ICCEPM 2022
The 9th International Conference on Construction Engineering and Project Management
Jun. 20-23, 2022, Las Vegas, NV, USA

Framework to Compute Vehicle Emission Costs Associated with Work Zones

K. Joseph Shrestha [1*], Jeremiah Adebiyi [2], Mohammad Moin Uddin[3], Roy Sturgill[4]

[1]*Department of Engineering, Engineering Technology, and Surveying, East Tennessee State University, 1276 Gilbreath Dr, Box 70552, Johnson City, TN 37614-1700, USA,* E-mail address: shresthak@etsu.edu mailto:
[2]*Department of Civil, Construction, and Environmental Engineering, Iowa State University, 394 Town Engineering, 813 Bissell Road, Ames, 50011 IA, USA, E-mail address:* adebiyia@iastate.edu
[3]*Department of Engineering, Engineering Technology, and Surveying, East Tennessee State University, 1276 Gilbreath Dr, Box 70552, Johnson City, TN 37614-1700, USA,* E-mail address: uddimn@etsu.edu
[4]*Department of Civil, Construction, and Environmental Engineering, Iowa State University, 394 Town Engineering, 813 Bissell Road, Ames, 50011 IA, USA,* E-mail address: sturgill@iastate.edu

Abstract: Active construction work zones will result in longer travel time and/or longer travel distances for road users because of reduced speed limits and/or detours. This results in increased fuel consumption and increased emissions of harmful gases such as Carbon Monoxide (CO), Nitrogen Oxides (NOx), and Sulfur Oxides (SOx), which causes discomfort to the environment and road users around the work zone. The impact of such emissions should be considered while designing work zones or determining the number of days the roadway will be allowed to be closed partially or fully. This study develops a methodology to compute additional road user costs associated with such work zones. To achieve this goal, a) an extensive literature review is conducted, b) a framework to compute emission cost is developed, c) emission rates are computed for all counties (95) of the state of Tennessee, and d) a case study is conducted to demonstrate the use of the framework to estimate the additional impact of emission because of the work zone. For the case study conducted, the emission cost was computed to be $10,653.60 for the duration of the project. State DOTs can account for such road user costs while selecting contractors using A+B bidding. Accounting for such impact of emission will also indicate the agency's willingness to consider sustainability as a part of the business practices.

Keywords: Emission Cost, Pollutant, Road-User-Cost, MOVES, Work-Zone

1. INTRODUCTION

An active construction work zone can result in the halting, queuing, idling, and speed changes of vehicles passing through the work zone. This alteration can result in traffic congestion that has been identified as a significant contributor to air quality degradation [1], [2]. Furthermore, active construction is likely to increase travel time and distance, increasing fuel consumption and increasing emissions of harmful gases from compression-ignition engines in gasoline-powered vehicles [3]. These gases can pollute the environment, negatively affect human health, and result in the depletion of the ozone layer.

The impact of vehicle emission in the work zone is rarely considered by most State Departments of Transportation (DOTs), as a study identifying the best practices for estimating Road User Cost (RUC) in the United States shows that most state DOTs do not consider the impact of vehicle emission in a work zone when calculating RUC for its use in the alternative contracting project [3]. The omission of the impact of vehicle emission on the road users may be primarily because of the lack of well-established methodologies to estimate the monetary value of the emission. With the increasing importance of sustainability in the construction and transportation industry, the importance of including the impact of vehicle emission while making construction project management decisions is increasing every day. Thus, a framework needs to be developed to account for the emission cost as a part of RUC while making various decisions such as contractor selection using A+B bidding.

This study develops a framework to compute vehicle emission costs in work zones that accounts for geographic variation in the emission costs. The proposed framework is expected to assist state DOTs in making more informed project management decisions.

2. LITERATURE REVIEW

This section summarizes existing studies and provide a) an overview of vehicle emission in a work zone, b) factors affecting vehicle emissions, c) existing emission rate and costs, and d) available sources to derive unit costs of the pollutants.

2.1 Vehicle Emission in Work Zone

Vehicle emission can be described as releasing harmful gases from the vehicle's mechanical operation's combustion process. [4]. Emissions can be categorized into Air pollutants and Greenhouse gases [5], [6]. Pollutants such as carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), particle matter (PM), and volatile organic compounds (VOCs) are examples of air pollutants that are released into the atmosphere and are harmful to the environment while also causing discomfort to road users [7], [8]. Examples of greenhouse gases include carbon dioxide and Ozone, and they contribute to increasing temperature of the earth [6]. Vehicle pollutants are local contributors of air pollutants such as CO to the environment, causing excess photochemical oxidants.

2.2. Factors Affecting Vehicle Emission

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 [2]. Several studies (such as [1], [9]) described how an increase in congestion in the traffic stream causes an increase in emission rate. Various factors affecting vehicle emission ranges from roadway characteristics, traffic characteristics, driver characteristics, vehicle characteristics, and weather characteristics [6], [8], [10], [11]. 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 [7].

2.3. Emission Rate and Cost

The Emission Cost (EC) accounts for several types of pollutants present in the work zone. The EC considers the cost of pollutants because they indirectly influence road users and are expressed in terms of the total cost of environmental damage. The derivation of EC requires extensive data from software models such as Motor Vehicle Emission Simulator (MOVES), Comprehensive Model Emission Model (CMEM), and the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURES) to calculate the emission pollutant and rates. Furthermore, there has not been a consensus on the financial value of each pollutant to date [8]. Several agencies calculate emission rates and factors based on their geographical location and population density, resulting in data variation for determining EC. Using such software models, which requires a lot of project-specific data, may not be achievable to calculate road user costs as most state DOT tend to neglect the calculation from the total road user cost. Nevertheless, the Federal Highway Administration (FHWA) recommends that the derivation of emission rate and unit cost associated with different pollutants in the work zone environment be considered to estimate the EC [8].

Emission rates derivation is categorized into two models: Static and Dynamic emissions model [8]. The Static emission model calculates emission rate based on the fuel consumption and constant vehicle condition, not actively considering the activities around the source of the pollutants [12]. In contrast, the dynamic emission model calculates emission rates based on the change in the vehicle's operating condition while also considering the environmental characteristic of the work zone [8].

Additionally, the static emission model requires a constant pollutant factor, which only accounts for vehicle speed and type and excludes changes in driving operations such as acceleration, deacceleration, cruise control, and idling, which are all driving operations that are likely to occur in a work zone [14]. As a result, the model can only be applied to a wide range of planning assessments to calculate emission rates and costs on a bigger scale [6], [8]. The dynamic emission model requires extensive data estimation to calculate emissions based on the work zone driving condition. The model considers emission factors based on driving conditions at various time intervals, speed fluctuations, and cycle lengths, among other things [13]. Because of consideration of the dynamic operations of the vehicle, the dynamic models achieve greater accuracy and capability in evaluating emissions than static models, as it helps to capture the current state of the environment in real-time [14].

2.4. Deriving Unit Cost of Pollutants

Each type of emission has a different level of impact to the environment and human health. As such, the unit cost of each type of pollutant are different. According to the Federal Highway Administration report, there has been no consensus on assigning a monetary value to specific pollutants [8]. The unit cost for each emission type is calculated based on the impact on society's health in the vicinity of the work zone. The cost is largely defined by the population density in the work zone, as a work zone with a higher population density will incur more health effects than a location with a lower population density, resulting in a higher proportion of dollar value in the densely populated area. The recommended unit cost can be derived from local environmental agencies in the work zone and reflects the monetary value based on the environment[8]. Furthermore, costs from national agencies such as the EPA and FHWA (HERS-ST Technical Report) can be used and adjusted to state and local values to produce an accurate estimate.

3. METHODOLOGY

This study proposes a framework (Figure 1) to compute the cost impact of emission on road users in the work zone, as it accounts for the total cost of pollutants and emissions in the construction zone. The emission cost methodology considers the types of pollutants present in the construction work zone and the rates at which each pollutant is emitted. The framework further evaluates the cost of each pollutant as it directly or indirectly affects road users. Therefore, the emission's total monetary impact is estimated by adding the emission cost associated with each pollutant.

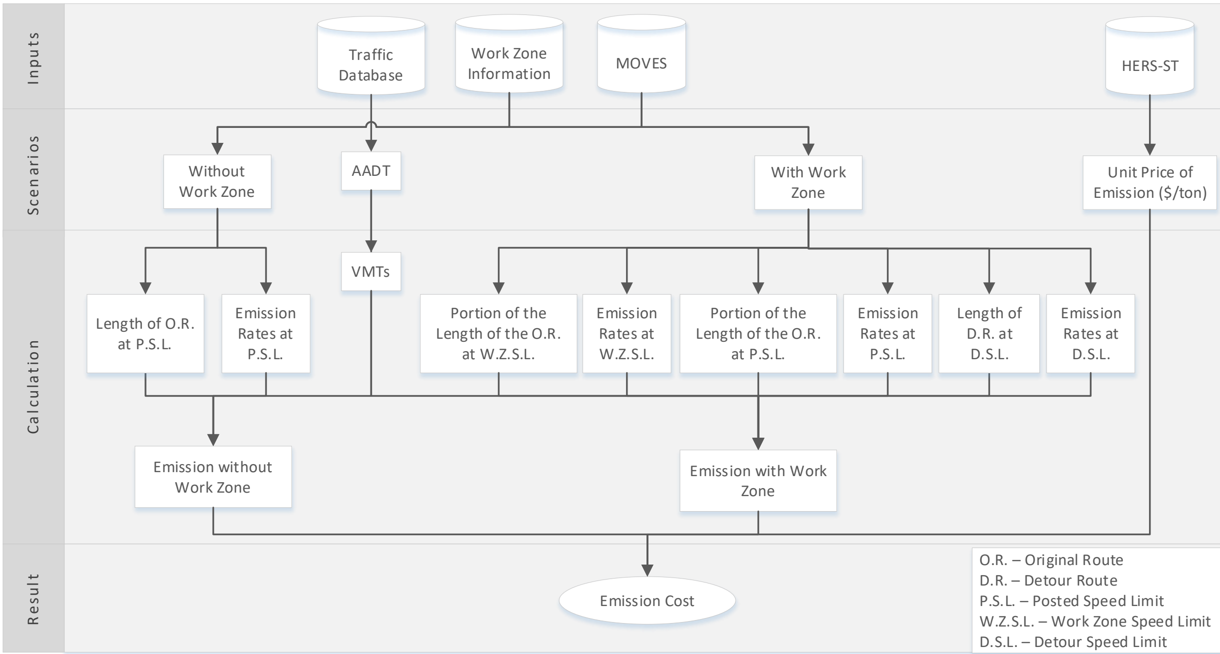

Figure 1: Framework to Estimate Emission Cost

The pollutants estimated in this framework are Carbon monoxide (CO), Nitrogen oxides (NOx), Sulfur oxides (SOx), Volatile organic compounds, Particulate Matter (PM 2.5), as these are significant pollutants in work zone areas [10], [15], [16]. However, other pollutants observed in the environment can be included in the calculation. The emission rate for these pollutants are generated using the MOVES software model developed by the Environmental Protection Agency (EPA) [8], as it accounts for emission rates based on extensive operating conditions such as idling, stopping, and running vehicles and also captures the current state of the environment in real-time [14]. It further derives emission rates based on spatial variation, such as deriving the emission rate for different counties and cities where estimation is needed.

The unit cost rate of each pollutant can be derived from reliable publications and agencies such as the FHWA report, Highway Economic Requirements System Software (HERS-ST) Technical Report, and local environmental agency [8]. The dollar value for each pollution should be estimated per vehicle mile as a function of vehicle speed, vehicle type, and roadway functional class to achieve a comprehensive unit cost.

3.1 Estimating the Emission cost (EC)

As described in Figure 1 above, the emission cost is estimated by deriving the emission rates of each pollutant from the MOVES software. The emission rates are further expressed in grams per mile and converted to tons per mile using the short ton conversion factor recommended by the USDOT 2020 BCA guideline (Equation 1). The emission cost for each vehicle operating speed is multiplied by the roadway section's length and the number of vehicles in each section to account for the emission (Equation 2).

$$Emission\ rate_{\frac{tons}{mile}} = \sum_{p}^{n} EF_{\frac{g}{miles}} \times 0.00000\,11023 \tag{1}$$

$$EC = \sum_{p}^{n} Emission\ rate_{\frac{tons}{mile}} \times Unit\ cost_{\frac{\$}{ton}} \times D.of\ road\ section \times AADT \tag{2}$$

Where P is pollutants, EF $_{g/miles}$ is the emission factor in grams per mile based on operating speed, Emission rate $_{tons/mile}$ is the emission rate converted to tons/mile for the various pollutant, Unit cost$_{\$/ton}$ the unit cost of emission for the various pollutant. Emission cost is based on posted speed, work zone speed, and detour speed limit, D. of the road section is the distance travelled at posted speed, work zone speed, and detour speed limit, AADT is the Average Annual Daily Travel of vehicles in each roadway section.

Based on different work zone configurations and activities, the framework further accounts for emission cost in the wok zone based on pre-construction speed and the work zone speed while also accounting for vehicles not taking detours and vehicles taking a detour. This ensures that the emission costs associated with the various sections of the road based on the work zone configuration are taken into consideration. Therefore, the Additional Emission Cost is estimated by deriving the number of vehicles based on the speed type and the distance for each vehicle operating speed and multiplied by the total emission cost for each operating speed. It is further estimated by subtracting the emission cost related to the posted speeds based on the work zone configuration, such as (detour, main work zone area, and around work zone area) from the estimated emission cost related to posted speed when there are no construction activities. This is further expressed in (Equation 4-6).

$$\text{Emission without Work Zone} = \text{Emission at the } Original\ Route\ at\ Posted\ Speed\ Limit \tag{4}$$

$$\begin{aligned}\text{Emission with Work Zone} &= Emisssion\ at\ Detour\ speed\ limit\ for\ detour\ length \\ &+ Emission\ at\ work\ zone\ speed\ limit\ for\ core\ work\ zone \\ &+ Emission\ outside\ the\ core\ work\ zone\ at\ posted\ speed\ limit\end{aligned} \tag{5}$$

$$\text{Additional Emission Cost} = \text{Emission with Work Zone} - \text{Emission without Work Zone} \tag{6}$$

4. CASE STUDY

A construction project in the rural area of Sullivan County, Tennessee, was analyzed using the developed framework to determine the emission impact cost. The work zone was 0.75 miles long, with a work zone speed limit of 55 mph, and was located along I-81 for 5.37 miles, with a posted speed of 65 mph. Due to ongoing construction and a duration of 120 days, an 8.45-mile detour route through US 11W with a speed limit of 55mph was provided as a detour. It is also estimated that 25% of AADT (i.e., 25% of 33,276) will take a detour. The emission cost was calculated for both the auto and truck vehicle, with the auto vehicle accounting for 69 percent of the total vehicle passing through the work zone.

The emission rates (gram/miles) of the major pollutants in the work zone environment (CO, NOX, SO2, VOC, and P.M 2.5) were calculated from the MOVES software. These datasets were based on the Sullivan County work zone environment with the rural area environment condition. The emission rate 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 speeds for both auto and trucks are shown in Table 1. The emission rate derived for each speed type is converted to tons per mile by multiplying each emission factor rate for different speed types by the short ton conversion factor of 0.00000110231.

Table 1. Pollutants Emission Rate

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 unit cost for emission was derived from the HERS-ST model, which factored in the unit cost of each pollutant based on the area type (Rural type). However, the unit cost is in 2000-dollar value and needed to be adjusted to the recent year value by multiplying the unit cost of each pollutant in 2000-dollar value by the adjustment factor based on the area type and the Consumers Price Index (CPI) adjustment value. Therefore, the unit cost of each pollutant and the adjusted value are shown in Table 2. The unit cost for each pollutant is multiplied by each pollutant's emission factor rates (ton per miles) to derive the unit cost based on the various posted speeds, as shown in Table 3 below. Table 4 further estimates the total emission cost based on the various operating speeds by estimating the number of vehicles passing through the work zone configuration and the distance in miles.

Table 2. Adjusted unit cost of pollutants

	CO	**NOX**	**SO2**	**VOC**	**PM 2.5**
Adjustment factor (rural area type)	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**

Table 3. Emission cost of each pollutant based on different operating speed

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 speed limit	55	$0.000092	$0.000386	$0.000024	$0.000036	$0.000003	$0.000541
Detour speed limit	5	$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

Table 4. Total emission cost based on different operating speed

Speed Type	**Vehicle Type**	**Number of Vehicles**	**Distance (miles)**	**Emission Cost**

Posted Speed Limit	Auto	22,960	5.37	$69.15
	Truck	10,316	5.37	$682.96
Work Zone Speed Limit	Auto	17,220	0.75	$51.61
	Truck	7,737	0.75	$508.47
Detour Speed Limit	Auto	5,740	8.45	$26.23
	Truck	2,579	8.45	$254.59

The additional emission cost because of the presence of the work zone is estimated by deducting the emission cost at the work zone (partly at the posted speed limit and partly at the posted work zone speed limit) and emission cost at the detour based on the detour operating speed limit from the emission cost along the original route without the work zone based on the posted speed limit, as shown in (Equation 4-6). Therefore, the emission cost derived is estimated to be $88.78 for a day; since the construction duration is for 120 days, the emission cost for the stated duration will be estimated at $10,653.6. This indicates the impact of emission in the construction environment of Sullivan County along the I-81 route original route and the US 11W route based on the stated distance provided is estimated at $10,653.6.

The Emission Cost is thus established and used in further estimating the RUC for the case study project by including the Emission Cost as one of the costs to be considered along with other costs such as vehicle operating cost, accident cost, and delay cost to achieve a better estimate of the RUC. Furthermore, estimating the emission cost for this project would allow for proactive emission reduction measures such as planning and designing alternative work zone configurations.

5. CONCLUSION

This study developed a framework for quantifying the impact of emissions in road construction. The framework is based on the FHWA-recommended procedure, in which the emission rate and unit cost of pollutants are used to calculate the impact. The MOVES software tool developed by the EPA was used to generate the environmental emission rates based on the changes in vehicle operation and the construction environment relating to area type, weather type, and geographical condition.

A case study was carried out to validate the application of the methodology and the quantification of the emission cost in the work zone located in Sullivan County, Tennessee. The Tennessee Department of Transportation has adopted the framework to estimate emissions costs during construction, combined with other costs to estimate RUC for alternative contracting projects. Other state transportation agencies are expected to adopt the framework to monetary quantify the impact of emission for construction work zone to design and plan effective strategies to minimize such impact, as the State Department of Transportation's consideration and inclusion of these impacts in construction project management decision making demonstrates its commitment to environmental sustainability. This study can be extended by developing a web-based tool that can store historical vehicle emission cost data.

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