EVALUATION OF THE IMPACT OF ROAD ROUGHNESS ON ROAD USER COST IN HIGHWAY CONSTRUCTION WORK ZONES

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Degree of Master of Science

Department of Civil Engineering

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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Abstract

A highway work zone is present in every part of the world due to the complete essentiality of such work. Roads are designed to a certain lifetime and once the lifetime is reached, the road needs rehabilitation. New roads are being built every day in a country like Sri Lanka where the infrastructure is still largely under development. However, unlike most countries, we do not have a lifecycle monitoring system to determine the optimum rehabilitation period nor the economic cost of rehabilitation of an existing busy road. When referring few of the previous feasibility reports, they have only considered the economic benefit gained after the road is built, but not the loss encountered while the road is being rehabilitated. This study provides insight to the exact issue of incorporating economic losses in the feasibility studies in order to increase the cost benefit ratio as much as possible. The economic cost includes vehicle operating cost, emission cost, delay time cost, and accident costs. However, in this study, only VOC and Delay time cost are monetarized while emissions are quantified without monetarizing. The simulations are carried out using World Bank's HDM-4 version 2 software calibrated to Sri Lankan Context. Here, multiple work zones are evaluated for roughness, vehicle speed, and safety while one complete case study is performed on the most critical work zone. It was found that with the current working conditions, economic loss is around 70% of the project cost and could be considerably reduced by proper management of traffic, pavement condition, and implementing other measures.

Keywords: Vehicle operating cost, Highway Construction, Road Maintenance, Economic Feasibility, Economic cost, Delay time cost, Emissions, HDM-4, Operating speed

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LIST OF ABBREVIATIONS

Abbreviation	Description
VOC	Vehicle Operating Cos
VOT	Value of Time
WZRUC	Work Zone Road User Cost
IRI	International Roughness Index
RDA	Road Development Authority
NRSS	National Road Safety Secretariat
FHWA	Federal Highway Administration

1. INTRODUCTION

1.1. Project background

Sri Lankan Governments over the past decade has undertaken major investments on transportation infrastructure projects such as Expressways, Highways, and Railways with the intention of uplifting the living conditions of the general public and attracting foreign investments, tourists, etc.

Rehabilitation of urban roads are a part of this effort carried out with the objective of reducing the congestion in urban road networks. The Road Development Authority and the respective Municipal Councils or Urban Councils are the undertaking these projects for the roads under their purview. However, it has been observed that, there are several issues that arise during the construction period that affect the road users and the general public due to poor management and standards maintained at the work zones of highway construction projects in urban areas.

1.2. Highway Construction in Sri Lanka

According to Federal Highway Authority [1], Highway work-zone is an area of a traffic way with highway construction, maintenance, or utility-work activities. A work zone is typically marked by signs, channeling devices, barriers, pavement markings, and/or work vehicles. It extends from the first warning sign or flashing lights on a vehicle to the "End of Road Work" sign or the last traffic control device.

However, this definition does not fit Sri Lankan context. The motorable area of a work zone is separated from the road users in normal context. But in Sri Lanka, the vehicles and pedestrians use the same road stretch that is being rehabilitated. Therefore, the need to assess roughness of these surfaces are of prime importance as these ill-maintained road stretches cause major impact to the economy in terms of Vehicle Operating Cost (VOC), Emissions increment, and Travel Delay cost. In these areas, Safety goes down drastically as well of both road users and construction workers.

Figure 1 Highway construction Zones (b) Temporary Lane in poor condition

(a) With a well maintained temporary lane

During the time of rehabilitation, there are many inconveniences caused to the general public. It includes road users and nearby residents, shops, hospitals, courts, etc. Specifically, the following have been identified as the major inconveniences caused by a highway rehabilitation work zone.

- Safety issues
- Air, Water, and noise pollution
- Vibrations causing damages nearby structures
- Social issues due to land acquisition
- Mismatch between bi-roads and main road (Access gradient, texture, roughness, width)
- Condition of the provided by roads and the part of the road open for traffic
- Issues in traffic management and on site traffic controlling
- Drainage issues
- Increase of vehicle operating cost

This is more pertinent in urban areas where traffic volumes on roads are high and there is high pedestrian flow and roadside development prevalent

1.3. Objectives

The main objective of this study is the evaluation of the increase in economic cost (related to vehicle operating costs, emissions, and delay cost) due to increase in roughness of highway construction areas in Sri Lanka

The sub objective is to propose minimum standards for work zones to follow based on findings to minimize the impact on economy.

1.4. Scope of Study

Highway Rehabilitation in many places in Sri Lanka are done in the same road section as the vehicles and pedestrians travel. Unlike other developed countries, where the work zone is separated from road users, in our context the road is being shared by the construction zone and road users which rise the issue of roughness increase of the road.

The scope of the study considers a scenario where a temporary road section is prepared for traffic to bypass the construction area. Figure 2 shows the current condition of temporary roads. This study refers as “work zone” for such type of construction zone.

Figure 2 Temporary road way in road construction zone in Sri Lanka

Further, a road passing through a highway construction zone sharing the same damaged road is also considered as a temporary road way for vehicles to traverse the work zone.

These construction zone practices in Sri Lanka needs reviving. The temporary road sections, where the construction is ongoing needs proper regulation in terms of roughness to keep the work zone road user cost at a possible minimum.

1.5. Arrangement of Dissertation

The dissertation is structured as follows.

Chapter one describes the background of the study including the issues identified at Sri Lankan highway construction zones, the scope of the study, objectives, and outcomes.

Chapter two is the literature review done for the study. It evaluates the current guideline for work zones in Sri Lanka. Further it evaluates the feasibility of using HDM-4 software for economic analysis, by evaluating the mathematical base of the software. It also evaluates the emission generation related to work zones and models developed. Also, the literature review evaluates how the safety is evaluated at a work zone. Finally, it evaluates the calculation methods of vehicle operating cost, emission levels, Accident costs, and other economic parameters related to highway work zones.

Chapter Three is the methodology and data collection where the methodology is explained and details about surveys, and HDM-4 simulations are presented.

Chapter Four presents the economic analysis of the work zones in Sri Lanka from data gathered in chapter 4. It is found that the economic loss is about 70% of the project cost. It also presents the finding of the study. It is calculated and presented how much savings could be achieved upon a proper implementation of work zone management practices.

Chapter Five concludes the study with recommendations to be implemented and comments on future studies that can be carried out in this area of study. Final section of chapter 5 proposes minimum standards of a work zone in relation to lowering economic cost as much as possible

2. LITERATURE REVIEW

The Literature review consists of two main sections. First section focuses on reviewing the existing guidelines of Sri Lanka and other countries in a comparative manner. The second section is about the theoretical aspects used in the analysis such as roughness, vehicle operating cost, emissions, etc.

2.1. Review on current guidelines on work-zone management in Sri Lanka

The specifications of the traffic control devices and regulations have been given in the Government Gazette No. 444/18 dated 13/03/87 [2]. Mainly, traffic signs, traffic cones, barricade tapes, road humps along with road markings, rumble strips, lamps or lighting devices, temporary traffic light signals and flagmen are mentioned as the traffic control devices in the Manual on Traffic Control Devices for Sri Lanka. In addition to that, typical examples of signing of work zones are also mentioned in the guideline. For example, maintenance operation of short duration on pedestrian sidewalk, edge working, survey on road or in close vicinity of the road etc. depending on the nature of the work and duration of it.

Manual on Traffic Control Devices [3] is the widely adopted manual in Sri Lankan context. From 1992, Road development authority of Sri Lanka (RDA) was aware of the need of a manual for traffic signs and markings. First guideline on traffic signs and road markings was introduced in 1997 and was prepared in accordance with the stipulations provided in Vienna convention. In 1999, the National Road Safety Secretariat (NRSS) was requested to conduct a revision on the above manual to identify its relevance, particularly to the proposed Expressways, by Ministry of Transport and Highways. During the process of revision, amendments and additions were made to the original document, including amendments to diagrams to ensure the applicability of them to the proposed expressways. The conformity to Vienna convention, 1995 was further ensured as well.

The traffic control devices recommended in the above report are:

- Traffic Signs
- Traffic Cones
- Barricade Boards
- Road Humps with markings
- Rumble Strips
- Lamps/ Lighting Devices
- Temporary Traffic Light Signals
- Flagmen

Some measures that should be constantly checked in work Zones

- Work zone planning, even if it is a small one
- Signing of road work areas should be uniform and consistent all over the road network
- All traffic control devices should be in good operating condition and checked for low light performance
- The behavior of workmen should be decent enough to maintain a good relationship with road users
- Ensure the removal of all temporary traffic signs after completion of the road
- Someone should be appointed to hold the responsibility of traffic control devices in the work site
- Use as few traffic control devices as possible but as many as necessary.

Factors that impact the quality and safety of the work zone

- Average daily traffic
- The capacity of the temporary lanes and existing roads
- The speed limits
- Availability of detours
- Any other projects in the area (pipe laying, telephone lines, etc.)

However, the said guideline has failed to specify the condition of the roadway surface of the temporary road in terms of roughness or such parameter.

2.2. Evaluation of existing issues in highway work zones

2.2.1. Inconvenience to the public

During the time of rehabilitation, there are many inconveniences caused to the general public. It includes road users and nearby residents, shops, hospitals, courts, etc. Specifically, the following have been identified by Griffith and Lynde [8] as the major inconveniences caused by a highway rehabilitation work zone.

- Effect of work zone on daily schedule of school bus drivers, bus drivers etc.
- Access issues for business owners in the work zone
- Utility interruptions for residents and business owners
- Inadequate law enforcement inside work zones
- Effect of low ground clearance vehicles like cars on the flow speed
- Effect on emergency vehicles

Further, Mettananda and Pasindu [9] have identified sound and air pollution, lack of planning, drainage disturbances, and not following of guidelines in addition to the above issues.

Although a set of guidelines which complies to a certain extent with guidelines of developed countries exist in Sri Lanka, the enforcement of these regulations cannot be observed in majority of the work zones. Contractors are not regularly checked to be following the guidelines nor are they imposed fines or penalties upon infringement. This approach has led to poor roadway conditions during road rehabilitations, which has resulted in loss of money to the economy. Therefore, it is necessary to carry out extensive checks on guideline application, and also to develop and implement improved set of guidelines for highway work zones.

One of the main issues with a highway work zone is the impact of it to the economy of the country, which is knows as work zone road user cost. The economic impact occurs in few main aspects.

- Vehicle operating cost
- Travel delay cost
- Emission cost
- Damage to the environment
- Safety cost

Out of these, vehicle operating cost (VOC) and travel delay cost are evaluated for a major arterial highway in Sri Lanka in this study.

2.3. Effect of roughness on vehicle operations in highway work zones

2.3.1. Introduction to pavement roughness

Pavement condition is represented by international roughness index (IRI), a globally recognized parameter to represent the condition of a road pavement. A higher IRR value would represent a road in poor condition with surface irregularities, unevenness and distresses. Typically, roads with IRR values of 6 above are considered to be in poor condition and IRR exceeding 10 are considered to be unsuitable for frequent movement of traffic [10].

2.3.2. Effect of roughness on fuel consumption

Chatti and Zaabar [11] developed speed and fuel consumption equation with the inclusion of roughness to demonstrate the effect of roughness on fuel consumption. Back in 1985, Patterson and Watantada [12] found out that a truck doing 80km/h in a gravel road uses 18% more fuel compared to a paved road. That was a direct indication of affect of roughness for fuel consumption. Effect of Roughness on Travel Time and Flow Speed.

Earlier, it was believed that roughness had no impact on the operating speed of the vehicle. But it is natural for drivers to drive faster on a smooth road as it is both comfortable and safe to do so. T. Wang et al [13] found out that vehicles achieve the best fuel economy around 60 to 80km/h. It is important that drivers can achieve those speeds to keep travel time at par and it affects the operating cost as well due to low fuel consumption. He has used the following regression model to demonstrate the impact of roughness on travel speed.

Equation 1: Regression model on impact of roughness on speed

$$y = 30.7368 + 1.0375RCI - 11.2421x_2 + 0.0062x_3^2$$

$$RCI = 7.254 - 9.984 \log IRI$$

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.

However, Paterson and Watanatada [12] 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. [14] 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. [15] 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.

2.4. Effect of roughness on tire consumption

Tires are another main aspect of vehicle operating cost. Tire wear can vary depending on the driving pattern, temperature, and the surface. Chatti and Zaabar [11] found out that for every 1m/km increase in roughness, tire wear is escalated by 1% for heavy trucks at 88km/h. Sandberg [16] found out that when IRI is increased from 1-10m/km, the rolling resistance increased by 19% at 54km/h. The same was 48% at 90km/h. Therefore it is clear that pavement roughness is proportional to tire consumption as well.

2.5. Effect of roughness on parts consumption

Chatti and Zaabar [11] found out that roughness of up to 3m/km had no impact on maintenance cost, but beyond that the cost will increase. An IRI decrease by 1m/km resulted in savings of 24 to 73 billion dollars per year in US context in repair and maintenance cost alone, as per their findings. IRI change of 3m/km to 4m/km resulted 10% increase of operating cost according to their study.

2.6. Effect of roughness on vehicular emissions

Slower speeds and congestion mean 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 and 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. Kalembo et al. [17] 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 [18] 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. [19] 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.

2.7. Delays in a work zone

Highway Work zones will result in narrowed roadways, closed down lanes, below standard temporary lanes etc. which will invariably cause delays to the road users [19]
.

Delay time is an aggregation of the following components:

- Speed change delay is the additional time necessary to decelerate from the upstream approach speed to the work zone speed and then to accelerate back to the initial approach speed after traversing the work zone under unrestricted (free) traffic flow.
- Reduced speed delay is the additional time necessary to traverse the work zone at the lower posted speed; it depends on the upstream and work zone speed differential and length of the work zone under both unrestricted and restricted (forced) traffic flow.
- Detour delay is the additional time necessary to travel the excess distance by selecting a detour route.
- Stopping delay is the additional time necessary to come to a complete stop from the upstream approach speed (instead of just slowing to the work zone speed) and the additional time to accelerate back to the approach speed after traversing the work zone under restricted traffic flow.
- Queue delay is the additional time necessary to creep through the queue under restricted traffic flow.

2.8. Developing a work zone road user cost calculation model using previous studies and reports

According to Federal Highway Administration's Work Zone Road User Costs Concepts and Applications Chapter 2, Work Zone Road User Costs [20]; Work Zone Road User Cost can be divided in to two main parts.

- Monetarized impacts
    - Travel time delay cost
    - Vehicle operating cost
    - Safety cost/accident cost
    - Emission cost
    - Impacts to nearby projects

- Non Monetarized impacts
    - Noise due to construction
    - Inconvenience caused by workers and machinery to the public
    - Impact on local businesses like shops etc.

2.8.1. Monetary value of time

- Travel Delay cost

Travel delay cost is calculated by estimating the delay caused to personal travelers, trucks, and freight transport due to the work zone and multiplying it by per hour (LKR/hr) rate.

- Delay Time

Delays occur when users need to cross the work zones at a limited speed or face temporary lane closures. Delays depend on the length of the work zone, the safe speed of traverse, and the traffic condition such as forced flow and free flow.

When you are traversing a work zone, you might have noticed that it requires an additional time than the usual travel time. This happens due to five main delay components occurring in a work zone. Following definitions were derived from FHWA website [20].

  - Delay in speed change: This is the additional time required to decelerate to WZ speeds and accelerate back to cruising speed after passing the WZ boundary
  - Reduced speed delay: This is the time lost when you travel at a reduced speed in a WZ
  - Detour delay: If you wish to or forced to take a detour, the added distance and incorporated delay is demarcated by this
  - Stopping delay: Time wasted for stopping in a work zone such as temporary lane closures, giving way etc.
  - Queue delay: This is the additional time needed to travel in a restricted flow in the work zone

- Monetary Value of Travel Time

Everything in the current world has a value. So does time. In the case of delays, we are pushed in to measuring how much have we lost due to a delay in terms of money. We feel that we could use the wasted time productively for something else. That is the value of time. When it is monetarized, it is called monetary value of time. According to FHWA report (REF) It is a sum of following components.

1. Currency value (eg. USD) of personal travel time (for passenger cars only)
2. Currency value of business travel time (for passenger cars only)
3. Value of truck travel time (for trucks)
4. Cost of freight inventory delays (for trucks)
5. Cost of vehicle depreciation (for all vehicles)

Deducing values for above criteria must be done using household income, population, number of hours of travelled per person etc.

2.8.2. Vehicle operating cost (VOC)

Vehicle operating cost (VOC) defines the cost incurred when using a vehicle. VOC includes running costs, and do not include fixed cost factors such as cost of insurance and car loan repayment, parking fees etc [20].

VOC consists of few major sections:

- Fuel consumption
- Tire consumption
- Lubricant consumption
- Depreciation cost
- Capital cost
- Maintenance labour cost

Determining VOC requires two sets of information [11]

- The economic cost of input such as labour, fuel, spares, replacement cost etc.
- The relationship between consumption of inputs and speed, congestion, and roughness by the type of vehicle.

For a work zone, there are few scenarios that occur, like in the previous section for delays [20].

- Speed Change VOC
- Stopping VOC
- Queuing VOC
- Detour VOC

There are few models available worldwide for determining VOC

- National Cooperative Highway Research Program (NCHRP) Report 133 method [21].

- World bank’s Highway Design and Maintenance standards model (HDM-IV) [22]
- COBA model or the British Cost Benefit Analysis program
- The Australian Road Research Board’s Road Fuel Consumption model.
- The National Association of Australian State Road Authorities’ Improved Model for Project Assessment and Costing (NIMPAC).
- The Swedish National Road and Transport Research Institute (VTI) Vejstandard og transportomkostninger (VETO) model.
- Texas Research and Development Foundation (TRDF) method. [23]
- HERS-ST method.20
- U.S. Environmental Protection Agency (EPA)’s Motor Vehicle Emission Simulator (MOVES) [24]—Only fuel consumption costs can be estimated using this tool.

NCHRP 133 methods provides various relationships to calculate VOC for different work zone conditions. These relationships were based largely on earlier work by Winfrey and Claffey. [25] [26]. Therefore, the accuracy depends largely on the accuracy of these reports. As these reports are developed for US context, it is not possible to use it for Sri Lanka due to fleet variety, vehicle models, fuel consumption, terrain conditions and various such reasons. Both this and TRDF method misses out on incorporating the vehicle technology and fleet changes.

The HERS-ST [27] model is derived from TRDF VOC relationships, with some adjustments made based on the findings in Zaniewski et al. [23] It also provides room for adjustment of vehicle improvements and cost fluctuations.

HERS-ST uses following equation to compute its VOC model

Equation 2 HERS-ST model

$$CSOPCSTRvtR = CSFC \times PCAFFC \times \frac{COSTFRvtR}{FEAFRvtR} + CSOC \times PCAFOC \times \frac{COSTORvtR}{OCAFRvtR} + 0.01 \times CSTW \times PCAFTW \times \frac{COSTTRvtR}{TWAFvt} + 0.01 \times CSMR \times PCAFMR \times \frac{COSTMRRvtR}{MRAFRvtR} + 0.01 \times CSVD \times PCAFVD \times \frac{COSTVRvtR}{VDAFRvt}$$ [20]

where,

CSOPCSTvt = constant speed operating cost for vehicle type

CSFC = constant speed fuel consumption rate (gallons/1000 miles)

CSOC =constant speed oil consumption rate (quarts/1000 miles)

CSTW = constant speed tire wear rate (% worn/1000miles)

CSMR = constant speed maintenance and repair rate (% of average cost/1000 miles)

CSVD = constant speed depreciation rate (% of new price/ 1000 miles)

PCAFFC = pavement condition adjustment factor for fuel consumption

PCAFOC = pavement condition adjustment factor for oil consumption

PCAFTW = pavement condition adjustment factor for tire wear

PCAFMR = pavement condition adjustment factor for maintenance and repair

PCAFVD = pavement condition adjustment factor for depreciation expenses

COSTFvt = unit cost of fuel for vehicle type

COSTOvt = unit cost of oil for vehicle type

COSTTvt = unit cost of tires for vehicle type

COSTMRvt = unit cost of maintenance and repair for vehicle type

COSTVvt = depreciable value for vehicle type

FEAFvt = fuel efficiency adjustment factor for vehicle type

OCAFvt = oil consumption adjustment factor for vehicle type

TWAFvt = tire wear adjustment factor for vehicle type

MRAFvt = maintenance and repair adjustment factor for vehicle type

VDAFvt = depreciation adjustment factor for vehicle type.

Out of the above, HDM-4 was decided to be used in this study due to the fact that the model was developed using multiple conditions such as urban, rural, developing country traffic and developed country traffic.

The fuel consumption model used in HDM-4 is given below [22].

Equation 3 VOC HDM-4 model

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

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
$\boldsymbol{\alpha}$ =Fuel consumption at idling (mL/s)
ξ =Fuel to power efficiency factor (mL/kw/s)

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

ξ_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

HDM-4 uses the following model to calculate tire consumption.

Equation 4 Tire consumption in HDM4

$$\mathrm{TC} = \frac{\mathrm{NW} * \mathrm{EQNT}}{\mathrm{MODFAC}}$$

Where:

TC=Tire consumption per vehicle (%km)

NW=Number of wheels

$EQNT$=Equivalent new tire (%km)

$MODFAC$=Tire life modification factor

The following model is used in HDM-4 for the calculation of parts consumption.

Equation 5 Parts consumption model

$$PARTS = (K0pc\ [CKMkp\ (a0\ +\ a1RI)]\ +\ K1pc)\ (1\ +\ CPCON \times dFUEL)$$

$RI\ = max\ (IRI, min\ (IRI0, a2\ + a3\ * IRIa4))$

$a2 = IRI0 - a5$

$a3 = \frac{a_5}{IRI0^{\frac{IRI0}{a_5}}}$

$a_4 = \frac{IRI0}{a_4}$

$a5 = IRI0 - 3$

LH = K0lh ($a6$ × PARTSa7) + K1lh

Where:

PARTS = Standardized parts consumption as a fraction of the replacement vehicle price per 1000 km

K0pc = Rotational calibration factor (default=1.0)

CKM = Vehicle Cumulative Kilometer

a0, a1,kp = Model constants

RI = Adjusted roughness

IRI = Roughness in IRI (m/km)

IRI0 = Limiting roughness for parts consumption in IRI (3m/km)

$a2$ to $a5$ = Model parameters

K1pc=Translational calibration factor (default = 0.0)

CPCON=Congestion elasticity factor (default = 0.1)

dFUEL=Additional fuel consumption due to congestion as a decimal

LH = Number of labor hours per 1000km

K0lh=Rotation calibration factor (default=1)

K1lh=Translation calibration factor (default=0)

a6,*a7* =Model constants

RI and a_3 would eliminate the effect of roughness at low IRI values.

2.9. Emission costs

This study has focused on increased emissions by road users due to work zone activities such as increased congestion, reduced speed, and vehicle queuing. Thompsan M.A. et al [28] and Nesamani K.S. [29] has listed the following as major contributing factors for emission increment.

- Carriageway Characteristics
    - Number of lanes and lane width
    - Characteristics of horizontal and vertical curves such as the curvature, frequency etc.
    - Pavement type
    - Roughness
    - Speed limit
    - Traffic control measures and their efficiency

- Traffic Characteristics
    - Volume/Capacity ratio
    - Vehicle composition
    - Flow speed

- Driver behavioral factors
    - Experience
    - Attitude
    - Gender
    - Age

- Vehicle Characteristics
    - Age, Condition, Maintenance history, Specifications, Engine size and combustion cycle technique (Direct injection, Atkinson Cycle etc.)
    - Active emission control measures (Diesel particulate filter, Catalytic converter, Emission gas recirculation etc.)
    - Performance, Power and Torque outputs per cubic centimeter
    - Tire condition, inflation level, type

- Weather
    - Humidity, Temperature, Pressure

2.9.1. Emission modelling

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) [6], 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 [30, 15] 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. In the report by Cambridge systematics Inc. [31], it was 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. Zang &

Batterman [32] 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 [18] 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.

There are two types of emission modelling available

- Static Emission Modelling

These models use emission factors to determine emissions depending on vehicle type, at a given speed, in given road conditions. They are used for large scale planning where average values are often accurate enough. They would not capture driver behavior, congestion idling, stop start scenarios but an overall value. For example, these models would not differentiate a section where there is stop go traffic at 20km/h to a smooth flowing 20km/h road. So this type is obviously not the one for estimation of emissions in a work zone.

- Dynamic Emission Modelling/ Instantaneous Emission Modelling

Unlike Static models, these incorporate real time changes in vehicle operating conditions. These models require high volume of data for operation for different conditions second-by-second. [29]. Few such models are given below

1. Motor Vehicle Emission Simulator (MOVES), USA. [24]

It is the state-of-the-art model that replaced Mobile 6.2 by EPA. This model can work both in micro and macro scale and is widely used in USA. The only downside for using this model for Sri Lankan condition is that it uses vehicle classification of Highway Performance Monitoring System (HPMS) [33]. This varies largely from our vehicle fleet.

2. Comprehensive Model Emission Model (CMEM) [34]

This model is suitable for application in small scale such as projects, selected road sections etc. It also has the same flaw as MOVES

3. HDM-4 [35]

Unlike the models 1 and 2, HDM-4 can be calibrated to a vehicle fleet, roadway conditions, and vehicle operating conditions. A brief overview of HDM-4 Emission model is given below.

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

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

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

α =Fuel consumption at idling (mL/s)

ξ =Fuel to power efficiency factor (mL/kw/s)

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

(2)

ξ_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

The HDM 4 model quantifies emission levels using the following functions.

$$TPE = EOE * CPF$$

Tail Pipe Emission (TPE) is predicted based on fuel consumption rates with the effect of catalytic converter (if available) taken into 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

However, similar to crash costing, the unit cost values for emission costing is not available for Sri Lankan context.

3. METHODOLOGY AND DATA COLLECTION

Evaluation of existing condition of road rehabilitation project work zones was done with respect to roadway conditions and traffic management. Evaluation was done by site visits, roughness measurements using miniROMDAS [36], and Google traffic API [37] for speed measurements.

Estimation of the increase in emission and fuel consumption due to congestion and poor road conditions at work zones was done using HDM-4 [35] software. Here, values were compared both before and after rehabilitation with Roughness and roadway characteristics taken as variables.

Quantifying the economic value of increase in vehicle operating cost, increase in emissions, and value of time in road rehabilitation project work zones were too estimated and compared using HDM-4 [35]. Here, it was analyzed how the values would change with changing roadway characteristics such as roughness. All the estimations were done for a range of vehicle types, doing different mean speeds in a range of roughness values to simulate good roads, roads needing rehabilitation, and roads under rehabilitation (Road section with work zones).

Reason for selecting HDM-4 [35], as explained in the chapter 3, was the ability of the software to be calibrated for local conditions.

The methodology is largely based on the findings from number of work zones around the country. These work zones were selected so that they would cover urban and high volume roads, a total rehabilitation, a less volume road, and an arterial road. This would prevent us from estimating the same economic loss for every road as one. This gives us room to decide on which recommendations matter most depending on the road section condition. After that, the calibrated HDM-4 software can provide the relevant results for analysis. These data were analyzed to find out the real economic cost of a work zone and the increment of emissions. Emission cost and crash cost were not monetarized due to lack of data as explained in chapter 3.

3.1. Evaluation of existing conditions in selected highway work zones

3.1.1. B84 Horana road: - Road stretch from Kesbewa junction to Kahathuduwa E01 interchange

The considered road stretch is undergoing a full scale widening project from Kesbewa Junction up to Kahathuduwa. The existing road was a single lane road with no hard shoulders and poor maintenance. Under the widening project, road will get 4 lanes, 2 for either direction, shoulders, walking paths etc. But since the existing road is so narrow, it has caused some considerable delays to the existing traffic due to space constraints.

The road stretch is undergoing base construction, culvert construction, landfills and cuts, demolition work due to widening, and utility relocations such as electric and telephone posts. The considered section is 6.5 km in length.

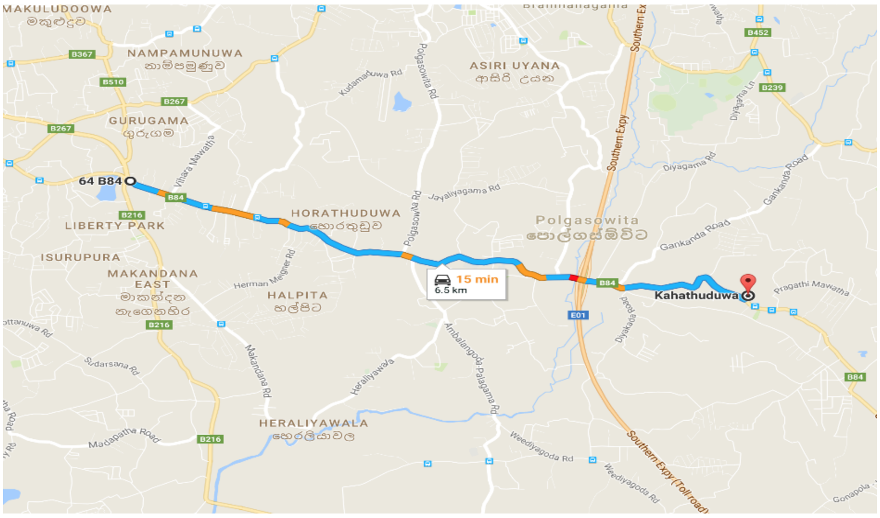


Figure 3: Considered road stretch B84 from Kahathuduwa to Kesbewa

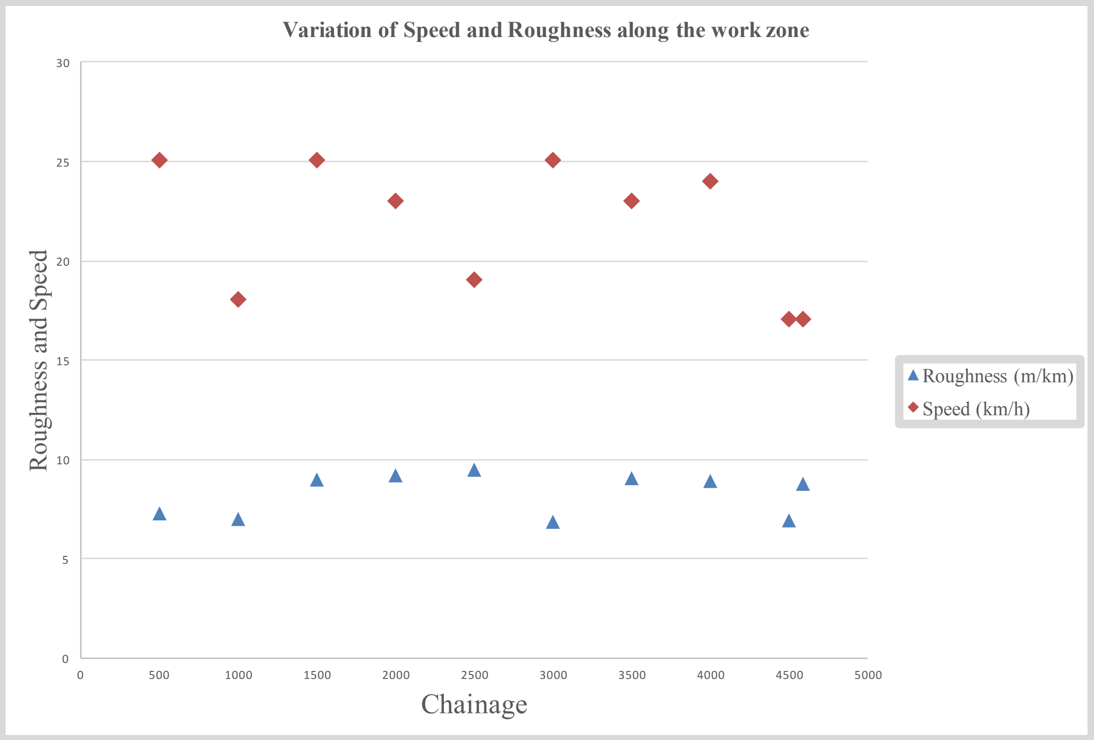
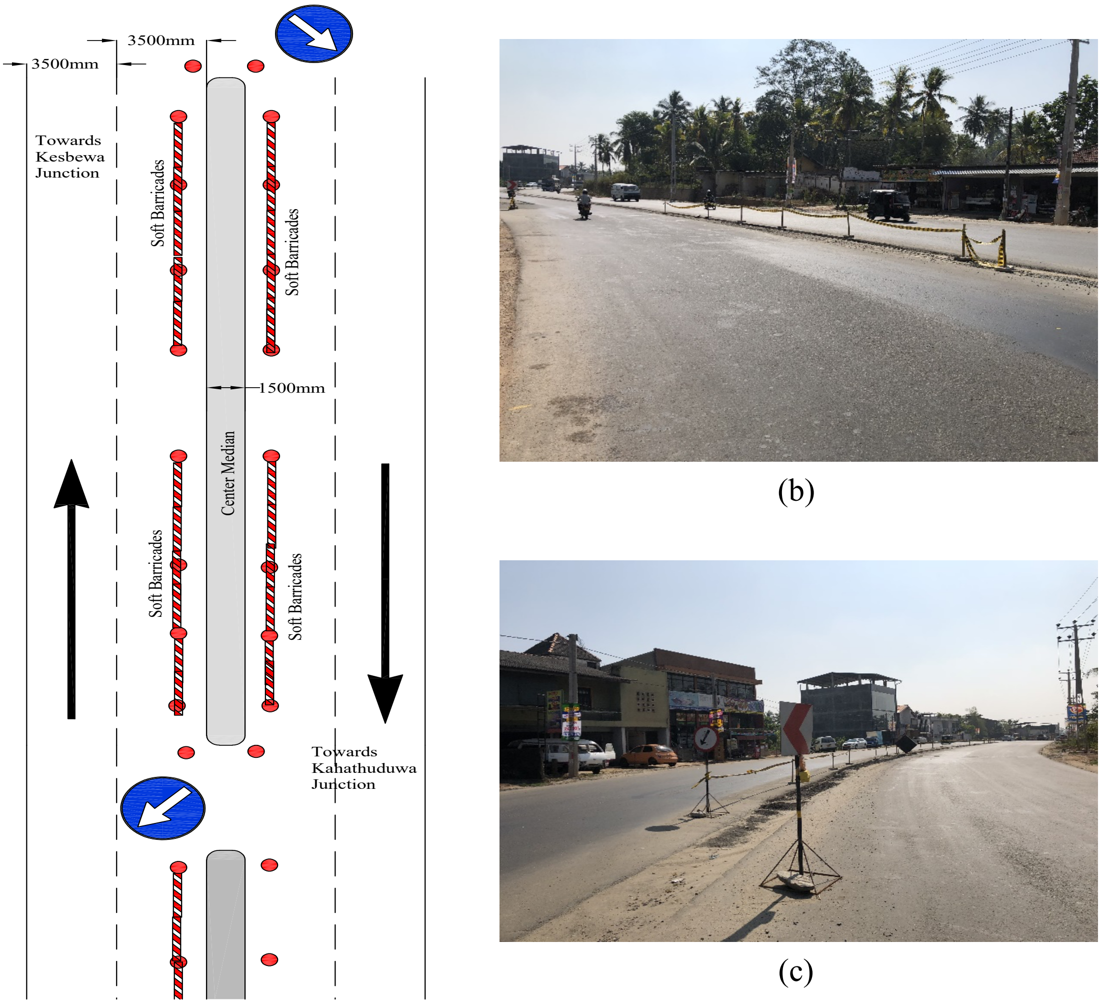


Figure 4: Variation of Speed and Roughness along B84

The high roughness values represent the work zone areas in the road stretch. The normal road had about 6.7-7 m/km roughness values while work zone areas had in excess of 8 m/km. The higher roughness value in the normal section is due to the age and the finish of the existing road. As mentioned above, it was a single lane, very old narrow road with about 6.5m wide carriage way and shoulder less than 1m to non-existent at some places. The existing road was tar-macadam road full of potholes and depressions, hence the higher roughness. Normal off peak travel time from Kesbewa to Kahathuduwa Expressway interchange was 20 minutes. During work zone operation period this got to 30-minute mark.

At the time of the writing of this thesis, the work zone is completed 100% and the same section takes 8 minutes to travel, saving 12 minutes from the original travel time.



(b)

(c)

(a) Layout

Figure 5: Work Zone Layout and Actual photos

(a) (b)

Figure 6: Completed road section with center median construction

These temporary roads have no roughness problem in the work zone as newly paved pavement is used to traverse the work zone.

- Culvert Construction

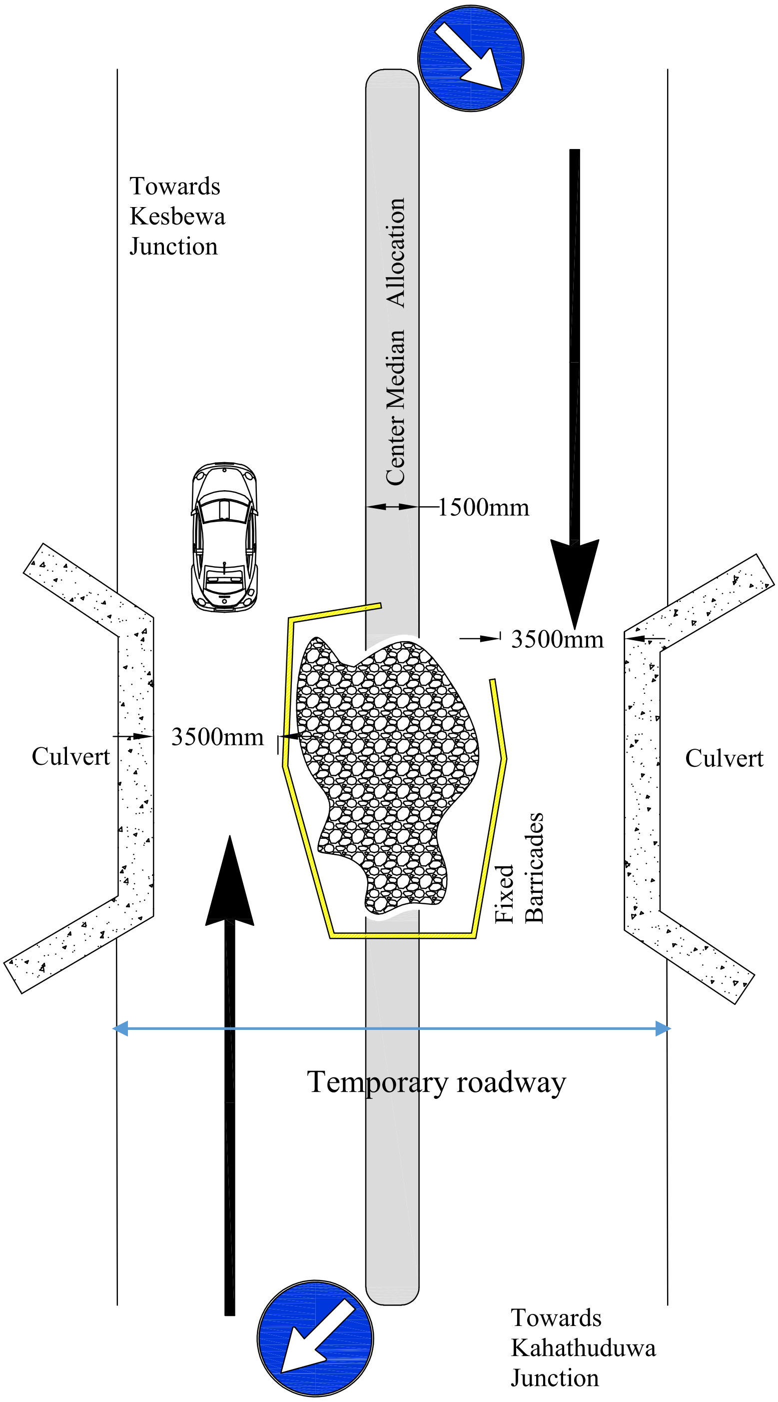


Figure 7: Layout of a culvert work zone in B84

Figure 8: Layout, actual photo

Figure 9: Culvert construction site

It can be observed that these road sections are of very low pavement quality. The temporary roadways are damaged and ill maintained. The roughness values of these areas are reaching higher than 8m/km.

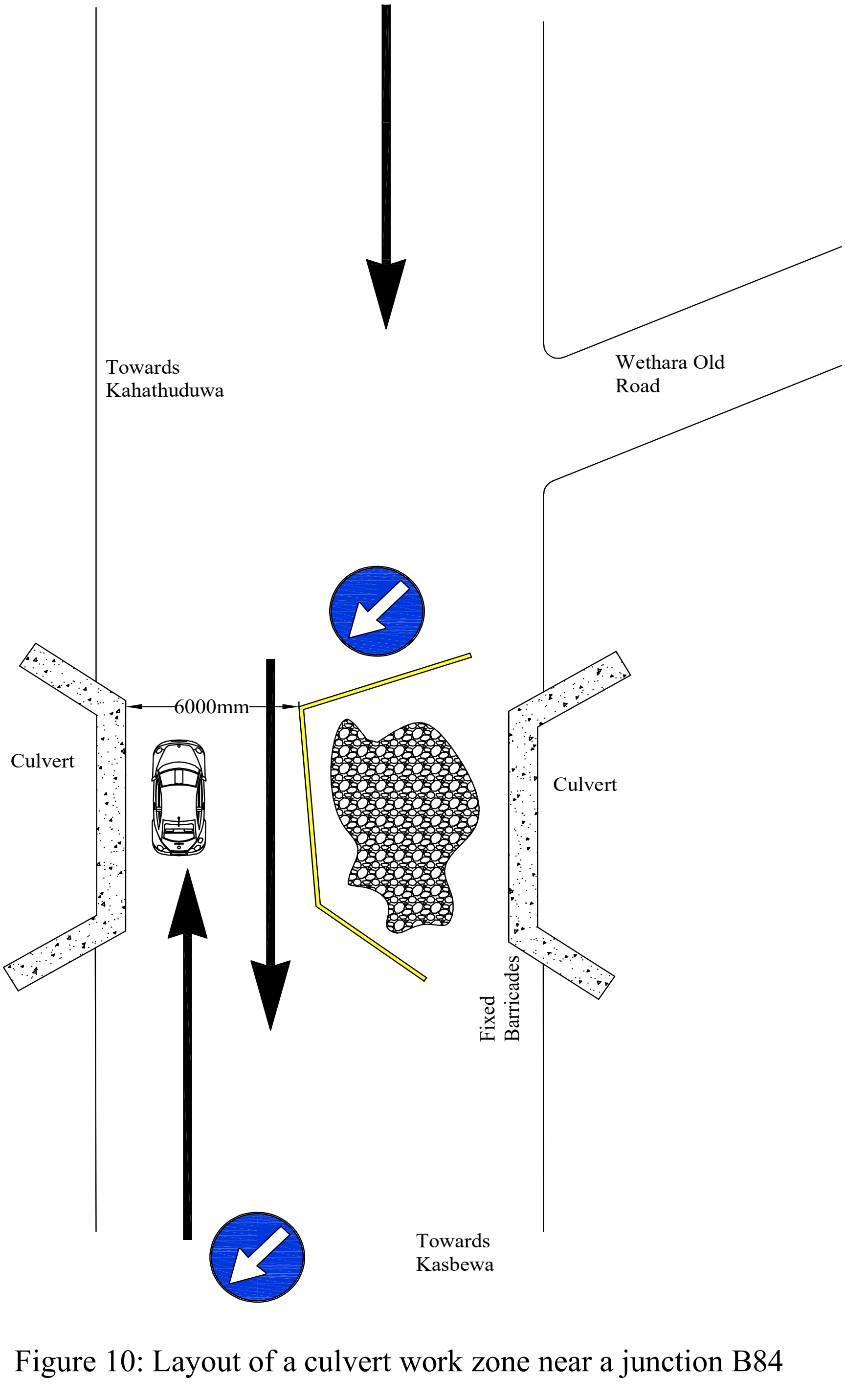


Figure 10: Layout of a culvert work zone near a junction B84

Figure 11: Photographs of the work zone

3.1.2. A1 Colombo Kandy highway, from Yakkala to Nittambuwa

Major works of this road section was started after pavement construction completion of the Belummahara- Yakkala section of the A1. Therefore, most places on this stretch are under construction. Activities such as widening, pavement laying, base and sub base construction, culvert construction, land acquisition, land filling etc. are ongoing. Since this road has a high flow, the rehabilitation process is creating a considerable delay for the road users. Screenshot below obtained by Google Maps in an off peak time of a weekday clearly shows the heavy traffic buildup in the work zone areas.

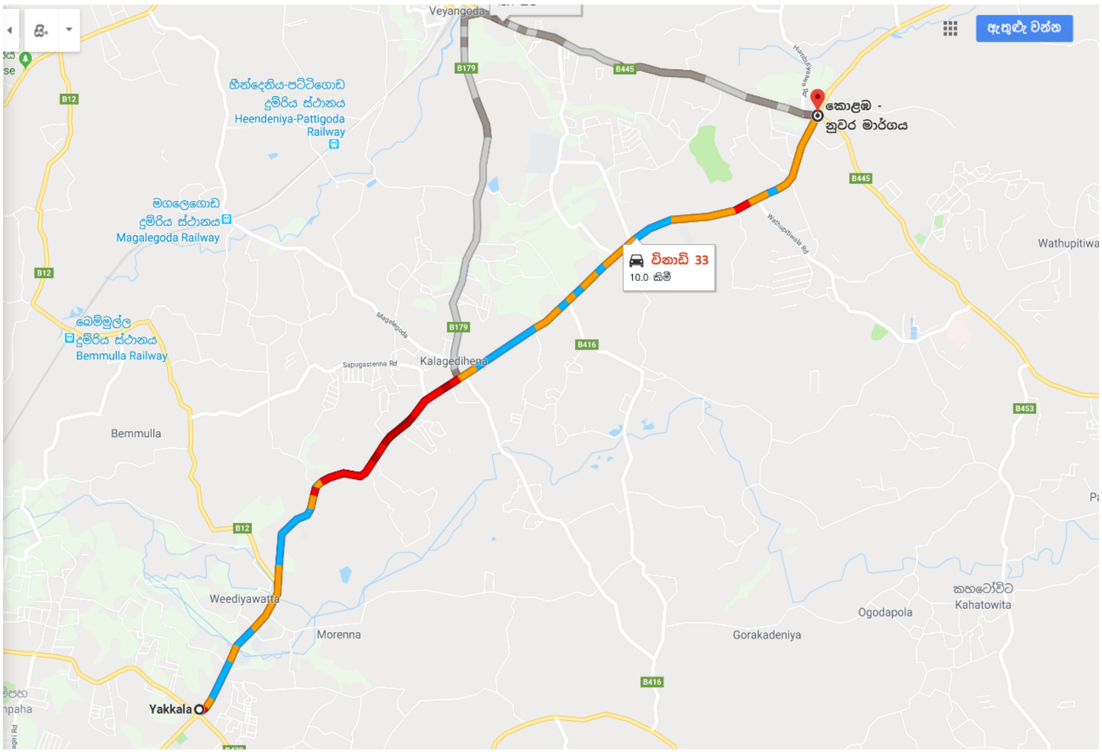


Figure 12: Location and Live Traffic view

The traffic count in this road section exceeds an Average Annual Daily Traffic (AADT) of 40,000 vehicles/day. Therefore, the widening and rehabilitation was a timely need. The new road comes with 4 lanes, a center median, and ample soft shoulder.

The project duration was exceeded by 10 months. An economic cost calculation was carried out for this section in the analysis part.

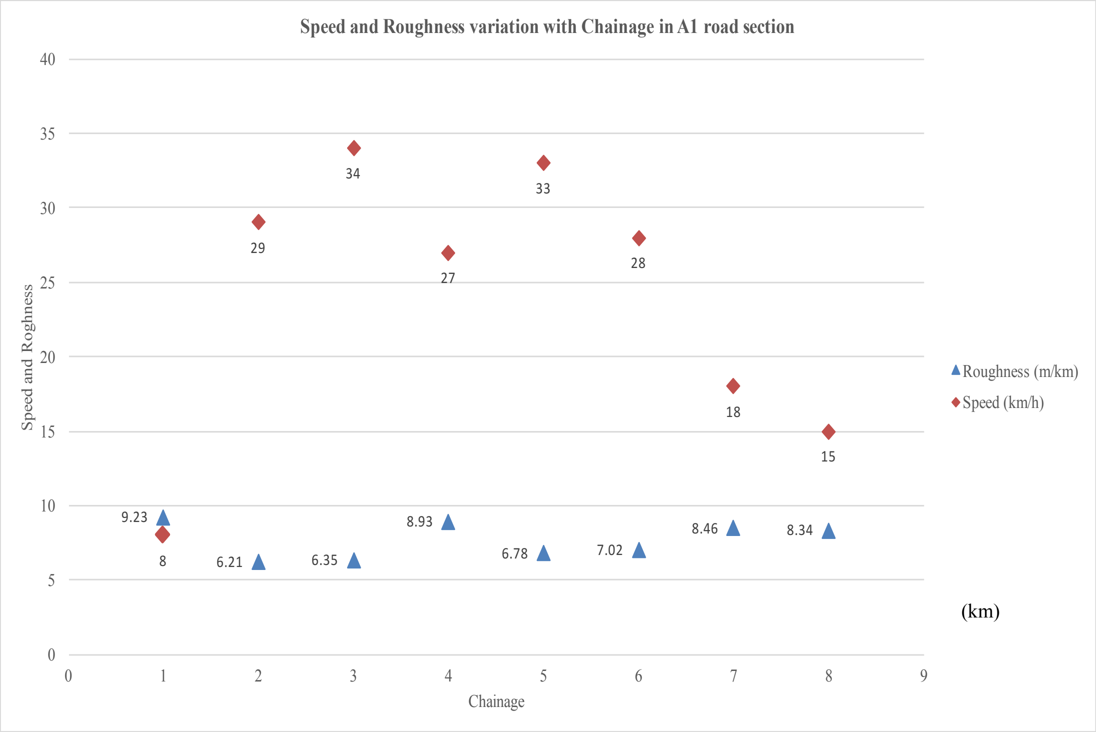


Figure 13: Speed and roughness Variation along A1 corridor

There were three work zones in the considered stretch, all of which were highlighted in the above graphs. However, the travel speeds are affected by traffic as well, so it does not fully reflect the effect of roughness.

- Base and Sub base constructions, Road widening

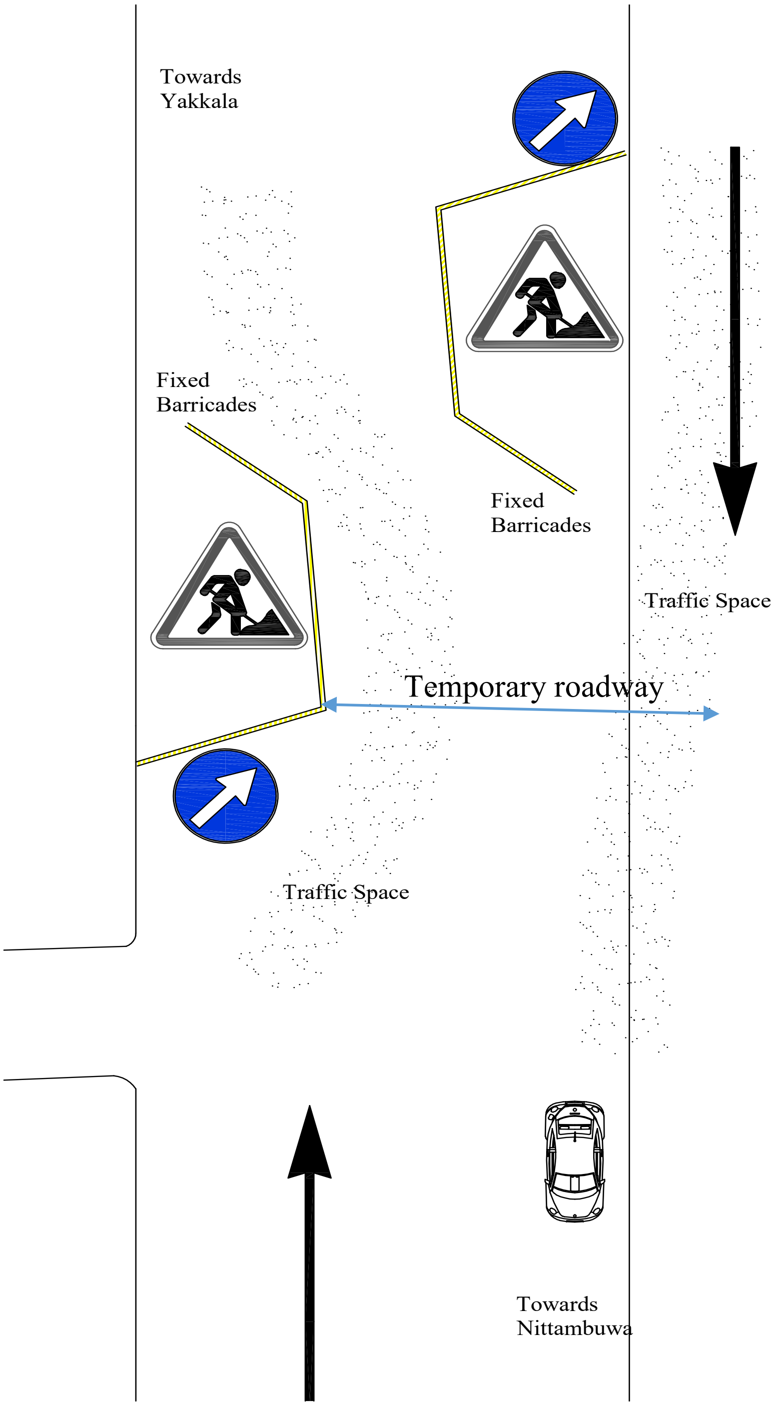


Figure 14: Layout of one of A1 corridor work zone

The mentioned stretch of the road in figure 26 has several work zones including a culvert construction, sub base laying, and base construction. Few places are being widened as well. The layout figures (Figure 26) shows a critical section of the said work zone where there is a junction, and bottleneck formation due to narrowing of the carriageway. Due to the sub base construction, the road section has narrowed significantly. The vehicles travelling towards Nittambuwa have to use the unpaved shoulder. The unpaved shoulder has become a temporary road for traversing this work zone. Therefore, the roughness of the road that vehicles travel is very high.

Figure 15: Pavement construction and widening

- Pavement Surfacing, Asphalt laying

This particular work zone extended from Ayurvedic hospital all the way up to Yakkala Junction. The work zone seemed to lack organizing, closing a large area at once for pavement laying. The motorable are was narrow and travel speeds were significantly lower compared to other sections. This was a major issue for a main corridor with very high amount of traffic flow. The queue observed in this area was about 1- 1.5km towards Nittambuwa side in the morning peak. The road section from Yakkala was completed by the time of observation, hence had two lanes per direction and not much of a queue build up. The layout of the work zone and some captured images are shown in figures 28 and 29. Also, the temporary road in use was surface scratched and ready to be demolished, and not in good condition.

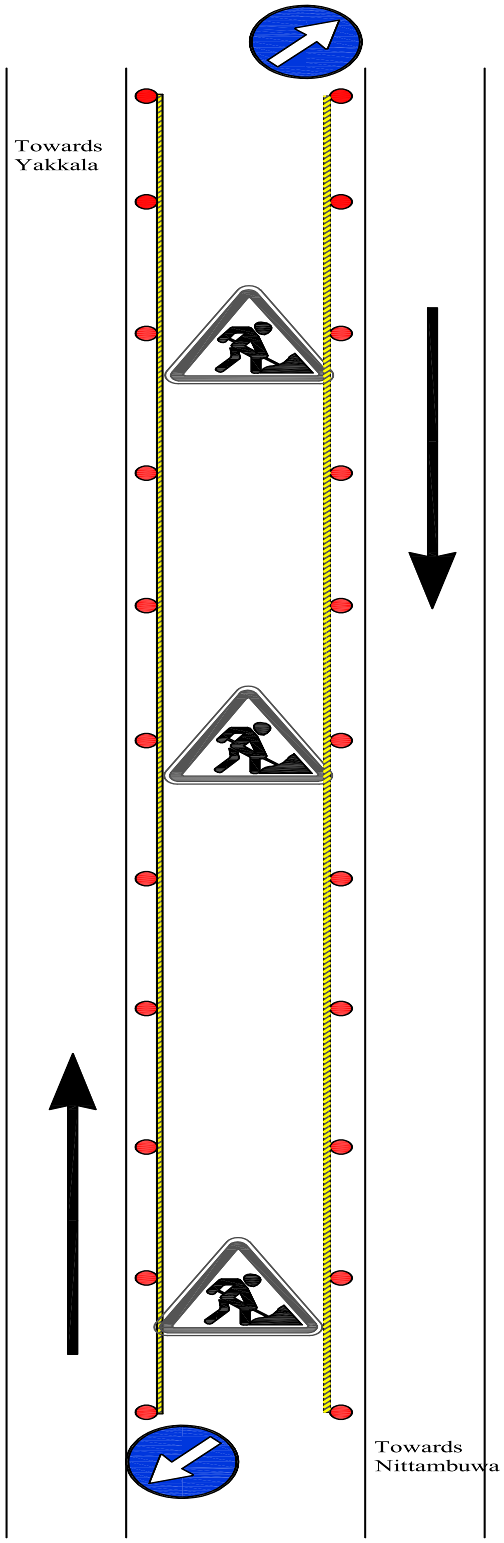


Figure 16: Layout near Yakkala of A1 corridor

Figure 17: Work zone near Yakkala Junction

3.1.3. B157 Aluthgama Road: Welipenna expressway interchange to Horawala

The mentioned road stretch was a narrow single lane road running from Welipenna to Matugama. However, now the road is undergoing a major widening project just like Kesbewa Kahathuduwa road stretch. But unlike that, the traffic here is very less. There are few major bridge construction sites going on in addition to base and sub base construction, land acquisition, culvert, and drainage construction. After completion, the road will have a two lane wide carriageway with hard and soft shoulder combination.

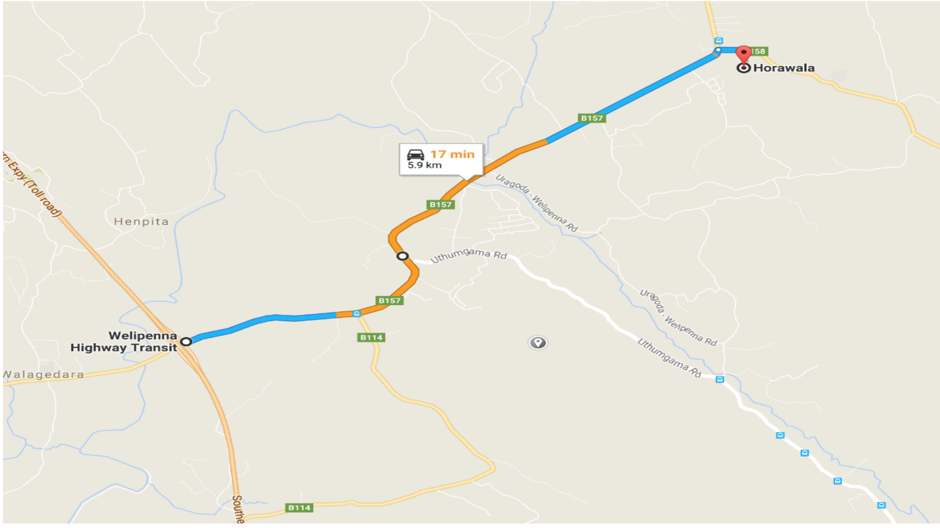


Figure 18: Welipenna work zone stretch

- Bridges in construction

In here also it was observed that no attention was paid for the condition of the road surface. In fact, this work zone recorded the highest IRI value (11m/km).

Figure 19: Bridge work zone

- Pavement construction

Figure 20: Pavement construction

The contractor has started working on full width of the road rather than doing part by part. The temporary lane is dusty and very rough. The loose gravel and aggregate was causing so much dust. High rough pavement means high operating cost to the road users as well.

3.1.4. Underground cable laying project, Baseline road from Dematagoda to Borella

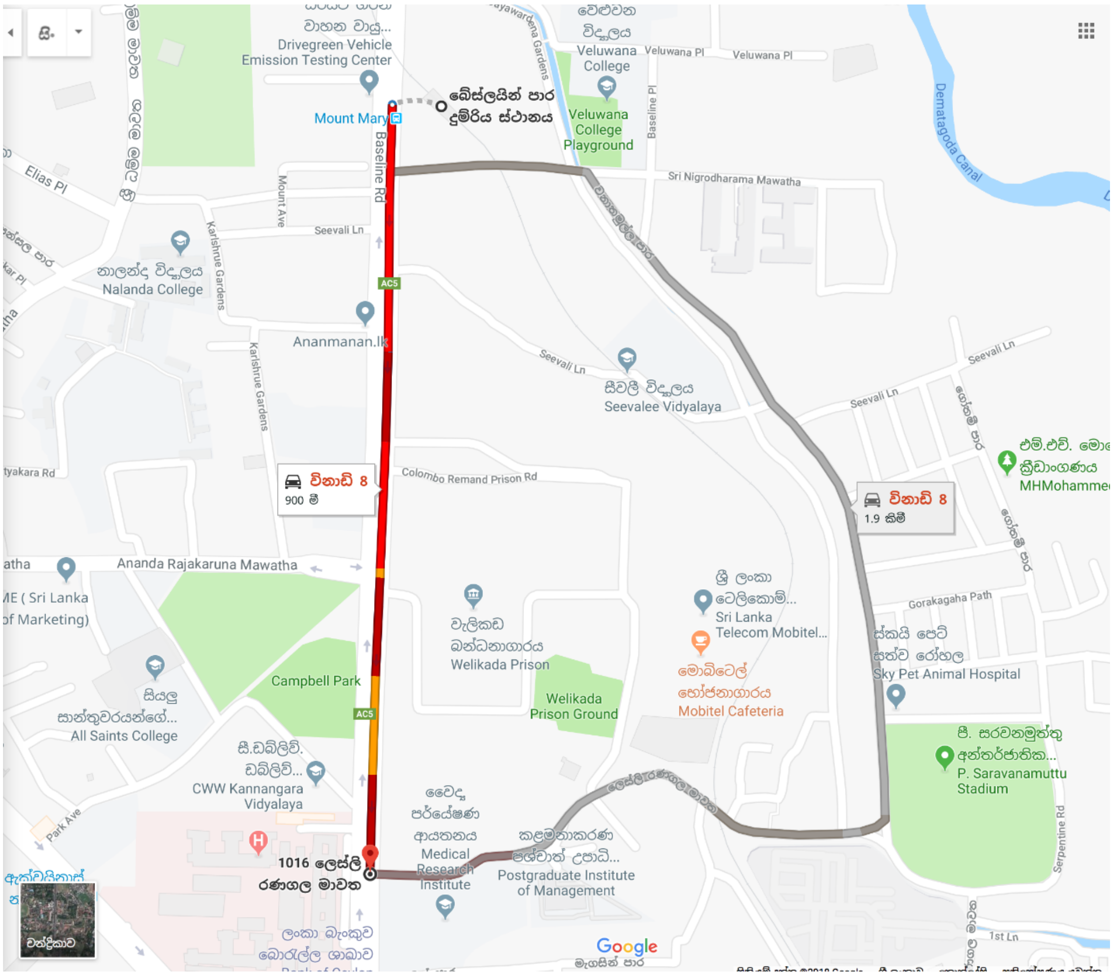


Figure 21: Work zone stretch of Baseline road

The client of the project is Ceylon Electricity board. Cable lying is carried out along the outer lane of the Baseline road towards Borella from Dematagoda direction. The main impact on traffic is the closure of outermost lane during the entire project duration. However, it is observed to be well managed. It is provided with proper separation for motorists and pedestrians. The motorable area is clearly demarcated using solid bargeboards. The temporary roadway is the existing Baseline road so the roughness issue is minimal in this work zone.

Figure 22: Some photos of Cable laying project

3.2. Summary of collected data

3.2.1. Roughness

Roughness data is collected for road segments near work-zones to evaluate their condition and this data will be used to assess the vehicle operating cost variation due to the change in work zone pavement condition.

A summary of roughness data collected from the above mentioned work zones are shown in the table below. Below data were collected from the miniROMDAS [36] bump integrator.

Table 1 Average Roughness values by section

Road Name	Road stretch	Section length(km)	Average Speed (km/h)	Average Section Roughness (m/km)
A1	Yakkala-Nittambuwa	1.6	30	8.7
B84	Kahathuduwa-Kesbewa	3.9	25	8.9
B157	Welipenna-Horawala junction	5.6	26	9.9
AC5	Baseline railway to Borella junction	1.8	21	6.1

Here, the speed was the average speed the survey vehicle was travelling and not the average speed of the section for all traffic.

3.2.2. Section speed

Average speed of vehicles travelling in a selected road link is a good measurement of the mobility of that certain link. Due to constraints in work zones such as damaged road sections, presence of construction machinery, equipment, and road workers, reduction of the road width and number of lanes, visibility constraints due to erected fences etc., the speed of such links reduce. It is not a desirable occurrence, as it will result in delays for the road users.

Speed data was collected by two methods.

- miniROMDAS bump integrator data: This collects the speed of the vehicle it is mounted on. It is not a very good interpretation of the speeds of all the vehicles in the link

- Google travel time data: This method calculates the average speed of the link by GPS data obtained through out the set time gap from the road users.

From Table 1, it can be seen that the average roughness value for work zones is between 8-10m/km in most cases and some work zones exceed 11m/km as well. Having such a high roughness can only result in increased road user cost. It can be identified as a major area for improvement in Sri Lankan context.

3.2.3. Google travel time data

Google travel time data was obtained on four of the selected work zones on the basis of traffic volume.

- Yakkala- Nittambuwa (A1)

This road stretch is currently undergoing a widening project. Existing road is a 2-lane road, which will be upgraded to a 4-lane road. The work zone traffic speed is about 26 km/h in the peak hour while it rises to an average of 33km/h in the off peak. Although day time is off peak normally, we can see a reduction in speeds up to 24-26km/h during day time in the work zone areas. Therefore, the work zone has created a considerable delay compared to normal road.

- Yakkala- Belummahara (A1)

This section has most of its work completed; hence the vehicles can travel at the designed speeds. Speeds reach 45km/h in the off peak times. At night time when the traffic is low or early morning, the speeds are about 50-55km/h as the road conditions are very good.

- Kesbewa-Kahathuduwa expressway entrance junction (B84)

This road section was previously a single lane (6 to 7m) wide road and now it is being upgraded to a 4-lane road. Still the culverts and places that have constraints are quite narrow and cause bottlenecks. The road experiences higher number of uses in the morning and evening, so long queus can be observed at those points. Also the harsh pavement conditions mean that the vehicles cannot really go fast even if there is no traffic.

- Narahenpita Baseline road underground cable laying project

One lane closure is observed over full 24h a day in this section. Three lanes are narrowed to two just after Baseline road railway station and continue up to Welikada Prison junction and little bit further beyond. Although it is a high volume road, the management of workzone is quite good to keep the delays to a minimum. They have established solid boundaries so that vehicles can use all the space up to the solid boards. Work zone situation is shown in the chapter two with images.

Table 2 shows the variation of speed during various times of the day in work zone condition and normal road conditions.

In A1, the completed section of the road is taken as a normal road section against the work zone prone section of Yakkala to Nittambuwa along the same corridor. In Narahenpita Baseline section, the work zone is mainly a lane closure. So stretch beyond the lane closure is taken as the reference for a normal road section.

- A1 Kandy Road

Table 2: Speed and Travel Time of A1

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

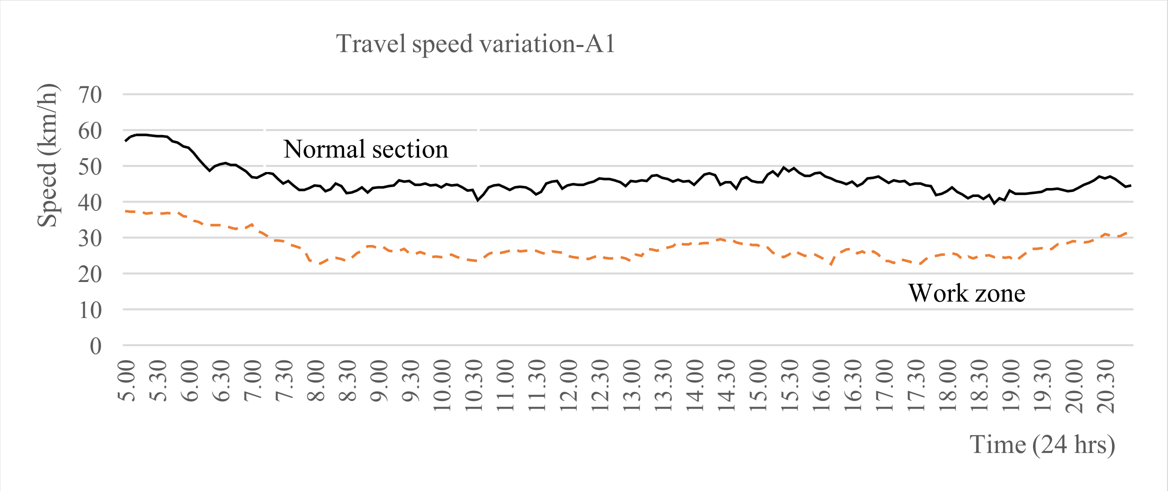


Figure 23: Speed variation in normal and work zone section

4. ECONOMIC ANALYSIS AND COST CALCULATION

4.1. Introduction

Work zone road user cost (WZRUC) is defined as the additional costs borne by motorists and the community at-large as a result of work zone activity. It can be defined under two categories.

Quantitative Impacts

- Travel delay costs
- Vehicle operating costs
- Emission costs
- Safety costs

Other impacts

- Noise Pollution
- Impact on livelihood of the local community

The Work zone road user cost (WZRUC) computations involve following steps

1. Data collection for impact assessment
2. Estimation of impacts
3. Computation of unit costs for each impact
4. Estimation of WZRUC component

Therefore, for this study, the economic cost of quantitative impacts is considered.

4.2. Vehicle operating cost

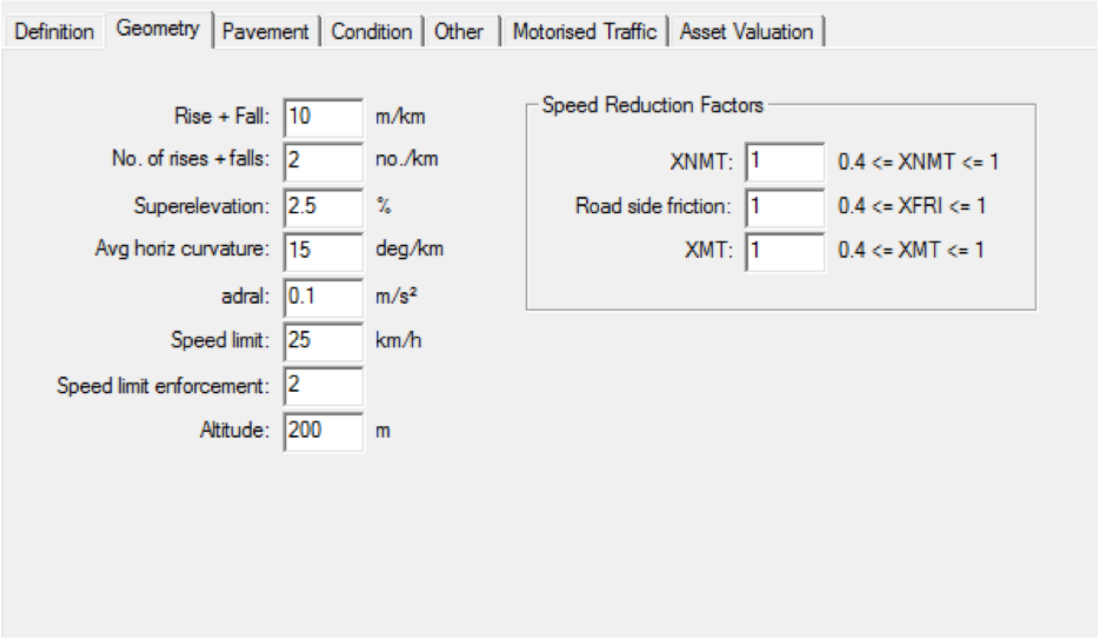
4.2.1. Calibration and Simulation parameters

Parameters include how bendy the road is, and how undulating the road is. Further, we have to state the pavement type and speeds as well.

- Terrain: Flat and straight, Rise and fall of 10m/km, Curvature of 15 degrees/kilometer
- Pavement- Asphalt
- Condition: Various Roughness values
- Speed: 10,20,30,40 km/h

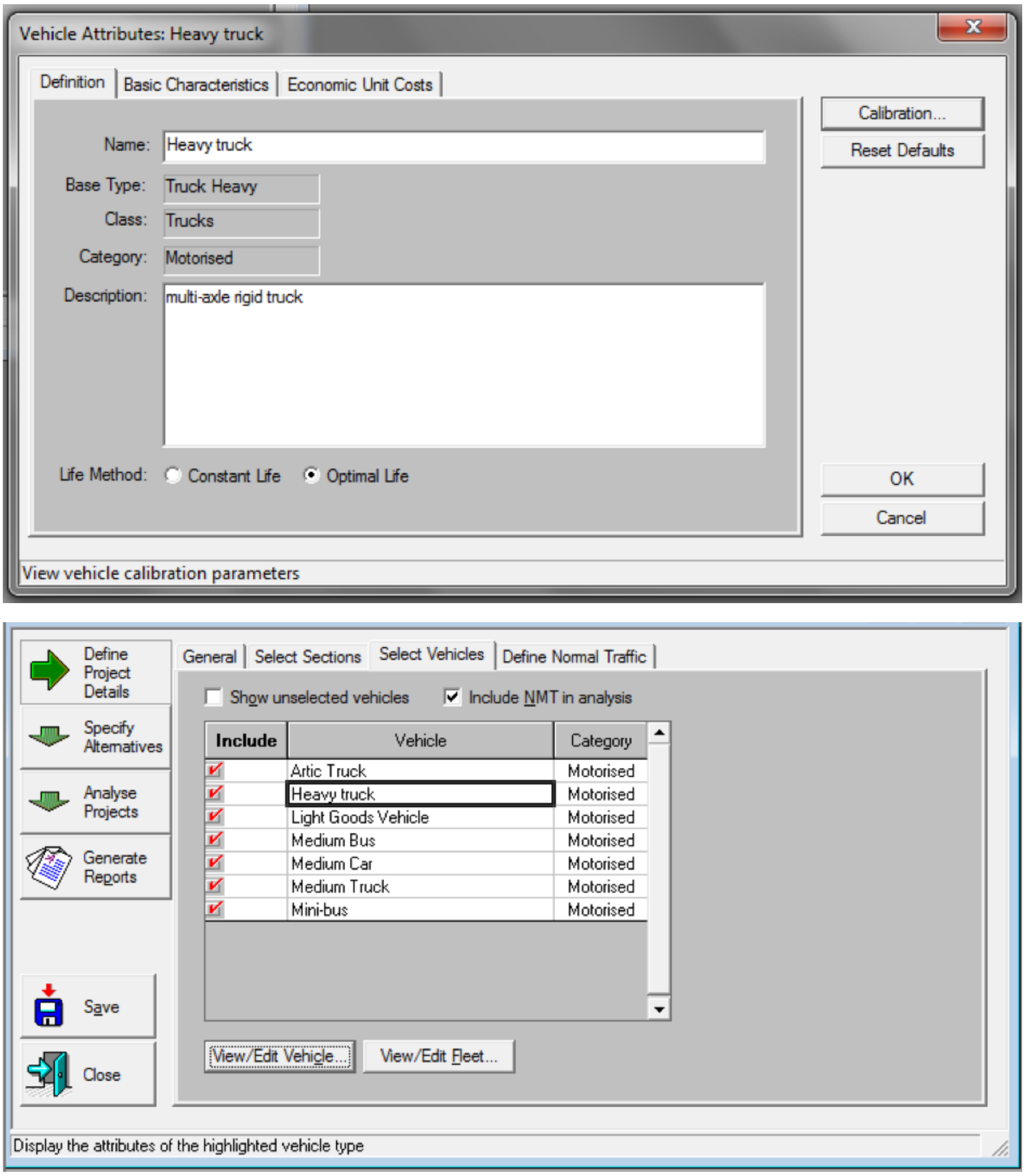
A complete table of calibration parameters such as axel loads, tire wear, fuel costs, depreciation costs etc. are included in annex 1.

Above simulations provide VOC values for varying roughness against speed, which can be used to calculate the increase of VOC in a work zone compared to a normal road. Given in table 4 to table 7 is a sample data sheet with VOC values, and Value of time (VOT) values obtained from HDM-4 simulation.



Rise + Fall: 10 m/km
No. of rises + falls: 2 no./km
Superelevation: 2.5 %
Avg horiz curvature: 15 deg/km
adral: 0.1 m/s²
Speed limit: 25 km/h
Speed limit enforcement: 2
Altitude: 200 m

Speed Reduction Factors
XNMT: 1 0.4 <= XNMT <= 1
Road side friction: 1 0.4 <= XFRI <= 1
XMT: 1 0.4 <= XMT <= 1



Name: Heavy truck

Base Type: Truck Heavy

Class: Trucks

Category: Motorised

Description: multi-axle rigid truck

Life Method: ○ Constant Life ● Optimal Life

View vehicle calibration parameters

☐ Show unselected vehicles ☑ Include NMT in analysis

Include	Vehicle	Category
☑	Artic Truck	Motorised
☑	Heavy truck	Motorised
☑	Light Goods Vehicle	Motorised
☑	Medium Bus	Motorised
☑	Medium Car	Motorised
☑	Medium Truck	Motorised
☑	Mini-bus	Motorised

Display the attributes of the highlighted vehicle type

Figure 24 Some screenshots from HDM-4

4.2.2. Variation of VOC with speed for chosen roughness values

As per chapter 4 findings, it was decided to simulate speeds of 10,20,30 and 40km/h in order to calculate the VOC differences related to work zones. Further, Roughness values from 5 m/km to 10m/km were used to simulate using HDM-4 [35].

All the values in the tables from Table 4 to Table 7 are in LKR (Sri Lankan Rupees) and are per single unit of vehicle travelling 1 km distance. Roughness values are in m/km (according to International Roughness Index (IRR))

Table 3: 10km/h Speed

Roughness	Total Cost - Rs.				
	Three Wheel	Car	Heavy Bus	Medium Truck	Motor Cycle
5	15.44	36.47	114.83	42.68	7.92
6	15.62	36.90	116.00	43.50	8.00
7	15.86	37.43	117.50	44.52	8.11
8	16.17	38.09	119.43	45.80	8.24
9	16.54	38.96	121.90	47.44	8.40
10	17.00	40.16	124.92	49.62	8.60

Table 4: 20km/h Speed

Roughness	Total Cost - Rs.				
	Three Wheel	Car	Heavy Bus	Medium Truck	Motor Cycle
5	10.3	36.47	58.62	42.68	4.21
6	10.5	36.90	59.80	43.50	4.29
7	10.7	37.43	61.30	44.52	4.39
8	11.1	38.09	63.23	45.80	4.53
9	11.4	38.96	65.70	47.44	4.68
10	11.9	40.16	68.72	49.62	4.88

Table 5: 30km/h Speed

Roughness	Total Cost - Rs.				
	Three Wheel	Car	Heavy Bus	Medium Truck	Motor Cycle
5	9.56	33.62	54.40	40.44	3.99
6	9.75	34.10	55.63	41.30	4.08
7	10.01	34.70	57.19	42.37	4.19
8	10.33	35.42	59.20	43.72	4.32
9	10.72	36.35	61.80	45.47	4.49
10	11.22	37.68	65.01	47.79	4.69

Table 6: 40km/h Speed

Roughness	Total Cost - Rs.				
	Three Wheel	Car	Heavy Bus	Medium Truck	Motor Cycle
5	8.50	29.33	48.45	37.57	3.79
6	8.70	29.80	49.66	38.42	3.87
7	8.96	30.38	51.19	39.47	3.98
8	9.28	31.11	53.17	40.83	4.11
9	9.68	32.08	55.77	42.64	4.28
10	10.20	33.57	59.26	45.07	4.49

It is clearly observed that VOC decreases as the speed increases up to 40km/h and increases as the roughness goes up. In a work zone, the roughness is higher and speeds are lower, hence inducing a heavy VOC increase. This increment is not consistent for every vehicle type. The variation is not linear either. Figures 25 to 29 show the variation of VOC for each vehicle type.

For viewer discretion purpose, the values from table 4 to 7 are exaggerated to 1000 vehicle kilometers (i.e 1000 units of vehicle travelling 1km)

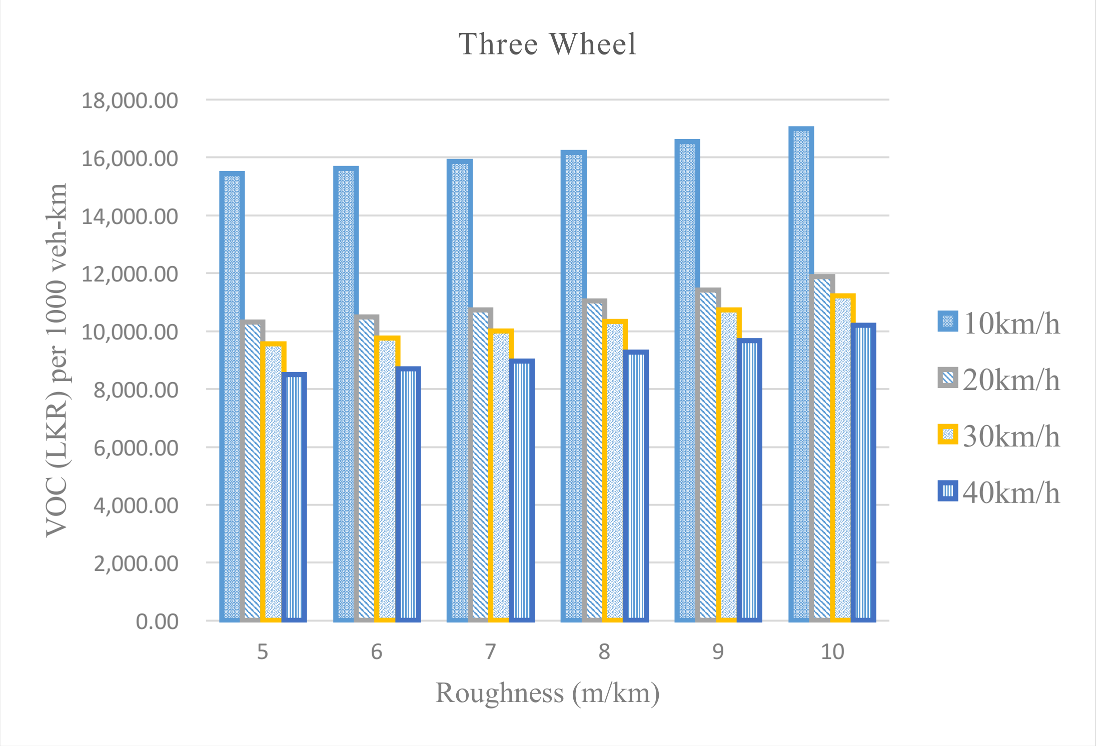


Figure 25: VOC for Three wheelers

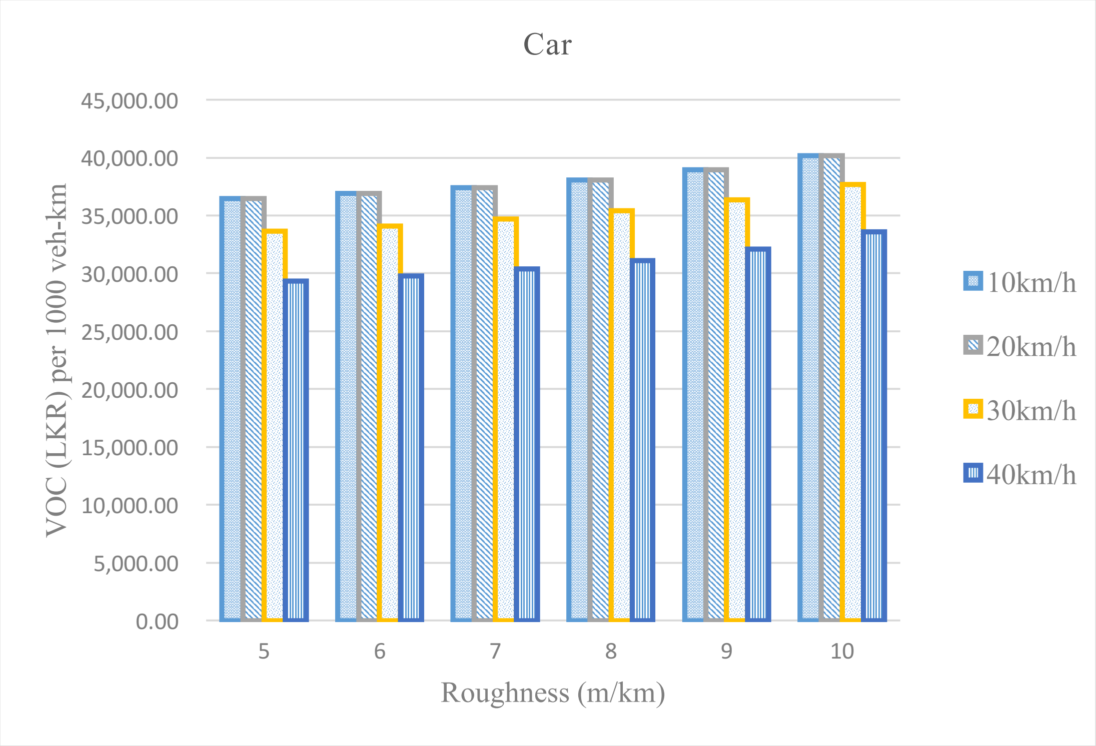


Figure 26: VOC for Cars

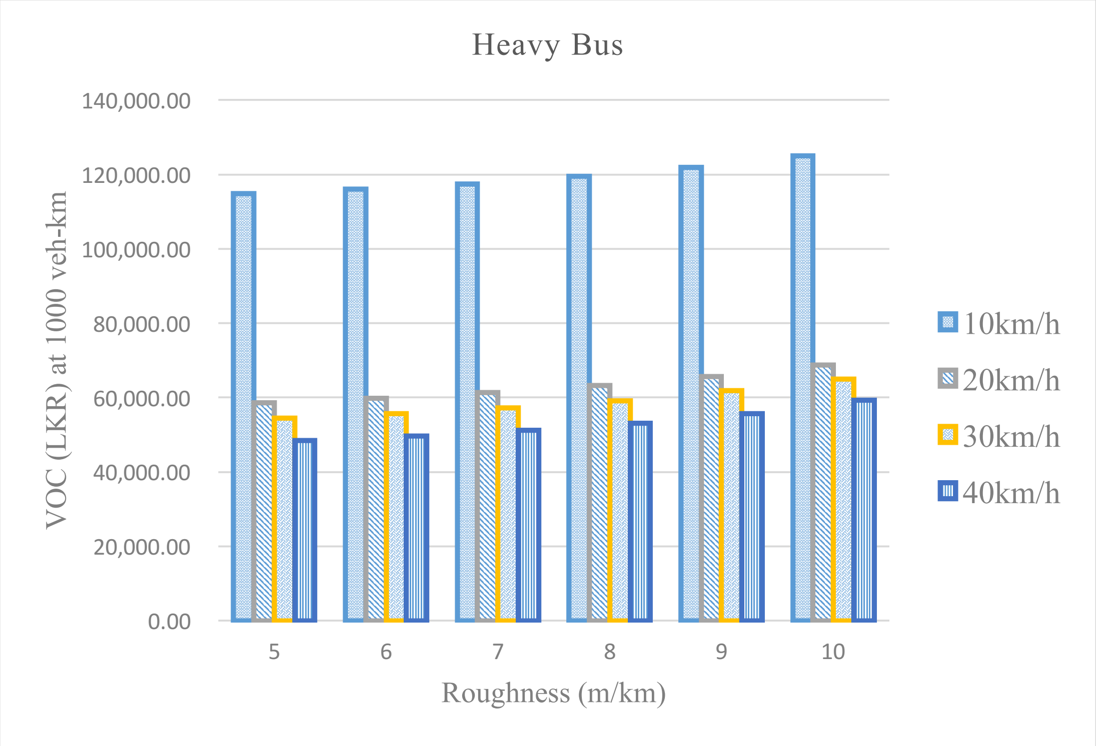


Figure 27: VOC for Heavy Bus

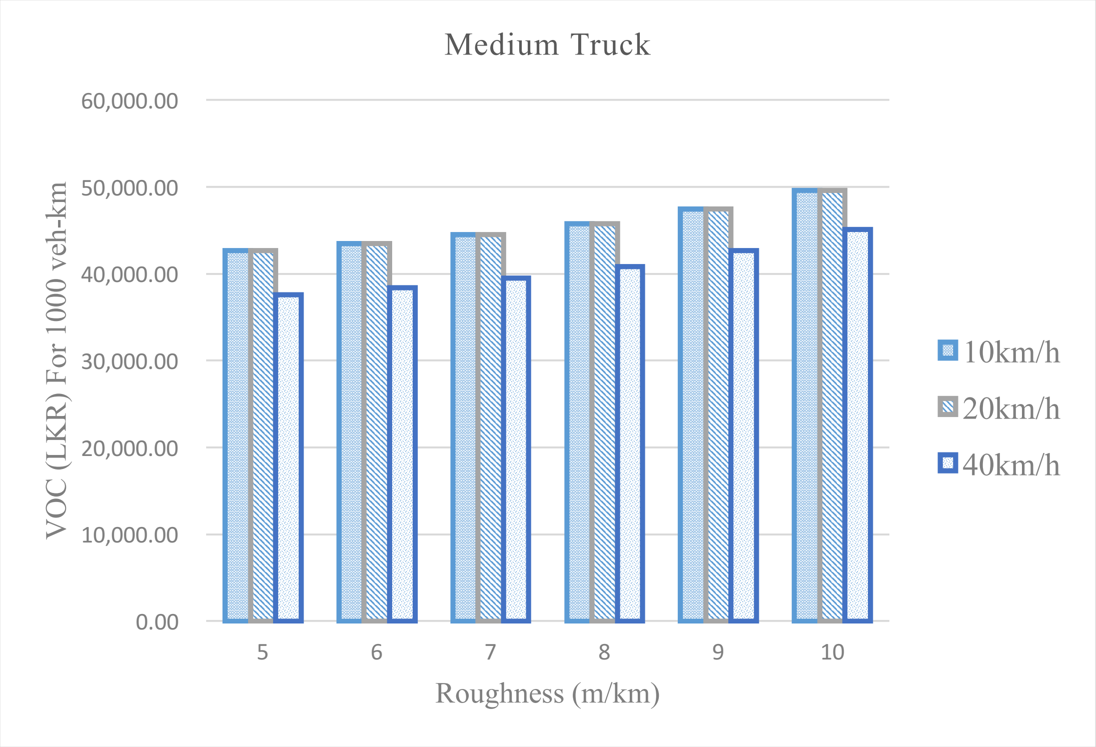


Figure 28: VOC for Medium Trucks

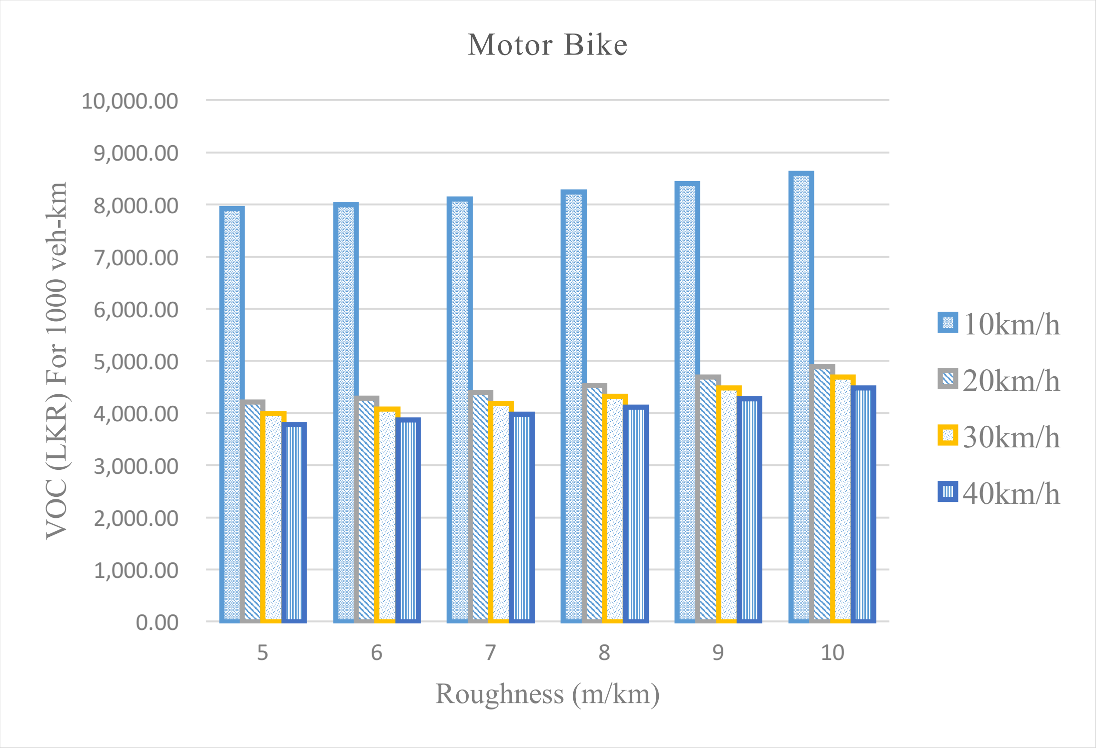


Figure 29: VOC for Motor Bikes

Figures 35 to 39 clearly show the increase of costs with roughness. Also it shows how the lowered speeds contribute to increase Vehicle operating cost. Note the increase of costs at 10km/h compared to 40km/h and roughness 5 m/km compared with roughness 10m/km which is found to be the average work zone roughness values in Sri Lanka.

For Example, a Bus travelling in a work zone where speed is 10km/h for 1km with roughness 10m/km against travelling at 40km/h for the same distance in a road with roughness 5m/km will cost LKR 76.50 more. A detailed comparison is done in the case study for A1 corridor.

Hence, economically, it is essential to maintain a low roughness value in work zones during the construction period.

4.3. Emission simulation

Using HDM-4 simulations, emission values were calculated for different roughness and speed values. These results can be related to the costs of emissions and used in economic cost calculations. These emission amounts obtained from the simulations are used to compare them with normal stretch of road. The following figure shows the variation of emission amount with speed, roughness, and vehicle type. It is visible that small vehicles have a lesser amount of impact compared to heavy vehicles and cars. But considering the composition, it can be shown that the roughness and operating speed are affecting emissions levels in a major level.

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

Table 8 provides the calibration parameters used in Sri Lankan Context for simulations. These data were derived from Department of Motor Traffic, Vehicle emission testing database, Sri Lanka.

Table 7: Emission Calibration indexes for HDM-4

Vehicle Type	aHC	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

A study done by Prasad and Swamy [40] for calibration of emission factors has revealed similar values but the HC value and aNox value is much higher as it was done in India. Further, another study done by Islam et al. [41] for HDM-4 compatibility relationships for Japanese conditions revealed that HDM-4 has overestimated the emission factors for Japanese Context. However, there was no way of validating the above factors apart from DMT documents referred.

Simulations were conducted based on few factors

- High roughness sections (Work Zones)
- Low roughness sections (Normal road, Completed sections)
- AADT values of 10,000, 20,000, and 40,000 in order to capture all the types of work zone traffic volume. This will facilitate the analysis of the effect and significance of traffic volume.

Analyzed speeds were limited to 40km/h, based on speed data obtained in the work zones. Speeds of 10km/h up to 40km/h were observed in the observed work zones.

4.3.1. Fuel consumption variation

Similar to VOC, five vehicle types were selected and simulated for roughness values up to 10m/km and speeds as mentioned in 5.3. Fuel consumption for 1000 veh-km is simulated.

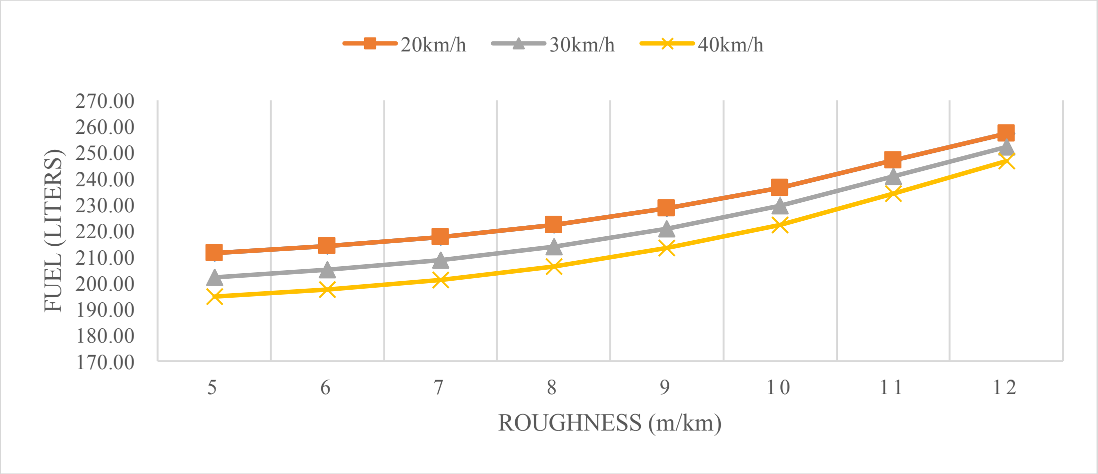


Figure 30: Fuel consumption of Medium Trucks

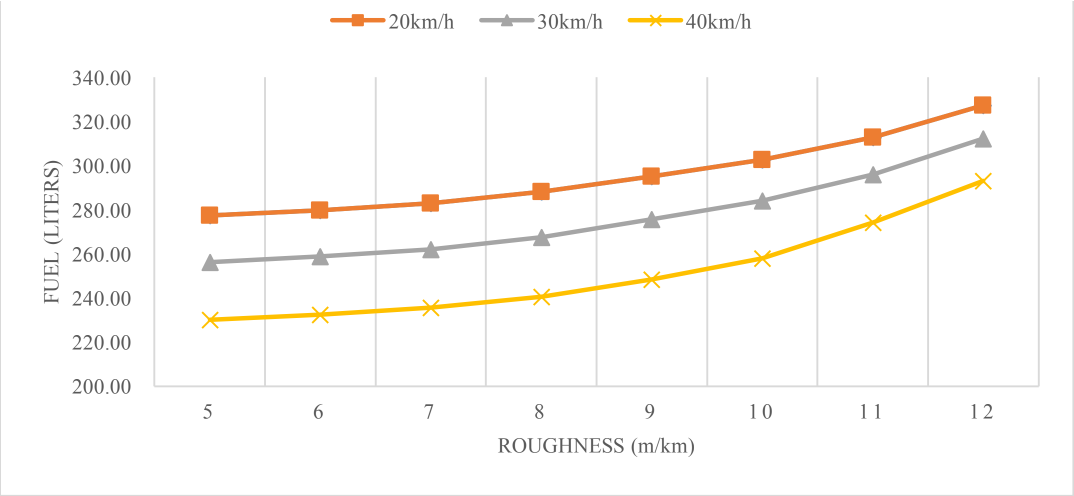


Figure 31: Fuel Consumption for Heavy Bus

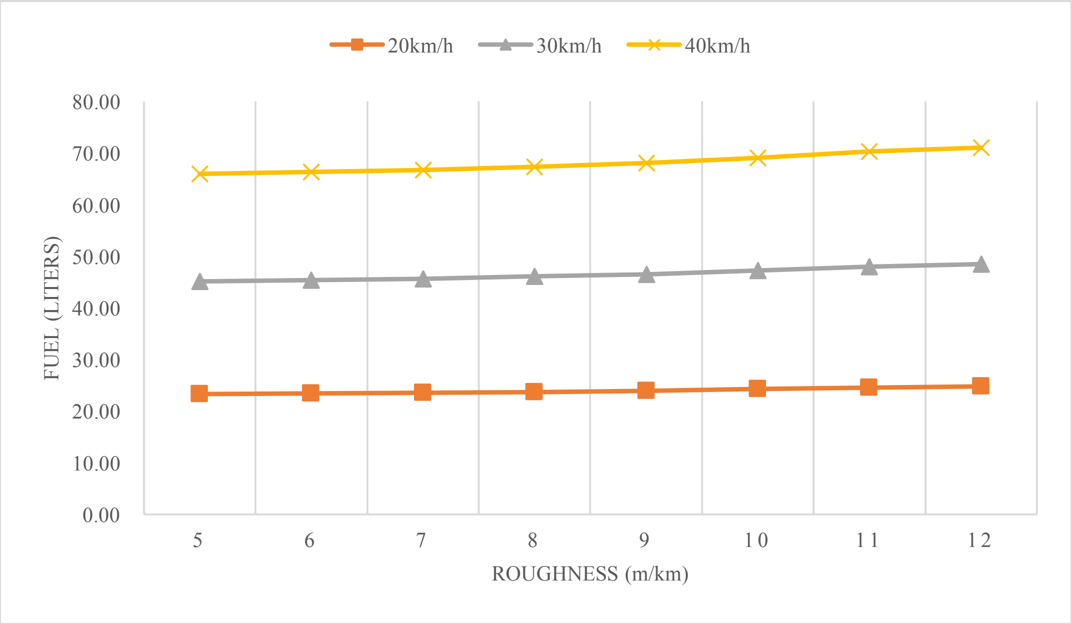


Figure 32: Fuel Consumption for Three Wheel

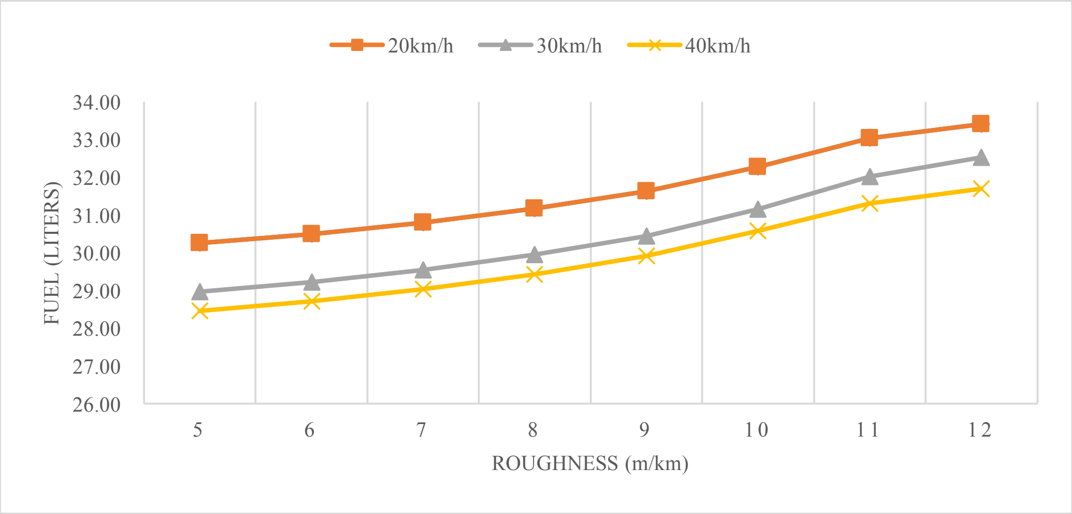


Figure 33: Fuel Consumption for Motor bikes

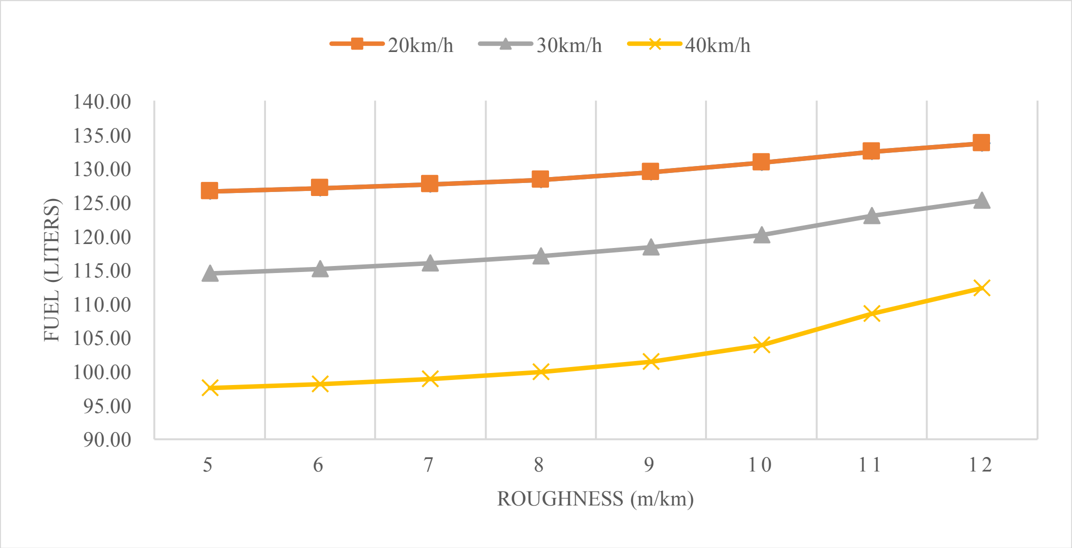


Figure 34; Fuel Consumption for Car

4.3.2. Emission Variation with Traffic Volume

Here, Variation of Traffic volume effects work zones in a significant level. It can be used to determine how much improvement is needed for the work zone. Therefore, three traffic volumes are analyzed as per section 5.3

- Roads with AADT of 10,000 vehicles/day

In these areas, the vehicle composition varies from a normal arterial road. That is, more three wheels and bikes could be seen. Figure 35 shows the normal composition

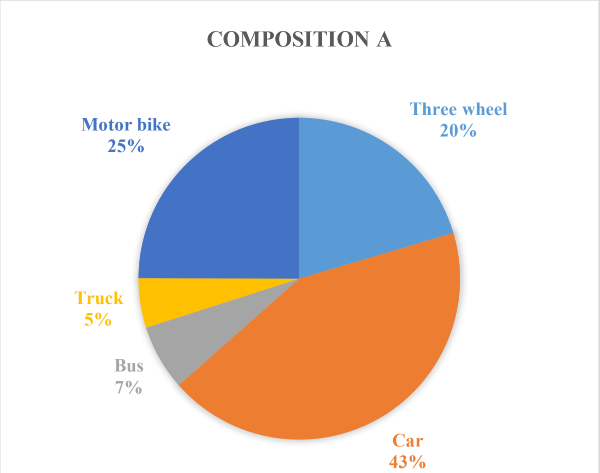


Figure 35: Normal Vehicle Composition

(Composition A) and figure 46 shows the adjusted composition (Composition B). There is a comparison done for emissions between these two compositions at the said AADT value

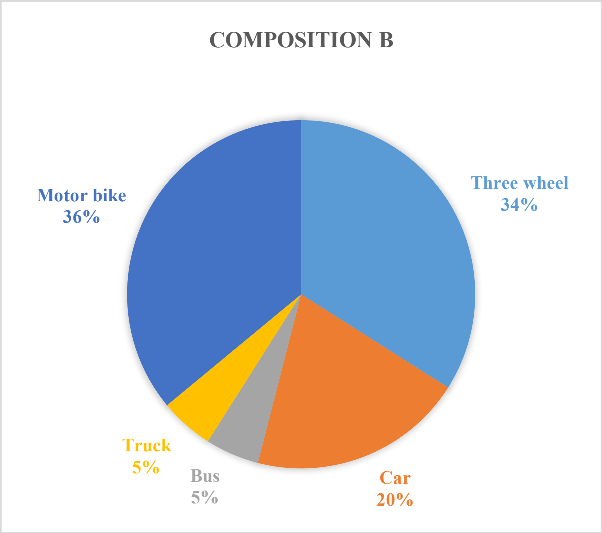


Figure 36: Alternative composition

Tables 9 and 10 shows the emission variation for different compositions simulated through HDM-4

Table 8: Composition A, Emission in kg/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	182	165	10.80%	132	118	11.60%	98	97	1.70%
5	192	174	10.70%	139	124	11.60%	104	102	1.70%
6	202	183	10.60%	146	131	11.60%	109	107	1.70%
7	213	193	10.50%	154	138	11.50%	115	113	1.70%
8	225	204	10.30%	163	146	11.50%	122	120	1.70%
9	238	216	10.20%	173	155	11.40%	129	127	1.80%
10	252	230	9.90%	184	165	11.20%	138	135	2.00%

Table 9: Composition B, Emissions in kg/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	197	176	12.00%	141	132	6.80%	110	112	-2.30%
5	208	185	11.90%	148	139	6.80%	116	118	-2.30%
6	219	196	11.80%	157	147	6.80%	122	125	-2.20%
7	231	207	11.60%	166	155	6.70%	129	132	-2.20%
8	245	220	11.40%	176	165	6.70%	137	140	-2.00%
9	260	234	11.10%	187	176	6.60%	146	149	-1.70%
10	278	251	10.80%	201	188	6.50%	157	158	-0.80%

- Roads with AADT of 20,000 vehicles/day

Here, a normal composition is used to simulate emissions.

Table 10: Composition A, Emissions in kg/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	12.80%	363	354	2.70%	295	298	-1.10%
5	543	482	12.70%	385	375	2.70%	313	316	-1.00%
6	576	511	12.70%	409	398	2.70%	332	334	-0.80%
7	613	545	12.50%	436	424	2.70%	353	355	-0.40%
8	662	590	12.10%	472	461	2.50%	384	382	0.60%
9	719	646	11.40%	516	505	2.30%	421	414	1.60%
10	783	715	9.50%	572	564	1.50%	470	464	1.20%

AADT 40,000 vehicles per day is analysed in the case study for Colombo Kandy highway (A1)

4.4. Case study for Colombo Kandy highway (A1)

Here, a comprehensive case study for A1 corridor is done to calculate the economic cost of a work zone in high volume road. The same approach can be used to calculate the economic impact of a work zone for any road in Sri Lanka with proper data and Calibration.

Project Details
Length: 29km
Project cost: 4 billion LKR
Project Duration: 2 years

A1 corridor was selected to emphasise on the effect of AADT on economic cost. AADT of A1 road was over 42000 veh/day in the time of study. So, this case study will serve as a demonstration of the method suggested in this study which can be applied to any work zone with any AADT value.

Table 11: 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

Table 12: Considered Traffic Scenario

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

4.4.1. Emission calculation

Sample calculation for emissions is given below

Total emission for a year = Peak emission (tons 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)

Here, the emission values are obtained from HDM-4 for calibrated traffic count and composition (Table 12) with a 5% increment year over year. From table 13, percentages of traffic are obtained. These are added for every traffic situation. 300 days of an year are considered to be behaving according to the considered scenario. Table 14 provides a sample calculation for a work zone with 8 m/km Roughness

Table 13: Emissions of a 8m/km Roughness road section

	Speed			
	20km/h(Peak) (kg/year)	30km/h(Off peak) (kg/year)	40km/h(Night time) (kg/year)	Total (kg/year)
AADT				
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

Vehicle operating speeds are taken from Figure 23.

Table 14 shows computed emission values in A1 corridor and a comparison between normal and work zone sections for different times of the day.

Table 14: Emission Comparison for AADT 42,000 veh/day in kilograms/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	16.00%	854	818	4.40%	681	682	-0.10%
5	1323	1148	15.20%	919	880	4.40%	734	734	0.00%
6	1400	1225	14.30%	980	938	4.50%	782	777	0.60%
7	1503	1362	10.40%	1090	1049	3.90%	874	863	1.30%
8	1624	1546	5.10%	1236	1225	0.90%	1021	1019	0.20%
9	1754	1685	4.10%	1348	1340	0.60%	1116	1115	0.10%
10	1804	1741	3.60%	1393	1387	0.50%	1155	1154	0.10%

Conclusion

Considering the values in table 14, a compact comparison can be obtained for emissions in a work zone with comparison of roughness values and speed. They are given in table 15.

Table 15: Comparison of Emission values

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 control and optimize emissions in many ways. Even though costing cannot be achieved yet, the mere quantity can be taken as a reference value to impose regulations on a work zone. For example, a work zone in a high volume road can be imposed with working hours such as lane closures at 10.00pm or such. The impact can be weighed against the cost benefit analysis to achieve a best case scenario. 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 and could save billions to the economy.

4.4.2. Vehicle operating cost calculation

Here, the scenarios, traffic composition, and work zone conditions considered are similar to section 5.4.1. Here, the normal road section is assumed to be operating at an average speed of 40km/h and 5m/km roughness whereas the work zone is assumed to be operating at 20km/h average speed with 9m/km roughness. These values are obtained through observations and measurements done in the said road section.

First, VOC values for 20km/h and 40km/h are simulated.

Table 16: VOC at 20km/h

Roughness	Total Cost per 1000 veh-km (LKR)				
	Three Wheel	Car	Heavy Bus	Medium Truck	Motor Cycle
5	10,317	36,472	58,625	42,683	4,207
6	10,499	36,897	59,795	43,501	4,286
7	10,744	37,425	61,302	44,518	4,393
8	11,052	38,088	63,233	45,797	4,525
9	11,420	38,957	65,696	47,439	4,685
10	11,879	40,164	68,719	49,622	4,884

Table 17: VOC at 40km/h

Roughness	Total Cost per 1000 veh-km (LKR)				
	Three Wheel	Car	Heavy Bus	Medium Truck	Motor Cycle
5	8505	29332	48454	37571	3786
6	8697	29799	49662	38419	3867
7	8955	30379	51193	39472	3976
8	9279	31107	53167	40829	4111
9	9676	32078	55774	42640	4275
10	10205	33568	59258	45074	4485
11	10850	35766	64183	48265	4714
12	11218	37182	67968	50621	4832

Table 18 compares the VOC increment in various scenarios

Table 18: VOC increase

Vehicle type	VOC (Roughness 8m/km, 20km/h)	VOC (Roughness 5m/km, 30km/h)	Difference
Three Wheel	11,052	9,555	1,496
Car	36,472	33,622	2,850
Bus	58,625	54,402	4,223
Truck	42,683	40,444	2,239
Motor Cycle	4,207	3,992	215
Total			11,022

To calculate the total vehicle operating cost increase, we have to factor in the number of vehicles of each type, and the length of the work zone. In this case, the work zone length is 10km. Therefore, the total loss adds up as per table 19.

Table 19: VOC increase per day

Vehicle Type	Difference(LKR)	Traffic Volume(Nos)	Cost increase(LKR)
Three Wheel	2,547	6,796	173,087
Car	8,756	15,291	1,338,909
Heavy Bus	14,779	4,672	690,478
Medium Truck	8,226	7,645	628,862
Motor Cycle	740	8,070	59,711
Total		42,474	2,891,047

Consider the scenario where roughness is reduced to 6m/km and the speed is increased to 30km/h. Table 20 demonstrates the comparison.

Table 20: VOC increase at 6m/km and 30km/h work zone

Vehicle Type	Difference	Traffic Volume	Cost Increase
Three Wheel	1,246	6,796	86,474
Car	4,771	15,291	729,575
Heavy Bus	7,181	4,672	335,506
Medium Truck	3,732	7,645	285,337
Motor Cycle	290	8,070	3,364
Total		42,474	1,458,456

The cost increase is reduced by 50% in the scenario in table 20

4.4.3. Calculation of value of time (VOT)

To find the VOT values, the report by Hamsath and Pasindu [39] was used. This report has comprehensively calculated VOTs for current Sri Lankan Context. Table 21: presents the VOT values for each vehicle type for different times of the day

Table 21: VOT for different times of the day in LKR

Vehicle type	VOT (LKR/hr)			
	Morning/Night	Morning peak	Mid-day	Evening Peak
Three wheel	104	377	245	321
Car	180	687	392	621
Bus	64	186	81	174
Truck	850	850	850	850
Motor Cycle	83	302	227	272

Observed delays throughout the day are as shown in Table 22. These are obtained by comparing the travel times of normal section and work zone

Table 22: Delay times

Early morning+Night	Morning peak	Mid-day	Evening peak
2100h to 0600h	0600h-0900h	0900h-1600h	1600h-2100h
0.08h	0.07h	0.12h	0.12h

By computing the VOT with delay times and multiplying it by the composition percentage and traffic volume, we can arrive at the values shown in Table 23. Table 24 depicts the total delay cost per day for an AADT of 42,474 veh/day.

Table 23: Delay cost per day

Vehicle type	VOT (LKR/day)
Three wheel	189,717
Car	752,684
Bus	58,309
Truck	610,875
Motor Cycle	206,437
TOTAL	1,818,023

It adds up to about 1.8 million rupees per day. Therefore, the total economic cost for the work zone in A1 considering VOT and VOC was computed as follows

Travel time delay cost+ VOC = Economic cost
2,891,047+1,818,023 = 4,709,070 LKR per day

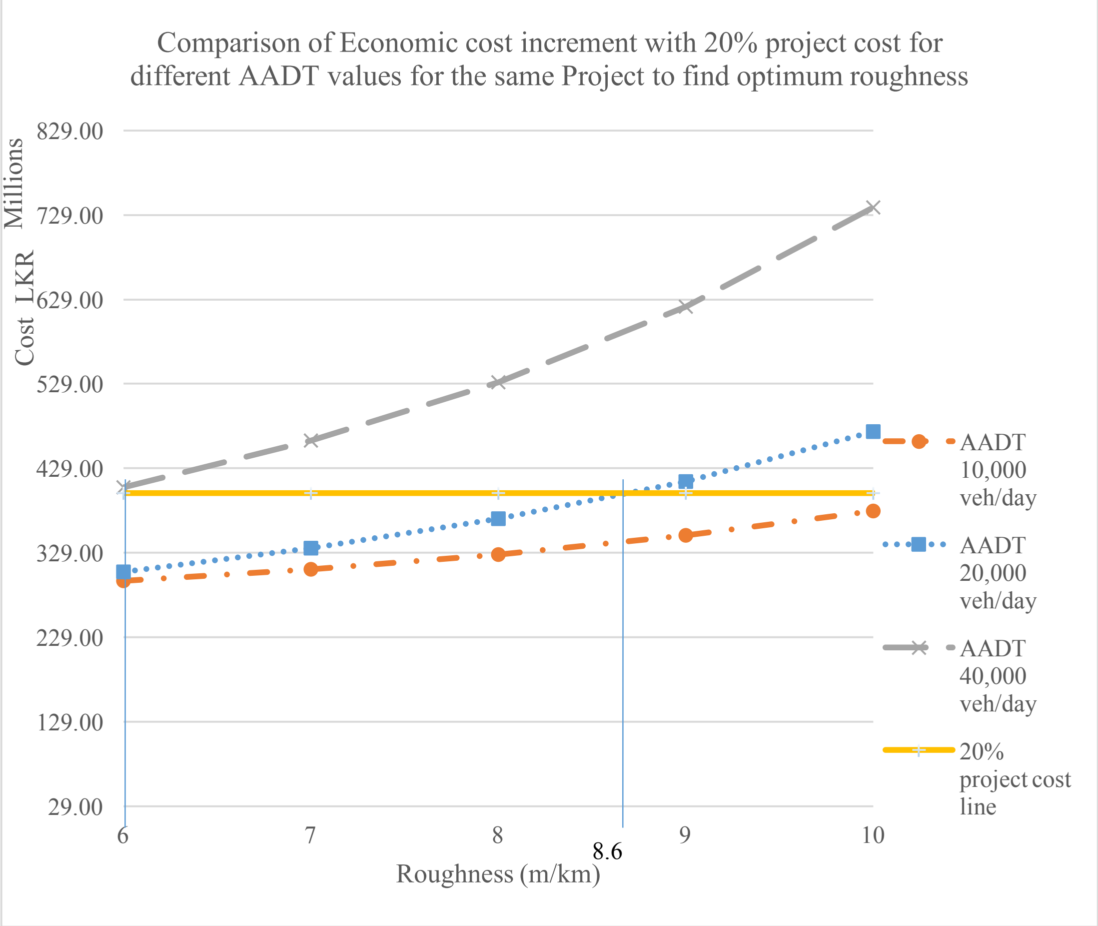


Figure 37: Comparison of the effect of AADT and roughness on a project

Analyzing figure 37, it can be observed that the optimum roughness is 8.6 m/km for AADT of 20,000 veh/day and 6m/km for AADT of 40,000 veh/day to keep the project cost at 20%. It's also visible that at 10,000 veh/day AADT, the cost is always below the 20% mark. The graph is a good reflection of how AADT affects the project cost along with roughness.

AADT values below 10,000km does not need a roughness ceiling as the 10,000AADT line does not reach 20% project cost line even at 10m/km roughness

It should also be noted that the roughness values implicate the delay costs as well. Therefore, in the figure 37, delay costs are considered on a weightage to AADT in order for the consistency of the analysis.

Economic cost is the addition of VOC and Delay cost as per the study. The delay cost is a function of speed, flow, work zone traffic management plan, and roughness of the pavement. Therefore, for each work zone, analyzing based on roughness alone is not correct. Therefore, the assumption of delay cost is reduced proportional to roughness

4.4.4. Evaluation of Economic Cost for different lengths of work zones

It was further evaluated to check if there is an impact of the work zone on the economic cost increment in a work zone when matching the 20% project cost line. Project cost was estimated at 200 million LKR per kilometer and assessed.

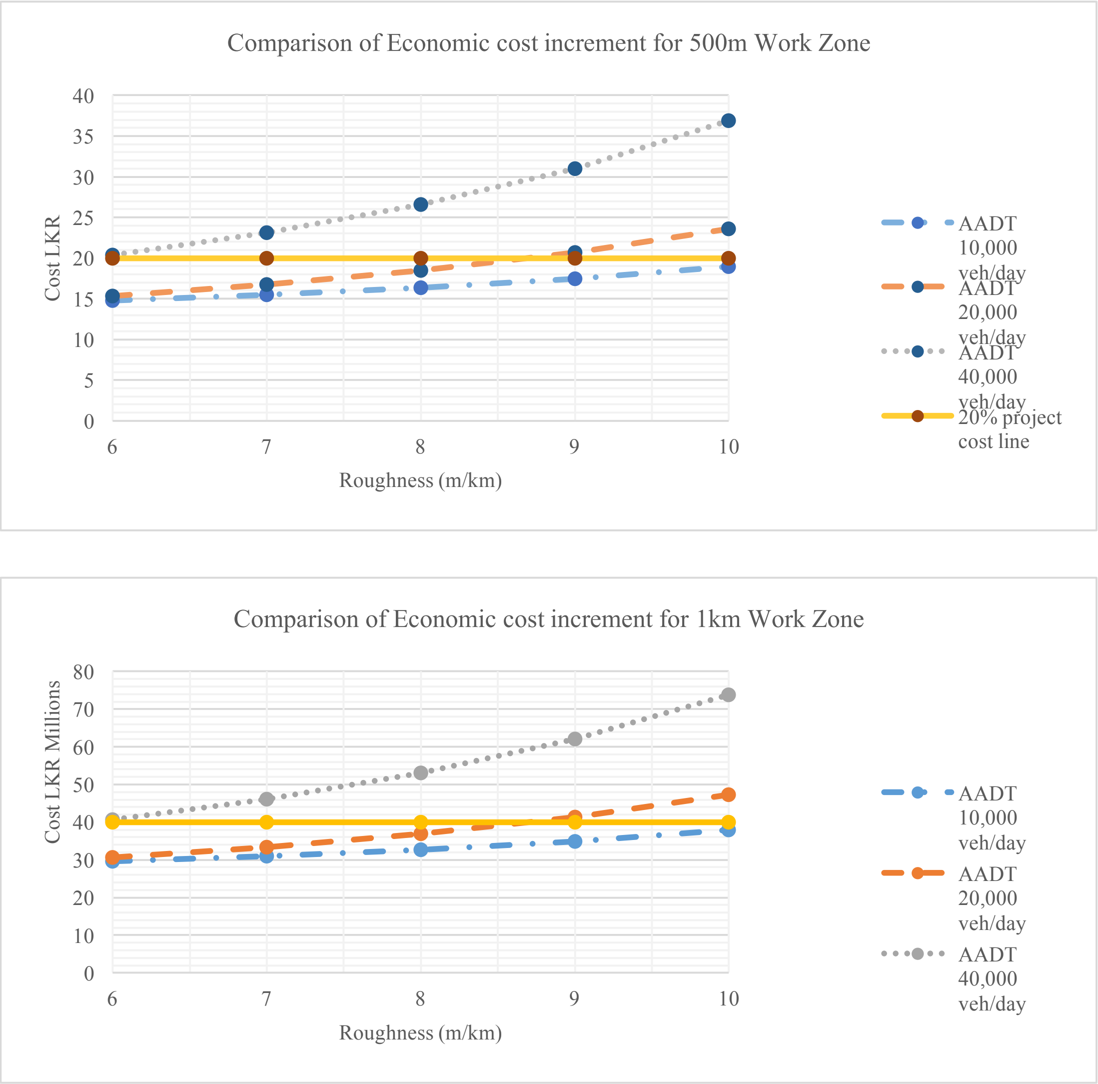


Figure 38 Cost increase per 500m and 1km work zones

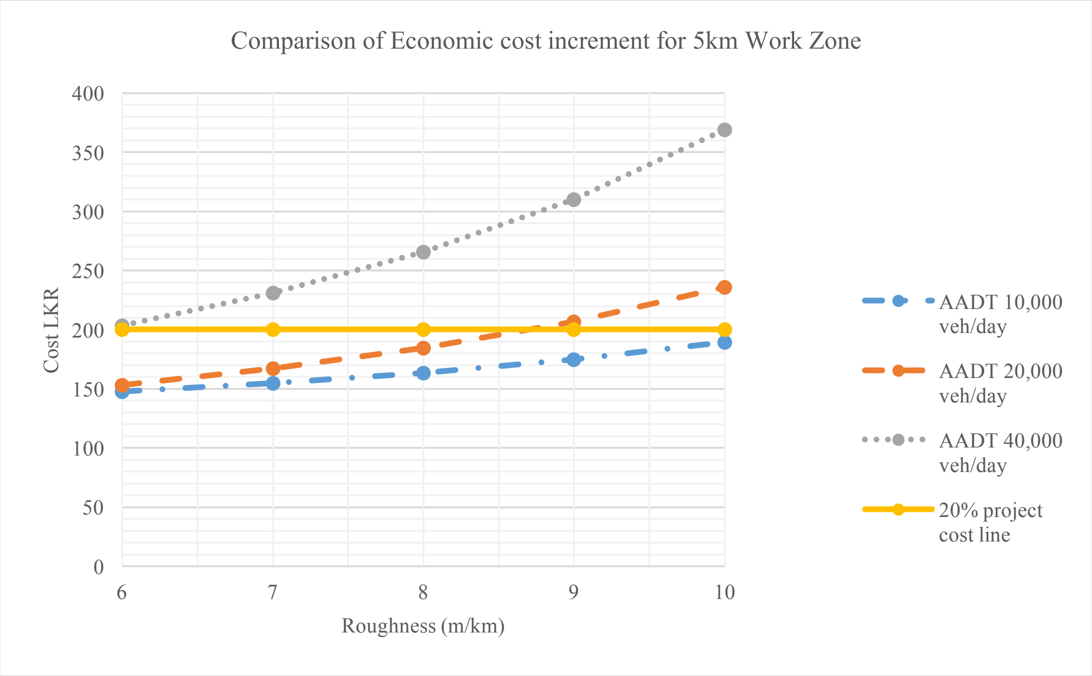


Figure 39 Comparison of economic cost for 5km work zone

The assessed project in section 4.4.3 is for a 10km road stretch with scattered work zones with varying length. The section average is considered for plotting the graph in figure 37. However, it can be observed that the pattern of the cost values follow the same trend line despite the increase in cost.

4.5. Discussion

A work zone normally operates for about 25 days per month. Therefore, for a year, the total economic loss would be about 1.4 billion LKR. Considering the total project duration is 2 years and the Project cost is 4 billion LKR, the economic loss is roughly 70% of the total cost.

A reduction of roughness to a value closer to 6m/km would result in a saving of approximately 31% of the economic cost which brings the economic loss due to work zone down to 49% from 70%.

The emissions, even though not costed here, would go down drastically upon proper maintenance of temporary lanes, and proper traffic control methods.

The increment of values from 5m/km to 8,9 and 10m/km are very steep. It ranges from 50 to 70% increment of emissions during peak hours due to the work zone.

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.

5. CONCLUSION

This research study was started with the objective of developing a methodology to calculate economic cost of work zones in highways in Sri Lankan context, and to propose minimum standards in order to keep the economic cost at a feasible rate. In the Literature review, it discusses the literature associated with the study along with how other developed countries tackle WZRUC. Further, it researches about calculating the cost parameters such as VOC, Travel time delay cost, and Emissions increment in a work zone in various context. Also it evaluates the available models to conduct calculations and selects the best model for Sri Lanka. Next up, the study focuses in to work zones and their properties such as shortcomings related to delays, pavement condition, etc. so that the study gets an idea about the existing condition for simulations. Selection of these work zones depended on the traffic volume, their location, and the type of work being carried out such as widening, rehabilitation etc.

Estimation of VOC increments were done using HDM-4 software. Delay costs were calculated using Google travel time API and traffic surveys. Here, it was analyzed that increased pavement roughness results in cost increment due to increments in VOC, travel time, and drop in mean speed.

It was found that most work zones operate at high roughness values of 7 to 11 m/km. It was identified that poor pavement management has led to the high IRI values. Further, observed delays are higher in high volume roads due to partial closure of lanes, temporary lanes being less motorable, and poor traffic management. Further, it was found that even though guidelines for work zones exist, most contractors ignore it and the enforcement of such regulations by authorities is lethargic.

Next, the economic analysis of work zones was done. Basically, VOC and travel time delay cost were simulated and calculated in this study. As crash costing and emission costing data are not available as per the time of this research, it paves way for future researchers to evaluate in to these areas.

The simulation was done for flat and straight road with rise and fall of 10m/km and curvature of 15 degrees per kilometer. Pavement type was asphalt and mean speed values used were 10,20,30, and 40km/h. It was found that all vehicle types behaved similarly with decreasing VOC with speed and increasing VOC with roughness. Emissions behaved in a similar way as well.

Also the effect of AADT was considerable to the economic cost as AADT increases. It was observed that low AADT values did not have a major effect on economic cost increment while work zones over AADT of 20,000 veh/day had outrun the 20% project cost mark at 8.6 m/km IRI mark.

A case study was conducted for Kandy-Colombo highway (A1) with AADT of 42,000 veh/day. It was found that there is an economic loss of 4.7 million LKR per day. The economic cost adds up to 70% of the project cost over the period of 2 years.

Major part of the economic cost is VOC. It adds to about 65% while the rest 35% is down to delays. However, the ratio might not stand the same for every work zone. Therefore, there needs to be a proper evaluation of delays, roughness, and traffic management plan for every work zone to apply this methodology. For example, the delay of a work zone could still be high with decent pavement condition. There, the VOC will go down and Delays would go up.

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.

It is clear that feasibility studies conducted for highway rehabilitation projects should include economic cost incurred during the construction stage, which is pretty much considerable. The analysis methodology of this study can be used to calculate the economic impact during the construction phase, and provide strategies to minimize it

It was observed that the attention paid to safety is not adequate in work zones, in terms of pedestrian safety, worker safety, and motorist safety. Method to collect accident data, developing crash severity criteria, and developing a methodology to calculate safety cost of a work zone will make work zones much safer places in the future. It is suggested to enforce existing guidelines on road safety for contractors through consultants or RDA itself.

Limitations of this study include using average speed for the sections. Study can be further improved by using driving cycle models. Also, the speed drop of each individual vehicle type from normal section to work zone is not considered. Further, even though economic cost normally includes VOC, VOT, Accident cost, Emission cost, and so many other factors, only the comparison for VOC and VOT was done due to limitations in data collection.

5.1. Proposed minimum standards

Mettananda and Pasindu [9] have suggested minimum standards for work zones regarding environmental, safety and traffic aspects. In this study, mainly the minimum standards that would reduce work zone road user cost (WZRUC) would be proposed.

5.1.1. Pavement condition

It is observed that roughness values currently found in work zones are quite high and they incur high WZRUC. Following roughness values are recommended for given traffic volumes depending on the VOC values simulated. Composition A is used for comparison.

Table 24: Minimum roughness values to be maintained

Traffic volume (AADT veh/day)	VOC per year at highest IRI	Recommended roughness range (m/km)
Below 10,000	793 million	Not exceeding 10
10,000-20,000	1.55 billion	Not Exceeding 8
20,000-40,000	3.05 billion	Not Exceeding 6
40,000 and above	3 billion	Not exceeding 6

Since travel delay is not only affected by roughness and traffic flow, but other roadway conditions, it is hard to simulate these conditions in this study. Therefore, the study estimates the economic increment with the IRI range to represent the pavement condition and delay for a set of traffic flow conditions such as mean travel speed.

It is recommended to do a complete economic analysis and determine the best roughness value to be maintained in the work zone against a given project cost. As figure 47 demonstrates, the economic cost can be kept below a pre-established percentage by properly managing the delays and pavement condition. It is suggested to establish the ceiling value for roughness before work zone starts and to enforce maintenance of it throughout the project duration. The pre-established percentage of project cost can be found by analyzing the project cost, economic cost, against the additional cost to maintain pavement condition and delay time.

Unpaved sections to be rolled and kept dustproof in order to keep the vehicle speeds above the decided level.

Managing the pavement will result in lowered emissions as well.

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APPENDIX 1

Calibration Parameters of HDM-4 for Sri Lanka

\	Vehicle Resources							Time Value			
Vehicle Type	New Vehicle Rs.	Replacement tire Rs.	Fuel Rs./ltr	Lubricating Oil Rs./ltr	Maintenance Labour Rs.	Crew Wages Rs.	Annual Overhead Rs.	Annual Interest	Passenger Working Time Rs./hr	Passenger Non-Working Time Rs./hr	Cargo Rs./hr
Motorcycle	78,699	2,951	100	620	100	0	1,615	8%	95	19	
Three wheeler	208,192	2,075	100	620	100	89	1,805	8%	118	24	
Car	1,744,384	4,650	97	850	100	4	49,600	8%	275	55	
Van	2,182,000	7,345	90	850	100	60	44,640	8%	130	26	
Medium Passenger Vehicles	2,190,100	12,980	90	660	100	175	36,050	8%	43	9	
Large Passenger Vehicles	3,739,670	22,040	90	660	150	244	67,010	8%	43	9	
Light Goods Vehicles	691,292	11,388	90	660	100	120	19,200	8%			375
Medium Goods Vehicles	1,530,714	28,470	90	660	150	175	41,050	8%			1800
Heavy Lorries	1,825,000	45,755	90	660	150	180	63,200	8%			3000
Three axle vehicles											
Farm Vehicles											

Bicycles											

	Physical						Utilization						Loading	
Vehicle Type	Passenger Car Equivalency	No. of Wheels	No. of Axles	Tyre Type	Base number of Re caps	Re tread cost %	Annual km	Working hours hr/yr	Average life yr	Private use %	Passengers	Work Related Passenger Trips %	ESAL	Operating Weight tons
Motorcycle	0.7	2	2	Bias ply			7500	250	12	100	1.2	75%	0.0	0.2
Three wheeler	0.8	3	2	Bias ply	1.3	30%	10000	400	10	0	1.4	70%	0.0	0.6
Car	1.0	4	2	Radial			8218	235	14	100	2.2	60%	0.0	2.0
Van	1.1	4	2	Radial	1.3	10%			15	30	3.0	61%	0.0	2.4
Medium Passenger Vehicles	1.6	4	2	Radial	1.3	20%	29150	1166	10	5	20	75%	0.2	5.6
Large Passenger Vehicles	1.7	6	2	Bias ply	1.3	25%	48583	1619	9	0	30	75%	0.6	9.9
Light Goods Vehicles	1.3	4	2	Bias ply	1.3	20%	30000	1200	12	0	0	0%	0.1	3
Medium Goods Vehicles	1.4	4	2	Bias ply	1.3	25%	42000	1680	12	0	0	0%	0.4	6
Heavy Lorries	1.6	6	2	Bias ply	1.3	25%	45600	1824	14	0	0	0%	7.7	15
Articulated Vehicles														
Farm Vehicles														
Bicycles														