Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2018) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

World Conference on Transport Research - WCTR 2019 Mumbai 26-31 May 2019

# Evaluation of emission level increment in urban and sub urban highway work zones

D.A.S.S.S. Ranawaka[a] ,H.R. Pasindu[b,]*

[a,b]*Transportation engineering division, Department of Civil engineering, University of Moratuwa, Moratuwa, Sri Lanka*

**Abstract**

A highway work zone is where a rehabilitation of an existing highway is being carried out. It can result in reduced flow, reduced capacity, and average speed. Also there is a high risk of safety involved in every work zone. Highway work zones are of particular importance when it comes to efficient travel operations of a road network, especially in areas where there is high traffic flow, such as urban areas. Impact of work zones related to emission and air quality monitoring is often overlooked in such projects. Impact of a work zone for emission is higher in a developing country due to the nature of vehicle fleet. In this study, in order to evaluate the impact of work zones in emission in urban highway work zones and major arterial roads in Sri Lanka, emission modelling was done for a major arterial road in Sri Lanka, using HDM-4 (2008) software for five main vehicle types. Analysis included two road sections, one where rehabilitation is carried out and one where the road is operating under normal flow conditions, for emission levels during peak and off peak, for each vehicle type, and various volumes. It was shown that emission levels significantly vary with vehicle type and volume, which suggests that vehicle composition and road traffic volumes are significant factors when considering the impact of a work zone. Also roughness variation has resulted in 50-70% increase on emissions over a normal section. Further, increase of motor bikes and three wheels has resulted in 8-12% in emission increase on the same type of road based on the roadway classification. These findings can be used to set up a minimum standard in work zone maintenance which could result in millions of cost savings to the economy.



*Keywords:* Vehicular Emission; Highway work zone; Roughness; Vehicle operating cost; Vehicle speeds; HDM-4

* Corresponding author. Tel.: +94711982553
*E-mail address:* pasindu@uom.lk

## 1. Introduction

The growth in motorization especially in the urban areas has led to increase vehicular demand on the road network. Invariably the infrastructure supply has struggled to keep pace with the growing demand. Therefore, the road agencies have to implement road upgrading works such as re-surfacing, road widening etc. regularly to meet the increased capacity requirement. The congestion on the roads where these works are carried out further aggravated during the construction period since often such work requires temporary lane closures, diversions via temporary roads etc. In addition, poorly managed work-zones increase travel time un-reliability, air, water pollution, road accidents, accessibility issues to the road users. Therefore, highway work zones are of particular importance when considering efficiency of the traffic operations of a road network, especially in the urban areas where traffic flows are generally high. This is especially relevant to developing countries where work zone management practices are not implemented during the construction project, although they are stipulated in the monitoring plan of the project.
The main issues identified in highway work-zones are as follows (Mettananda and Pasindu) (2015).

- Traffic Congestion and time wastage (increment of travel time)
- Increment of vehicle operating cost (possibility of damaging the vehicles)
- Safety issues (higher possibility facing traffic accidents)
- Water, Air and Noise pollution
- Vibration; subsequently damaging the adjacent private properties
- Disturbance to the accesses
- Disturbance to the existing drainage
- Temporary interruption to the utility lines

The delay and travel time reliability issues are often highlighted as impacts from highway work-zone. However, impact on air quality is similarly an important aspect which is often not given due consideration. The main reason, is that the impact is not readily visible as with impacts such as delay which can be observed in terms of a queue formation. This is even more relevant in developing countries, whose vehicle fleet is not operating at a high efficiency level with respect to fuel consumption. Any major reduction is travel speed due inefficient traffic management or poor roadway conditions at a highway work zone may result in significant increase in emission levels during the construction period. The Intergovernmental Panel on Climate Change (IPCC) (2007), in its assessment report has clearly stated that burning of fossil fuel is the most important contributor to the rise of greenhouse gasses. Majority of these originate from automobiles that burn fossil fuel. Chin S.M et al (2002) stated that Work zones are the second largest contributor to non-recurring delay on freeways and principal arterials and are estimated to account for nearly 24% of all non-recurring delay. Cambridge systematics, Inc. (2004) found that work zones cause 10% of the delay experienced in the entire United States and 80-90% of delay experienced in rural areas. When it comes to emissions, the increased congestion directly affects the ambient air quality of the region. Kai Zang et al. (2013) has mentioned that the ever increasing severity and duration of traffic congestion greatly increased emissions which have degraded air quality, particularly near major roadways. Environmental protection agency (EPA) stated in their website that Vehicular emissions add up to about 60-70% of total Carbon Monoxide and 60% of Nitrogenous oxides. Therefore, it is evident that the delays caused by highway work-zones pose a significant environmental risk. Considering the above, evaluation of emission level variations due to highway work zone is of significant importance to improve the overall assessment of work zone impact on road users and the environment. This is especially relevant to countries such as Sri Lanka where at times, strict environmental monitoring regulations are not enforced stringently at highway construction project sites.

An arterial road in Sri Lanka (Colombo Kandy Highway) from Kadawatha to Nittambuwa was selected to obtain the necessary data for this study. This road is one of the main corridors to travel in and out of the capital of Sri Lanka. The section considered was under rehabilitation during the study period. The section selected had no major complications to disturb the study, such as heavy urban environment, or excess number of bi roads, or special vehicle composition, factories etc. The geography of the selected section was mostly flat with little to no undulations. Hence the speed drops due to such factors were a minimum, which could affect simulation results.

## 2. Objectives

The main objective of the study is to evaluate the impact of a highway work zone on the emission level from the traffic flow in the work-zone road segment. A national road in Sri Lanka where a major road rehabilitation project is being carried out as a case study to demonstrated the methodology. Based on the study findings, a relationship between roughness and emission levels is computed for the traffic volume and the composition of the selected road in the case study.

## 3. Factors affecting vehicle emissions

### *3.1. Effect of Roughness on fuel consumption*

The general form of the HDM-4 (2008) fuel consumption model is expressed conceptually by the following equation

$$IFC = f\left(P_{tr} P_{accs} + P_{eng}\right) = \frac{1000}{v} * (\max(\alpha, \xi * Ptot * (1 + dFuel))) \quad (1)$$

Where:

IFC =Instantaneous fuel consumption (mL/km)

$V$ =Vehicle Speed (m/s)

$P_{tr}$ =Power required to overcome traction forces (kW)

$P_{accs}$ =Power required for engine accessories (eg:fan,belt,alternator etc) (kW)

$P_{eng}$ =Power required to overcome internal engine friction

$\alpha$ =Fuel consumption at idling (mL/s)

$\xi$ =Fuel to power efficiency factor (mL/kw/s)

$$\xi = \xi_b \left(1 + ehp \frac{\left(P_{tot} - P_{eng}\right)}{P_{max}}\right) \quad (2)$$

$\xi_b$ = Base fuel to power efficiency (depends on the technology type: gasoline vs. diesel)

$P_{max}$ = Rated engine power (kW)

$ehp$ = Proportionate decrease in efficiency at high output power (dimensionless)

$P_{tot}$ = Total power (kW)

$dFuel$ = Excess fuel conception due to congestion as a percentage

Roughness of the surface has a direct effect on the fuel consumption. This was proven over and over in many researches over the world. Chatti and Zaabar (2012) developed The NCHRP report with the inclusion of roughness effect in both fuel and speed equations to reflect the effect of roughness on VOC much more effectively. They found that between roughness and surface texture: "For fuel consumption, the most important factor is surface roughness (measured using IRI). An increase in IRI of 1 m/km (63.4 in./mi) will increase the fuel consumption of passenger cars by about 2% irrespective of speed. For heavy trucks, this increase is about 1% at normal highway speed (96 km/h or 60 mph) and about 2% at low speed (56 km/h or 35 mph)". Further, Paterson and Watanatada (1985) found that a truck doing 80km/h uses 18% more fuel on a gravel road than on a paved road. They further stated that concrete and asphalt pavement have a lower IRI value and increases fuel efficiency. This lead to the conclusion that there is a strong correlation between roughness and fuel efficiency. Therefore, as fuel consumption directly affects emission levels, the fuel consumption at the observed roughness levels has to be taken in to consideration for this study.

### *3.2. Effect of roughness on operating speeds*

As mentioned by T. Wang et al. (2013), it was believed that pavement roughness had no role in the vehicle operating speed at first. But since the comfort level increases with the decrease of pavement roughness (T. Wang et al. (2013)), drivers tend to drive the vehicles faster in smooth roads. He further stated that most vehicles achieve the best fuel economy between 60km/h to 80km/h. He has provided the following regression model to depict the impact of .roughness on vehicle speed

$$y = 30.7368 + 1.0375RCI - 11.2421x_2 + 0.0062x_3^2 \quad (3)$$

$$RCI = 7.254 - 9.984 \log IRI \quad (4)$$

Where, y is the average highway speed in kilometres per hour (km/h); $x_2$ is the ratio of traffic volume to the total capacity of roadway; $x_3$ is the speed limit, in km/h; IRI is the International Roughness Index, in m/km.

However, Paterson and Watanatada (1985) showed that travel speed is insensitive to roughness values less than 6m/km. This can be used as a benchmark to decide roughness values to be considered in this study. Above study also revealed that in roughness levels over 6m/km, drivers actually slowed down due to the increasing roughness. Chandra S. (2004) found that the free flow speed decreased with increasing roughness, and that the effect was more on heavy vehicles compared to light vehicles. Further, Cooper et al. (1980) observed the increases in the mean speeds after resurfacing for different vehicle types. They found that there is an increase of 2 km/h for private cars, 2.3 km/h for light goods vehicles, 2 km/h for medium goods vehicles and 2.6 km/h for heavy goods vehicles, for a decrease of roughness from 4m/km to 1.9m/km. Although this claim might not be valid for today as vehicles fleets and traffic volumes have vastly changed since 1980s, it is still useful to understand that there is a speed reduction with the increase of roughness.

### *3.3. Vehicular emissions*

Slower speeds and congestion means the travel time and the engine idle times increase. Also running on low gears and higher rpm increases fuel consumption due to high engine speeds. Further, stop go situations increase acceleration noise which too results in increased fuel consumption. These factors have a positive correlation to the emission output from the vehicle. Celine Kalembo et al. (2012) evaluated the effect of roughness on emission cost. They primarily considered the greenhouse gas emissions. The results showed that there were reductions of $CO_2$ gas emissions for lower roughness values until 266 inch/mile. Further, United States Environmental Protection Agency (EPA) claims that a typical passenger vehicle emits about 4.6 metric tons of carbon dioxide per year. They assume that an average gasoline vehicle on the road today has a fuel economy of about 22.0 miles per gallon and drives around 11,500 miles per year. Every gallon of gasoline burned creates about 8,887 grams of $CO_2$.

Ozbey et al. (2001) developed a function to estimate emissions quantities generated by vehicles. It assumes that the amount of pollutants is proportional to the fuel consumption. Since fuel consumption increases with roughness, that concludes the fact that emission quantities go up with increasing roughness.

## 4. Methodology

A rehabilitation project carried out on a major arterial road in Sri Lanka was selected for the case study. The road is a four lane road with a ADT of 40000 vehicles/day, the length of the work-zone considered is 4000 m with works of road widening, resurfacing, and culvert construction is being carried out along the segment considered. First step of the methodology adopted in the study involves collection of roadway and traffic data of the selected road segment. Data collected included Speed data, roughness values measured in terms of IRI, hourly traffic flow rate on the road, and corresponding vehicle composition. The roadway parameters of the studied road section were obtained as well, for analysis purpose, such as horizontal and vertical curves, width, number of lanes etc.

Emission modelling was done using the world bank's HDM-4 (2008) software. The HDM 4 model quantifies emission levels using the following functions.

$$TPE = EOE * CPF \tag{5}$$

Tail pipe Emission(TPE) is predicted based on fuel consumption rates with the effect of catalytic converter (if available) taken in to account to obtain the TPE. TPE is the actual emission observed by the environment.
EOE (Engine out Emission) is the emission produced by engine upon burning fuel.
CPF (Catalyst pass fraction) is the factor included to count in the effectiveness of catalytic converter in reducing emissions.
Following types of emissions are modelled in HDM-4 and the models used are mentioned further below.

- Carbon dioxide
- Carbon monoxide
- Sulphur dioxide
- Nitrous oxide
- Hydrocarbons
- Particulate matter
- Lead

*4.1.1. Carbon Monoxide*

$$EOEco = aco * FC \tag{6}$$

Where $EOE_{co}$(g/km) is the engine output of Carbon monoxide and $a_{co}$ is the model coefficient. FC is the fuel consumption in g/km.

*4.1.2. Sulphur Dioxide*

Amount of Sulphur released from the engine is directly proportional to the available amount of Sulphur in the fuel. Hence that is taken as $aSO_2$ coefficient. $aSO_2$ coefficient is defined as grams of $SO_2$ emitted per gram of fuel consumed (gso2/gfuel). Other terms carry the same meaning as in earlier equations.

$$EOESO_2 = 2\,aSO_2 * FC \tag{7}$$

$EOE_{SO2}$ is the $SO_2$ output emission in gram/km

*4.1.3. Nitrogenous oxides*

$$EOENOx = max\left[aNOx\left(FC - \left(FRNOx / V\right)*1000\right), 0\right] \tag{8}$$

$a_{NOx}$ is measured in grams emitted per gram of fuel consumed, similar to $aSO_2$ coefficient. $FR_{NOx}$ is a fuel threshold parameter. Below that, the emission of NOx is negligible. Other terms carry the same meaning as in earlier equations.

*4.1.4. Hydrocarbons*

Hydrocarbons are assumed to be coming from two sources. One is the amount of HC in the fuel, which is $a_{HC}$, and $r_{HC}$ accounts for HC produced during incomplete combustion. Other terms carry the same meaning as in earlier equations.

$$EOEHC = aHC * FC + rHC / V * 1000 \tag{9}$$

*4.1.5. Particulate matter*

$$EOEHC = aHC * FC + rHC / V * 1000 \tag{10}$$

Terms carry the same terminology as earlier.

*4.1.6. Lead*

Part of the Lead present in the fuel is assumed to be emitted in combustion at the engine. $a_{Pb}$ is found assuming that scenario.

$$EOEPb = Prop\_Pb * aPb * FC \tag{9}$$

Proportion of lead (Prop_Pb) is the proportion of lead emitted. Other terms carry the same meaning as in earlier equations.

*4.1.7. Carbon Dioxide*

Most of Carbon present in CO, HC, and PM is converted to $CO_2$ by the catalytic converter. Hence the model takes the following form.

$$TPECO2 = 44.011\left[\left(FC/12.011 + 1.008aCO2\right) - \left(TPECO/28.011\right) - \left(TPEHC/13.018\right) - \left(TPEPM/12.011\right)\right] \tag{10}$$

$a_{CO2}$ represents the ratio of carbon atoms to hydrogen atoms in the fuel. Also, EOEx is the engine output emission of x, and TPEx is tailpile emission of x where x are the emission types. Other terms carry the same meaning as in earlier equations.

HDM-4 simulations were run in order to obtain emission quantities for 5 main vehicle types, car, three wheeler (Tuk Tuk), large bus, medium truck, and motor cycle.

Vehicle characteristics, economic parameters, and emission parameters were fed in, which were obtained from study done for HDM-4 calibration for Sri Lanka by Ranawaka and Pasindu (2017).

The emission level analysis was done by comparison of two road sections along the selected corridor, work zone, and completed section. This study analyzed emission quantities computed from HDM-4 simulations from the above mentioned sections for different roughness and travel speeds. Emission data is calculated for each vehicle type as well. Hence, the sensitive vehicle types for emission variation was identified. Furthermore, the analysis also revealed the roughness and speed values for which emissions levels were highly sensitive. These could be adapted in the work-zones to minimize the emission increase due to construction of the particular highway.

HDM-4 simulations were conducted for 3 nos of average annual daily traffic (AADT) values, 10000, 20000, and 42000, against roughness levels from 4m/km to 10m/km, in order to simulate all the road surface conditions from normal section to work zone.

Speeds and durations of each traffic scenario were obtained from traffic surveys.

Table 1. Considered traffic scenarios

| Scenario | Peak | Off peak | Night time |
|---|---|---|---|
| Duration | 6 hours/day | 8 hours/day | 10 hours/day |
| Traffic percentage | 50% | 30% | 20% |
| Speed WZ/Normal (km/h) | 20/30 | 30/40 | 40/50 |

Table 2. Sample calculation for IRI 8m/km in a work zone section

| | Speed | | | |
|---|---|---|---|---|
| AADT | 20km/h(Peak) (Emissions in g/year) | 30km/h(Off peak) (Emission in g/year) | 40km/h( Night time) (Emission in g/year) | Total Annual Emission (g/year) |
| 10000 veh/day | 656,904 | 595,388 | 534,137 | 186,163 |
| 20000 veh/day | 1,933,517 | 1,724,047 | 1,681,427 | 554,213 |
| 40000 veh/day | 4,742,531 | 4,512,871 | 4,470,750 | 1,416,666 |

Sample calculation

Total emission for a year = Peak emission (tones per year) x 50% x (6 hours/ 24 hours) +off peak emission x 30% x (8 hours/24 hours) + Night time emission x 20% x (10 hours/24 hours)

Data analysis included comparison of two road sections along A1 corridor, work zone, and completed section. This study analysed emission quantities obtained from HDM-4 simulations from the above mentioned sections against roughness and travel speeds. Also emission data is calculated for each vehicle type as well. Hence, the sensitive vehicle types for emission variation was obtained. Also, the sensitive roughness and speed values for emissions were found. These could be adapted in the work-zones to minimize the emission increase due to construction of the particular highway.

There were few important parameters collected as inputs to HDM-4. The road selected was A1 Colombo Kandy road, which is the main corridor for travellers from Colombo to other cities in the upper part of the country. Following table shows the summary traffic data collected during surveys.

Table 3. Traffic data of A1 corridor as of 31.12.2017

| | Three wheel | Car | Bus | Truck | Motor cycle | AADT |
|---|---|---|---|---|---|---|
| Percentage | 16% | 36% | 11% | 18% | 19% | 100% |
| Traffic count | 6796 | 15291 | 4673 | 7646 | 8071 | 42477 |

### *4.2. Vehicle operating speed*

Speed surveys were done at the location during peak and off peak times, using miniROMDAS bump integrator and google travel time data. Manual surveys using speed guns were done for the verification purpose. Following figure shows the speed variation of the same road, where Kadawatha-Belummahara shows a completed section while the other section is a work zone.

Table 4. Speed and travel time distribution

| Time | Work zone (9880m) | | Completed Section(8250m) | |
|---|---|---|---|---|
| | Yakkala-Nittambuwa (km/h) | Travel time(s) | Kadawatha-Belummahara(km/h) | Travel time(s) |
| Morning (Up to 6.00am) | 33 | 1010 | 49 | 608 |
| Morning peak(6.00-9.00am) | 26 | 1360 | 41 | 718 |
| Mid-day | 26 | 1615 | 47 | 635 |
| Evening peak(6.00-9.00pm) | 26 | 1660 | 40 | 672 |
| Night (beyond 9.00pm) | 38 | 992 | 50 | 598 |

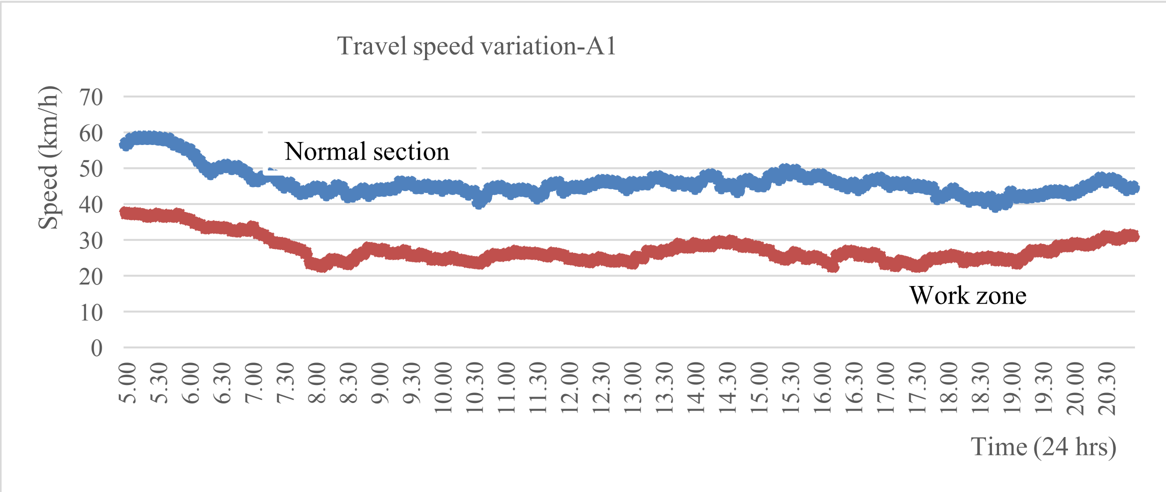


Figure 1. Speed variation between work zone and normal road stretch with time

These observations were used in determining speed values mentioned in Table 1. Here, the blue line represents the normal section where no road work is ongoing. Here, the road behaves normally in terms of traffic, flow speed, and headway. The red line refers to work zone condition where the flow is restricted due to road construction. Hence the lower flow speeds.

*4.3. Roughness levels observed*

Roughness was measured using miniROMDAS bump integrator mounted to a 1986 Land Rover Defender. Calibration was done according to the manufacturer recommendation by following the user manual. Calibration included ODOMETER calibration and calibration for roughness using ROMDAS Z250. Readings were taken for completed road section and section under construction, as shown in figure 2. Work zone starts at chainage 2416m.

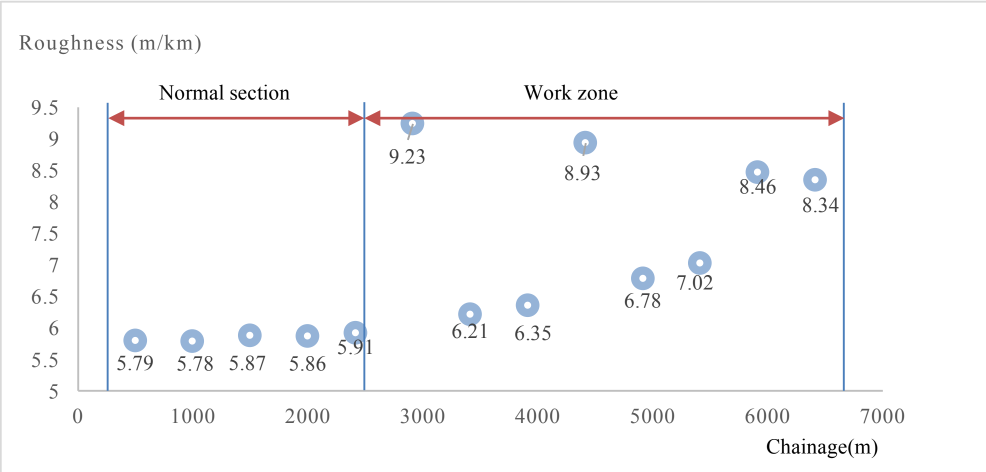


Figure 2. Roughness variation along A1, normal section followed by work zone

### *4.4. HDM-4 Calibration*

Calibration of HDM-4 was done by conducting number of surveys on Sri Lankan vehicle fleets to identify the cost parameters such as tire retread cost, tire replacement costs, fuel costs, depreciation, capital costs, and other economic cost parameters. Also, the road characteristics of A1 were provided as input to the software.

The road characteristics are as follows

- Rise and fall: - 10m/km (Flat road)
- No of rises and falls: - 2 nos/km
- Average horizontal curvature: - 15 degrees (Fairly straight road section)

Also the emission input calibration values are shown in the following table. These values are obtained from HDM-4 itself for a straight and level road section for different kinds of vehicles.

Table 5. Calibration factors for emission model of HDM-4

| Vehicle Type | Hydrocarbon aHC | Hydrocarbon rHC | aCO | aNox | FRNOx | $aSO_2$ | aPM | rPM | $aCO_2$ | aPb | Lead Prop_Pb |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Three wheel | 0.06 | 0 | 0.2 | 0.02 | 0 | 0.0005 | 0.0001 | 0 | 1.8 | 0.000537 | 0.75 |
| Car | 0.012 | 0 | 0.1 | 0.055 | 0.17 | 0.0005 | 0.0001 | 0 | 1.8 | 0.00053 | 0.75 |
| Heavy bus | 0.04 | 0 | 0.08 | 0.027 | 0 | 0.005 | 0.0032 | 0 | 2 | 0 | 0.75 |
| Medium Truck | 0.04 | 0 | 0.08 | 0.027 | 0 | 0.005 | 0.0032 | 0 | 2 | 0 | 0.75 |
| Motor bike | 0.06 | 0 | 0.2 | 0.02 | 0 | 0.0005 | 0.0001 | 0 | 1.8 | 0.000537 | 0.75 |

## 5. Analysis

Analysis was conducted in comparison of both work zone and normal road sections. The analysis is conducted for total emissions, considering all the emission types described in section 4.1.

- Work Zone with higher roughness

- Completed road section which has a lower roughness.
- AADT values of 10000, 15000, and 40000 veh/day.

Analyzed speeds were limited to 50km/h, even though the speed limit was 70km/h, and lower portion being 20km/h based on speed data obtained in the sections. However, speeds of 20,30,40, and 50km/h were analyzed for the purpose of achieving more accurate conclusion.

*5.1. Variation of fuel consumption with roughness, speed, and vehicle type*

Here, effect of travel speed and roughness are compared against fuel consumption. Following results were computed using HDM-4 for 5 main vehicle types for 1000veh-km. Roughness range of 4-12m/km is used.

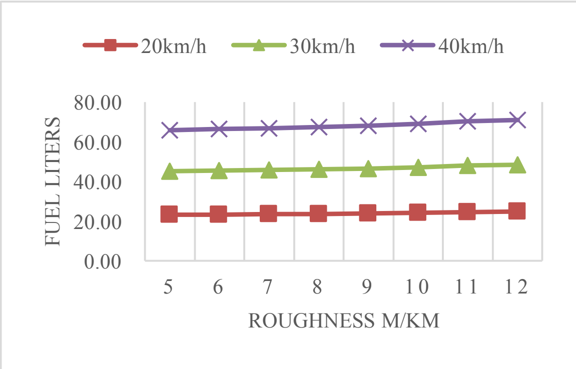


Figure. 4. Three wheel

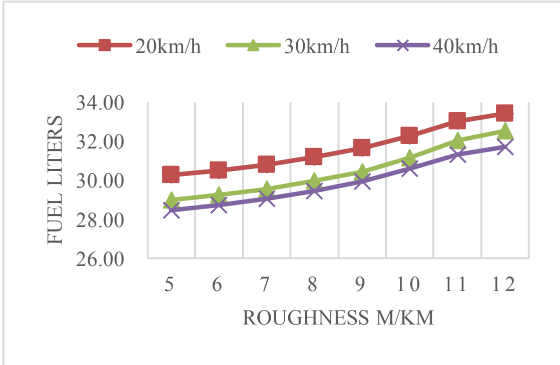


Figure. 3. Motor bike

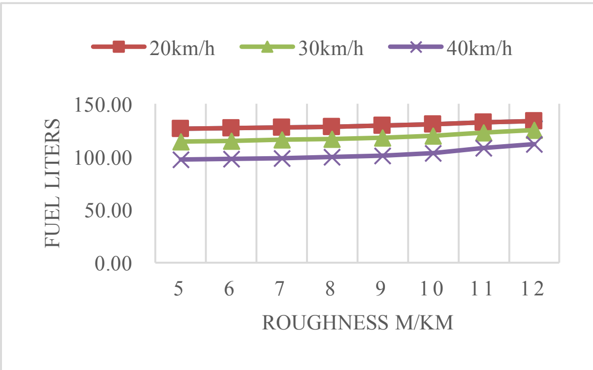


Figure. 5. Car

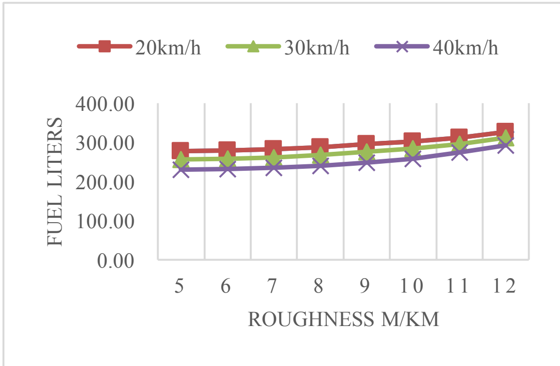


Figure. 6. Heavy Bus

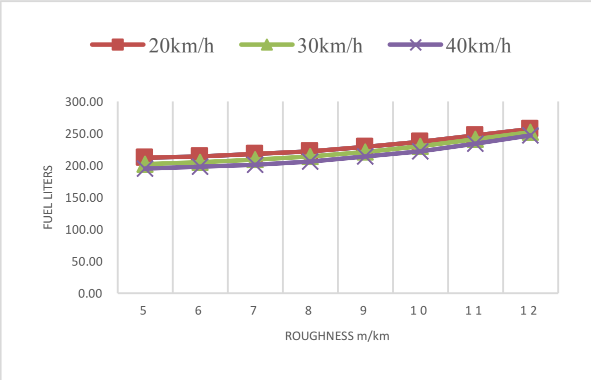


Figure. 7. Medium Truck

### *5.2. Emission variation with traffic volume*

The variation of emission levels for few types of road is analyzed here. Those are low AADT roads (10000 veh/day), Medium volume (20000 veh/day), and high volume roads (40000 veh/day).

#### *5.2.1. Roads with an AADT of 10000 veh/day*

This section simulates low traffic volume, like a rural area where roads are not congested but can vary in roughness. There are two sections analyzed, one with higher Three wheel and Motor bike composition (rural composition) while the other with normal composition observed during above data collection. This is to cover both aspects observed in low volume roads in Sri Lanka. Composition A is the typical composition on major arterial roads and Composition B is the typical composition of rural roads, where there is a higher amount of two wheelers and three wheelers.

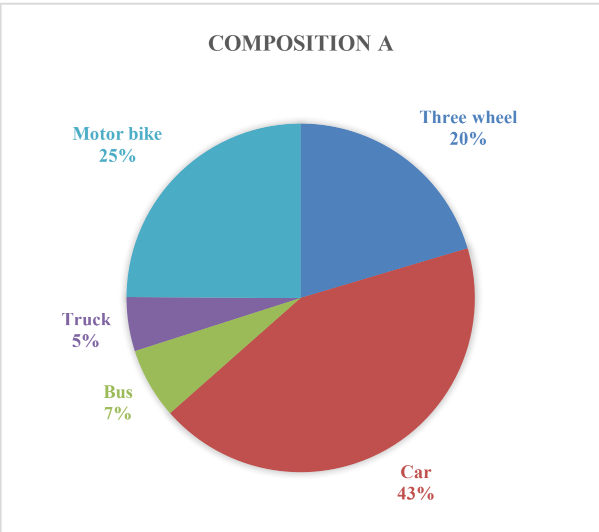


Figure. 8. Composition A

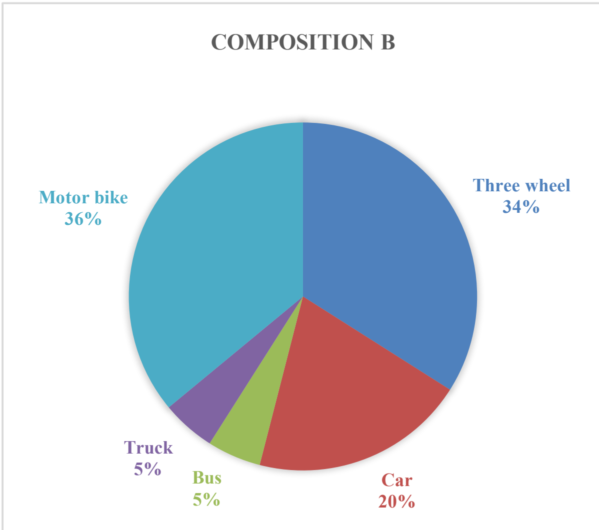


Figure. 9. Composition B

Following tables show the emission in tons for various roughness in peak and off peak for 10000 veh/day AADT.

Table 6. Emissions in kg per day with composition A

| IRI (m/km) | Peak | | | Off peak | | | Night | | |
|---|---|---|---|---|---|---|---|---|---|
| | Work zone (20km/h) | Normal (30km/h) | % increase | Work zone (30km/h) | Normal (40km/h) | % increase | Work zone (40km/h) | Normal (50km/h) | % increase |
| 4 | 182 | 165 | 10.8% | 132 | 118 | 11.6% | 98 | 97 | 1.7% |
| 5 | 192 | 174 | 10.7% | 139 | 124 | 11.6% | 104 | 102 | 1.7% |
| 6 | 202 | 183 | 10.6% | 146 | 131 | 11.6% | 109 | 107 | 1.7% |
| 7 | 213 | 193 | 10.5% | 154 | 138 | 11.5% | 115 | 113 | 1.7% |
| 8 | 225 | 204 | 10.3% | 163 | 146 | 11.5% | 122 | 120 | 1.7% |
| 9 | 238 | 216 | 10.2% | 173 | 155 | 11.4% | 129 | 127 | 1.8% |
| 10 | 252 | 230 | 9.9% | 184 | 165 | 11.2% | 138 | 135 | 2.0% |

Table 7. Emission in kg per day with composition B

| IRI (m/km) | Peak | | | Off peak | | | Night | | |
|---|---|---|---|---|---|---|---|---|---|
| | Work zone (20km/h) | Normal (30km/h) | % increase | Work zone (30km/h) | Normal (40km/h) | % increase | Work zone (40km/h) | Normal (50km/h) | % increase |
| 4 | 197 | 176 | 12.0% | 141 | 132 | 6.8% | 110 | 112 | -2.3% |
| 5 | 208 | 185 | 11.9% | 148 | 139 | 6.8% | 116 | 118 | -2.3% |
| 6 | 219 | 196 | 11.8% | 157 | 147 | 6.8% | 122 | 125 | -2.2% |
| 7 | 231 | 207 | 11.6% | 166 | 155 | 6.7% | 129 | 132 | -2.2% |
| 8 | 245 | 220 | 11.4% | 176 | 165 | 6.7% | 137 | 140 | -2.0% |
| 9 | 260 | 234 | 11.1% | 187 | 176 | 6.6% | 146 | 149 | -1.7% |
| 10 | 278 | 251 | 10.8% | 201 | 188 | 6.5% | 157 | 158 | -0.8% |

### *5.2.2. Road with an AADT of 20000 veh/day*

This represents a normal volume road where severe congestion is not there. Mostly small towns, populated villages and away from the city, arterial roads etc. Here, the composition is similar to the above ‘Normal Composition’.

Table 8. Emissions in kg per day

| IRI (m/km) | Peak | | | Off peak | | | Night | | |
|---|---|---|---|---|---|---|---|---|---|
| | Work zone (20km/h) | Normal (30km/h) | % increase | Work zone (30km/h) | Normal (40km/h) | % increase | Work zone (40km/h) | Normal (50km/h) | % increase |
| 4 | 512 | 454 | 12.8% | 363 | 354 | 2.7% | 295 | 298 | -1.1% |
| 5 | 543 | 482 | 12.7% | 385 | 375 | 2.7% | 313 | 316 | -1.0% |
| 6 | 576 | 511 | 12.7% | 409 | 398 | 2.7% | 332 | 334 | -0.8% |
| 7 | 613 | 545 | 12.5% | 436 | 424 | 2.7% | 353 | 355 | -0.4% |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 8 | 662 | 590 | 12.1% | 472 | 461 | 2.5% | 384 | 382 | 0.6% |
| 9 | 719 | 646 | 11.4% | 516 | 505 | 2.3% | 421 | 414 | 1.6% |
| 10 | 783 | 715 | 9.5% | 572 | 564 | 1.5% | 470 | 464 | 1.2% |

### *5.3. Road with an AADT of 42000 veh/day, Study of A1 corridor*

#### *5.3.1. Emission levels for existing roughness values and operating speeds*

Emission distribution between vehicle types is shown in the following figure. It can be seen that due to higher fuel consumption, Larger vehicles have the major portion of emissions.

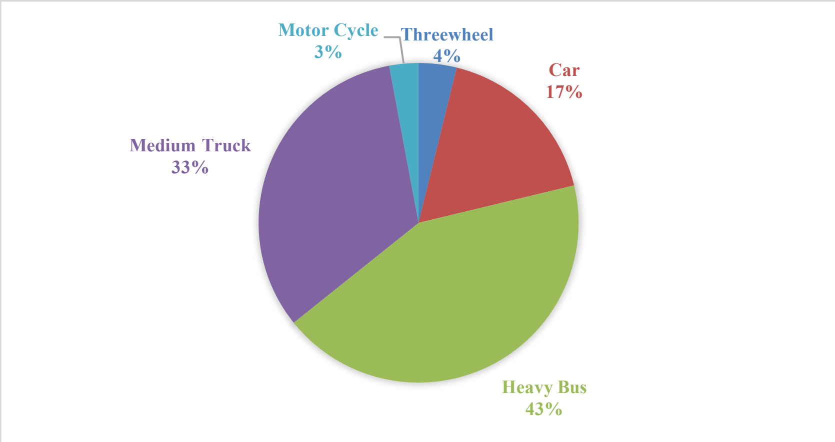


Figure 10. Emission distribution among vehicle types

For the above AADT values, computed emission amounts in kilograms is given in table 9. Even at the same speeds, the road condition deterioration trend is affecting the emissions in a considerable amount.

Table 9. Emissions in kg per day

| IRI (m/km) | Peak | | | Off peak | | | Night | | |
|---|---|---|---|---|---|---|---|---|---|
| | Work zone (20km/h) | Normal (30km/h) | % increase | Work zone (30km/h) | Normal (40km/h) | % increase | Work zone (40km/h) | Normal (50km/h) | % increase |
| 4 | 1238 | 1068 | 16.0% | 854 | 818 | 4.4% | 681 | 682 | -0.1% |
| 5 | 1323 | 1148 | 15.2% | 919 | 880 | 4.4% | 734 | 734 | 0.0% |
| 6 | 1400 | 1225 | 14.3% | 980 | 938 | 4.5% | 782 | 777 | 0.6% |
| 7 | 1503 | 1362 | 10.4% | 1090 | 1049 | 3.9% | 874 | 863 | 1.3% |
| 8 | 1624 | 1546 | 5.1% | 1236 | 1225 | 0.9% | 1021 | 1019 | 0.2% |
| 9 | 1754 | 1685 | 4.1% | 1348 | 1340 | 0.6% | 1116 | 1115 | 0.1% |
| 10 | 1804 | 1741 | 3.6% | 1393 | 1387 | 0.5% | 1155 | 1154 | 0.1% |

#### *5.3.2. Analysis for Case study*

Table 9 provides an insight on how much the roughness and speed is affecting the emission increment over a normal section, for a work zone. The most significant effect is in the peak hour. The following table is an attempt to give an idea on how much emissions, as a percentage, is emitted in excess as a result of both drop in speed and increase in roughness in a work zone.

Table 10. Comparison of work zone emissions with that of the normal section

| IRI increase(m/km) | Peak hour | Off Peak | Night time |
|---|---|---|---|
| 4 to 6 | 31% | 20% | 15% |
| 4 to 8 | 52% | 51% | 50% |
| 4 to 9 | 64% | 65% | 64% |
| 4 to 10 | 69% | 70% | 69% |

This result can be used to optimize emissions in many ways. Based on emission costs, it can be found when the work zones should operate. For example, a work zone can operate only at night or during off peak and night, if the extra cost and project extension are justified by reduced emission cost. This has to be done with proper costing for emissions. Such optimization could make highway work zones much more efficient and cleaner compared to the current situation.

## 6. Conclusion

In order to identify the relationship between IRI, speed, and emission, speed data, roughness data etc. were collected on A1 road. IRI values of the section varied from 10m/km to about 6m/km due to work zones. The speed variation was from 20km/h to 50km/h.

It can be seen that the emission levels at low capacity road is about 10% of that of a high volume road. Therefore, work zones become much critical as AADT goes up. Also, results suggest that work zones have the highest impact on emissions during the peak times of the day. Also, the roughness is affecting the emissions in the most critical manner. Therefore, maintaining roughness at an acceptable level would drastically reduce emission levels due to work zones. As per Table 10, the jump from IRI 4 to 8,9, and 10 are comparatively massive. If a work zone can be managed at IRI of 6m/km, the emissions can be controlled by around 30% compared to 8m/km. It is about 46% more if the work zone is 10m/km in roughness.

In the analysis conducted by changing composition of vehicles in a low volume road, increase of bikes and three wheels to 60% of the traffic volume has caused the rise of emissions by 8% to 12% compared to normal composition of traffic.

Limitation of the research is the use of average speeds to obtain emission levels. This can be further improved by integrating a driving cycle model for work zones in order to simulate the stop go effect of a work zone. Also, speed variation between vehicle types can be integrated as well.

Further, the results of this study can be used in implementing regulations for minimum standards for work zones in terms of maintaining speed and roughness in order to reduce emissions. Highway project contractors can be regulated to maintain a better road condition as well as a fair traffic flow speed. Savings on emission levels would result in less money spent for fuel, healthcare, and other emission related expenses.

## Acknowledgements

This research was funded by Department of Motor traffic - Vehicular Emission Test Trust Fund, Sri Lanka.

## References


Mettananda T.M.M.B., Pasindu H.R.,2015. Road safety and highway: Transport Research Forum 2015, Department of Civil engineering, University of Moratuwa, Sri Lanka.

Pachauri, R.K., Reisinger, A., 2007. Climate Change 2007: Synthesis Report*,* IPCC, Geneva, Swizterland.

Chin, S. M., Franzese, O., Greene, D.L., Hwang, H.L., Gibson, R.C., 2002. Temporary Losses of Highway Capacity and Impacts on Performance. Technical Report No.ORNL/TM- 2002/3. Oak Ridge National Laboratory, Oak Ridge, TN.

Cambridge Systematics, Inc., 2004. Traffic Congestion and Reliability: Linking Solutions to Problems. Federal Highway Administration.

Kai Zhang , Stuart Batterman., 2013. Air pollution and health risks due to vehicle traffic.

Environmental protection agency (EPA), USA. https://www.epa.gov

Chatti, E. K., Zaabar, I., 2012. NCHRP Report 720: Estimating the Effects of Pavement Condition on Vehicle Operating Costs. Transportation Research Board of the National Academies, Washington, D.C.

Paterson, W., Watanatada, T., 1985. Relationships Between Vehicle Speed, Ride Quality, and Road Roughness. Measuring Road Roughness and Its Effects on User Cost and Comfort. Philadelphia: American Society for Testing and Materials.

Wang, T., Harvey, J., Lea J.D., Kim, C., 2013. Impact of Pavement Roughness on Vehicle Free-Flow Speed.

Chandra, S., 2004.Effect of road roughness on capacity of two-lane roads.

Cooper, D.R., Jordan, P.G., Young, J.C., 1980.The effect on traffic speeds of resurfacing a road (Supplementary Report, SR571). Wokingham: TRL.

Celine Kalembo, Mansoureh Jeihani, Anthony Saka*.,*2012. Evaluation of the Impact of Pavement Roughness on Vehicle Gas Emissions in Baltimore County. Department of Transportation and Urban Infrastructures Studies School of Engineering, Morgan State University, Baltimore, Maryland.

Ozbay, K., Bartin, B., Berechman, J., 2001. Estimation and evaluation of full marginal costs of highway transportation in New Jersey. Journal of Transportation and Statistics 4: 81-103.

Ranawaka S., Pasindu H.R., 2017. Estimating the vehicle operating cost used for economic feasibility analysis of highway construction projects. Moratuwa Engineering Research Conference- MERcon 2017, Moratuwa, Sri Lanka.

HDM-4 version 2 by world bank, 2008. http://www.hdmglobal.com

miniROMDAS by ROMDAS, https://romdas.com