000000002	0.000000009	0.000000001
TRUCK						
Speed type	**Speed (mph)**	**CO (tons/mile)**	**NOX (tons/mile)**	**SO2 (tons/mile)**	**VOC (tons/mile)**	**PM 2.5 (tons/mile)**
Posted speed limit	65	0.00000096	0.00000214	0.00000001	0.00000005	0.00000005
Work zone speed limit	55	0.00000098	0.00000202	0.00000001	0.00000005	0.00000005
Detour speed limit	55	0.00000098	0.00000202	0.00000001	0.00000005	0.00000005

The next step is to covert the Emission unit cost in 2000-dollar value derived from HERS-ST model to the recent dollar value. The HESRT unit cost also converts the unit cost based on a rural or urban area type by using an adjustment factor (see Appendix A, Table A.12). The unit cost for recent year based on rural area type noted in the project information is derived by multiplying the Unit Emission Cost in 2000-dollar value by the adjustment factor and the CPI adjustment value, further expressed below.

$$\text{2021 unit cost dollar value} = \text{Adjustment factor based on ruarl area type} \times \text{2000 unit cost dollar value} \times 1.0202^{(2021-2000)}$$

The result for each pollutant is thereby expressed in Table 44 below.

Table 44

Emission Factor Unit Cost Adjusted to Recent Year

	CO	NOX	SO2	VOC	PM 2.5
Adjustment factor	0.5	1.0	1.0	1.0	0.5
Unit Emission Cost in 2000-dollar value	$100	$3,625	$8,400	$2,750	$4,825
Unit cost in 2021- dollar value	**$76.05**	**$5,513.35**	**$12,775.77**	**$4,182.54**	**$3,669.23**

The unit cost for each pollutant is therefore multiplied by the emission factor rates (ton per miles) for each pollutant to derive the unit cost based on the various posted speeds. The result is shown in Table 45 below.

Table 45

Emission Rate Cost Based on Speed Limit and Area Type

AUTO							
	Speed	**CO**	**NOX**	**SO2**	**VOC**	**PM 2.5**	**Total**
Posted speed limit	65	$0.000096	$0.000405	$0.000024	$0.000033	$0.000003	$0.000561
Work zone	55	$0.000092	$0.000386	$0.000024	$0.000036	$0.000003	$0.000541

speed limit							
Detour speed limit	55	$0.000092	$0.000386	$0.000024	$0.000036	$0.000003	$0.000541
TRUCK							
	Speed	**CO**	**NOX**	**SO2**	**VOC**	**PM 2.5**	**Total**
Posted speed limit	65	$0.000073	$0.011808	$0.000076	$0.000206	$0.000165	$0.012329
Work zone speed limit	55	$0.000075	$0.011155	$0.000072	$0.000211	$0.000170	$0.011683
Detour speed limit	55	$0.000075	$0.011155	$0.000072	$0.000211	$0.000170	$0.011683

The next step involves estimating for the additional EC. This is therefore derived using the data set information in Table 46.

Table 46

Data Attributes to Estimate the Emission Cost

Data Attributes	**Values**
AADT	33,276.00
Area Type	Rural
Percentage of Car	69%
Percentage of Vehicles Taking Detour	25%
Length of Work Zone (Reduced Speed Limit)	0.75
Length of Original Route	5.37
Length of Detour Route	8.45
Posted Speed Limit	65
Work Zone Speed Limit	55
Detour Speed Limit	55

The number of vehicles based on the speed types is first derived and further estimated with the distance for each vehicle operating speed and further multiplied with the total EC for each operating speed. It is further expressed below in Table 47.

Table 47

Calculation Steps to Compute Emission Cost

Speed Type	**Vehicle Type**	**Speed**	**Number of Vehicles**	**Distance (miles)**
Posted Speed Limit	Auto	65	$33276 \times 69\% = 22{,}960$	5.37
	Truck	65	$33276 \times (1 - 69\%) = 10{,}316$	5.37
Work Zone Speed Limit	Auto	55	$33276 \times (1 - 25\%) * 69\% = 17{,}220$	0.75
	Truck	55	$33276 \times (1 - 25\%) * (1 - 69\%) = 7{,}737$	0.75
Detour Speed Limit	Auto	55	$33276 \times 25\% \times 69\% = 5{,}740$	8.45
	Truck	55	$33276 \times 25\% \times (1 - 69\%) = 2{,}579$	8.45

The number of vehicles estimated based on the different speed type is multiplied with the distance in miles and the total emission rate shown in Table 47.

Speed Type	**Vehicle Type**	**Emission Cost**	
Posted Speed Limit	Auto	$22960 \times 5.37 \times 0.000561$	\$69.15
	Truck	$10316 \times 5.37 \times 0.012329$	\$682.96
Work Zone Speed Limit	Auto	$17220 \times 0.75 \times 0.000541$	\$51.61
	Truck	$7737 \times 0.75 \times 0.011683$	\$508.47

Detour Speed Limit	Auto	$5740 \times 8.45 \times 0.000541$	\$26.23
	Truck	$2579 \times 8.45 \times 0.011683$	\$254.59

The additional EC is thereby estimated by deducting the work zone and detour EC based on the operating speed limit from original route in the absence of work zone based on the posted speed limit. It is further expressed below in Table 48.

Table 48

Additional Emission Cost Estimate

Additional Emission Cost	$= (\$51.61 + \$508.47 + \$26.23 + \$254.59) - (\$682.96 + \$69.15)$	\$88.78

Therefore, the additional cost for each component is computed together to derive the total RUC. It is further expressed below in Table 49. Furthermore, the construction day is multiplied with the total RUC computed to estimate for the RUC based on the number of working days.

Table 49

Total Road User Cost for Case Study One Project Located in Sullivan County

RUC Component	**Cost**
Delay Cost	$15,788.86
Vehicle Operating Cost	$16,020.91
Crash Cost	$15,578.52
Emission Cost	$88.78
Total Road User Cost Per Day	**$47,477.07**

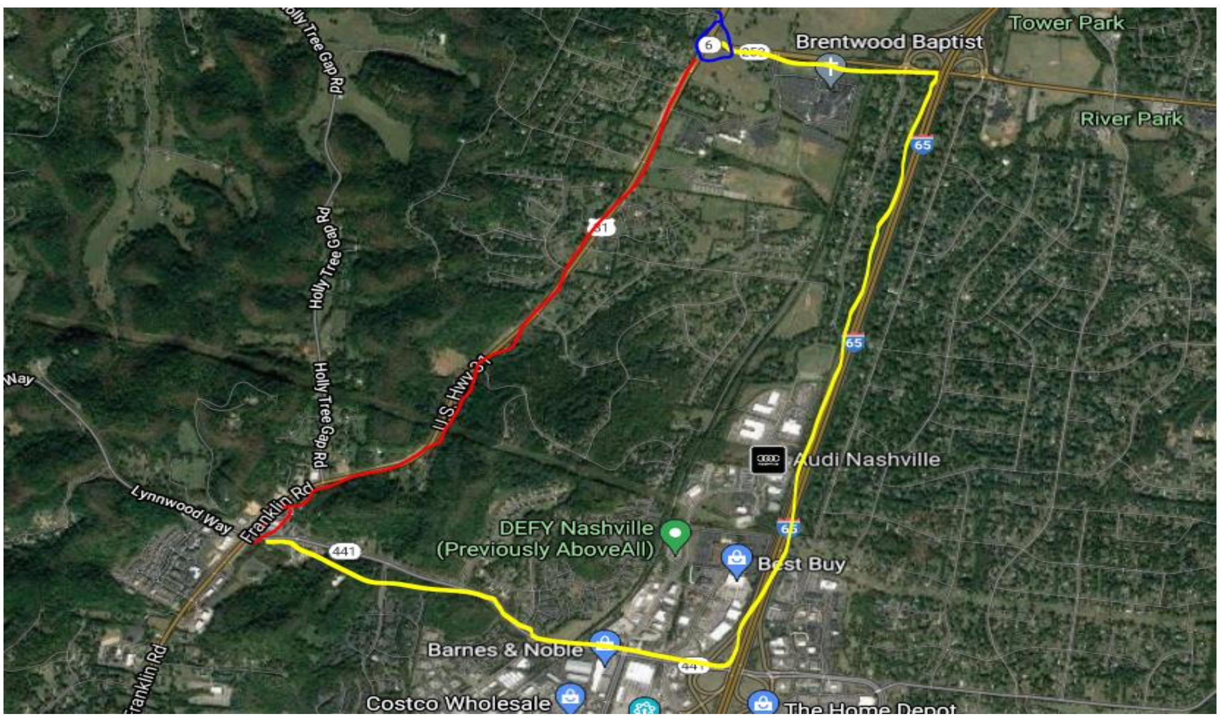
Total Road User Cost for the Duration of Construction	**5,697,248.4**

Case Study Two

Case study two involves a project for State Route (S.R.) 6 (US 31/Franklin Road), from south of SR 441 (Moores Lane) to SR 253 (Concord Road) in Williamson County, TN. The project involves a roadway construction and widening for approximately 2.63 miles through SR 6. The proposed improvements are intended to address congestion, improve safety, and accommodate growth in this rapidly developing area as stated in the TDOT website.

Figure 23

Work Zone Environment Showing Detour Route and Original Route in Williamson County



The work zone location in Figure 23 can be seen as located in along the red line, while a detour route is indicated with the yellow line. The work zone length is stated as 2.63miles, while the detour route distance is estimated to be 6.9miles. Assumptions made to calculate the total road user cost per day involves:

1.) 50% of the AADT will take a detour.

2.) Assuming an Intercity trip mode, which involves using an intercity trip mode multiplier.

The RUC accounts for four components of and result is shown in Table 50.

Table 50

Total Road User Cost for Case Study Two Project Located in Williamson County

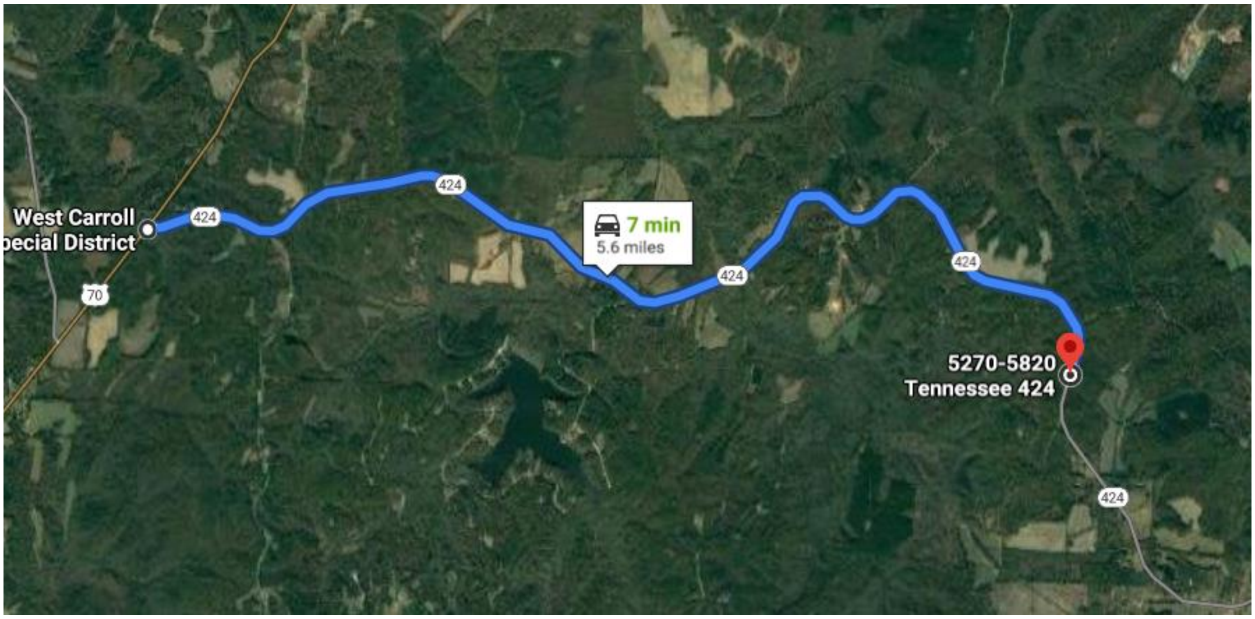
RUC components	**Cost**
Delay Cost	$46,068.84
Vehicle Operating Cost	$23,612.40
Crash Cost	$60.35
Emission Cost	$43.30
Total Road User Cost Per Day	**$69,784.89**
Total Road User Cost for the Duration of Construction	**$4,187,093.4**

Case Study Three

Case study three involves a resurfacing roadway project on S.R 424 form U.S. 70 (State Route 1) to near Cook Road in Carroll County as shown in Figure 24 below.

Figure 24

Work Zone Environment Showing Work Zone Route in Carroll County



The project involves the resurfacing of the roadway route 424 for 5.6 miles starting from the exit road of U.S 70 to S.R. 424. The proposed resurfacing is for the road route maintenance and to aid smooth travel through the roadway. In addition, as seen from the figure above, the work zone environment does not have a detour route and assumes a local trip mode for road user travelling through the route. The total RUC for this work zone location is expressed in the Table 51 below.

Table 51

Total Road User Cost for Case Study Two Project Located in Carroll County

RUC components	**Cost**
Delay Cost	\$223.42
Vehicle Operating Cost	\$16.59
Crash Cost	\$353,18
Emission Cost	\$0.47

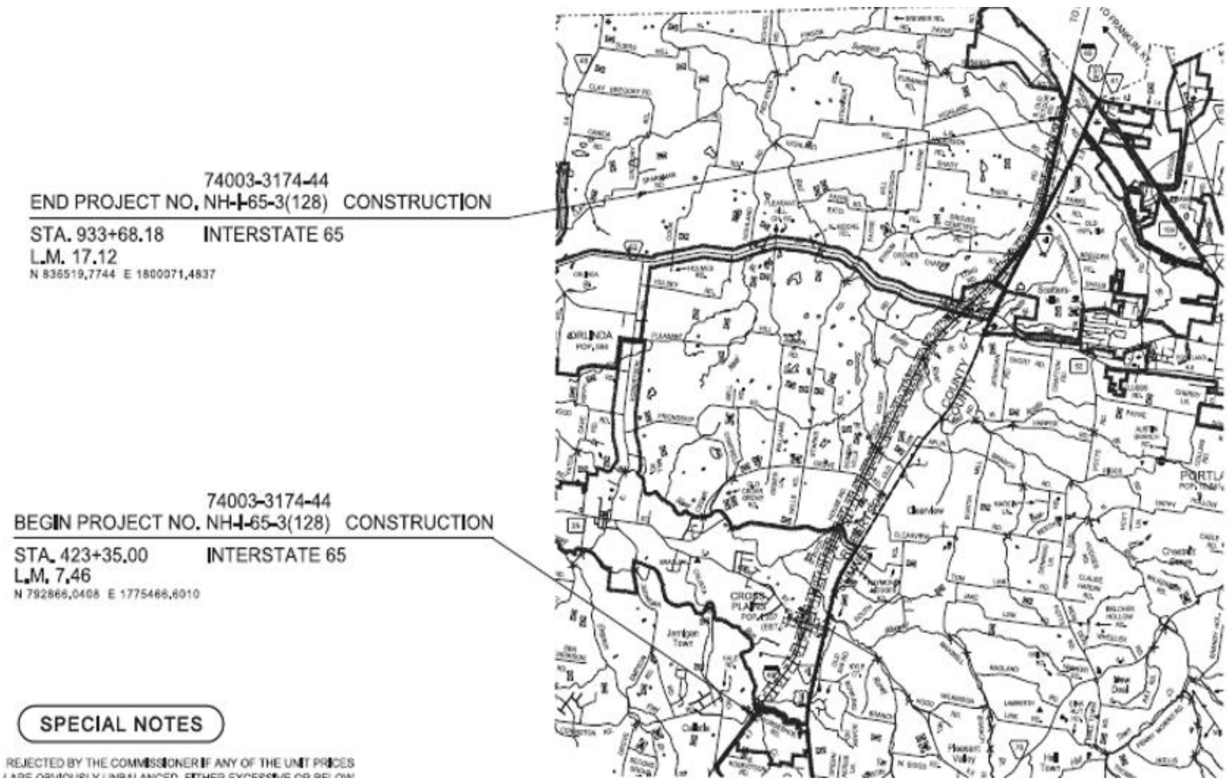
Total Road User Cost Per Day	**$593.66**
Total Road User Cost for the Duration of Construction	**$15435.2**

Case Study Four

This case study involves the widening of I-64 from near SR-25 to near SR-109. Figure 25 below shows the work zone length and coordinates.

Figure 25

Work Zone Environment Showing Work Zone Route in Robertson County



The project includes the widening of the road from a four-lane to a six-lane with a 12-foot width. The improvement is stated to increase traffic capacity, improve safety, and allow for future expansion. In addition, as seen from the figure above, the work zone environment does not have a detour route and assumes an intercity trip mode for road users traveling through the roadway. The total RUC for this work zone location is expressed in Table 52 below.

Table 52

Total Road User Cost for Case Study Two Project Located in Robertson County

RUC components	**Cost**
Delay Cost	$63,546.98
Vehicle Operating Cost	$8,006.56
Crash Cost	$0.00
Emission Cost	$0.76
Total Road User Cost Per Day	**$71,267.54**
Total Road User Cost for the Duration of Construction	**$104,050,608.4**

Chapter 7. Conclusion and Recommendation

This study has evaluated and discussed RUC utilization and calculation. This has been done by reviewing existing studies on RUC application and calculation, conducting a survey to understand better and determine the best practice to compute RUC, developing an enhanced framework to compute RUC, and implementing this framework with case studies. This section presents the highlights and major findings, the limitations of the study, and recommendations for future studies.

Highlights from RUC Study

The concept of RUC has been established as early as 1965. Over the years, the RUC concept and methodology was used innovative contracting procedures. FHWA, ASSTHO, and the National Cooperative Highway Research Program (NCHRP) have acknowledged the essential inclusion of RUC in roadway project. The literature review identified five components to compute RUC, which are the Delay Cost (DC), Vehicle Operating Cost (VOC), Crash Cost (CC), Emission Cost (EC), and the Local and Business Impact Cost (LBIC), however, many State DOTs only use DC and VOC in their RUC calculations.

Major Findings

Significant findings from the research were mostly based on the survey findings in terms of current practices of calculating and utilizing RUCs among state DOTs. Based on the 37 state DOTs that responded to the survey questionnaire, 34 state DOTs currently calculate RUC for their roadway projects. Most state DOTs have developed their state-specific methodologies to estimate the RUC for use in innovative contracting procedures such as determining and calculating early completion incentive and disincentives for highway projects, evaluating the best bidder in A + B contracting, and as lane rental costs for special contract types. However, most of the state-specific methodologies are based on the recommended methodologies developed by the FHWA and the ASSTHO, most state DOTs prefer using an Excel-based spreadsheet to implement RUC, because of ease of inputting data and adjusting the data set. Most state DOTs do not include more than three components in the RUC computed methodology. The DC and VOC are indicated as the major component to consider when calculating the RUC, as these two costs represent a significant percentage of the RUC.

Highlights from Framework

The developed framework methodology was based on the existing methodologies and feedback from the survey. The developed framework accounted for four components: DC, VOC, EC, and CC. Further highlights of the developed framework and each component are stated below.

Delay Cost

- In estimating the VOT, the methodology accounts for an “All trip" mode in terms of travel mode to account for the hourly dollar value of road users. The All-trip mode is derived by taking the average hourly dollar value for local and intercity trip modes.
- Estimated DC incorporates two free flow scenarios: traveling through the work zone and traveling through a detour. Its further accounts for the DC based on the current scenario in the work zone environment compared to the base scenario when there is no work zone.

Vehicle Operating Cost

- Accounted for the VOC by using a hybrid methodology, which involves merging the fuel cost derived from AASTHO fuel consumption rate values in gallon per mile value with non-fuel cost derived from the AAA and ATRI cost per mile values to derive a total operating cost.

Crash Cost (CC)

- Accounted for the increase in the crash rate for vehicles taking the detour and travelling through the work zone.
- Adjusted the comprehensive crash cost unit (recommended from FHWA's Crash Costs for Highway Safety Analysis) to state-specific values.
- Used a hybrid method to generate CC.

Emission Cost (EC)

- Used the Motor Vehicle Emission Simulator (MOVES) software developed by the U.S. Environmental Protection Agency (EPA) to derive emission rates for different project locations in Tennessee.
- Accounted for EC based on the project’s location and area type (Rural and Urban)

In summary, the major highlight from the framework includes a) accounting for the spatial variation of the RUCs using location indexes, b) accounting for the temporal variation of the RUCs using an inflation index, and c) requires minimal time, effort, and data to compute RUCs while accounting for most of the impacts.

Limitation

The limitation of the study is based on the authenticity and accuracy of the datasets used in computing the DC, VOC, AC, and EC. Even though the datasets such as the unit cost and attributed values used in estimating each component were derived from prominent sources such as FHWA, ASSTHO, and the BLS website, there was no way to check or reassert the accuracy of the datasets. The developed methodology uses datasets from stated sources based on the year of publication, and the study tried to adjust such values to recent years using the CPI.

In addition, the LBIC component was not included in the RUC methodology. The developed framework is targeted to be an enhanced methodology in which data attributes will be easily derived. However, estimating the LBIC necessitates additional studies and surveys of the business area, such as understanding the business's revenue in the nearby areas and quantifying decrease in the revenue as a percentage of the original revenue to quantify the cost. In addition, it requires more location-specific data that are not easily assessable as the impact on businesses will vary in different locations.

Recommendations

Through the reviews of various existing studies, findings from a nationwide survey, and the development of the simplified methodology to compute RUC, the following recommendations are given.

- The inclusion of more components such as the CC, EC, and LBIC should be considered in computing RUC, as most state DOTs currently include only the VOT and VOC components. The inclusion of more components will establish a more comprehensive and accurate result.
- Updating the data set to compute each component should be derived from reliable and prominent transportation and highway publications such as the FHWA, AASTHO, AAA, ATRI, BLS, HSM, and HCM. Updating those data sets will help to derive a more consistent and accurate RUC value.
- Developing the RUC methodology by accounting for spatial variation based on the location of the work zone.

- Accounting for more delay scenarios in a forced flow work zone environment, including stopping, queuing, and idling to estimate more comprehensive DC and operating cost during such delay in the work zone.
- More business impact studies in construction zone should be conducted to generate ways to quantify the LBIC cost.

In conclusion, the RUC is an important component that should be considered for projects that cause significant inconvenience to the road users while evaluating contracts bid or liquidated damages. Therefore, state DOTs should have a consistent and efficient method for computing RUC to derive accurate and effective results in terms of contract bidding around the state's transportation department to meet the needs of the State DOT. If the RUC methodology is not consistent, it might be misleading in approving contractors' bids. This could further result in disputes and legal actions, whereby contractors might argue that they would have easily won a bid if the RUC calculation was consistent. Furthermore, the RUC should be tailored to the need and availability of datasets value of the state DOT for ease of calculating and developing a tool. Preferably an Excel-based tool or a web-based tool is to be developed to implement the RUC computed by the state DOT. Moreover, when such tools are developed, there should be proper training and provision of user manuals provided to engineers and analysts to aid the easy navigation and utilization of the tool.

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APPENDICES

Appendix A: Standard Datasets

Table A.1

Distribution of Vehicle Miles by Trip Purpose

Travel Type	**Recommended Values**	
	Personal	**Business**
Local Travel	95.4%	4.6%
Intercity Travel	78.6%	21.4%

(Source: Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis (*Revised Value of Travel Time Guidance.Pdf*, *2015*.)

Table A.2

Recommended Percentage Value of Time as the Hourly Multiplier Based on Trip Mode and Purpose.

Transportation Mode and Trip Purpose	**Recommended Value of Time**
Auto	
Personal (Local)	50% of the wage rate
Personal (Intercity)	70% of the wage rate
Business	100% of the wage rate
Truck	
In-Vehicle Business	100% of total compensation
Excess (waiting time) Business	100% of total compensation

(Source: U.S. Department of Transportation. 1997)

Table A.3

Average Vehicle Occupancy Factor for Travel Time Reliability Measure by FHWA

Vehicle Type	Average Vehicle Occupancy Factor
Auto	1.7
Trucks	1.0

(Source: FHWA National Household Travel Survey (2018)

https://www.fhwa.dot.gov/tpm/guidance/avo_factors.pdf)

Table A.4

Fuel Consumption (Gallon per Miles)

Operating Speed (mph)	Auto	Trucks
5	0.117	0.503
10	0.075	0.316
15	0.061	0.254
20	0.054	0.222
25	0.050	0.204
30	0.047	0.191
35	0.045	0.182
40	0.044	0.176
45	0.042	0.170
50	0.041	0.166
55	0.041	0.163
60	0.040	0.160
65	0.039	0.158

(Source: AASHTO (2010))

Table A.5

RUC Passenger Vehicle Operating Cost per Mile (2019)

Cost Element	Weighted Average
Fuel	$0.12
Maintenance, Repair, Tire	$0.09
Insurance	$0.10
License, Registration, Taxes	$0.07
Depreciation	$0.29
Finance Charges	$0.08

Source: AAA and TTI (TXdot. (2020) *RUC Memo*. https://www.txdot.gov/inside-txdot/division/construction/road-user-costs.html)

Table A.6

Estimate of Truck Costs per Mile: 2019

Estimated Cost Per Mile	2019
Fuel	$0.39
Truck/Trailer Lease or Purchase Payment	$0.27
Repair and Maintenance	$0.18
Truck Insurance Premiums	$0.09
Permits and Licenses	$0.03
Tires	$0.04
Tolls	$0.03

Source: AAA and TTI (TXdot. (2020) *RUC Memo*. https://www.txdot.gov/inside-txdot/division/construction/road-user-costs.html)

Table A.7

Additional Data Sources

Data	Source	Update Frequency
Median household income Auto	U.S. Census Bureau -State and County Quick Facts Per capita money income in the past 12 months, https://www.census.gov/quickfacts/fact/table/US/PST045219.	Annual
Wages and Benefits for Truck Drivers	U.S Bureau of labor statistics for occupational employment and wages, https://www.bls.gov/oes/current/oessrcst.htm	Annual

Table A.8

Crash Cost for Highway Safety Analysis (2018)

Crash Type	Crash Cost
Fatal (K)	$11,295,400
Disabling Injury (A)	$655,000
Evident Injury (B)	$198,500
Possible Injury (C)	$125,600
PDO (O)	$11,900

Table A.9

Unit Cost Crash by Crash Severity Corresponding to the Equivalent Property Damage Only (EPDO)

Crash Type	Comprehensive Crash cost	Weight Compared to PDO
Fatal (K)	$6,229,446.05	567.05
Disabling Injury (A)	$330,101.17	30.05
Evident Injury (B)	$120,586.72	10.98
Possible Injury (C)	$67,962.11	6.19
PDO (O)	$10,985.72	1.00

Table A.10

Adjusted Current Dollar Value to Tennessee state

Crash Type	Comprehensive Crash Cost (Data Year)	Adjusted for Tennessee for Current Dollar Value
Fatal (K)	$11,295,400.00	$10,928,065.28
Disabling Injury (A)	$655,000.00	$633,698.92
Evident Injury (B)	$198,500.00	$192,044.63
Possible Injury (C)	$125,600.00	$121,515.40
PDO (O)	$11,900.00	$11,513.00

Table A.11

Work zone CMF for Temporary Lane Closure on Freeway (FHWA, 2011)

Crash Severity	CMF
K - Fatal Injury	1.90
A - Incapacitating Injury	1.60
B - Non-Incapacitating	1.60
C - Possible Injury	1.60
O - Property damages only	1.90
All	1.77

Table A.12

HERS-ST Unit Cost of Emission (2000 Dollar Values)

Pollutant	Damage Cost ($/ton)	Adjustment Factors	
		Urban	Rural
Carbon Monoxide	$100	1	0.5
Volatile Organic Compounds	$2,750	1.5	1
Nitrogen Oxides	$3,625	1.5	1
Sulfur Dioxide	$8,400	1.5	1
Fine Particulate Matter (PM 2.5)	$4,825	1	0.5

Table A.13

Emission factor (g/mile) derived from EMFAC Model year 2020.

Mode	Speed	CO	CO2	NOX	PM10	SOX	VOC	PM2.5
Auto	0	2.7812	66.6818	0.2922	0.0022	0.0007	0.3837	0.0020
	5	2.4569	766.8891	0.1849	0.0119	0.0076	0.2149	0.0110
	10	1.9844	614.9120	0.1436	0.0075	0.0061	0.1299	0.0069
	15	1.7883	507.6205	0.1295	0.0050	0.0050	0.0908	0.0046
	20	1.5712	420.0952	0.1132	0.0036	0.0042	0.0632	0.0033
	25	1.3770	357.4551	0.0984	0.0026	0.0035	0.0461	0.0024
	30	1.2549	317.0704	0.0916	0.0020	0.0031	0.0369	0.0019
	35	1.1821	296.0934	0.0894	0.0017	0.0029	0.0316	0.0016
	40	1.1209	288.1362	0.0885	0.0015	0.0029	0.0284	0.0014
	45	1.0739	289.8098	0.0893	0.0014	0.0029	0.0273	0.0013
	50	1.0264	298.9480	0.0901	0.0013	0.0030	0.0268	0.0012
	55	0.9822	310.5357	0.0919	0.0013	0.0031	0.0274	0.0012
	60	0.9104	319.1575	0.0901	0.0014	0.0032	0.0279	0.0013
	65	0.9090	329.1834	0.0936	0.0016	0.0033	0.0326	0.0015
	70	1.0279	343.9031	0.1062	0.0017	0.0034	0.0399	0.0016
Truck	0	0.9305	9.0247	0.6741	0.0002	0.0002	0.0657	0.0002
	5	3.6942	2632.6795	8.9241	0.1305	0.0246	1.0958	0.1248
	10	2.8209	2043.8428	5.7722	0.0812	0.0190	0.6560	0.0776
	15	1.8191	1353.1687	3.0661	0.0440	0.0129	0.3083	0.0420

Mode	Speed	CO	CO2	NOX	PM10	SOX	VOC	PM2.5
	20	1.3283	1231.0692	3.0712	0.0401	0.0117	0.1986	0.0383
	25	1.0386	1070.3899	2.7759	0.0338	0.0102	0.1458	0.0323
	30	0.8902	1005.0638	2.6795	0.0333	0.0095	0.1239	0.0318
	35	0.7880	1027.6114	2.7688	0.0353	0.0096	0.1094	0.0337
	40	0.7016	1020.4777	2.6601	0.0366	0.0095	0.0947	0.0350
	45	0.6288	987.8008	2.5124	0.0382	0.0093	0.0824	0.0366
	50	0.6419	870.7248	2.3359	0.0362	0.0083	0.0752	0.0346
	55	0.5428	980.7255	2.6768	0.0559	0.0093	0.0819	0.0535
	60	0.4645	1123.7146	2.8172	0.0661	0.0106	0.0811	0.0633
	65	0.4374	1223.5407	2.9594	0.0651	0.0116	0.0745	0.0623
	70	0.5398	1211.7072	3.1534	0.0638	0.0115	0.0828	0.0610

Source: California Air Resources Board, EMFAC 2017

Table A. 14

Emission factor (g/mile) for Sullivan County derived from MOVES, 2021

Mode	Speed	CO	NOX	SO2	VOC	PM 2.5
Auto	0	5.599724	0.114109	0.010948	0.089139	0.004087
	5	3.479790	0.093460	0.006107	0.048046	0.002535
	10	2.439431	0.081280	0.003699	0.027442	0.001705
	15	2.130607	0.073628	0.002917	0.020462	0.001322
	20	1.925691	0.067900	0.002471	0.016505	0.001120
	25	1.665657	0.066209	0.002199	0.014068	0.000972
	30	1.559450	0.062721	0.001994	0.012282	0.000932

	35	1.404798	0.062523	0.001901	0.010856	0.000907
	40	1.272550	0.062846	0.001840	0.009765	0.000889
	45	1.169693	0.063097	0.001793	0.008917	0.000875
	50	1.105523	0.063085	0.001749	0.008255	0.000851
	55	1.096303	0.063436	0.001716	0.007765	0.000826
	60	1.093150	0.064076	0.001695	0.007365	0.000815
	65	1.142434	0.066599	0.001711	0.007120	0.000848
	70	1.322919	0.072109	0.001772	0.007176	0.000922
	75	1.742416	0.079496	0.001871	0.007491	0.001082
Mode	**Speed**	**CO**	**NOX**	**SO2**	**VOC**	**PM 2.5**
Truck	0	7.982445	19.822557	0.023120	0.488192	0.325646
	5	4.950213	10.925429	0.013611	0.268158	0.175549
	10	3.248447	6.555142	0.009041	0.148060	0.113687
	15	2.614162	5.159119	0.008126	0.108034	0.106035
	20	2.070589	4.225890	0.007381	0.085760	0.096635
	25	1.802771	3.686261	0.006811	0.074278	0.089961
	30	1.597122	3.375265	0.006643	0.067388	0.085857
	35	1.322935	2.759207	0.005792	0.058966	0.065749
	40	1.190576	2.503222	0.005679	0.055353	0.061015
	45	1.087631	2.304122	0.005591	0.052544	0.057333
	50	0.982969	2.062254	0.005355	0.049149	0.050194
	55	0.891539	1.835460	0.005100	0.045812	0.042133

	60	0.863025	1.795740	0.005150	0.044226	0.038755
	65	0.872218	1.942973	0.005432	0.044619	0.040905
	70	0.880093	2.069173	0.005673	0.044956	0.042748
	75	0.896061	2.209730	0.005932	0.046196	0.045574

Table A. 15

State DOT and Components Included in RUC Calculation Methodology

State	**Delay Cost**	**Vehicle Operating Cost**	**Crash Cost**	**Emission Cost**	**Local Impact Cost**
Alabama	X	X	-	-	-
Arizona	X	X	-	-	X
Arkansas	X	X	X	-	-
Colorado	X	-	-	-	X
Delaware	X	X	-	-	-
Florida	X	X	X	-	X
Georgia	X	X	-	-	-
Hawaii	X	X	-	-	-
Idaho	X	-	-	-	-
Indiana	X	X	-	-	-
Iowa	X	X	X	-	-
Kansas	-	-	-	-	-
Kentucky	X	X	-	-	-
Louisiana	-	-	-	-	-
Maine	X	X	X	-	-
Maryland	X	X	-	-	-
Michigan	X	X	-	-	-
Minnesota	X	X	-	X	-
Mississippi	X	-	-	-	-
Missouri	X	X	-	-	-
Montana	X	X	-	-	-
New	X	X	-	X	-
New Jersey	X	X	-	-	-
North Dakota	X	X	-	-	-
Ohio	X	X	-	-	-
Oregon	X	X	-	-	-

Pennsylvania	X	-	-	-	-
Rhode Island	X	X	-	-	-
South	X	-	-	-	-
South Dakota	X	X	-	-	-
Tennessee	X	X	-	-	-
Utah	X	-	-	-	-
Vermont	X	-	-	-	-
Virginia	X	X	-	-	-
Washington	-	-	-	-	-
Wisconsin	X	X	-	X	-
Wyoming	X	X	-	-	-

Appendix B: Nationwide Survey

Survey on Road User Cost Calculation Methodology

Dear Highway Agency Representative,

Thank you for participating in this survey on Road User Cost calculation methodologies! This survey is a part of a research project funded by the Tennessee Department of Transportation (TDOT).

Construction activities impact the mobility of road users, which is quantified as the road users' cost. The goal of this survey is to understand the current practices of calculating road user cost in various highway agencies.

The results of the survey will be used to develop an improved road user cost calculation methodology and automation tool for TDOT. The survey should take about 15 minutes. If any questions are not relevant, you can skip the question. You can save the survey anytime and resume it via the original link. If you have any questions, you may contact K. Joseph Shrestha (shresthak@etsu.edu, 702-518-1175).

Thank you!

K. Joseph Shrestha

Assistant Professor

East Tennessee State University

Survey Questionnaire

General Information
Job Title ______________________________

State

- ○ Alabama
- ○ Alaska
- ○ Arizona
- ○ Arkansas
- ○ California
- ○ Colorado
- ○ Connecticut
- ○ Delaware
- ○ Florida
- ○ Georgia Hawaii
- ○ Idaho
- ○ Illinois
- ○ Indiana,
- ○ lowa
- ○ Kansas
- ○ Kentucky
- ○ Louisiana
- ○ Maine
- ○ Maryland
- ○ Massachusetts
- ○ Michigan
- ○ Minnesota Mississippi
- ○ Missouri
- ○ Montana
- ○ Nebraska
- ○ Nevada
- ○ New Hampshire
- ○ New Jersey
- ○ New Mexico
- ○ New York
- ○ North Carolina
- ○ North Dakota

- ○ Ohio
- ○ Oklahoma
- ○ Oregon
- ○ Pennsylvania
- ○ Rhode Island
- ○ South Carolina
- ○ South Dakota
- ○ Tennessee
- ○ Texas
- ○ Utah
- ○ Vermont
- ○ Virginia
- ○ Washington
- ○ West Virginia
- ○ Wisconsin
- ○ Wyoming

Applications of Road User Cost

Does your DOT calculate road user cost for roadway projects?

- ○ Yes
- ○ No

At which stage do you use the road user cost?

- ☐ Planning and Environmental
- ☐ Bidding and Contracting
- ☐ Roadway Construction

What are the current uses of road user cost in your DOT?

- ☐ To calculate early completion incentives (such as
- ☐ liquidated savings)
- ☐ To calculate late completion disincentive (such as
- ☐ liquidated damages)
- ☐ In accelerated construction contracts (such as no excuse bonus or locked incentives)
- ☐ As a lane rental cost for special contract types
- ☐ To evaluate special contracts such as Cost (A) + Time (B)
- ☐ To conduct Benefit-Cost Analysis
- ☐ Evaluate construction phasing options (such as nighttime construction) Others

If Others, please list ______________________________

What are the criteria your DOT uses when determining whether road user cost needs to be included in the contract?

- ☐ Dollar value of the project
- ☐ Location of the project
- ☐ Duration of the project
- ☐ Complexity of the project
- ☐ Specific contract type only
- ☐ Others

If Others, please list

Road User Cost Calculation Methodologies

What method does your DOT use to calculate road user cost?

- ☐ AASHTO based method.
- ☐ FHWA based method.
- ☐ Your agency specific method
- ☐ Flat rates as defined by legislation.
- ☐ Standard tools (e.g., QUEWZ, CA4PRS, VISSIM, etc.)
- ☐ No formal method
- ☐ Others

If Others, please list ______________________________

How would you classify your current road user calculation method/tool?

- ☐ Spreadsheet-based tool
- ☐ Desktop tool

	☐ Web-based tool ☐ Others
If Others, please list	____________________________
What type of road user cost calculation tool would you prefer the most?	☐ Spreadsheet-based tool ☐ Desktop tool ☐ Web-based tool ☐ Others
Please provide a web link, if available, about your DOT's road user cost calculation method.	
Please upload user manual, document, information about your DOT's road user cost method, if available.	
Please upload road user cost calculation spreadsheet that your DOT uses, if available.	
Which of the following components are included in road user cost calculation in your DOT?	☐ Delay Cost ☐ Vehicle Operation Cost ☐ Crash Cost ☐ Emission Cost ☐ Local Impact Cost ☐ Others

If Others, please list

Please mark the importance of the following components of road user costs.

	Required	Very Important	Somewhat important	Not Important
Delay Cost	○	○	○	○
Vehicle Operating Cost	○	○	○	○
Crash Cost	○	○	○	○
Emission Cost	○	○	○	○
Local Impact Cost	○	○	○	○

Please mark the importance of the following components of road user costs.

Yes		No	I do not know
○	○	○	○

Please mark the importance of the following components of Vehicle Operating Costs

	Required	Very Important	Somewhat important	Not Important
Fuel Consumption	○	○	○	○
Oil Consumption	○	○	○	○
Tire wear	○	○	○	○
Maintenance and Repair	○	○	○	○
Depreciation	○	○	○	○

Data Requirements for Road User Costs

What traffic data do you use for road user cost calculation?

☐ Hourly demand data
☐ Peak hour demand data
☐ Average daily traffic data
☐ Annual average daily traffic data
☐ Others

If Others, please list ______________________________

What vehicle types do you use for traffic composition?

☐ Motorcycle
☐ Passenger car
☐ Passenger truck
☐ Light commercial truck
☐ Bus
☐ Single unit truck
☐ Combination truck
☐ Others

If Others, please list ______________________________

What would like to change to improve the current practice of calculating and utilizing road user cost, if any?

What are the work zone configuration inputs for road user cost estimation?

☐ Number of lanes in each direction
☐ Number of open lanes through the work zone in each direction
☐ Length of the lane closure
☐ Lane width
☐ Lateral clearance restrictions
☐ Turn restrictions.

	☐ Availability and traffic characteristics of alternative routes ☐ Hours of lane closure (begin and end time) ☐ Hours of work activity (begin and end time) ☐ Signalization ☐ Type of work zone
What is the input for work zone capacity?	○ passenger cars per hour per lane (pcphpl) ○ vehicles per hour per lane (vphpl)
Which of the following method is used for the estimate of work zone capacity?	○ Highway Capacity Manual (HCM) ○ recommendation ○ Work zone capacity model ○ Your agency specific estimating method ○ Others
If Others, please list	______________________________
Please provide any additional comments about road user cost.	
What are the inputs for travel speeds?	☐ Free flow speed ☐ Work zone speed

VITA

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Publication and Presentations: Shrestha, K. J., Uddin M.M, and Adebiyi J.A., "Current Practices and Methodologies of Calculating Road User Costs in the United States" Canadian Society for Civil Engineers (CSCE, Conference Paper) May,2021.

Adebiyi J.A., Shrestha, K. J., and Uddin M.M., "Identification of the Best Practices to Compute Road User Costs," ETSU Appalachian Student Research Forum (ASRF, 2021) March 8, 2021, https://dc.etsu.edu/asrf/2021/presentations/7

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Shrestha, K. J., Uddin M.M, and Adebiyi J.A. (2020), "Current Practices of Calculating and Utilizing Road User Costs" Transportation Estimators Association – Project Users Group (TEA-PUG) 2020 Conference.