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Estimation of Vehicular Emissions and Fuel Consumption on Road links Using HDM-IV in Ghana - A Case Study on the George Walker Bush Motorway (14.1km) Accra

By

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DECLARATION

I hereby declare that this submission is my own work towards the MSc. and that, to the best of my knowledge, it contains no material previously published by another person nor materials which has been accepted for the award of any other degree of the University except where due acknowledgement has been made in the text.

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ABSTRACT

Fuel consumption and vehicular emissions from traffic are major constraints in sustainable environmental development. Vehicular emissions and fuel consumption have increased in recent years due to rapid growth in world traffic resulting in an increase in associated problems such as cancers, respiratory diseases, global warming etc. Thus, strategies for the reduction of road traffic-generated fuel use and emissions have become issues worth examining. This study looks at the estimation of vehicular emissions and fuel consumption on the 14.1km section of the George Walker Bush Motorway in Accra, Ghana. The Highway Development and Management Tool was used for the estimation of fuel use and vehicle emissions using data from secondary sources. Key data collected were traffic volume and composition, vehicle characteristics, pavement characteristics and climate data of the study area. Three options were analyzed using the HDM-4 software; the base case or do nothing consisted of the road as two-lane asphalt surfaced road with routine maintenance only for the life span of the road. The two project case options were also explored; two lane road with routine maintenance and an overlay in the second year. Also, reconstruction of the road into a 3-lane dual carriageway. This option also will routinely maintain and overplayed in the 10 year intervals. Each project case was analyzed and compared with the do minimum case. The study showed that, total emissions (CO_2, CO and NOx) in 2012 on the study road saw a reduction of about 5,056 tonnes for the 3-lane dual carriageway as against the 'do nothing' alternative. Comparing with the overlay alternative, the 3-lane dual carriageway also recorded a reduction of emissions (CO_2, CO and NOx) of about 3,093 tonnes. On the average, increment in exposure to road users and environment of total CO, CO_2, and NOx is expected to be 945.25tonnes per annum for the 3-lane option. Fuel consumptions also recorded reduction of 25.7 litres per 1000veh/km for the 3-lane dual carriageway as against the 'do nothing alternative' for small cars and also a reduction of 281.52 litres for heavy trucks. Comparing the 3-lane alternative with the overlay option, again fuel consumption also saw a reduction of 266.021litres per 1000veh/km for heavy trucks and 23.22 litres for small cars. The study also showed a strong correlation between average roughness and yearly emission levels in all alternatives. The study revealed that emissions of CO and NOx by each vehicle class compared with the US Environmental Protection

Agency's standards for Tier 0 and Tier1 vehicle groups were beyond the acceptable limits for human health and environmental sustainability. It was revealed that fuel consumption is directly linked to average roughness with a strong coefficient of correlation of 0.9987.

Finally, the study also showed that timely overlay interventions gave good results on the 3-lane dual carriageway.

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LIST OF ABBREVIATIONS

AADT	Average Annual Daily Traffic
AFCOM	Association for Computer Operation Management
ANOVA	Analysis of Variance
ARRB	Australian Road Research Board
CMEM	Comprehensive Modal Emission Model
COPERT	Computer Programme to calculate Emission of Road Transport
CO_2	Carbon dioxide
CO	Carbon monoxide
DVLA	Driver Vehicle Licensing Authority
ECOWAS	Economic Community of West African State
EPA	Environmental Protection Agency
EMFAC	EMission FACtors
FC	Fuel Consumption
GHA	Ghana
GHG	Green House Gases
HC	Hydrocarbons
HDM-4	Highway Development Management Tool versions 4
IEA	International Energy Agency
IRI	International Roughness Index
MOBILE	Mobile Source Emission Model
MOVES	MOtor Vehicle Emission Simulator
MRH	Ministry of Roads and Highways
MT	Motorize Traffic
N01-016EB	National Route 1 Link 16 East Bound
NO1-016WB	National Route 1 Link 16 West Bound
NMT	Non Motorize Traffic
NOx	Nitrous Oxides
NDLI	N.D. Lea International
Par	Particulate Matter
PEMS	Portable Emission Measuring System
Pb	Lead
PVI	Pavement Vehicle Interaction
RDM	Road Deterioration Model
RUE	Road User Effect

SO_2	Sulphur Dioxide
US	United States
USEPA	Unites States Environmental Protection Agency
VMT	Vehicle Mile Travel
VSP	Vehicle Specific Power
VT-Micro	Virginia Tech Microscopic
VT-Meso	Virginia Tech Mesoscopic
WHO	World Health Organization

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And finally, I am grateful to the Almighty God for giving me the strength to successfully complete my postgraduate studies. It's by his strength even if I can write with a stroke of pen. *'Who am I that you are so mindful of…Psalm 8:4'*

DEDICATION

I dedicate this thesis to God, my Maker and King. To my grandfather and mentor Prof. E.Y Safo-Adu and to my mum Gladys Sarpong who worked to the bone of her hand to bring me up. Not forgetting my supportive wife Tina and children Liza and Eldad.

CHAPTER 1:

INTRODUCTION

1.0 Introduction

Road transportation is a key component to the socio-economic growth of every nation but it exerts negative externalities to society such as air pollution, accident and noise. The situation is getting worse each day due to the ever increasing vehicle fleet and associated deterioration in air quality due to increase in congestion in urban areas. The ever-increasing vehicle fleet of about 6.9% per annum has resulted in increase in traffic congestion, fuel consumption and air pollution. Studies in Ghana by Environmental Protection Agency Ghana shows that emission in 2005 was 52,666.17 tonnes and it is expected to be 151,650.38 tonnes in 2025. (EPA 2007). Nesamani et al. (2007) made an assertion that transportation is the single largest source of air pollution in urban areas. Traffic congestion has caused vehicular emissions to increase significantly.

Vehicular emissions are major challenge to planners, engineers and policy makers with the responsibilities to ensure an efficient urban transportation system. Estimation of fuel consumption and emissions inventories is therefore important in assessing the effects of man-made activity on the atmospheric pollution and the determination of efficient abatement strategies. . Agyemang-Bonsu et al. (2010) also reiterated it is the single largest source of air pollution in urban areas. However, current measurements by EPA do not adequately reflect the extent of exposure on human health due to its limitation to point measurements.

1.1 Problem Statement

Air quality is fast deteriorating as a result of air pollution from vehicular exhausts due to increasing vehicle population and congestion in cities. There is consistent increase in global warming and illnesses such as lung cancer, heart diseases, asthma etc. The World Health Organization country health profile (2014) for Ghana shows that, the percentage of people living in urban areas is 51.9% and the population proportion between 30 to 70 years is 30.9%. The proportion mortality (% of total deaths, all ages and both sexes) for cardio vascular diseases is 18%, 5% for cancer and 2% each for chronic respiratory diseases and diabetes. The probability of a person dying between the ages 30 to 70 years from the four main non-communicable diseases is 20%. This is worrying and it is expected to deteriorate further due to the age of vehicles imported into the country, poor exhaust emission regulations in Ghana, poor roads and congestions in our cities and so on. EPA (2000) as cited by Agyemang-Bonsu et al. (2010) also identified that, in Ghana the main cause of global warming is exhaust emissions.

1.2 Research Objectives

The specific objectives of this study are to;

- ❖ Estimate the changes in the levels of pollutants (CO_2, CO and NOx) as a result of vehicular emissions over the design life of the new highway.
- ❖ Explore the relationship between International Roughness Index (IRI) and vehicular emission levels.
- ❖ Investigate the effect of periodic maintenance intervention on fuel consumption and emissions and make recommendations on policy direction for road maintenance works standards in Ghana.

1.3 Justification for Research

It is important to estimate the emissions on our roads, assess the effect of emissions and evaluate their acceptability for human health and also environmental sustainability. The HDM-4 model has the capability to estimate fuel consumption and vehicle emissions as it adequately captures the effects of driving, vehicle dynamics and road condition. These are important features employed in the estimation of emissions and fuel consumption, and the HDM-4 which is the analytical tool has already been calibrated for Ghana situation. EPA Ghana is developing guidelines for emission standards to be used in the country. At the moment, EPA Ghana looks up to and often refer to standards from the European Union, World Health Organization, the United States Environmental Protection Agency (US EPA), the United Kingdom and Japan. According to the Environmental Protection Agency, ambient air quality index (AQI) monitoring is limited to Accra alone with particular emphasis on particulate matter (PM_{10}). Measurements of other gases are not made public but limited to internal reports only. As at now the Driver and Vehicle Licensing Authority (DVLA) do not have instruments such as portable emission measurement systems (PEMS) to check emission levels of various categories of vehicles as they come for roadworthiness tests.

1.4 Scope of Research

The scope of the work covers the following;

- Review of relevant literature on fuel consumption and vehicular emission models and works done in Ghana and beyond in the estimation of fuel consumption and vehicular emissions.
- Collection of data on before (feasibility report) and after construction of the George Walker Bush Motorway (14.1km) and estimation of vehicular emission levels in terms of pollutions quantities exposed to road users and fuel consumption.

Very little primary data collection was undertaken for road roughness because of the availability of existing roughness data from the Ghana Highway Authority's Annual Road Condition Survey Reports. And also the availability of all the necessary parameters for the study due to the availability of the design report used for the implementation of the project. However, limited data was collected to validate the secondary data.

1.5 Structure and Outline of Thesis

This thesis is structured in five chapters. Chapter (1) gives introduction to the research and a brief statement of the problem as well as objectives of this research. It further provides a justification for the study. The rest of the chapters are as follows, Chapter (2) presents literature review on related studies on fuel consumption and vehicular emissions in the transportation sector. Chapter (3) gives a description and profile of the study corridor. It describes in detail the general design of the research and the methodology for data collection. It shows details of the work standards on the project alternatives and analysis. Chapter (4) firstly, presents the validation of the predicted IRI results from the HDM-4 model against the actual results obtained by direct roughness measurements on the road. It then presents results and discussions on results obtained from further analysis. Chapter (5) presents the conclusions of the study and recommendations. There are also suggestions for further studies, limitation of the study and the assumptions made.

CHAPTER 2:

LITERATURE REVIEW

2.1 Global Outlook on Emissions and Fuel Consumption

According to IEA (2015), road transport is one of the highest energy consumption sectors, with large dependence in fossil fuels and contributes to global greenhouse gas emissions. Over several decades, rapid growth in travel has increased congestion, especially in metropolitan areas and the world energy demand is expected to grow by one-third. Between 2013 and 2040, energy-related carbon emissions are expected to be 16% higher. Nesamani et al. (2007) Stated that, transportation is the single largest source of air pollution in urban areas.

The general trend of increasing urban sprawl has led to more car trips, higher traffic loads, higher emissions and fuel use (Huzayyin & Salem, 2013). According to Lu et al. (2009) the steady growth in vehicle population has put environmental stress on urban centres in various forms particularly causing poor air quality. A thirty-year investigation by Huzayyin & Salem (2013) confirmed the impact of city growth on fuel consumption and emissions from transport in Cairo. The investigation concluded that, fuel use and emissions in Cairo increased respectively. Sierra (2016) in the estimation of road transport fuel consumption in Ecuador, evidenced that the road transport sector released 14.3million tons of CO_2 in 2012 constituting 0.04% of the global share. The study also concluded that in 2012 alone, Ecuador's energy demand was 57 million barrels of oil equivalent of which the transport sector accounted for 77%. Solís & Sheinbaum (2013) indicated that, out of Mexico's 39% energy demand for the transportation sector in 2010, road transport accounted for 92%.

A study on trends in vehicular emissions in China's mega cities by Wang et al. (2010) from 1995 to 2005 showed that, the vehicular CO_2 emissions have respectively increased 260%, 180% and 220% in Beijing, Shanghai and Guangzhou during the past decade and still continue to rise. Zeng et al. (2016) forecasted that, if no control measures are implemented, the annual oil demand by China's road vehicles will reach 363 million tonnes by 2030. From India's perspective, Bhandari et al. (2013) said in 2007, the transport sector emitted 142.04 million tonnes of CO_2 equivalent. Road transport, being the dominant mode of transport in the country, emitted 87% of the total CO_2 equivalent emissions from the transport sector. Lu et al. (2009) estimated that, Taiwan's vehicles numbers in 2025 are expected to be between 30.2 and 36.3 million vehicles with the traffic fuel consumption between 25.8 million kiloliters and 31.0 million kiloliters. The corresponding emission of CO_2 will be between 61.1 and 73.4 million metric tons in the low-and high-scenario profiles. Seref (2007) concluded that, total CO_2 equivalent emissions from Turkish road transport was 51, 368. 77 kilo tonnes of which 71.8% is from CO_2 emissions and 21.7% is from NOx emissions.

2.1.1 Ghana's Situation

In Ghana, the situation is no different. Anin & Annan, (2013) stated that available statistics show that the average demand for crude oil annually is between 5 and 7% of annual budgets in Ghana. This is expected to increase due to continuous rise in car ownership. Agyemang-Bonsu et al., (2010) concluded that, fuel consumption in Kumasi increased steadily from 7.82 million tonnes in 2000 to 12.92 million tonnes. in 2005. Fuel consumption in urban areas was considered as high as 55% compared to 22% on rural and 23% on highways.

It also showed that vehicles manufactured before 1994(Euro I) and conventional vehicle accounted for fuel consumption of 32.2% and 55.8% respectively. Vehicles manufactured between 1996 and 2000 (Euro II) and those manufactured between 2000 and 2005 (Euro III) consumed 8.2% and 3.8% respectively. The study by EPA GHA (2007) showed total emission levels including greenhouse gases other than particulate matter increased from 0.032 million tonnes in 2000 to 0.053tonnes in 2005 at 16.7% per annum. The sensitivity parameters were vehicle fleet numbers and fuel consumption. It was predicted that, with the vehicle population growth rate of 6.9%, expected vehicular emission were to move from 0.053,million tonnes in 2005 to 0.072, million tonnes by 2010, 0.112 million tonnes in 2015 and by 2025 vehicular emissions would have reached
0.152, million tonnes.

2.1.2 Minimizing Fuel Use and Emissions

Xie et al. (2012) investigated several alternative petroleum for roadway vehicles, including hydrogen, ethanol, compressed natural gas, liquefied natural gas, liquefied petroleum gas, and electricity, which are actively being considered to minimize emissions and fuel consumption rate. Results from Boubaker et al. (2016) also underscores the importance of intersection types and hybridization and electrification of vehicle fleet as an alternative means to reducing fuel consumption and emissions.

Ericsson et al. (2006) researched on driver support tool such as navigation system as a means to optimize route choice based on lowest fuel consumption and emissions instead of traditional short distance travel. Zeng et al. (2016) conducted a similar work in vehicle dynamics based on CO_2 emission model and an eco-routing approach to address the problem of finding the most eco-friendly path in terms of minimum CO_2 emissions constrained by a travel time budget. Other methods include, encouraging public transit, carpooling or non-motorized transportation, while others may also consider integrated corridor management systems with optimized traffic signal controls to mitigate congestion and improve air quality. Legal limits on allowable emissions thresholds also works. Kang et al. (2013) have developed a new dimension that is gaining currency by incorporating geometric design methods to minimize vehicular fuel consumption and improving safety on highways.

2.2 Sources of Vehicular Emissions

Pollution from exhaust of vehicles are mainly; Hydrocarbon (HC), Carbon monoxide (CO), Nitrous Oxide (NO_x), Sulphur dioxide (SO_2), Carbon dioxide (CO_2), Particulate Matter (Par) and Lead (Pb) according to Odoki & Kerali (2000). These arise as a result of the turning of the engine, fuel type and driving condition (road characteristic and vehicle characteristic).

Vehicular emissions are generally from exhausts which result from the combustion of fossil fuels and evaporative losses. They are mainly diurnal, running loses and hot soaked loses. Vehicular emissions which are mobile sources from on and off the road are mainly from the combustion of fossil fuel and evaporation of volatile compounds in the fuel from cars, trucks, coaches, among others. These exhaust emissions are produced from incomplete combustion of fuel such as petrol, diesel, gasoline, etc. Perfect combustion using enough oxygen in the air converts all the hydrocarbons to water and all the carbon into carbon dioxide.(US EPA 2007) and (Greenbaum 2013).

2.3 Vehicular Emissions Effects

Studies have demonstrated the effects of vehicular emissions and its serious threats to the environment and human health. Emissions cause about 3 million deaths each year according to IEA (2016). Vehicular emissions pose special risk among the aged and children, people with lung diseases, asthma, cardiovascular diseases and diabetes.

Claxton (2015) found out that, in addition to diesel exhaust being carcinogenous, it increases the risk of bladder cancer and like most fuel emissions, diesel and gasoline exhaust contain toxic respirable particles. It is also responsible for the ailment such as eye and throat irritation, chronic obstructive pulmonary diseases, cardiovascular diseases and cancer. Environmental effects include acid rains caused by ozone form in the presence of hydrocarbons and nitrous oxides, and climate change. Direct effect includes heat weaves, flood and drought. Other effects are disturbances to complex physical and ecological processes, such as changes in the amount and quality of water and in the patterns of infectious diseases according to WHO (2005).

2.4 Factors Influencing Fuel Consumption and Emissions

Literature has shown that there are several factors that influence fuel use and emissions. Yu et al. (2016) concluded that for emissions and fuel consumption, the influence of passenger load became significant when the vehicle is traveling at high speed above 30km/h while no obvious impact was observed at low speed below 30km/h. Ericsson (2001) investigated the effect of independent driving pattern factors on emissions and fuel use and revealed that in addition to speed, acceleration and power demand as well as gear changing behavior of drivers are important explanatory variables for emissions and fuel consumption. Ma et al. (2015) also remarked that fuel consumption under normal running process is sensitive to road condition and driving style.

A study in Rome by Carrese et al. (2013) indicated that, driving behavior can lead up to 27% fuel savings and load factor can impact on fuel consumption between 7% and 26%. Bennett & Greenwood (2001) postulated that, driver behavior, vehicle characteristic, and traffic condition coupled with gradient, roughness, texture and curvature affect fuel consumption. Other factors such as tyre, engine design, frontal area and design and vehicle mass, ambient temperature and wind direction also play vital roles in fuel consumption.

Pandian et al. (2009) also revealed that traffic parameters such as traffic-flow density, fleet speed, queue length and mean-lay, vehicle mix, driving mode, and traffic density all influence emissions and fuel consumption. To buttress Pandians observations, Carrese et al. (2013) observed that, around 50-60 km/h speed range, the specific emission factors of pollutants (CO and NOx) reached the minimum values. Moreover the number of stop and go and the acceleration phase can play an important role. This is confirmed by Bakhit et al. (2015) whose experiment demonstrated that, fuel consumption varied directly with different degrees of acceleration. It was noticed that the fuel consumed in case of aggressive acceleration was less than that of mild acceleration by 8 %. While the normal acceleration consumed about 3.8% more than mild acceleration.

The study further stressed that, road characteristics such as type of road, speed humps and driving style all affect fuel use and emissions on our roads, vehicle characteristics such as type, age, engine capacity, emission control equipment, ambient temperature, engine load, vehicle weight and size as well as maintenance culture all influence fuel use and emissions. Pandian et al. (2009) showed that vehicle characteristics that are known to affect the vehicle emission rates can be classified into vehicle parameters, fuel parameters, vehicle-operating conditions and environmental conditions. Vehicle parameters include vehicle class, weight, engine size, vintage, mileage computer control system, control system tampering, and inspection and maintenance record. Fuel parameters mainly comprises fuel type, oxygen content, fuel volatility, sulphur content, benzene content, lead and metals content and trace sulphur (catalyst effects). However, Abreu et al. (2015) narrowed the most influential variable to be vehicle type when vehicle, drivers and routes were considered in his study.

The investigation of vehicles operating along different routes and slopes by Tsang et al. (2011) showed that, hilly routes had the highest global emission factors and fuel consumption than on the flat roads. The urban route has the second largest with the suburban and the highways with the least of emissions and fuel consumption. This means that the grade of roads and land use pattern also greatly influence emissions and fuel consumption.

Another important factor that account for fuel consumption and emissions is the vehicledriving mode. Even though Tong et al. (2016) found out that, transient driving modes such as deceleration and acceleration, were more significantly polluting than steady state driving (cruising and idling) for a typical urban driving. The study showed that, idling and low speed contributed a high percentage of emissions over a vehicle trip. This perhaps may be due to heavy traffic in urban centres and driving condition.

Finally, with road roughness (IRI), Carlson et. al (2013) stated that, the effect of higher speed as a result of small IRI lead to increased fuel use for passenger cars and trucks. The same speed effect is present for rut depth (RUT). The 14-year study by Greene & Ulm (2013) observed that, IRI alone contributed to additional 30,000 gallons of fuel per mile of the representative road section for the study period and equates to the release of 300 tons of CO_2 per mile of pavement. The conclusion was that, the level at which fuel efficiency is affected is heavily tied to the condition of the roads, or the pavementvehicle interaction (PVI). Roughness is the leading influence of PVI and, therefore, is a key indicator of fuel efficiency. The rolling resistance force (due to the pavement-vehicle interaction) is greatly influenced by pavement conditions, so that a 3m/km reduction in a pavement International Roughness Index (IRI) would lead to a 10% decrease in rolling resistance, which in turn would result in 1-2% reduction in fuel consumption Zaabar (2010) as cited by Akbarian et al. (2012)

2.5 Methods of Evaluating Vehicle Fuel Use and Emissions

Conceptually, two main approaches are used to estimate on-road transportation greenhouse gas (GHG) emissions as defined by US EPA (2012). The two are "topdown", and the "bottom-up" approaches. The top-down approach is fuel-based and the bottom-up approach is based on vehicle mile travel (VMT). The "top-down" approach relies on fuel consumption by fuel type to determine emissions. The 'top-down' estimate is a methodology which starts from values of annual emissions assessed at national level. These emissions are spatially disaggregated at different levels, such as the provincial and municipal by means of statistical indicators (population, roads, land-use,)

The 'bottom-up approach', typically applied at the regional, municipal or local level relies on estimates of VMT data and fleet fuel efficiency or emission factors to calculate GHG emissions. The "bottom-up" approach begins from local data at municipal level or even from the specific object of the emission (example is road profile or the industry location). Using this information and proper emission factors, hourly emissions are assessed directly at local level. Example of a typical 'bottom-up' approach was that used by Bellasio et al. (2007) in emission inventory for the road transport sector in Sardinia (Italy).

Achour & Olabi (2016) described methods of estimation of vehicle emissions to include; the conventional method which is driving a vehicle through a pre-determined driving cycle on a rolling road dynamometer and collecting the pollutant emissions formed. These emissions are analyzed, and then a system is devised so each value for emission output is assigned to each section of the driving cycle. This normally results in a value for the mass of the pollutant species evolved over a given distance in (g/km). The next method is on-road emission monitoring technique usually divided into two types;

a. Monitoring Equipment: - used to measure the emission concentrations in ambient air. This type of technique uses a pump to sample the ambient air and sometimes samples of PM or HC emissions collected and analyzed in a laboratory.
b. On-road remote sensing: - used where some tools are set up on a roadside to measure the emissions from a single car when it passes.

Computer programmes are used in estimation of emissions from road transport. They describe emissions in terms of grams per kilometer travelled (g/km). The models are functions of vehicle speed, power and so on. Examples include COPERT, HDM-4, MOVES models etc.

2.6 Model Concepts of Evaluating Vehicle Emissions

According to Carrese et al. (2013) and Song et al. (2013), three different approaches have been defined for modeling estimation of emissions and fuel consumption over the last few years. These are macroscopic, microscopic and mesoscopic approaches. Macroscopic is based on vehicle average speed and other aggregated values. Macroscopic does not account for time, deceleration time and vehicle specific power thereby having a low precision. Macroscopic models takes into account, vehicle type and size (passenger cars, light-duty trucks, heavy-duty trucks, urban and school buses, motorcycles), vehicle age and accumulated mileage, fuel type used (gasoline, diesel, others), ambient temperature, maintenance condition(well maintained, in need of maintenance, presence and condition of pollution control equipment) and how the vehicle is driven (e.g., long cruising at highway speeds, stop-and-go urban congestion, typical urban mixed driving). Technically, emissions calculation is based on specific annual passenger mileage and fuel consumption is based on average in-use fuel economy. Examples of macroscopic models include, US federal's MOBILE6 and

California's EMFAC and so on.

However, Wang et al., (2012) stated that, these vehicular emission models such as COPERT and MOBILE which are based on average speed used and assumptions such as average emission factors for a given pollutant and vehicle type are not accurate. Since a trip may have different driving characteristics. Using the same average speed which is a macroscopic character to generalize the trip could not account for different emission levels in the microscopic characters in the trip.

Another widely and more accurate model is the microscopic models such as the Comprehensive Modal Emission Model (CMEM), the Virginia Tech Microscopic (VTMicro) model and Motor Vehicle Emission Simulator (MOVES) recently developed by the US EPA. The concept is based on vehicle speed/acceleration data or on the use of chassis dynamometer data of vehicles. The microscopic approach can substantially improve the emission estimation, but requires laborious input data. Microscopic models have two types, statistical and physical. A statistical model such as the VT-Micro model uses non-linear regression and multiple regressions for analysis. Physical models are based on vehicle power usage. Examples of physical models include CMEM, Physical Fuel and Emission Model (PFEM) and MOVES. These models estimate instantaneous vehicle emission rates using either vehicle engine power usage or vehicle speed/acceleration data.

Song et al. (2013) also indicated that, macroscopic models ignore the transient variation of vehicle emissions associated with different traffic conditions, while microscopic emission estimation tools need numerous input data and that, it is more appropriate to utilize link-based mesoscopic emission models.

The most accurate, widely and recently used approach is the mesoscopic emission models. The mesoscopic approach constructs synthetic drive cycles and it constitutes an interesting alternative to microscopic models for cases in which detailed speed and acceleration data are not available.

The approach is based on average vehicle speed, number of vehicle stops and stopped delay. An example of such models is Virginia Tech Meso (VT-Meso) and HDM-4. The concept incorporates the use of vehicle specific power (VSP). VSP integrates the vehicle speed, vehicle acceleration, road grade, aerodynamic drag and tire rolling resistance. It is generally defined by Yu et al. (2016) and Song et al. (2013) as the instantaneous power per unit mass of the vehicle.

The HDM-4 tool which is a mesoscopic model adequately captures the dynamics of different driving conditions and hence was employed in this study. Detail concept of the HDM-4 model is elaborated in the following section.

2.7 Vehicular Emission Model in HDM-4

From literature, vehicular emissions in terms of pollutant quantities are strongly influenced by the changes in road characteristics, vehicle technology and traffic congestion. The HDM-4 emission model was adapted from the concept of the Comprehensive Modal Emission Model(CMEM) developed by Barth et al. (1997). The concept is based on vehicle modal emission models (emissions based on vehicle modes of operation). The model uses physical power-demand modal modeling approach. The model is based on parameters according to vehicle type, engine and emission technology. The majority of the parameters are stated by vehicle manufacturers such as vehicle mass, engine size, aerodynamic drag coefficients etc. The model also takes into account operating modes, maintenance, accessory use and road grade.

The model predicts tailpipe emissions as a function of fuel consumption and speed. Speed is also dependent on road characteristics and the vehicle characteristic. Thus, changes in emission can be analyzed as a result of maintenance interventions or improvement works or when there is a significant change in vehicle fleet. Hence, net differences in pollutant quantities can be assessed for each investment option. Etsu (1997) indicated that, exhaust emissions considered in the HDM-4 are mainly, Hydrocarbon (HC), Carbon monoxide (CO), Nitrous Oxide (NO_x), Sulphur dioxide (SO_2), Carbon dioxide (CO_2), Particulate Matter (Par) and Lead (Pb).

Emissions given out are treated by catalytic converter and the basic model is given as; TPE i= EOEiCPFi

TPEi - Tailpipe Emissions in g/veh-km for emission i
EOEi - Engine Out Emissions in g/veh-km for emission i
CPFi - Catalyst Pass Fraction for emission i
Ri: - deterioration factor for emission i in %/year

AGE - vehicle age in years and

MDFi - maximum deterioration factor for emission i (default = 10)

- maximum catalyst efficiency for emissions

Bi - stoichiometric CPF coefficient

IFC - instantaneous fuel consumption (including congestion effects) in mL/s

Massfuel - mass of fuel in g/mL

ε_i $CPF_i = [1 - \varepsilon_i \exp(-b_i IFCMassFuel)] min \left[1 - \frac{r_i}{100} AGE)MDF_i\right]$ …………….(2.1)

Where,

The quantities of the different emission components are predicted using the relationships together with default parameter values. Detailed equations for specific pollutant such as CO, CO_2 and NOx can be found in Appendix 2A.

The following primary data is required for modelling vehicle emissions:

- Traffic volume on the road section - The annual traffic volume during each flow period (vehicles per year).
- Length of road section
- Vehicle speeds – These are calculated within the RUE module.
- Fuel consumption - The instantaneous fuel consumption, for each vehicle type, in each traffic flow period is calculated within the RUE module.
- Vehicle service life and model parameters - Defined with other Vehicle Fleet data.

Odoki & Kerali, (1999) stated that, the comparison of each pair of investment options is based on the changes in the annual net difference in the predicted quantities of emissions by component. Thus, for each pair of investment options *m* and the base case *n* the annual net difference in the predicted quantities of emissions of component *i* is calculated as follows:

$\Delta EYRi_{(m-n)} = EYRi_n - EYRi_m$ ……………………………………………..(2.2)

Where,

$\Delta EYRi_{(m-n)}$ the annual net difference in the quantity of emissions component *I* The HDM-4 takes into account congestion modeling using level of details such as microscopic (sec-by-sec vehicle data) and mesoscopic parameters (speed, acceleration) for facility modeling. Figure 2-1 shows the level of details.

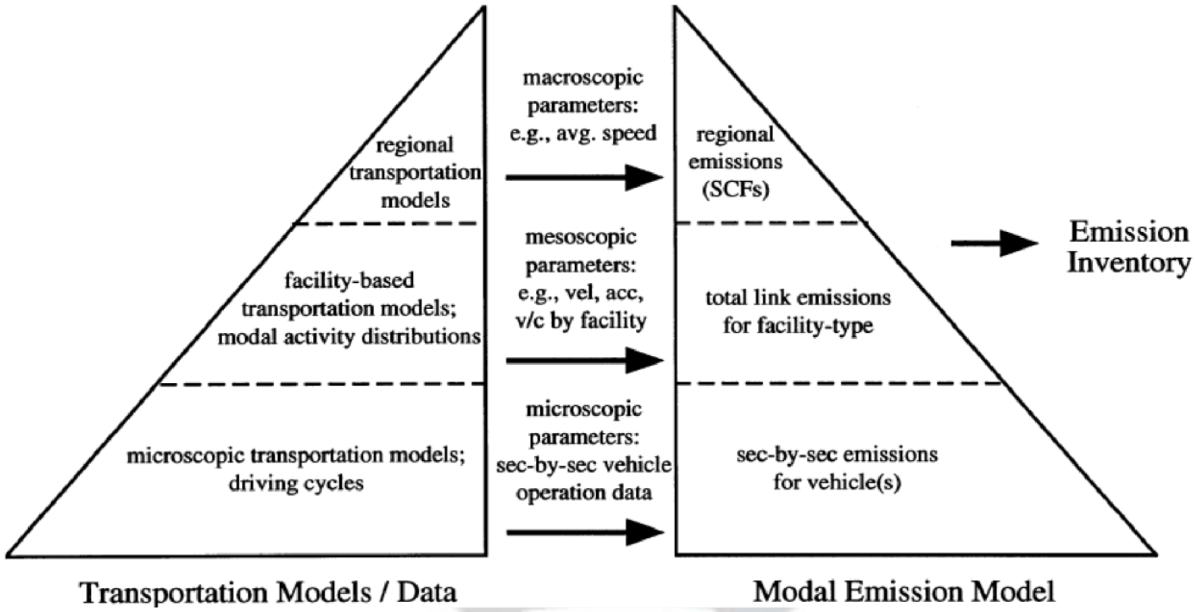

Figure 2-1. Level of Details

Source: (n, F., Barth M. 1997)

Important factors in traffic such as flow, speed, and density are related by $speed = \frac{flow}{density}$ and is considered in the model. In taking into account microscopic characteristics in modeling of vehicle acceleration, gap was considered to be significant as it show the behavior of drivers. Vehicle spacing is inferred and not directly used as is calculated from the reciprocal of the vehicle density.

2.8 Fuel Consumption Model in HDM-4

2.8.1 Introduction

Fuel consumption is a vital component of vehicle operation cost and is influenced by traffic congestion, road condition and road alignment. Vehicle characteristics and driving style also influence fuel consumption making it sensitive to any investment decision on the road network. Research by Bennett & Greenwood (2001) showed that, fuel consumption account for 20% to 40% of vehicle operation cost.

According to research, on the total fuel consumed by vehicle, over 60 per cent of the total energy is used as heat through the coolant system and the exhaust. Only 18 per cent of the total energy in the fuel is used to propel the vehicle along the road under typical urban driving conditions but for highway driving conditions, over 25 per cent, primarily by reducing the standby component.

Empirical methods of estimating fuel consumption which is speed related and a mechanistic model which is force related were reviewed. However, the latter is superior to the former and hence its adoption in this study.

2.8.2 Empirical Models

Earlier models developed related fuel consumption as a function of vehicle speed. The frequently used empirical model is given by Chesher & Harrison, (1987) and IRC, (1993) as cited by Greenwood and Dunn (2003) as;

$$FC = a0 + \frac{a1}{S} + a2\ S2 + a3\ RISE + a4\ FALL + a5\ IRI \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.3)$$

Where; FC is the fuel consumption in L/1000 km

S is the vehicle speed in km/h

IRI is the international roughness index in m/km (or mm/m)

RISE is the rise of the road in m/km

FALL is the fall of the road in m/km a0

to a5 are constants

Studies done in Kenya, East Africa, Caribbean, India and Asia gave a relationship between fuel consumption (per unit distance) and vehicular speed in km/h as a U-shaped graph. The optimum fuel consumption was found to be around the speed of 40-60km/h and high fuel consumption at low and high speeds. Figure 2-2 shows the effect of speed on passenger car fuel consumption.

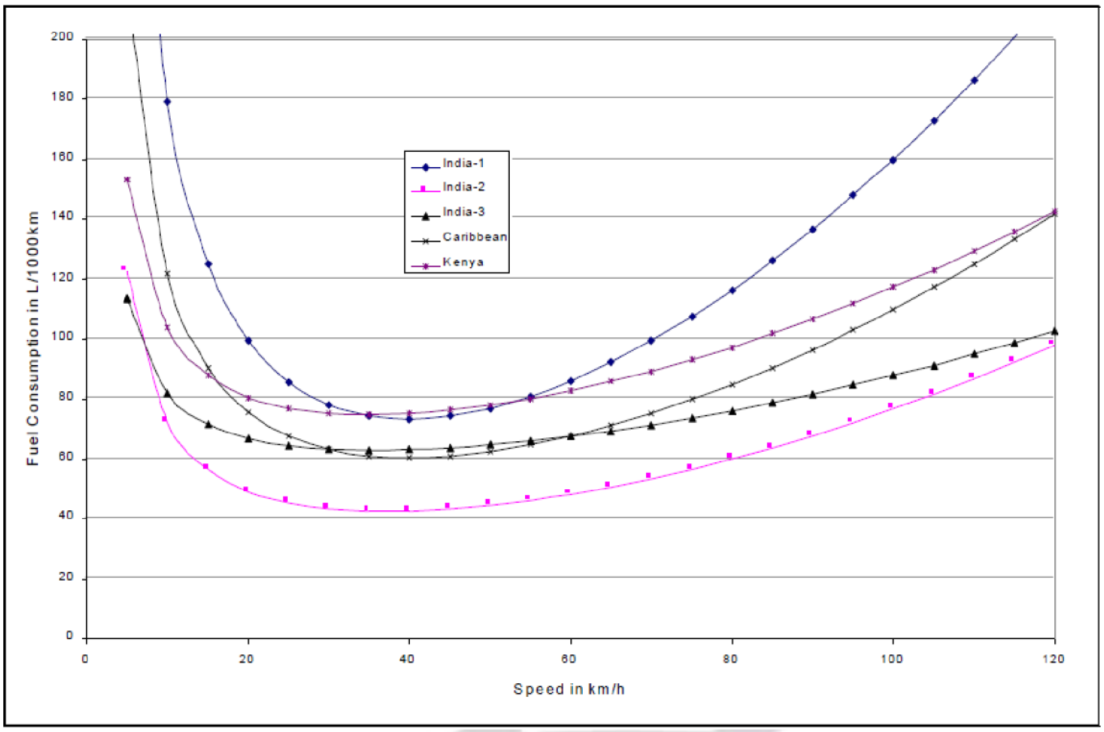

Figure 2-2. Effect of speed on passenger car fuel consumption

Source:(NDLI 1995)

The above studies produced coefficients for the equation showing the effect of speed on different vehicle types. Table 2.1 presents the coefficient estimated for empirical fuel consumption.

Table 2-1. Coefficients Estimated for Empirical Fuel Consumption

Vehicle	Country	a_0	a_1	a_2	a_3	a_4	a_5	Other Vehicles	Source
Passenger	India	10.3	1676	0.0133	1.39	-1.03	0.43		
Cars	India	21.85	504	0.0050	1.07	-0.37	0.47		IRC (1993)
	India	49.8	319	0.0035	0.94	-0.68	1.39		Chester&
	Caribbean	24.3	969	0.0076	1.33	-0.63		$+0.00286FALL^2$	Harrison(1987)
	Kenya	53.4	499	0.0059	1.59	-0.85			
Light	India	30.8	2258	0.0242	1.28	-0.56	0.86		IRC (1993)
Commercials	India	21.3	1615	0.0245	5.38	-0.83	1.09		Chester&
	Caribbean	72.2	949	0.0048	2.34	-1.18		$+0.0057FALL^2+$	Harrison(1987)
	Kenya	74.7	1151	0.0131	2.91	-1.28		1.12(GVW-2.11)RISE	
Heavy Bus	India	33.0	3905	0.0207	3.33	-1.78	0.86		IRC (1993)
	India	-12.4	3940	0.0581	0.79		2.00	+0.0061CKM	Chester&
									Harrison(1987)
Trucks	India	44.1	3905	0.0207	3.33	-1.78	0.86		IRC (1993)
	India	141.0	2696	0.0517	17.75	-5.40	2.50		Chester&
	India	85.1	3905	0.0207	3.33	-1.78	0.86	-6.24PW	Harrison(1987)
	India	266.5	2517	0.0362	4.27	-2.74	4.72	-6.26PW	
	India	71.7	56970	0.0787	1.43			-9.20-3.98WIDTH	
	Caribbean	29.2	2219	0.0203	5.93	-2.60		+0.85(GVW-	
	Kenya	105.4	903	0.0143	4.36	-1.83		$7.0)RISE+0.013FALL^2$	

Source; NDLI, (1995)

2.8.3 Mechanistic Models

The mechanistic model is an improvement of the empirical model. This is due to its flexibility in applying to different condition and allowance for changes in vehicle characteristics. The model states that fuel consumption is proportional to the forces acting on the vehicle. As a result of the above advantage, it is employed in the HDM-4 fuel consumption model. Thus quantifying the magnitude of forces opposing motion, one can establish the fuel consumption (Greenwood & Dunn 2003).

These opposing forces are; aerodynamic resistance (Fa), rolling resistance (Fr), gradient resistance (Fg), curvature resistance (Fr) and inertial resistance (Fi). The figure 2-4 below shows the forces acting on a vehicle on a gradient.

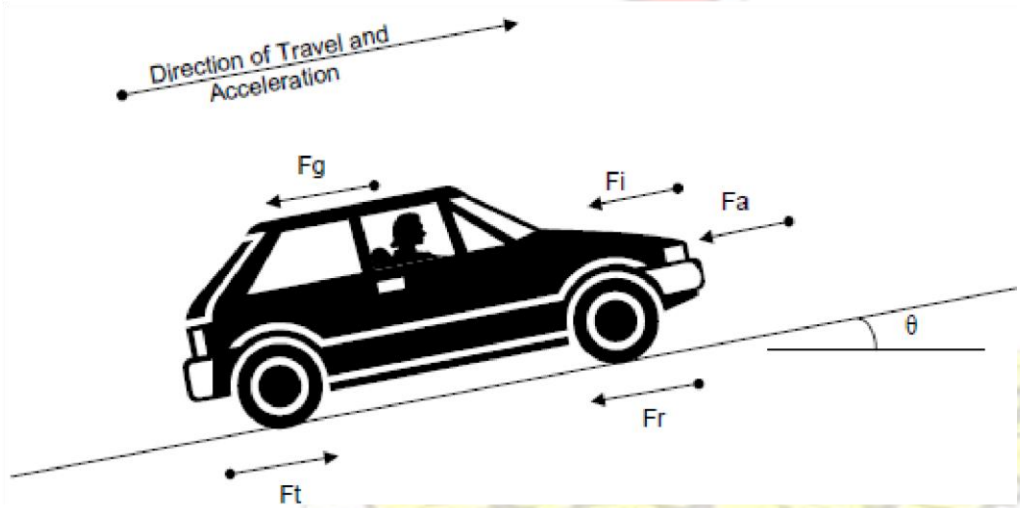

Figure 2-3. Forces Acting on vehicle on a gradient

After NDLI, (1995)

The most elaborate mechanistic approach to estimating fuel consumption is the ARRB ARFCOM method. The method states that, the total power requirement is dependent on the tractive forces (Ptr), the power usage to run accessories (Pacs) and internal engine friction (Peng). The total power usage is proportional to the fuel consumed. The ARRB emission model approach is summarized in the flow chart in figure 2-4.

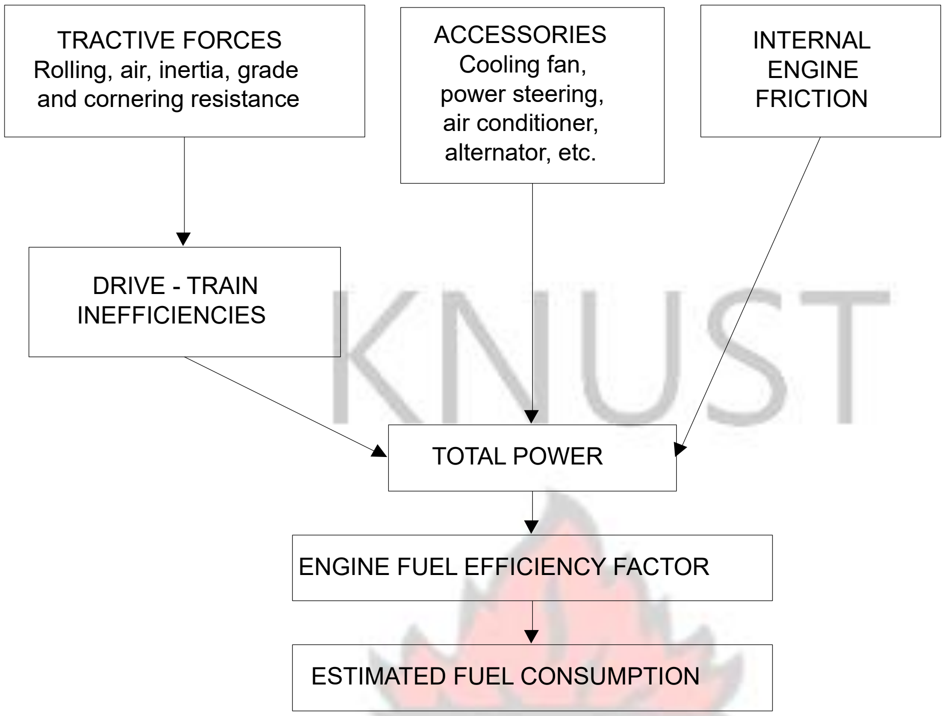

Figure 2-4. ARRB Emission Model Approach

Source: (NDLI 1995)

Research in South Africa by Bester, (1981) and in Australia by Biggs, (1987, & 1988) as cited by Greenwood & Dunn (2003) developed mechanistic models. The models were used to experiment on fuel consumption and other data to calculate fuel efficiency factor (ξ). According to Greenwood & Dunn (2003), the efficiency factor is used for the conversion of total power usage to fuel consumption. Fuel consumption is dependent on the fuel type, engine size and power output. The fuel consumed was found to be the product of the total power usage and the efficiency factor. The following expressions summaries fuel consumption by the model as indicated by NDLI, (1995)

IFC=max (α ,□Ptot) ……………………………………………………………..(2.4)

where,

α : is the idle fuel consumption in mL/s

IFC : is the fuel consumption in mL/s

Ptot : is the total power requirements in kW

□ : is the idle fuel consumption in mL/s

□□ is the fuel-to-power efficiency factor in mL/kW/s

□ = 0.220 D - 0.0193 D2 where D is the engine capacity in litres

2.8.4 Congestion Modeling in the HDM-4

Another concept that account for the accurate estimation of fuel consumption by the HDM-4 model is the use of the concept of 'acceleration noise'. 'Acceleration noise' is the standard deviation of the accelerations. Acceleration noise occurs as a result of traffic congestion. As flow increases, traffic interactions also increase. As vehicle to vehicle interactions increases so do acceleration and deceleration of the vehicles. Interactions of traffic increase due to volume or capacity, roadside friction, non-motorized traffic and road roughness, driver behavior and road geometry. Figure 2-5 shows congested and uncongested situation for acceleration noise.

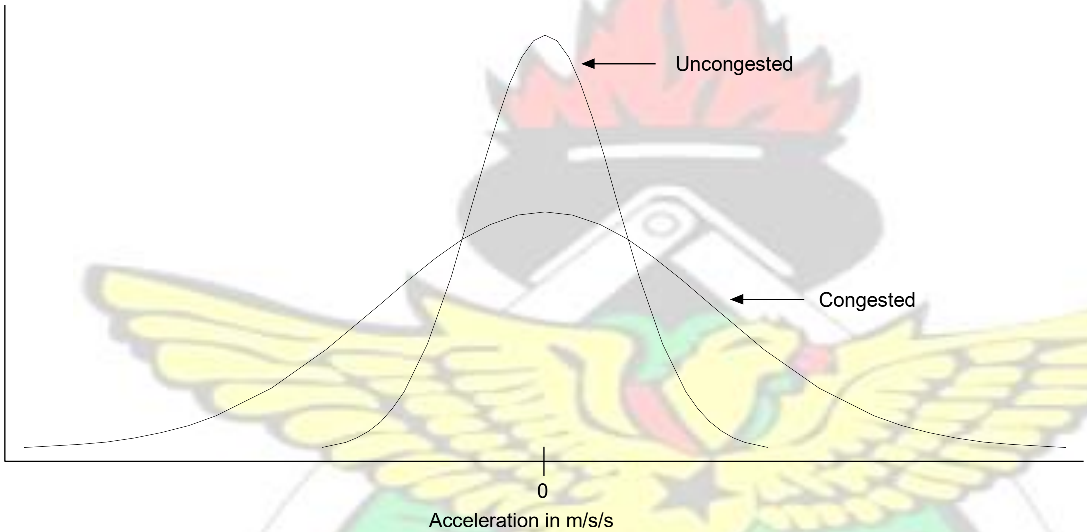

Figure 2-5. Congested and uncongested situation for accelerated noise

Source: Odoki & Kerali, (1999)

Table 2-2 shown below also shows accelerated noise associated with each speed.

Table 2-2. Accelerated Noise and Speed

Vehicle Class	Speed (km/hr)	Acceleration Noise in m/s2			
		0.05	0.1	0.7	0.75
Car	10		0.0063	0.0701	
	15		0.0095	0.1386	
	20		0.0083	0.1813	
	90		0.1092	0.1959	
	95		0.1133	0.1877	
	100		0.1255	0.189	

Bus	10				
	15				
	20				
Truck	10				
	15				

Source: Odoki & Kerali, (1999)

Pavement performance prediction and estimation of vehicular resource consumption is significantly improved when the predictive model such as the HDM4 is calibrated to mimic the observed pavement deterioration on the roads where the model has been used.

2.8.5 Speed Flow

The average speed of each vehicle influences the calculation of vehicle operating costs, travel time, energy use and emissions. The speed is also in turn influenced by a number of factors, which include:

- Vehicle characteristics
- Road severity characteristics, for example, road alignment, pavement condition, etc
- The presence of non-motorised transport (NMT)
- Roadside friction, for example, bus stops, roadside stalls, access points to roadside development, etc.
- Total MT traffic volume

The speed-flow model adopted for each motorized transport (MT) is the three-zone model proposed by Hoban et al. (1994.) as cited by Koranteng-Yorke, (2012). This model is illustrated in figure 2-6.

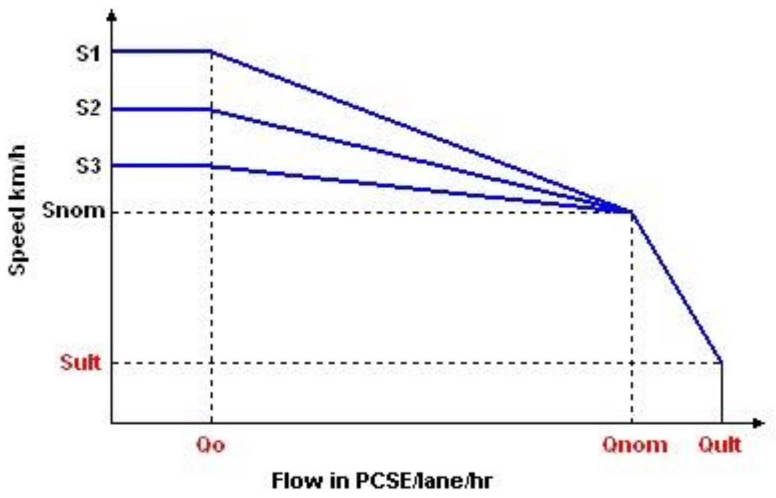

Figure 2-6. Speed flow model

The following denotions apply to figure 2-6

Q_o - the flow level below which traffic interactions are negligible in PCSE/h

Q_{nom} - nominal capacity of the road (PCSE/h)

Q_{ult} - the ultimate capacity of the road for stable flow (PCSE/h)

S_{ult} - speed at the ultimate capacity, also referred to as jam speed (km/h)

S_{nom} - speed at the nominal capacity (km/h)

S_1 to S_3 - free flow speeds of different vehicle types (km/h)

PCSE - passenger car space equivalents

The model predicts that below a certain volume there are no traffic interactions and all vehicles travel at their free speeds. Once traffic interactions commence the speeds of the individual vehicles decrease until the nominal capacity where all vehicles will be travelling at the same speed, which is estimated as 85% of the free speed of the slowest vehicle type. The speeds can then further decrease towards the ultimate capacity beyond which unstable flow will arise. Table 2-3 shows capacity and speed flow model parameters

Table 2-3. Capacity and Speed Flow Model Parameters

Speed Flow Type	**Width (m)**	**XQ1 = (Q_o/Q_{ult})**	**XQ2 = (Q_{nom}/Q_{ult})**	**Q_{ult}(PCSE/ hour/lane)**	**S_{ult} (km/hr)**
Feeder 2-Lane Narrow	<	0.1	0.8	1350	23
Feeder 2-Lane Standard	7	0.1	0.9	1400	25
Urban 2-Lane Narrow	7	0.1	0.8	1350	23
Urban 2-Lane Standard	7	0.1	0.9	1400	25
Urban 2-Lane Wide	>7	0.2	0.9	1600	30
Trunk 2-Lane Narrow	7	0.1	0.9	1400	25
Trunk 2-Lane Standard	>7	0.1	0.9	1400	25

2.8.6 Traffic Flow Pattern

Koranteng-Yorke (2012) stated that, the level of traffic congestion varies with the hour of the day and on different days of the week and year. To take account of this, the number of hours of the year for which different ranges of hourly flows are applicable need to be considered. Defining the distribution of hourly flows over 8760 hours of the year allows the AADT data to be converted to hourly flows.

2.8.7 Representative vehicles

The studies by Koranteng-Yorke (2012) also established that, ten (10) motorized and three (3) non-motorized vehicles were found on our network with the working hours of ten (10) and 300 days for one year. It further assumed constant life cycle for the depreciation of the private cars and optimal life cycle for commercial cars. It can be said that, the mass of vehicles also influences the fuel consumption and tyre consumption especially on gradients. Representation vehicle masses in Ghana were adopted from the study and are presented in Appendix B.

2.9 Effect of Maintenance on IRI, Emissions and Fuel Consumption

Maintenance standards applied on the road to repair pavement defects such as cracking, potholes, raveling, rutting etc. or to preserve the integrity of the pavement such as surface treatment, overlay etc impose limits on the pavement deterioration to the level it is supposed to reach according to Kerali (1988). Kerali (1988) further stated that the road condition at any point of the pavement's life cycle is dependent on the maintenance or improvement standards applied to the road. The impact of the maintenance standards on the riding quality in terms (IRI) results in the pavement performance as illustrated in the figure 2-7.

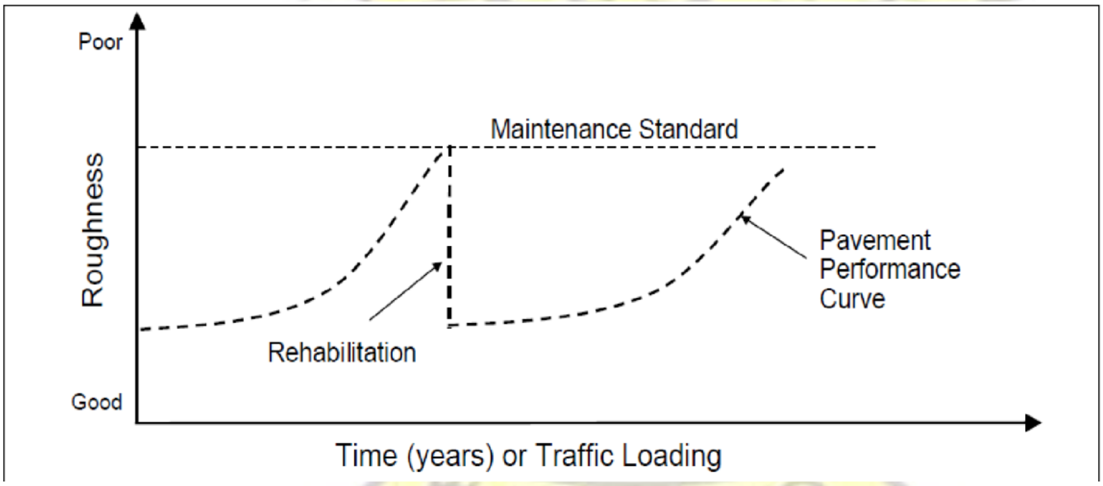

Figure 2-7. Effect of Maintenance Standards on IRI

From figure 2-7, as routine maintenance is applied on the road, it follows the curve line until IRI reaches poor condition. When a periodic intervention such as rehabilitation is applied, IRI reduces drastically downward following the vertical straight line to a good state. Then the cyclic continues. The impact of road condition in terms of IRI on road users is measured in terms of user cost and social and environmental effects as stated by Kerali (1988). The social and environmental effects include fuel consumption and vehicular emission. User cost include fuel cost, tyre cost etc. Figure 2-7 shows that, as maintenance standards are applied, IRI is controlled to the minimum. Thus, road user cost in terms of fuel consumption reduces and environmental effects such as vehicular emissions are also kept to the minimum. Figure 2-8 shows the effect of IRI on the road user cost of which fuel consumption cost is a component. Figure 2-8 show fuel consumption increases with increasing IRI.

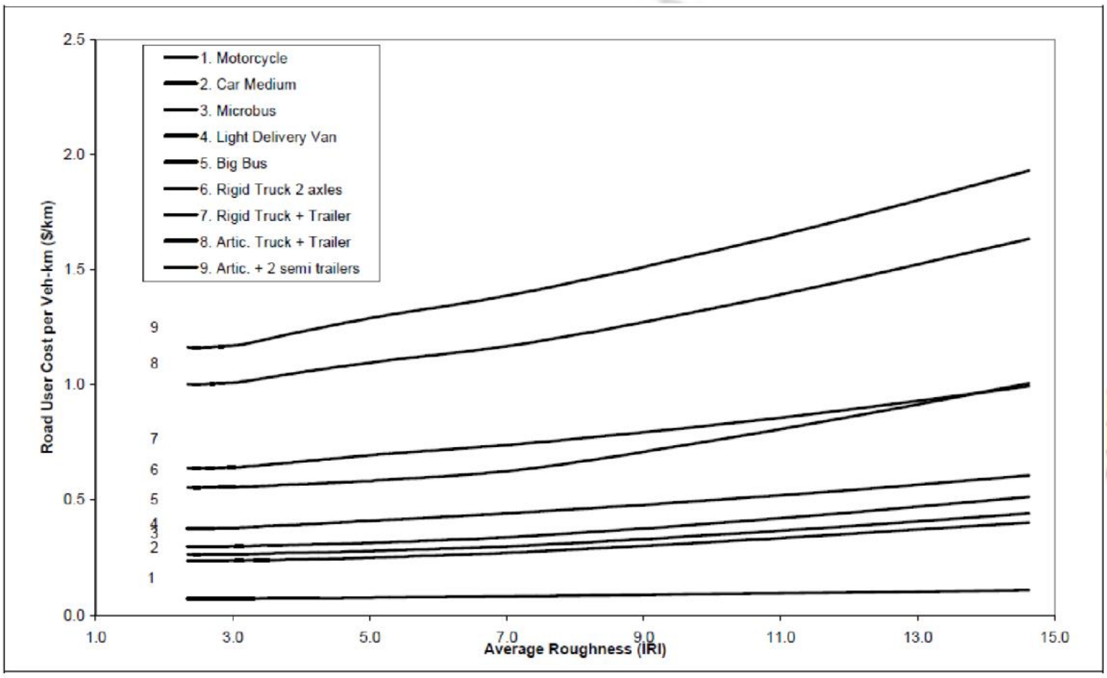

Figure 2-8. Effect of IRI on road user cost(fuel consumption

CHAPTER 3:

RESEARCH DESIGN AND METHODOLOGY

3.1 Overview

This chapter presents the research process; the methodology employed in the data collection, the data requirements of the project analysis and the description of the location of the study road.

3.2 Research Design

The research employed existing knowledge and findings from previous work underlying estimation of fuel consumption and vehicular emissions. Data on key variables relevant to the study were collected through field surveys and from secondary sources. Data was collected specifically from the Feasibility Study Report and the Design Report used for project implementation.

The processed data was inputted into the HDM-4 and run for 20 years analysis period. Life cycle analysis was conducted using the prior construction case as the 'base alternative ' and the post construction case as the 'project alternative. Overlaying asphalt on the existing was also considered as the third alternative (Overlay Alternative)'. The HDM-4 automatically calculates the vehicle speeds within the road user effect model (RUE) which further uses the vehicle speeds to calculate the instantaneous fuel consumption for each vehicle type for each traffic flow period.

The emission model then uses the vehicle speeds and fuel consumption calculated by the RUE model to predict quantities of emission by comparing each case option based on annual net difference in predicted quantities in investment *m* and base *n*. Results in emissions are calculated in annual net quantities, annual total quantities, annual average quantities and quantities of emissions.
At the same time, the road deterioration model (RD) in the HDM-4 calculates predicted International Roughness Index (IRI) for each year for the 20 years analysis period. Field survey was done to collect primary data on IRI for the period of 2016 and available IRI data extracted for 2013, and 2012 from the Ghana Highway Authority's Annual Road Condition Survey Report.

The predicted IRI were validated by comparing with the actual roughness measurements. If there is a statistical difference and weak confident level between the actual data and the predicted IRI, the HDM-4 settings were adjusted to mimic the facility under study.

On the other hand, if there is insignificant difference and a good confidence level between the predicted and actual IRI measurements indicated data validity. A relation is then drawn from the predicted IRI and the predicted total emission levels ie. CO_2, CO and NOx using excel spreadsheet. Again, emissions by each vehicle class were also compared with the US EPA standards 1997 to see if the emissions by each vehicle class are within accepted threshold.

Furthermore, relationship is also drawn from the predicted IRI's and the total fuel consumption for each year for the 3-lane dual carriageway reconstruction alternative.

Based on the outcomes, discussions were made and conclusions drawn. Based on the conclusions recommendations were made. Figure 3-1 is a flow chart of the research design and methodology.

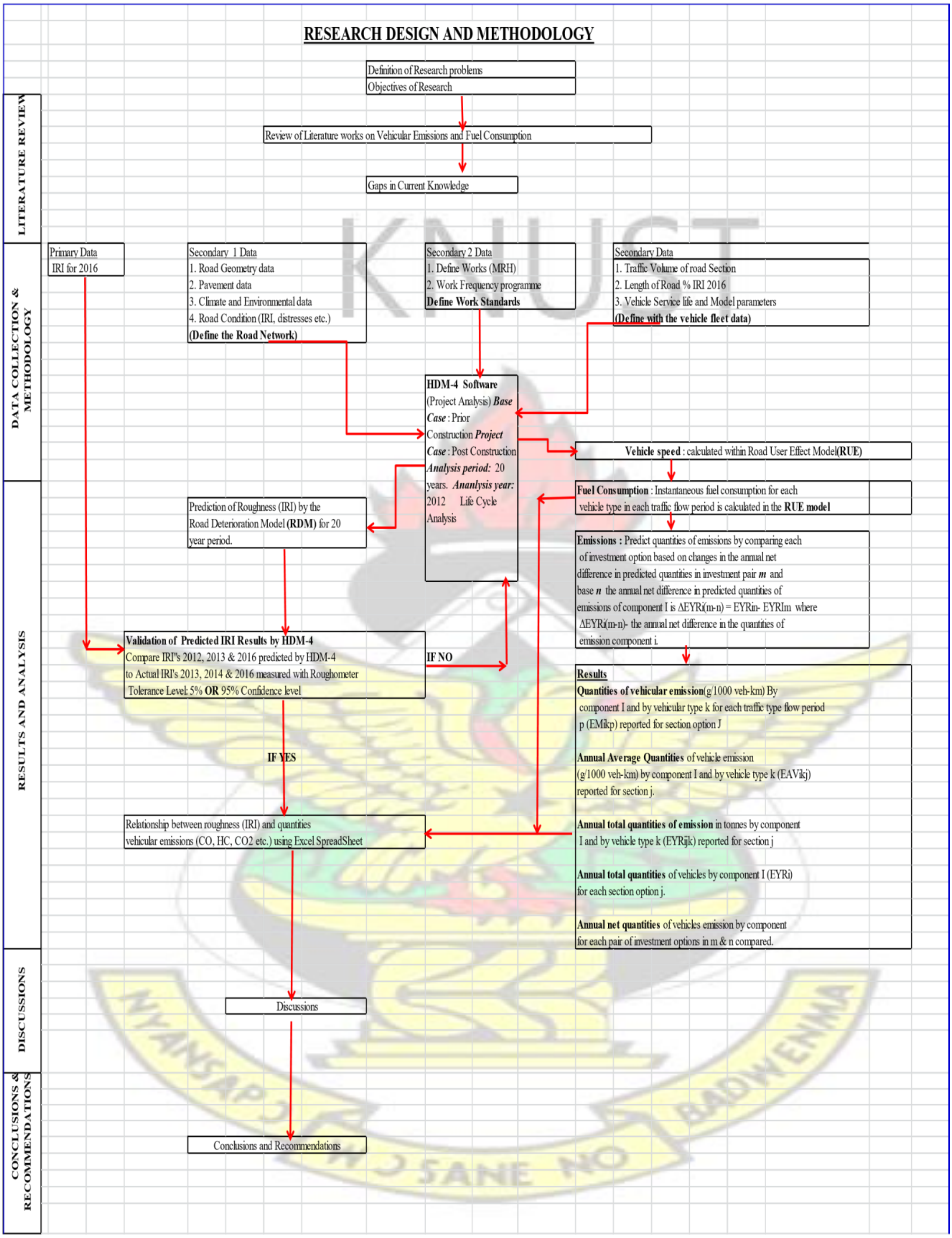

Figure 3-1 Flow Chart of Research Design and Methodology

3.3 Analysis Tool

The HDM-4 is a widely acclaimed to undertake life cycle analysis among other tools. It is a powerful tool for road management and investment options. This is a computerized base tool used to predict pavement deterioration over the life cycle of the pavement typically for the period between 15-40 years (Kerali et al 1998). Kerali et al (1998) further defined the predictions of road performance by the HDM-4 as a function of traffic volumes and loading, road pavement types and strength, maintenance standards and environment/climate.

The rate of pavement deterioration is directly affected by the standard of maintenance applied to repair the pavement surface such as cracking, raveling, pothole etc. or to preserve the pavement structural integrity (for example surface treatment, overlays etc). The strength of the pavement, the weather and traffic volume and load also determine the rate of road deterioration.

Key data requirements for the analysis are grouped into four namely; road network data, vehicle fleet data, works standards, and HDM4 configuration data. Details of the data requirement are elaborated as below.

3.4 Key Data Requirements

The data collected for the analysis met the requirements of the World Bank (1998) information quality level (IQL). Due to the enormous data requirements, key data input parameters for the analysis are summarized into four main categories mainly; road network, vehicle fleet data, works standards and HDM-4 configuration data. The road network data describes the physical characteristic of the road section to be analysed and included the following,

- Road Class: Functional hierarchy such as. primary or trunk, secondary or main, tertiary or local
- Speed-flow type: The effects of traffic volume on speeds to enable the economic consequences of road capacity improvements to be determined.
- Traffic pattern: Data on the differing levels of traffic congestion at different hours of the day, and on different days of the week and year. By defining the distribution

of hourly flows over the 8760 (365 days x 24 hours per day) hours of the year, the AADT data is converted to hourly flows.

- Climate zone: The climate in which the road is situated has a significant impact on the rate at which the road deteriorates, and on some aspects of road user costs. Important climatic factors are related to temperature and precipitation.
- Traffic volume: For each road section, traffic level is specified in terms of average annual daily traffic (AADT) flow. Detailed data values are associated with these in terms of the mean AADT are Description (e.g., low, medium, high)Road surface class - The road surface class to which the traffic band applies (that is, bituminous, concrete or unsealed),Mean AADT
- Geometry class: Road geometry is defined in terms of various parameters reflecting horizontal and vertical curvature. These represent geometry classes and apply to the road.

The following detailed data defines a geometry class: Description (e.g., mostly straight and gently undulating),Average rise plus fall (m/km),Number of rises and falls per kilometre (n°/km),Average horizontal curvature (deg per km),Super elevation (at bends),Speed limit (km/h),Speed limit enforcement factor (default = 1.1),The ratio of mean speed to posted speed limit, Speed reduction factors due to Non-motorised Transport (NMT), Motorised Transport (MT) and Road side friction factor

- Pavement characteristics: The parameters that are used in HDM-4 to describe pavement characteristics for bituminous pavement are the structural adequacy. This defined the strength of pavement by their structural adequacy to carry traffic loading. The detailed data values relating to these are in terms of the Adjusted Structural Number of the Pavement (SNP).
- Road condition: Road condition data are grouped as follows; ride quality, surface condition and surface texture: Ride quality is an indication of the roughness of the road. It is an important parameter for indicating road condition and maintenance needs, and for predicting vehicle operating costs. Ride quality is defined in terms of qualitative measures such as good, fair and poor. The detailed data values related to these are in terms of roughness IRI (m/km), and are assigned by road class. Surface condition is modelled by a number of distress modes. These includes,Year for which following condition measures apply,Roughness in IRI m/km (RI),Total area of cracking as % of total carriageway area (ACRA),Ravelling area as % of

total carriageway area (ARV),Number of pothole units (0.1m²) per km (no./km) (NPT),Broken edge in m^2/km (VEB), Mean rut depth in mm (RDM), Texture depth in mm (TD) Skid resistance (measured at 50 km/h) (SFC50) etc Surface texture is defined by the following parameters

(i) Calibration factor for the texture depth model (Ktd)

(ii) Calibration factor for skid resistance model (Ksfc)

(iii)Calibration factor for skid resistance speed effects (Ksfcs)

❖ **Pavement history**

The actual data details to be specified relate to construction defect indicators.

Vehicle fleet data defines the types of vehicles and their characteristic as they operate on the road network. The following define the vehicle fleet,

- ✓ *Basic Characteristic;* such as passenger car space equivalent factor, the number of wheels per vehicle, the number of axles per vehicle, type of tyre for motorised vehicle type: radial ply, bias ply or super-single, the base number of recaps per tyre carcass, retread cost as a percentage of new tyre cost (%), the average number of kilometres driven (km), the average operating weight of the vehicle type.
- ✓ *Economic unit cost:* economic cost of new vehicle, economic cost of a replacement tyre, economic cost of fuel per litre, economic cost of lubricants per litre. economic cost of maintenance labour per hour Other parameters include speed factors; force factors, maintenance calibration, fuel calibration etc

Works standards and costs; work standards such as the type of activity (maintenance and improvement) and frequency of operation were obtained from the Ministry of Roads and Highway.HDM4 Configuration; defines default data to be edited to reflect local conditions and environment.

3.5 Project Location

The George Walker Bush Motorway is an asphalt overlay 14.1km dual carriageway road. It is 10.5m wide and consists of 3 lanes with each lane 3.5m. The main corridor is for thorough traffic with service lanes of 6.0m and median of 3.0m. It features grade separations at km 3+800 (Achimota) and km 14 + 000 (Mallam).

The road stretches from Tetteh Quashie interchange to Mallam Junction in the southern part of Accra. It forms part of the trunk road network of roads designated as route N1. The road is also part of the ECOWAS Trans-West African Coastal Highway. The road is designed as a motorway with access control. The road lies entirely in the Greater Accra Region. The N1 highway serves as a by-pass to the Central Business District (CBD) of Accra for road users to and from the Central, Western and Eastern Regions of the country. This section of the N1 Highway runs through residential area with the immediate adjoining lands being used for stores, offices, retail shops, etc. The built up areas along the road makes it a typical urban trunk road.

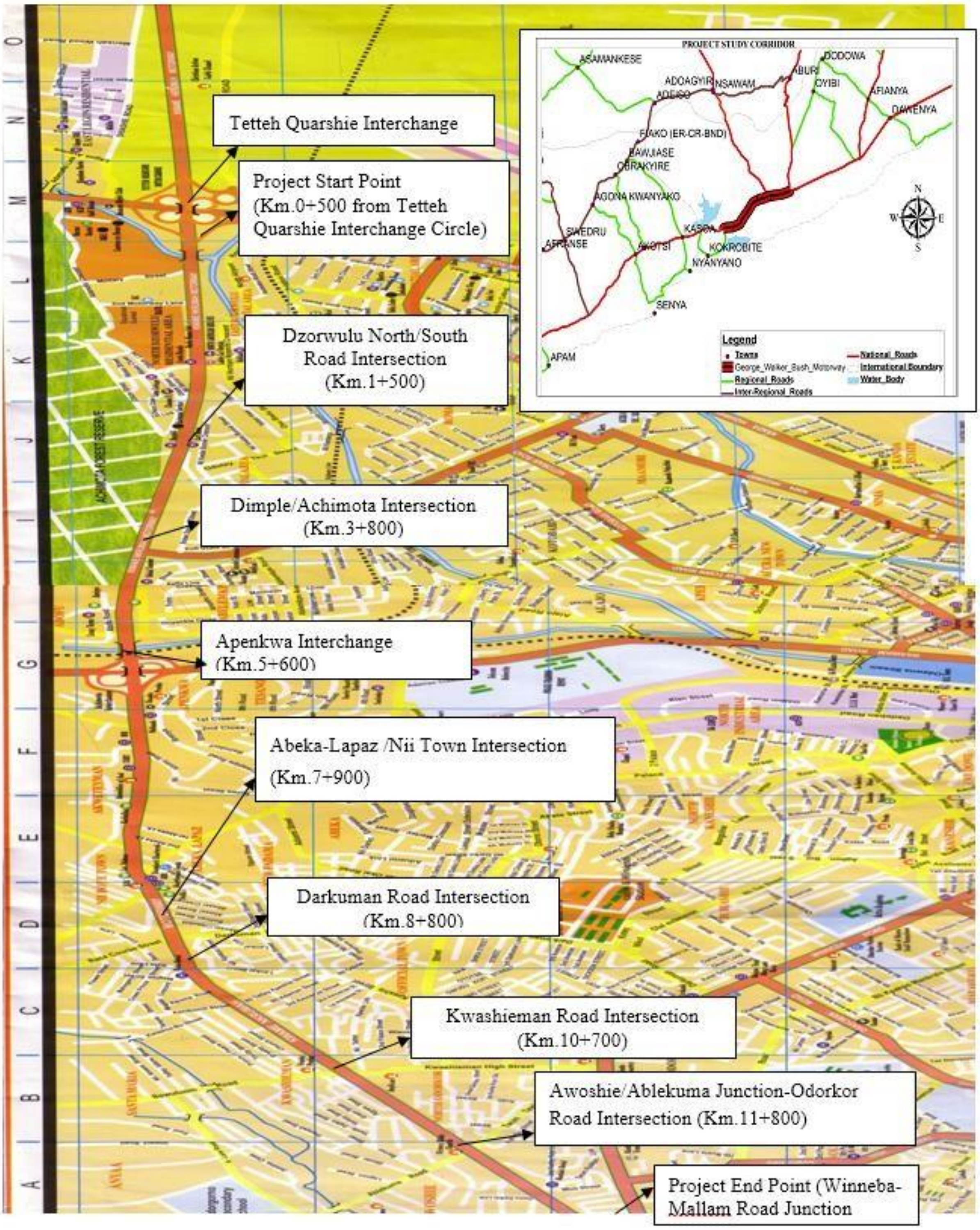

Figure 3-2 Location map of the study road

Topography

Generally, the terrain of the road corridor can be classified as flat to mild rolling. The road runs longitudinally eastwards from an embankment of 2-3m high form Km 0 + 00 ie Tetteh

Quashie interchange and rising as high as 4.0m high at km 3+800 and descending and rising sharply to km 5+600 ie Apenkwa Interchange (N6) and Eastern Rail line on a huge embankment. It then extend flat to km 8+800 at Darkuman intersection and descend to an embankment of about 3-5km to km 10+700. The alignment of westbound carriageway continues on an embankment through Awoshie to Mallam whilst the eastbound changes into a cut until Awoshie and then through an embankment over the Densu basin to Mallam Junction.

Climate

The road corridor features a climate of wet and dry tropical marked by warm to hot temperatures throughout the year. Major rainfall season is in April to June and August to October is the minor rainy season a typical of southern Ghana. The annual rainy season is between 750-1000mm. Accra has warm to hot temperatures throughout the year due to its closeness to the equator and relatively low elevations. The average annual temperature is 27 degrees Celsius and relative humidity of 95% to 100% during night and early mornings. Under the influence of dry Tropical continental Air Mass called Harmattan, the humidity can go as low as 20% to 30%.

Geology

Accra is made up of Precambrian Dahomeyan schists, granodiorites, granites, gneiss and amphibolites to late Precambrian Togo series comprising mainly quartzite, phyllites, phylitones and quartz breccias.

Other formations found are the palaeozoic accraian sediments - sandstone, shales and interbedded sandstone-shale with gypsum lenses. The coastline of Accra comprises a series of resistant rock outcrops and platforms and sandy beaches near the mouth of the lagoons.

The first 3.2km of the road shows soil type of dark alluvial and yellowish/grey mottled residual clays of low bearing capacity and highly expansive form over the heterogeneous assemblage of sericitic, biotitic, or chloritic quartz schist. There are massive thickbedded reddish well-consolidated medium-grained sandstones to the next 1.3km and continuing is a small band of pebbly colluvium quartzites between km 4+650 and 5+400 ending at the easting rail line. There are several intrusions of chloritic quartz schists rocks in many places between Abofu and Apenkwa i.e. km 5+500km and 6+500. Between km 6+500 to

Darkuman Junction to km 10+100 shows a thin silty clay layer of about 0.5 m overlying concoidal quartzites cobbles.

Weathered quartzites and cobbles predominates the subgrade soils to just around the Mallam Junction where weathered quartzites and the alluvial deposit of the Densu River intersects. Figure 3.2 below shows the project corridor.

3.6 Data Collection

The input parameters for the analysis were derived from different sources and these include data from, HDM-4 Configuration and Calibration Report (2007) by the Ministry of Roads and Highways (MRH), Vehicular Emission Inventory Ghana EPA 2008, Ghana Highway's Annual Road Condition Survey Reports, Feasibility and Final Design Report of the George Walker Bush Motorway and some default provisions in the HDM-4 model.

Extracted data from the Feasibility and Design Report include summary of section attributes on existing data (Prior Construction), the climatic features of the location of the road as defined from information provided by the Meteorological Services Department.

Also extracted is traffic flow characteristic for the road section, normal traffic obtained from the average daily traffic count, diverted and generated traffic projections from base year traffic count. Other information includes traffic composition from the different vehicle classes in the twenty-four hour traffic counts and traffic growth rate derived from the counts. Also derived is speed flow relationship and hourly flow analysis of the road capacity. Annual Average Daily Traffic (AADT) was estimated to be 27,737 for the census year of 2008. Details of AADT including percentage proportions of all vehicle are seen in Appendix B.

The future growth rates (by vehicle type) were derived whilst non-motorized annual traffic growth rate is given as 2%. Additional information include detail data on road capacity and speed flow relationships,

The vehicles for this study were selected from the pre-defined National Vehicle Fleet obtained from the Final Report on HDM-4 Configuration and Calibration, MRH (2007). The national vehicle fleet has 10 representative motorised and 3 non-motorized vehicles. There are no restrictions on vehicle movement on the entire national road networks in

Ghana. The vehicle fleet is assumed to have working hours of 10 hours for 300days in a year.

Data extracted contains information on the characteristics of the different types of vehicles plying the road. It comprises a mix of eleven (10) vehicle types that use the road network. A set of representative vehicles were used to define the physical and performance characteristics. They were grouped into two categories as motorised and non-motorised vehicles. Motorised vehicles include cars, pickups, trucks, buses and trailers whilst non-motorised vehicles include bicycles. Information on vehicle utilisation and costs were derived from calibrated HDM-4 information used by the Ministry of Roads and Highways (MRH).

The vehicle mass influences the vehicles, fuel and tyre consumption and as a result of its heavy vehicle damage factor, has a major impact on the rate of pavement deterioration. This was adopted from HDM-4 Configuration and Calibration Final Report (MRH).

Emission factors for the representative vehicles in Ghana which relate the quantity of pollutant released into the atmosphere were extracted using available data from the studies done by the EPA Ghana (2007). HDM-4 model specific factors were derived from National Road Transport Emission factors from the EPA Ghana.

3.6.1 Calibration of the HDM-4 Emission Model

Model emission factors for the HDM-4 were derived for each pollutant using appropriate model equations in Appendix A for carbon dioxide (CO_2), carbon monoxide (CO) and nitros oxide (NOx). The results of HDM-4 model emission factors such as aCO_2 for carbon dioxide, aCO for carbon monoxide and aNOx for nitrous oxides for each specific vehicle class were also presented in Appendix B.

3.6.2 Calibration of the HDM-4 Fuel Consumption Model

Fuel-to-power conversion factors for the representative vehicles were adopted from the HDM-4 Calibration and Configuration Final Report (2007). These were developed based on on-road raw fuel consumption by vehicles travelling at different speeds in different parts of Ghana on gravel, surface treated and asphalt concrete roads. Consumption for different road conditions was observed (free flow and congested – medium and high). Using HDM4 default idle fuel rate, total power requirements were calculated. Fueltopower conversion factors were also developed. Fuel-to-power efficiency factor can be seen in Appendix B.

The cases considered for analysis were the base alternative, the overlay alternative and the 3-lane dual carriageway reconstruction. The details of the do nothing situation comprises of an overlay with other maintenance interventions on crack sealing, patching, edge repair, etc. whilst the project case comprise of a major reconstruction with routine maintenance interventions. The adopted standards specifications and costs were derived from the Ministry of Roads and Highways standards.

The discount rate used for the analysis was chosen as 15 % per the Feasibility and Design Report and the analysis was conducted for a design period of 20 years to match the projected life cycle of the project. Road condition data was also derived from the feasibility report in order to obtain the baseline data for the analysis. The base year was 2008

Structural Numbers for the before and as-built road were derived by calculation assuming drainage coefficients to be unity. Mid-range structural coefficients were taken based on the road condition of the roads before and after construction. Appendix B includes all the relevant data employed in the analysis.

3.6.3 Roughness Measurements

Average roughness for 2012 and 2013 were extracted from the Ghana Highway Authority's Annual Road Condition Report whilst that of 2016 was based on on-the road field measurements. Table 3-1 indicates the summary of the IRI's obtained.

Table 3-1. Summary of IRI values employed.

Year of Survey	Average IRI
2012	1.93
2013	1.75
2016	1.88

The observed IRI's were adjusted due to calibration issues with the instrument to mimic the actual IRI when the road was open for traffic. IRI of the road when it was open to traffic was 2.50 for 2012. Hence adjustment was obtained by addition of 0.8 to the values. Table 3-2 indicates the summary of the adjusted IRI's obtained.

Table 3-2. Summary of IRI values employed.

Year of Survey	Average IRI	Adjusted IRI
2012	1.70	2.50
2013	1.80	2.60
2016	1.88	2.80

The following briefly describes the procedure undertaken for the on-road roughness measurement. On-road roughness measurement for 2016 IRI was done using a Roughometer II mounted on a pickup. The test was done at night between the hours of 10pm to 12am due to the high vehicular speeds on the road on the 22nd February, 2016. The setup consisted of a sensor which was mounted directly on the rear axle of a vehicle such that the weight of the vehicle's characteristics of the suspension components has very little influence on the sensor. Traveling at a constant speed between 40-60km/h, it measured the road profile using the accelerometer sensor on the axle. The profile was then fed into the same International Roughness Index (IRI) algorithm used by a laser profiler. The International Roughness Index measurement setup and results of raw data are shown in Appendix C,

3.6.3 The Existing 2-lane Single Carriageway Road

The George Walker Bush Motorway, before construction was a 2-lane single carriageway road with 7.3m width and a shoulder of 1.5m. The history of the road has seen in the early 80's, 50 mm asphalt concrete layer was placed directly on compacted lateritic gravels and crushed quartzitic aggregates bases and subbases of 200 mm total thickness by Ways and Freitag of Germany. Due to persistent failures by the road, 50mm asphalt overlay was also laid by on top by Construction Pioneers in 2000. Within a year of repairs and overlay of the year 2000, cracks, rutting and shoves have appeared in several locations. Messrs Kasap of Ghana undertook repairs, overlays and reconstruction of the Dzorwulu Junction and the Apenkwa to Lapaz section in 2002. Figures 3-3 and 34 show the pictures of the existing 7.3m width single lane carriageway with defects.

Figure 3-3. Existing 2-lane road showing ruts

Figure 3-4. Existing 2-lane road showing severe cracks

3.6.4 The 3-lane Dual Carriageway Reconstruction Option

This consist of a dual carriageway with of 3-lane of 10.5m. This has a median strip of 3.0m and service lanes of 6.0m. The shoulder with is 2.0m. The figure 3-4 shows the picture for the 3-lane dual carriageway reconstruction project.

Figure 3-5. 3-lane dual carriageway after reconstruction

3.7 Life Cycle Analysis

Life cycle analysis was conducted using the HDM-4 software. Twenty (20) year analysis period was used. The survey year was 2008 and analysis start year was 2009. The first three years of construction period was considered as the road was open to traffic in 2012. Full pavement life cycle analysis of newly constructed road in 2012 was considered. Three scenarios were modelled into the software for analysis. These were the 'base alternative' (do minimum), overlay on the existing 2-lane alternative, and the 3-lane dual carriageway reconstruction alternative.

3.7.1 Base Alternative (Do minimum)

The 'Base Alternative' (do minimum) involved the application of routine maintenance such as pothole patching, edge repairs on the exiting 2-lane paved road effective in 2009.

3.7.2 The Overlay Alternative

Maintenance overly of about 50mm asphalt on the existing 2-lane road in 2009 followed by routine maintenance such as pothole patching, edge failure repairs in 2010.

3.7.3 The 3-lane Dual Carriageway Alternative

The third alternative which is 3-lane dual carriageway reconstruction, involved the reconstruction of the 7.3m width single carriageway into 3-lane dual carriageway of 10.5m width and 3.0m median in 2009. This is followed by routine maintenance such as pothole patching, edge failure repair etc in 2012 after three-year reconstruction period and there after maintenance overlay every ten years during the project life cycle. Table 33 shows the summary of roadwork standards as applied for each project alternative and the effective year for the analytical framework.

Table 3-2. Summary of Road Work Standards as Applied on each Project Alternatives

Project alternative	Section ID	Intervention	Road Works Standards	Effective from year	Maintenance works/ Improvement type
Base Alternative	N01-016	M	Patching and Overlay cracking paved road (MTCEGB)	2009	Patching (PTPTCH)
					Over Cracking (OverCr)
Overlay on the Existing 2-lane	N01-016	M	Maintenance Overlay	2009	Overlay George Walker Bush (OVLAY)
		M	Patching and Overlay cracking paved road (MTCEGB)	2010	seag(CRSL)
					Patching (PTPTCH)
					Over Cracking (OverCr)
3-lane Dual Reconstruction Alternative	N01-016	I	3-lane Dual Reconstruction	2009	Reconstruction of George Walker Bush Motorway (REGWBM)
		M	Patching and Overlay cracking paved road (MTCEGB)	2012	
					Patching (PTPTCH)
					Over Cracking (CRSL)

CHAPTER 4:

RESULTS AND DISCUSSIONS

4.1 Overview

This chapter presents the results of the study and discusses the findings. It is organized in five parts; the first focuses on the validation of the predicted data by comparing the actual roughness measurements and the predicted IRI measurement from the HDM-4. The second part presents the levels of exposure in terms of pollutant quantities. The third part explores and attempts to establish a relationship between the predicted IRI and the predicted quantities of vehicular emissions such as the total CO_2, CO and NOx. The fourth part dwells on the annual fuel consumption with respect to changes in predicted IRI. In the final part, road deterioration and maintenance work standards applied to various options are evaluated in a comparative analysis of the effect of maintenance intervention on emissions and fuel consumption.

4.2 Validation of Predicted IRI results

The means of the predicted roughness (IRI) from the HDM-4 and the means of the IRI' adopted IRI's from actual measurements were compared by performing an Analysis of Variation (ANOVA). The actual IRI values after adjustment were used as the predictors or constants and the predicted IRI values from the HDM-4, the dependent variables. The significance level of 5% error margin was set. The Null hypothesis tested was;

Ho: The mean IRI values are the same and

H_1: The mean IRI values are different

Table 4-1 shows the result of the analysis of variation (ANOVA)

Table 4-1. Analysis of Variation of the Actual IRI and the Predicted IRI

ANOVA[b]

Model	Sum of Squares	df	Mean Square	F	Sig.
	.017	1		6.199	.243[a]

1 Regression	.003	1	.017		
Residual			.003		
Total	.020	2			

a. Predictors: (Constant), Actual_IRI

b. Dependent Variable: Predicted_IRI

The results of the validation of the predicted data gave the analysis of variance (ANOVA) of the actual IRI values measured and the predicted IRI values from the HDM-4 analysis. The ANOVA gave significance value of 0.243, which is greater than 0.05. Scientifically, this means that, the variability in the two conditions is not significantly different or the variability in the two data is the same. Hence, the differences in the means of the two data are not statistically significant. This implies that, the road under study was well simulated to mimic the behavour and deterioration of the actual road pavement under study, under traffic loading and local weather conditions. The models for the predicting roughness were deemed to be calibrated to reflect the field conditions and were therefore applied in the analysis.

4.3. Emission Levels in terms of Exposure

Emission levels for each year are also presented in Appendix E. A graph of total of CO, CO_2 and NOx emission was plotted against year to obtain the trend. The Figure 4.1 below shows a plot of year versus total emissions for the 3-lane dual carriageway reconstruction and the overlay option.

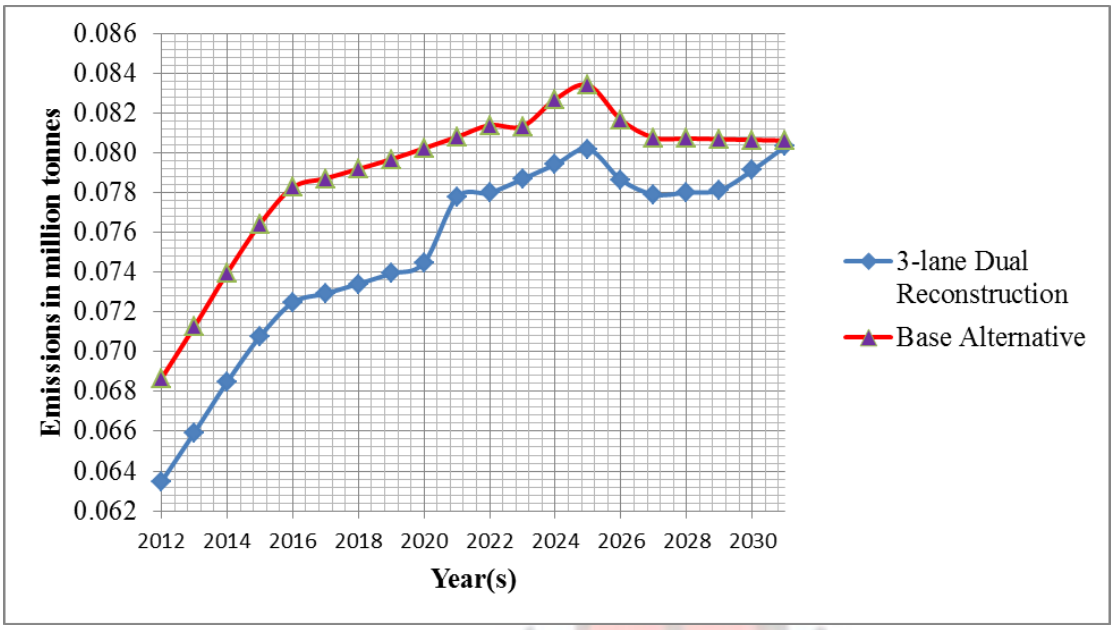

Figure 4-1 Total Emissions of CO_2, CO and NOx for the base alternative and the 3-lane Reconstruction alternative.

From figure 4.1, total emission of CO_2, CO and NOx in 2012 when the road was opened to traffic was around 63,473.9 tonnes for the 3-lane dual carriageway as compared to 68,659.59 for the base alternative (do minimum) and is expected to be about 72,471.11 tonnes in 2016 as against 78,263.24 for the base alternative, 74,487.04 tonnes in 2020 and 79,121.21 tonnes by the year 2030 as against 80,231.78 and 80,651.99 tonnes respectively for the base alternative The emissions for the base alternative are higher than the 3-lane dual carriageway alternative..

Figure 4-2 shows comparison of total emissions of CO_2, CO and NOx for the 3-lane dual carriageway and the overlay option considered.

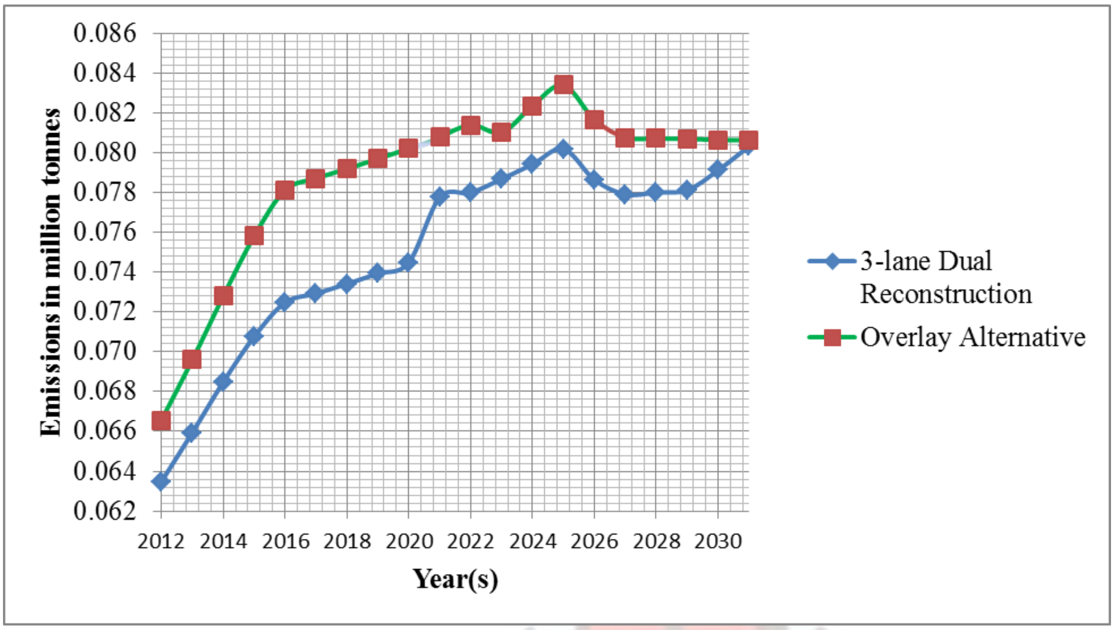

Figure 4-2 Total emissions of CO_2, CO and NOx for the 3-lane dual carriageway and the overlay option.

Also, total emission for the 3-lane dual reconstruction alternative for 2012 was 63,473.9 tonnes, 72,471.11 tonnes in 2016 and is expected to be 74, 4871.04 in 2020 and 79,121.11 in 2030. In the case of the overlay option of 66,566.31 tonnes in 2012, 78,117.71 tonnes in 2016 and an expectation of 80,213.07 tonnes in 2020 and 80651.99 in 2030. The rise in emission for the overlay option was also seen to be higher than the 3lane dual carriageway option. Again, a comparison of total emission for the base alternative and the overlay alternative is shown in figure 4-3.

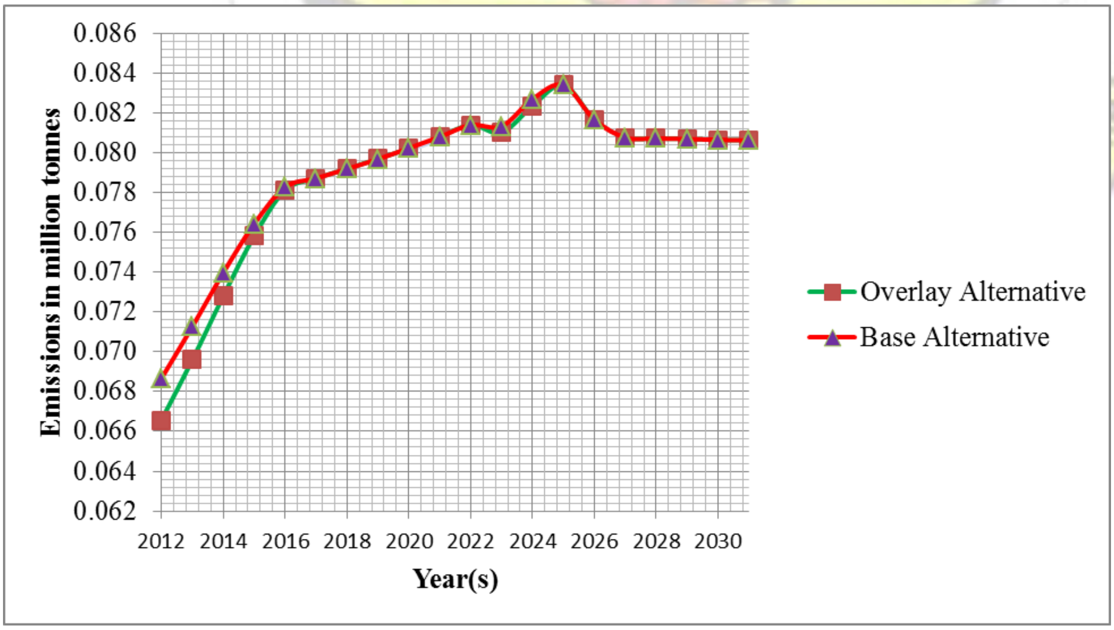

Figure 4-3 Total emissions of CO2, CO and NOx for the overlay alternative and the Base Alternative.

A total emission for the base alternative for 2012 was 68,659.59 tonnes as against 66,566.31 for the overlay option. Both continue to rise steeply to 78,715.04 tonnes in 2017 when convergence occurs and 2031 when the life cycle of the pavement is over.

4.4 Relationship between IRI and Emissions

In order to explore the relationship between road surface roughness and vehicular emission levels from vehicles using the road, the average IRI's were also plotted against each year. This is to determine the trend in road deterioration by year. Figure 4-4 below shows road deterioration by year for the 3-lane dual reconstruction alternative.

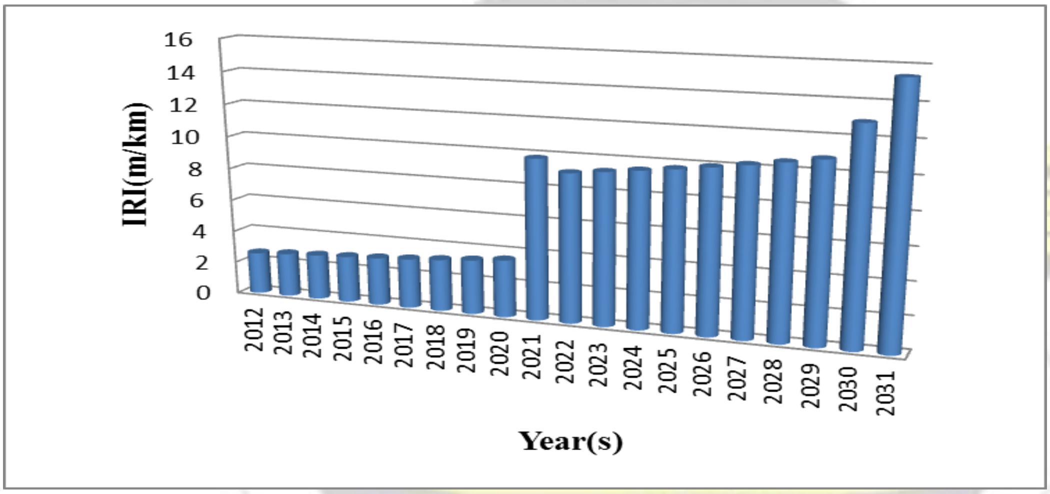

Figure 4-4 Average Roughness by Year for 3-lane reconstruction option.

From figure 4.4, the road deterioration graph shows a gradual increase in IRI from 2.59 in 2012 to 3.53 in 2020 and then increased to 9.81 in 2021. After receiving maintenance intervention it drops to 9.09 and further rises to 10.23 in 2027 when it begins to rise again to the close to the highest terminal value of 16 where it level out during subsequent years in the life cycle of the pavement. The terminal value of 16 is as in accordance with the International Roughness Scale which has the highest value of 16 adapted from Sayers et al (1986) as cited by Greene & Ulm (2013). Figure 4.5 also presents a graph of average International Roughness Index as against total emissions of CO, CO_2 and NOx over the 20-year analysis period for the 3-lane dual carriageway reconstruction.

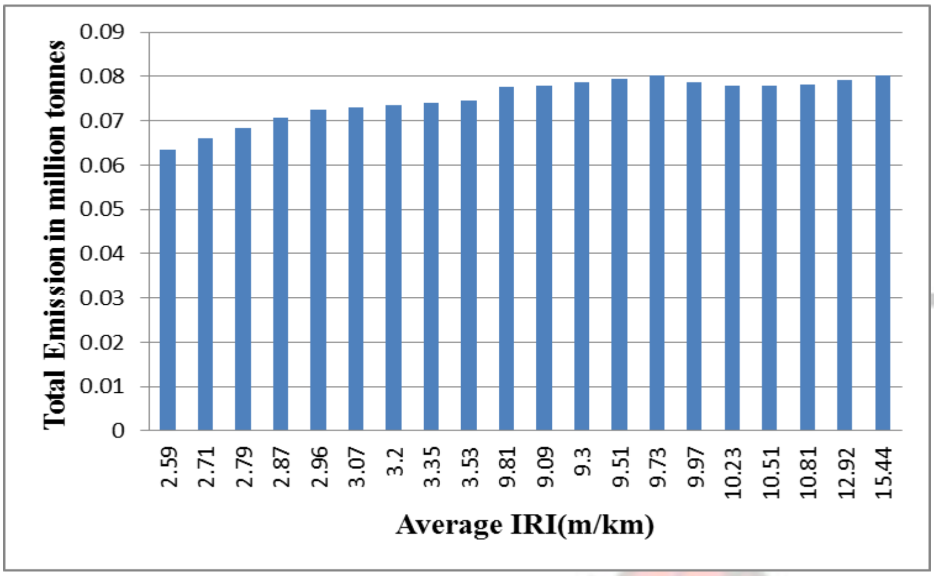

Figure 4-5 A graph of Total Emissions against Roughness for the 3-lane dual carriageway reconstruction

From the graph, it is evident that total emissions increases with increase in annual average IRI's. For a good bituminous road with IRI of 2.59, total emissions of 63,473 increases gradually upwards when the IRI reaches the highest value of 9.81 for emissions of 77755.02. It then increases gradually to 80325.76 in 2031. Figure 4-6 shows logarithmic relationship between IRI and total emissions.

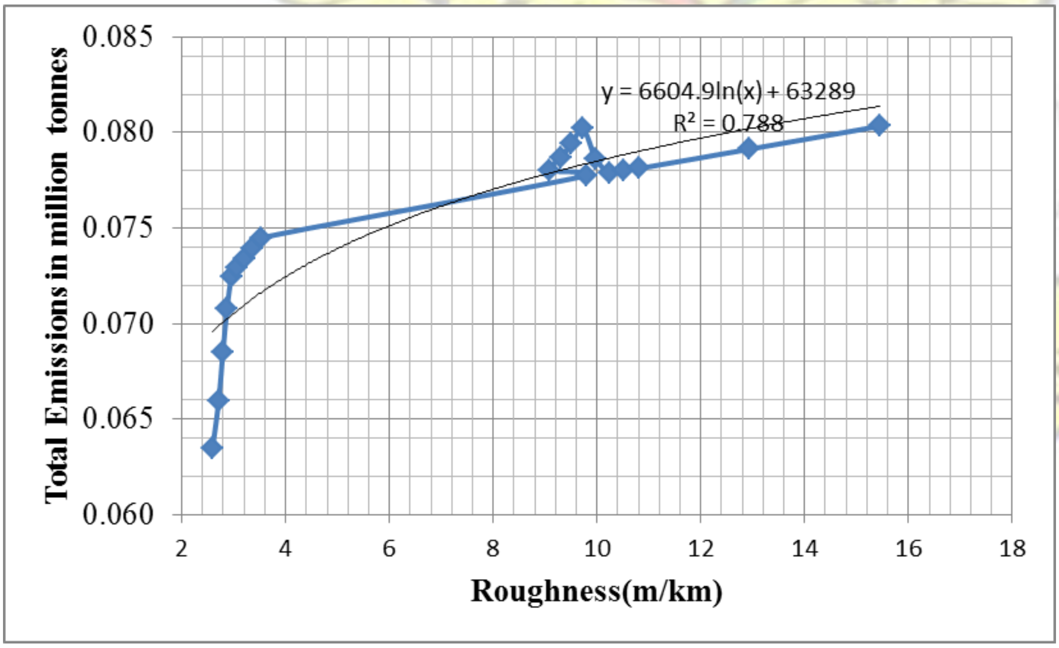

Figure 4-6 A Logarithmic Relationship between IRI and Total Emissions for the 3-lane dual reconstruction road.

Again, the graph of figure 4.6 showed a logarithmic relationship between average IRI and emissions. There is a strong coefficient of correlation (R^2) of 0.788. It presupposes that there is a strong relationship between average IRI and total emissions on the study road. The correlation shows changes in average IRI directly influences total emission. However, this change in emissions may be attributed not entirely traffic AADT but also to several other factors such as weather, congestion, and vehicle age distribution and composition. Temperature and driving style can also be contributory factors to the total emissions. The model equation y = 6604.91ln(x)+63289, predicts emissions and IRI's where, y is the emission in tonnes and x the corresponding IRI and the constant of 63289 indicating the emissions due to idle time from stop and go for the total vehicle fleet in a year. This equation is applicable to the study corridor alone and applicable with an initial AADT of about 27,800.

4.5 Predictions on Fuel Consumption

Each vehicle has different fuel-to-power factor and as a result the rate of fuel consumption is different. The different fuel consumption is as a result of different vehicle weights, speed, vehicle specific power, etc. Appendix F presents fuel consumption of each vehicle class for each flow period. Figure 4.7 shows average fuel consumption by each vehicle category for the 3-lane dual carriageway.

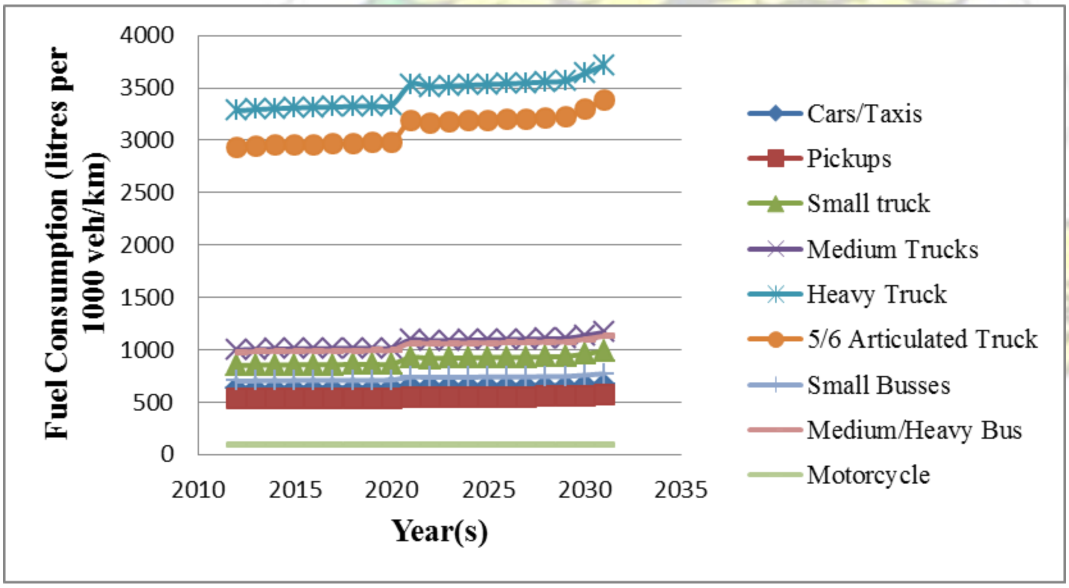

Figure 4-7 Fuel Consumption by each Vehicle Class for 3-lane dual carriageway

From the graph, it is shown that, small cars have the average fuel consumption of 649.98 litres per 1000 veh/km travel with the highest fuel consumption being heavy trucks with 3449.68litres per 1000 veh/km followed by articulated trucks 3104.11 litres per 1000 veh/km and motorcycle being the least with 95.65litres per 1000 veh/km. Total fuel consumption for the entire vehicle fleet was 244,502.6 litres per 1000 veh/km for the 20 years analysis period. Figure 4-8 shows fuel Consumption by each Vehicle Class for the base alternative

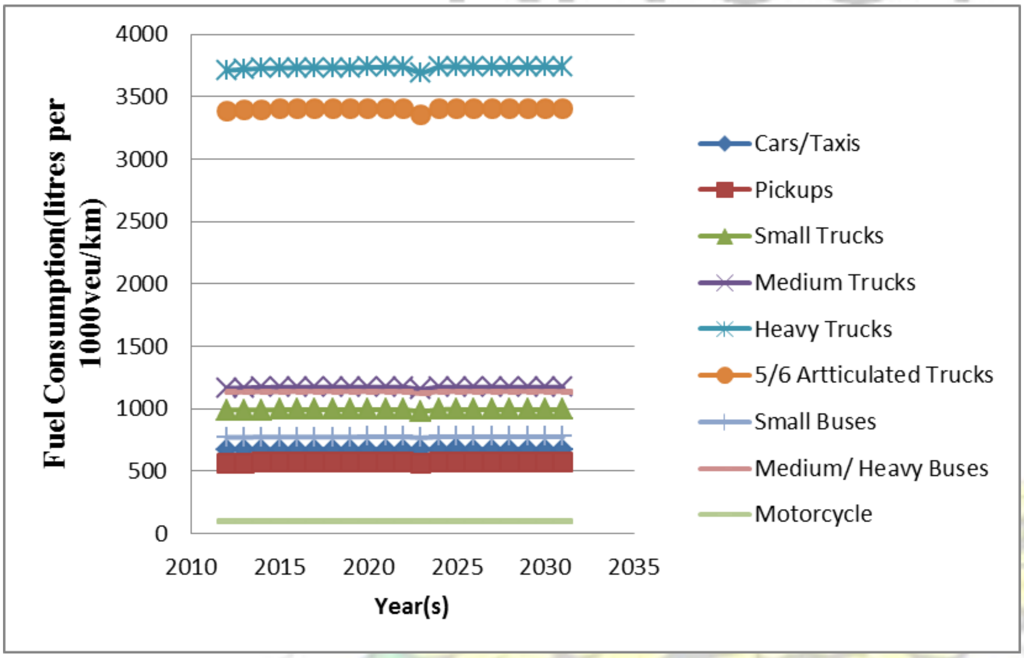

Figure 4-8 Fuel Consumption by each Vehicle Class for the base alternative

For the base alternative, it is shown in figure 4-8 that, small cars have the average fuel consumption of 675.60litres per 1000veh/km travel with the highest fuel consumption being heavy trucks with 3,731.20litres per 1000 veh/km followed by articulated trucks 3,399.89 litres per 1000 veh/km and motorcycle being the least with 101.14 litres per 1000 veh/km. Total fuel consumption for the entire vehicle fleet was 264,639.99 litres per 1000 veh/km for the 20 years analysis period.

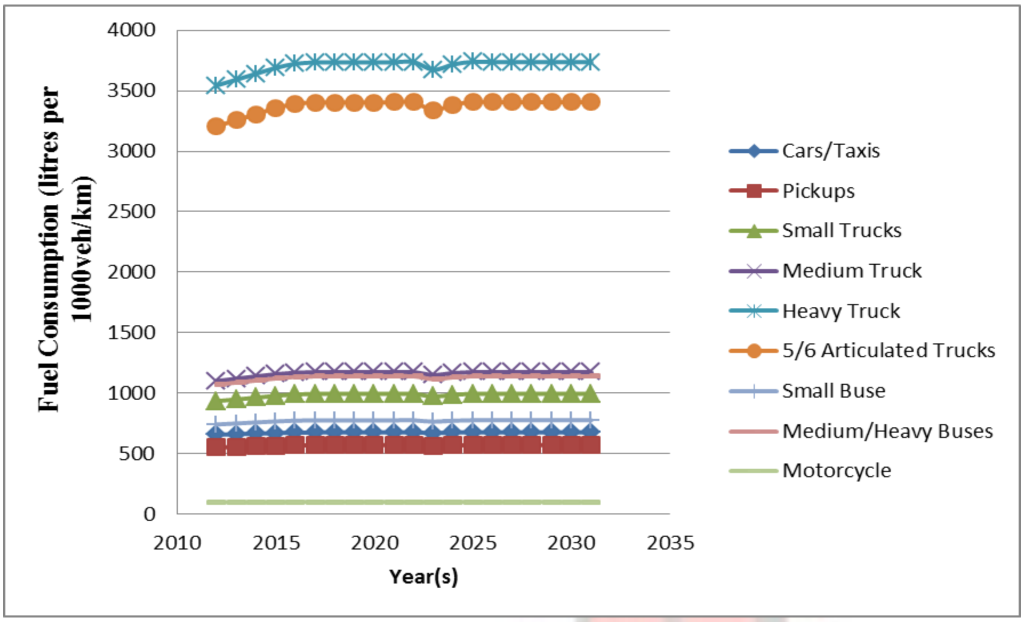

Figure 4-9 Fuel Consumption by each Vehicle Class for the overlay alternative

Results of the overlay alternative as indicated in figure 4-9 show, small cars have the average fuel consumption of 673.20 litres per 1000 veh/km travel with the highest fuel consumption being heavy trucks with 3,705.89 litres per 1000 veh/km followed by articulated trucks 3,373.41 litres per 1000 veh/km and motorcycle being the least with 100.65 litres per 1000 veh/km. Total fuel consumption for the entire vehicle fleet was 262,921.34 litres per 1000 veh/km for the 20 years analysis period.

Figure 4.10 shows a graph of average IRI against fuel consumption for small cars for the 3-lane dual carriage reconstruction road.

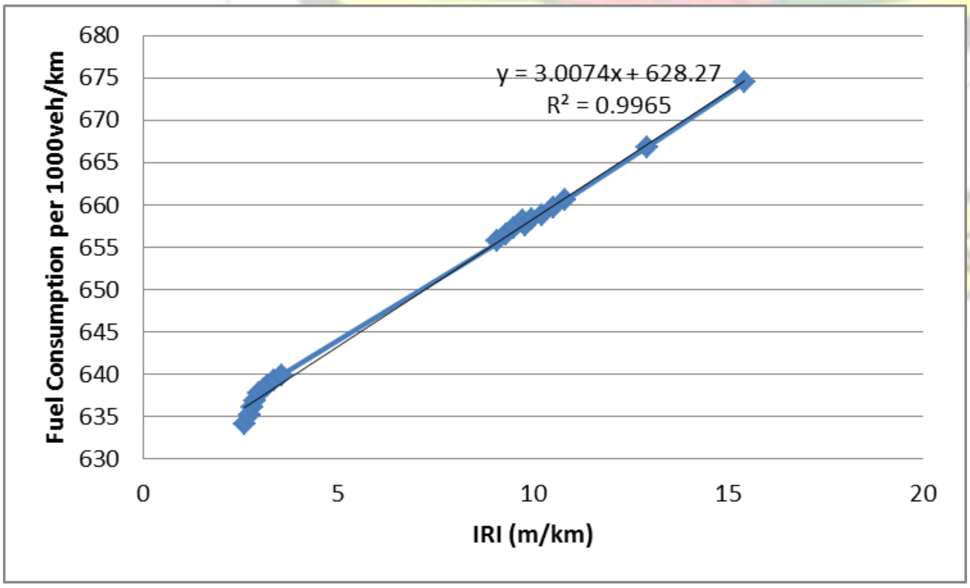

Figure 4-10 A Graph of relationship between Fuel Consumption and Average Roughness for the 3-lane dual carriageway reconstruction

Figure 4-10 indicated fuel consumption for small cars against roughness for the 3-lane dual carriageway reconstruction road. Roads with high IRI values increase the amount of resistance a vehicle experiences as it travels down the road and requires additional fuel to maintain a certain speed. Increased resistance translates to an increase in fuel consumption. Therefore, the level at which fuel efficiency is affected is heavily tied to the condition of the road or the pavement-vehicle interaction. According to figure 4.6, the study shows a very strong correlation between fuel consumption and average roughness with R^2 of 0.9965. This shows that a change in IRI has a strong effect on the amount of fuel consumed by the vehicles. Again, the relationship show a linear graph with the equation $y = 3.0074x + 628.27$. This indicates that, a small change in IRI will result in fuel consumption of about 3.0 litres or 0.79 gallons of fuel.

4.6 Emissions by Vehicle Category

Figure 4-7 shows a comparison of emissions of CO of each vehicle class with the US EPA standards 1997. US EPA emission standards 1997 is presented in Appendix G. Emission standards are legal requirements governing air pollutants released into the atmosphere. Emission standards set quantitative limits on the permissible amount of specific air pollutants that may be released from specific vehicle over specific timeframe designed to achieve air quality standards to protect human health. Majority of Ghana's vehicle fleet are 10 to 20 years (DVLA). As such, predicted emission levels of each vehicle category were compared with the US federal standards for Tier 0 or Euro I (vehicle manufactured year 1979-2000) and Tier 1 or Euro II (vehicle manufactured year 2001-2004) vehicle class. Figure 4-11 presents the results.

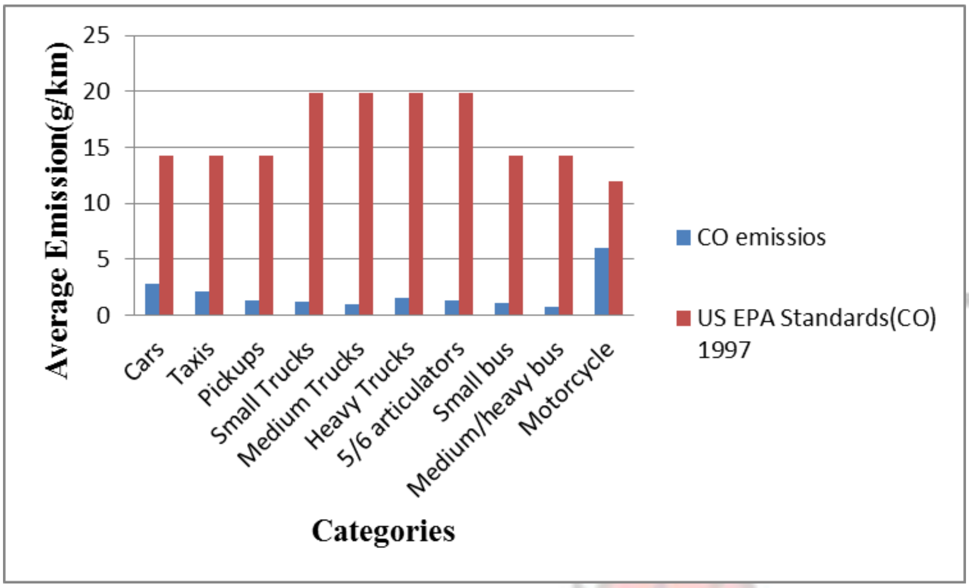

Figure 4-11 Comparison of CO with the US EPA standards

From figure 4-11, it can be deduced that emissions of CO by all vehicle types are in acceptable range as they are below the required limit. Again, figure 4-12 shows a graph of emissions of CO_2 of each vehicle class compared with the US EPA standards.

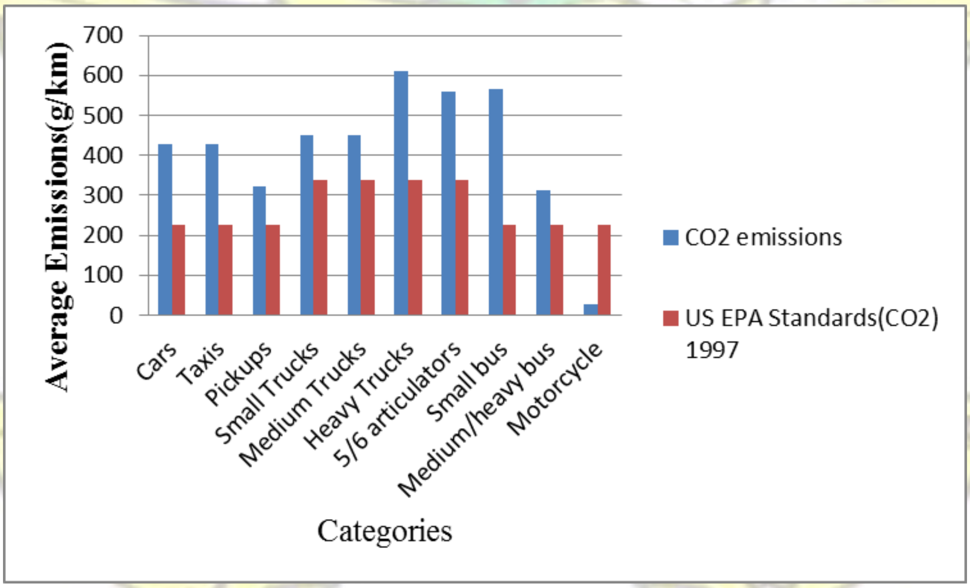

Figure 4-12 Comparison of CO_2 with the US EPA standards

From the figure 4-12, it is observed that, average emissions from passenger cars (cars, taxi, small bus and large bus) were about 90% above the required limit. Light duty vehicles and trucks were in excess of 40% and 70% respectively. Lastly, figure 4-13 also shows graph of emissions of NO_x of each vehicle class compared to the US EPA standards.

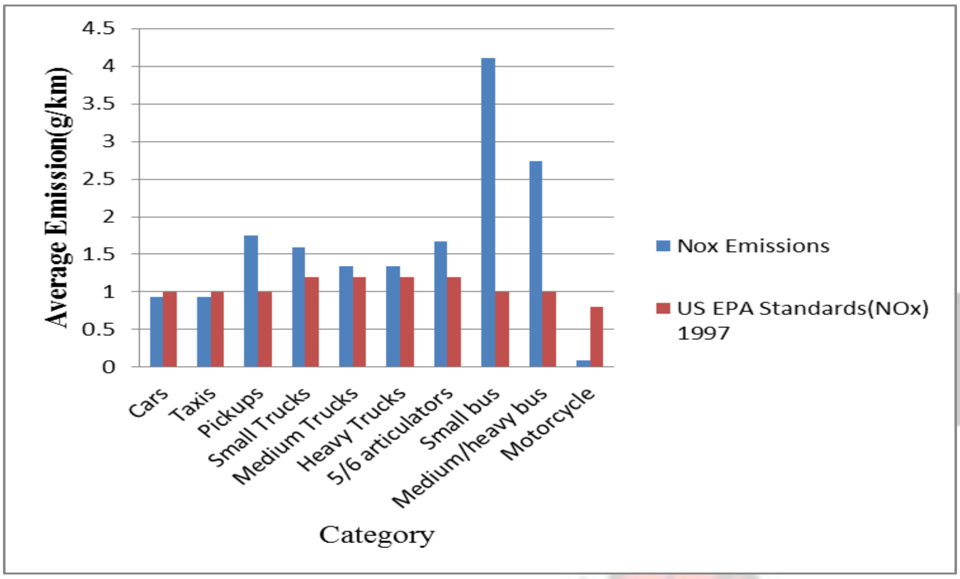

Figure 4-13 Comparison of NOx with the US EPA Standards

Figure 4-13 shows that cars, taxis and motorcycles are less polluting and fall within the legal limit whilst light duty, heavy trucks and buses exceed the required threshold by 50%, 20% and 240% respectively.

4.7 Road Deterioration and the MRH work standards

Figure 4-14 shows the graph of road deterioration with work standard application over the life cycle of the road pavement.

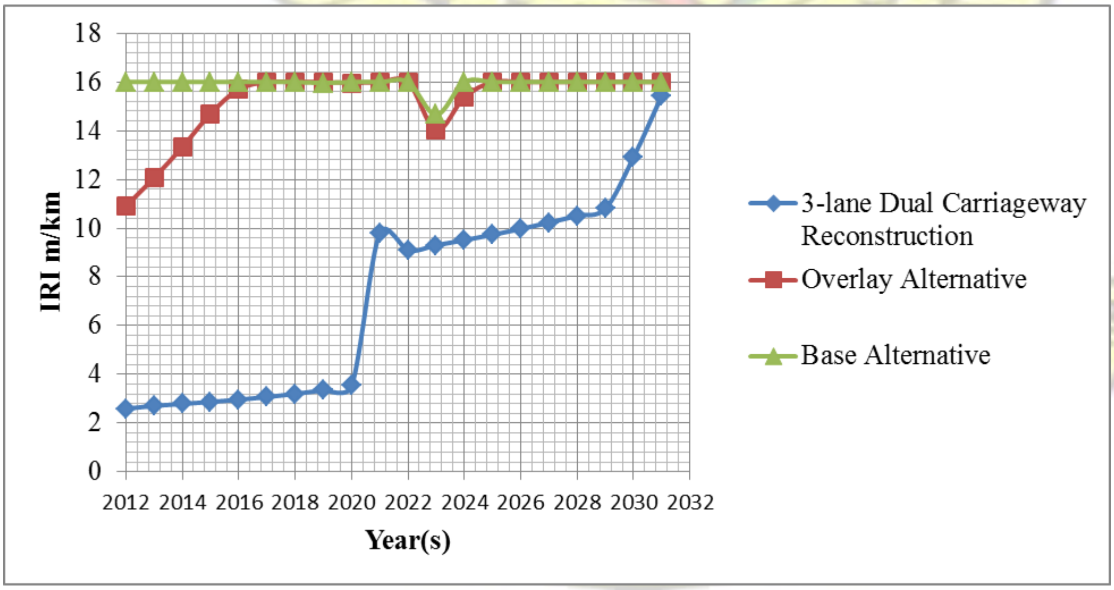

Figure 4-14 Road Deterioration with work standards applied

The discussion is to review the effect of MRH work standards as applied on the study road. It can be seen that the average IRI with only routine maintenance work application for the

3-lane dual carriageway increased gradually from 2.59 to 3.53 and rose suddenly from 3.53 to 9.81 at the year 2021. Upon receiving maintenance overlay intervention, it dropped to 9.07 in 2022. Routine maintenance was then applied after the overlay. IRI then rose gently form 9.07 to 10.81 in 2029. Subsequently, IRI rose sharply from 10.81 to 12.92 and then to 15.44 close to the terminal value of 16. From the same graph, for maintenance overlay, the average IRI increased gradually from 10.91 in 2012 to a maximum of 15.7in 2016 and then increased to 16 in 2017 when only routine maintenance works were applied using the intervention limits. Then after, IRI remained at 16 for the entire life cycle for the overlay option. For the base alternative, routine maintenance work standards such as pothole patching, edge repairs and resealing were applied in the entire life cycle of the pavement. IRI rose sharply form 10.91 in 2009 to 16 in 2012 and then remained fairly unchanged during the entire life of the road. Despite the routine maintenance application, no significant drop in IRI was recorded.

CHAPTER 5:

CONCLUSION AND RECOMMENDATIONS

5.1 Overview

This chapter discusses the conclusions drawn from the outcome of the study. It also outlines a list of recommendations to deepen the policy direction in road maintenance work timings in Ghana. And finally, on suggestions for further research on the subject matter.

5.2 Conclusion

The study showed that, total emissions of CO_2, CO and NOx in 2012 when the road was opened to traffic was around 63,473.906tonnes and is expected to be about 72,471.11tons in 2016, 74,487.04tonnes in 2020, and 79,121.11tonnes by the year 2030. An average yearly increase of 991.71 tonnes of total emissions of CO, CO_2, and NOx is expected in terms of exposure to road users and the environment.

The study also showed a strong correlation between average IRI and total emissions levels. The correlation showed that a change in average IRI directly influenced the total emission on the study road. Total emission prediction by year after exploration followed the logarithmic mathematical equation $y = 991.71\ln(x) + 67946$ where y is total emissions of CO_2, CO and NOx and x the IRI values. This equation which remains a hypothesis was obtained under the initial traffic condition of AADT of about 27,800 for good bituminous roads of 3-lane dual carriageway.

Again, it was indicated that fuel consumption is directly linked to average IRI with coefficient of correlation (R^2) of 0.9965 (very strong). Small cars have the average fuel consumption of 649.98litres per 1000veh/km travel with the highest fuel consumption being heavy trucks with 3449.68litres per 1000veh/km followed by articulated trucks, 3104.131litres and motorcycle being the least with 95.65litres per 1000veh/km for the 3lane dual carriageway.

It is evident emissions on our roads are beyond acceptable standards. A comparison of emission levels by vehicle class on the study road with the standards from the US Environment Protection Agency 1997 indicated higher values. Average emissions of carbon dioxide by each vehicle showed that, passenger cars (cars, taxi's ,small buses and large buses) emits about 90% more than the required threshold whilst light duty vehicle and heavy trucks are in excess of 40% and 70% respectively. For Nitrous Oxide emissions, light duty vehicles, heavy trucks and buses exceeded their thresholds by 50%, 20% and 240% respectively. Carbon monoxides for each vehicle were observed to be within the range of required limits.

From the relation y= 3.0007x + 628.27, it is evident that a unit decrease in IRI causes a decrease in fuel consumption of 3.0litres which is about 0.79 gallons. This is supported by the studies done by Zaabar (2010) as cited by Akbarian et al. (2012) which said that a 3m/km reduction in a pavement IRI would lead to a 10% reduction in rolling resistance which will result in 1-2% reduction in fuel consumption.

MRH interventions limits were found to be effective when strictly applied on the study road. It was found out that, routine maintenance works applied did not reduce IRI however reconstructing the existing two lane into 3-lane dual carriageway greatly reduced the road's IRI from poor to excellent condition.

Finally, based on the National Emission Factors obtained from Environmental Protection Agency Ghana, model emissions factors for HDM-4 were developed CO_2, CO and NOx and were used in the calibration of the vehicle fleet to suit Ghana's condition. See Appendix B.

5.3 Recommendations

In order to minimize fuel use and emission on our roads, the following recommendations are made:

- It is recommended that the MRH implementation agencies adhere strictly to the MRH work standards. This will put the road in passable state and control IRI within acceptable limits thereby minimizing emissions and fuel use. As this study has revealed a strong correlation with increasing IRI with increasing fuel use and exhaust emissions.
- Strick enforcement of legal limits of emissions of vehicles by the DVLA is also an effective way to control fuel use and emissions on our roads.

- ❖ During project appraisal and design, efforts aimed at reducing road roughness, minimizing fuel use and improving safety should be included in the environmental impact assessment.

5.4 Future Research

The following are recommended for future research.

- ❖ Studies to investigate the health effect of the emissions along the corridor by taking data from hospitals and clinics along the study area.
- ❖ The effect of intersections along the road corridor on fuel use and emissions as stop and go is found to influence fuel use and emissions.

5.4.1 Limitation of Emissions and IRI model

- ❖ It can only be applied when predicting emissions on good bituminous asphalt roads during project appraisal.

5.4.2 Key Assumptions

1. It was assumed that a common national vehicle fleet is used on the entire road network as there are few restrictions on vehicles moving on the national road networks.
2. The intersections on the study road were considered as control points for exit and entry into the study road corridor.

REFERENCES

Ã, Seref. Soylu. (2007). Estimation of Turkish road transport emissions, *35*, 4088–4094. http://doi.org/10.1016/j.enpol.2007.02.015

A. Carlson. U. Hammarstrom, Olle Eriksson (2013). Models and methods for the estimation of fuel consumption due to infrastructure parameters Modelling Infrastructure Influence on Road Vehicle Energy Consumption, 1–40.

Abreu, J. De, Moura, F., Garcia, B., & Vargas, R. (2015). Influential vectors in fuel consumption by an urban bus operator : Bus route, driver behavior or vehicle type ?, *38*, 94–104. http://doi.org/10.1016/j.trd.2015.04.003

Achour, H., & Olabi, A. G. (2016). Driving cycle developments and their impacts on energy consumption of transportation. *Journal of Cleaner Production*, *112*, 1778–1788. http://doi.org/10.1016/j.jclepro.2015.08.007

Agyemang-Bonsu, K. W. Dontwi, I. K. Tutu-Benefoh, Bentil, D. E, Boateng, O, G. Asuobonteng, K, Agyemang (2010). Traffic-data driven modelling of vehicular emissions using COPERT III in Ghana : A case study of Kumasi Environmental Protection Agency, Ghana, Energy Resources and Climate Change Unit Kwame Nkrumah University of Science and Technology, Ghana (Departm, *134350*, 32–40).

Akbarian, M., Ulm, F., & Hub, C. S. (2012). Model Based Pavement - Vehicle Interaction Simulation for Life Cycle Assessment of Pavements, (April).

Anin, E. K., & Annan, J. (2013). Evaluating the Role of Mass Transit and its Effect on Fuel Efficiency in the Kumasi, 107–116.

Bakhit, P., Said, D., & Radwan, L. (2015). Impact of Acceleration Aggressiveness on Fuel Consumption Using Comprehensive Power Based Fuel Consumption Model, *7*(3), 148–157.

Bank, W. (1998). Data requirements, (March 1997), 1–6.

Barth, N, F..,Norbeck N. J. and Ross, M. A. (1997). Development of Comprehensive Modal Emissions Model Operating Under Hot-Stabilized Conditions, (970706), 52–62.

Bellasio, R., Bianconi, R., Corda, G., & Cucca, P. (2007). Emission inventory for the road transport sector in Sardinia (Italy), *41*, 677–691. http://doi.org/ 10.1016/ j.atmosenv.2006.09.017

Bennett, C. R., & Greenwood, I. D. (2001). *Modeling Road User and Environmental Effect in HDM-4. Volume 7. The Highway and Development Management Series: Asian Development Bank*.

Bhandari, K., Parida, P., & Singh, P. (2013). Estimation of Carbon Footprint of Fuel

Loss Due to Idling of Vehicles at Signalised Intersection in Delhi. *Procedia - Social and Behavioral Sciences*, *104*, 1168–1177. http://doi.org/10.1016/j.sbspro.2013.11.213

Boubaker, S., Rehimi, F., & Kalboussi, A. (2016). Impact of intersection type and a vehicular fleet's hybridization level on energy consumption and emissions. Journal of Traffic and Transportation Engineering (English Edition). http://doi.org/10.1016/j.jtte.2016.05.003

Carrese, S., Gemma, A., & La, S. (2013). Impacts of driving behaviours, slope and vehicle load factor on bus fuel consumption and emissions : a real case study in the city of Rome. *Procedia - Social and Behavioral Sciences*, *87*, 211–221. http://doi.org/10.1016/j.sbspro.2013.10.605

Claxton, L. D. (2015). Mutation Research / Reviews in Mutation Research The history, genotoxicity, and carcinogenicity of carbon-based fuels and their emissions. Part 3 : Diesel and gasoline §. *Mutation Research-Reviews in Mutation Research*, *763*, 30–85. http://doi.org/10.1016/j.mrrev.2014.09.002

EPA, U. (2012). Using MOVES for Estimating State and Local Inventories of On-Road Greenhouse Gas Emissions and Energy Consumption.

Ericsson, E. (2001). Independent driving pattern factors and their influence on fuel-use and exhaust emission factors, *6*.

Ericsson, E., Larsson, H., & Brundell-freij, K. (2006). Optimizing route choice for lowest fuel consumption – Potential effects of a new driver support tool, *14*, 369–383. http://doi.org/10.1016/j.trc.2006.10.001

Etsu. (1997). Emissions Modelling Framework for HDM-4, (1).

Greene, S., & Ulm, F. (2013). Pavement Roughness and Fuel Consumption This research was carried out by the CSHub @ MIT with sponsorship provided by the Portland Cement Association (PCA) and the Ready Mixed Concrete (RMC) Research & Education, (August).

Greenwood, I. D., & Dunn, A. R. C. M. (2003). A New Approach To Estimate Congestion Impacts For Highway Evaluation -Effects On Fuel Consumption And Vehicle Emissions.

Huzayyin, A. S., & Salem, H. (2013). Research in Transportation Economics Analysis of thirty years evolution of urban growth, transport demand and supply, energy consumption, greenhouse and pollutants emissions in Greater Cairo q. *Research in Transportation Economics*, *40*(1), 104–115. http://doi.org/ 10.1016/ j.retrec.2 012.06.035

IEA. (2015). World Energy Outlook 2015 factsheet global energy trends to 2040 world energy outlook 2015 factsheet The energy sector and climate change in the runup to COP21, 2014–2016.

IEA. (2016). Energy and Air Pollution.

Kang, M., Shariat, S., & Jha, M. K. (2013). New highway geometric design methods for minimizing vehicular fuel consumption and improving safety. *Transportation Research Part C*, *31*, 99–111. http://doi.org/10.1016/j.trc. 2013.03.002 Kerali, Henry G R, J.B. Odoki, Eric E. S. (1999). Overview of HDM-4.

Koranteng-yorke, J. B. (2012). A proposed framework for asphaltic concrete pavement design for tropical soils – case study of Ghana by John Bernard KorantengYorke a thesis submitted to the University of Birmingham for the degree of doctor of philosophy School of Civil Engineering Univ, (March).

Lu, I. J., Lewis, C., & Lin, S. J. (2009). The forecast of motor vehicle, energy demand and CO 2 emission from Taiwan's Road Transportation sector. *Energy Policy*, *37*(8), 2952–2961. http://doi.org/10.1016/j.enpol.2009.03.039

Ma, H., Xie, H., Huang, D., & Xiong, S. (2015). Effects of driving style on the fuel consumption of city buses under different road conditions and vehicle masses. *Transportation Research Part D*, *41*, 205–216. http://doi.org/10. 1016/ j.trd.2015.10.003

NDLI. (1995). Modeling Road User Effect In HDM-4.

Nesamani, K. S., Chu, L., Mcnally, M. G., & Jayakrishnan, R. (2007). Estimation of vehicular emissions by capturing traffic variations, *41*, 2996–3008. http://doi.org/10.1016 j.atmosenv.2006.12.027

Odoki, J. B., & Kerali, H. G. R. (1999). Analytical Framework and Model Descriptions.

Pandian, S., Gokhale, S., & Kumar, A. (2009). Evaluating effects of traffic and vehicle characteristics on vehicular emissions near traffic intersections. *Transportation Research Part D*, *14*(3), 180–196. http://doi.org/10.1016 /j.trd.2008.12.001

Sierra, J. C. (2016). Estimating road transport fuel consumption in Ecuador. *Energy Policy*, *92*, 359–368. http://doi.org/10.1016/j.enpol.2016.02.008

Solís, J. C., & Sheinbaum, C. (2013). Energy for Sustainable Development Energy consumption and greenhouse gas emission trends in Mexican road transport. *Energy for Sustainable Development*, *17*(3), 280–287. http://doi.org/10 .1016/ j.esd .2012.12.001

Song, Y., Yao, E., Zuo, T., & Lang, Z. (2013). Emissions and Fuel Consumption Modeling for Evaluating Environmental Effectiveness of ITS Strategies, *2013*.

Tong, H. Y., Hung, W. T., & Cheung, C. S. (2016). On-Road Motor Vehicle Emissions and Fuel Consumption in Urban Driving Conditions On-Road Motor Vehicle Emissions and Fuel Consumption in Urban Driving Conditions, *3289*(May). http://doi.org/10.1080/10473289.2000.10464041

Tsang, K. S., Hung, W. T., & Cheung, C. S. (2011). Emissions and fuel consumption of a Euro 4 car operating along different routes in Hong Kong. *Transportation Research Part D*, *16*(5), 415–422. http://doi.org/10.1016/j .trd.2011.02.004

Wang, H., Fu, L., Wang, H., & Fu, L. (2012). Developing a High-Resolution Vehicular Emission Inventory by Integrating an Emission Model and a Traffic Model : Part 1 — Modeling Fuel Consumption and Emissions Based on Speed and Vehicle-Specific Power Developing a High-Resolution Vehicular Emission In, *2247*(December 2015). http://doi.org/10.3155/1047-3289.60.12.1463

Wang, H., Fu, L., Zhou, Y., Du, X., & Ge, W. (2010). Trends in vehicular emissions in China's mega cities from 1995 to 2005. *Environmental Pollution*, *158*(2), 394–400. http://doi.org/10.1016/j.envpol.2009.09.002

Xie, Y., Chowdhury, M., Bhavsar, P., & Zhou, Y. (2012). An integrated modeling approach for facilitating emission estimations of alternative fueled vehicles. *Transportation Research Part D*, *17*(1), 15–20. http://doi.org/10.1016/j.trd.2011.08.009

Yu, Q., Li, T., & Li, H. (2016). Improving urban bus emission and fuel consumption modeling by incorporating passenger load factor for real world driving, *161*, 101–111. http://doi.org/10.1016/j.apenergy.2015.09.096

Zeng, W., Miwa, T., & Morikawa, T. (2016). Prediction of vehicle CO_2 emission and its application to eco-routing navigation. Transportation Research Part c, *68*, 194–214. http://doi.org/10.1016/j.trc.2016.04.007

APPENDICES

Appendix A	Model Equations of CO, CO_2 and NOx
Appendix B	Summary of Sectional Attributes on Existing Road
Appendix C	International Roughness Index Measurements and Results
Appendix D	International Roughness Index Prediction from the HDM-4
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Appendix G	US EPA federal Emission Standards 1997

APPENDIX A: HDM-4 MODEL EQUATIONS FOR CO, CO_2 AND NO_X

EQUATIONS OF CO, CO_2 AND NO_X IN THE HDM-4

1. ***Carbon Monoxide***

$EOE_{CO} = a_{CO} FC$ where,

EOE_{CO} - Engine-out carbon monoxide emissions (g/veh-km)

a_{CO} - ratio of engine-out emissions per gram of fuel consumed for emission CO (gCO/gfuel)

All other variables are as defined previously

2. Nitrous Oxide

$$EOE_{NOX} = \max\left[a_{nox}\left(FC - \frac{FR_{NOX}}{v}1000\right), 0\right]$$

Where,

EOE_{NOX} - Engine-out nitrous oxide emissions (g/veh-km)

a_{nox} - ratio of engine-out emissions per gram of fuel consumed for

emission

NOx (gNOx/gfuel)

FR_{NOX}

- is a the fuel threshold below which NOx emissions are very low in g/s

All other variables are as defined previously.

3. Carbon dioxide

$$TPE_{CO2} = 44.011\left[\left(\frac{FC}{12.011 + 1.008a_{CO2}} - \frac{TPE_{CO}}{28.011} - \frac{TPE_{HC}}{13.018} - \frac{TPE_{PM}}{12.011}\right)\right]$$

TPE_{CO2} - Tail pipe carbon dioxide emissions (g/veh-km)

a_{CO2} - fuel dependent model parameter representing the ratio of hydrogen to carbon atoms in the fuel

All other variables are as defined previously

APPENDIX B: SUMMARY OF SECTIONAL ATTRIBUTES ON EXISTING DATA

Pavement Characteristics, Alignment and Geometry

Length	14.125km
Speed Flow	Two Lane Standard
Carriageway width	7.3
Shoulder Width	2.0
Number of Lanes	2.0
Surface Class	Bituminous
Pavement Type	Asphaltic Mix on Crushed Rock Base
Average Rise + Fall	15.8m/km
No. of Rise	2 per km
Average Horizontal Curvature	12 degree/km
Average Speed Limit	25km/hr

Average Roughness	4 IRI

(source: Feasibility and Final Design Report George Walker Bush Motorway)

Climatic Characteristics of Study Zone

Name of Climatic Zone	**Rest of Ghana**
Moisture Classification	Sub Humid
Moisture Index	0
Duration of Dry Season	0.5
Mean Monthly Precipitation	100mm
Temperature Classification	Tropical
Mean Temperature	$27^{o}C$
Average Temperature Range	5 $_{o}$C
Days Temperature Exceeds 32oC	90 days
Freeze Index	0
Percentage of time driven on water covered roads	20

(source: Feasibility and Final Design Report George Walker Bush Motorway)

Road Capacity and Speed Flow Relationships

General	
Name	Trunk Two lane Standard
Capacity	
Road Type	Three lane Road
Ultimate capacity	1400 PCUs/lane/hr
Free flow capacity	0.1
Nominal capacity	0.9
Jam speed at capacity	25km/hr
Speed Related	
Maximum Acceleration Noise	$0.65m/s^2$
Desired Speed Multiplication Factor	1

Traffic Flow Pattern	Urban Traffic Flow
Year of Traffic Record	2,008
Flow Direction	Two Way

(source: Feasibility and Final Design Report George Walker Bush Motorway)

Normal traffic Count for the Survey year

Census Points		Vehicle category-wise AADT, Survey Year 2008											AADT (all vehicles in Nos.)
	Cycle	2 - Wheeler	Car	Taxi	Utilities	Small Bus	Medium & Large Bus	2 Axle Truck	3 Axle Truck	4 Axle Truck	5 Axle Truck	6 Axle Truck	
Dzorwulu	229	468	9190	4908	5798	5555	574	1825	709	364	176	445	30241
Achimota	236	346	8747	5985	3837	5598	720	1767	442	237	115	289	28319
Darkuman	308	378	8221	6498	2439	8085	546	1191	280	165	77	199	28387
Awoshie	229	326	6633	4590	3561	6333	348	1296	423	97	45	119	24000
Average AADT	250.5	379.5	8197.8	5495.3	3908.8	6392.8	547.0	1519.8	463.5	215.8	103.3	263.0	**27736.8**
% Composition	**0.90**	**1.37**	**29.56**	**19.81**	**14.09**	**23.05**	**1.97**	**5.48**	**1.67**	**0.78**	**0.37**	**0.95**	**100.00**

(source: Feasibility and Final Design Report George Walker Bush Motorway)

Traffic growth rate

Vehicle	**Annual Traffic Growth Rate (%)**					
	2008-2011	**2012-2016**	**2017-2021**	**2022-2026**	**2027-2031**	**Average**
Motorized 2-Wheelers	7.5	7.8	6.6	6.1	6.1	6.8
Cars	6.4	6.6	6	5.5	5.5	6.0
Taxi & Utilities	7	7.2	6.6	5.5	5.5	6.2

Buses	4.1	4.4	4.1	3.9	3.5	5.3
Trucks	5.1	5.5	5	4.7	4	4.4

(source: Feasibility and Final Design Report George Walker Bush Motorway)

Details of Vehicle Characteristics

Name of Vehicle Type	Base Type	ESALF	PCUs	No. of Wheels	No. of Axles	Tyre Type
Car	Medium Car	0.0001	1.00	4	2	Radial ply
Taxi	Medium Car	0.0001	1.00	4	2	Radial ply
Pickups	Four Wheel Car	0.12	1.00	4	2	Bias ply
Light Truck	Light Truck	0.24	1.30	6	2	Bias ply
Medium truck	Medium Truck	6.53	1.40	6	2	Bias ply
Heavy Truck	Heavy Truck	8.06	1.60	10	3	Bias ply
4 or 5 axle Articulator	Articulated Truck	13.32	1.80	14	4	Bias ply
Small Bus	Mini Bus	0.91	1.20	4	2	Radial ply
Medium/Heavy Bus	Medium Bus	3.15	1.50	6	2	Bias ply
Motorcycle/Scooter	Motorcycle	0.00	0.50	2	2	Bias ply

Source: Development of Capacity to use HDM-4 for Planning, Programming, and Budgeting: HDM-4 Configuration and Calibration

Vehicle masses

Vehicle Type	$m = \frac{Pe\,TARE + Ph(0.5TARE + 0.5GVW) + Pf(GVW) + Po(zoGVW)}{100}$ …(6) Where *Pi* is the percentage of vehicle empty, half full, full or overloaded; GVW the manufacturer's gross weight, TARE the empty weight and zo the overloaded weight relative to the GVW in decimal
Bicycle	100
Car	1600
Pickup	2000

Light Truck	6250
Medium Truck	11,620
Heavy Truck	27,300
Small Bus	3,720
Medium/Heavy Bus	9,000
Articulated Truck	38,000
Motorcycle	200

Source: Development of Capacity to use HDM-4 for Planning, Programming, and Budgeting: HDM-4 Configuration and Calibration Final Report (MRH)

National Road Transport Emission Factors EPA Ghana

Sector	Subse	Legislation	CO_2	CH_4	N_2O	NO_x	VOC	CO	PM
Passenger	Gasol	Uncontrolled	318.14	0.02	0.03	1.62	1.02	2.14	0.00
Passenger	Diesel		313.44	0.00	0.03	0.79	0.36	0.73	0.23
Passenger	LPG	Uncontrolled	366.29	0.03	0.01	0.78	0.44	1.62	0.00
Light Duty	Gasol	Uncontrolled	318.14	0.03	0.03	1.67	1.01	2.86	0.00
Light Duty	Diesel		318.14	0.00	0.02	1.03	0.38	0.84	0.26
Heavy Duty	Diesel		318.14	0.03	0.03	0.94	0.46	0.71	0.08
Urban Buses	Diesel		318.14	0.06	0.03	2.27	0.17	0.57	0.08
Coaches	Diesel		318.14	0.07	0.03	2.77	0.42	0.70	0.13
Mopeds	Gasol	Uncontrolled	318.14	0.04	0.00	0.01	1.83	3.00	0.00
Motorcycle 2-stroke	Gasol	Uncontrolled	318.14	0.15	0.00	0.02	3.73	10.00	0.00
Motorcycle 4-stroke	Gasol	Uncontrolled	318.14	0.20	0.00	0.12	0.43	8.35	0.00

NB: Uncontrolled catalytic converters assumed virtually nonfunctional EPA (2007) generated from

Calibration of HDM-4 model emission factors for Ghana

Vehicle Type	Fuel Consumption (FC) (L/1000 km)		FC/Power Total	FC (g/km)	TPE CO2	TPE Nox (g/km)	TPE CO (g/km)	TPE PM (g/km)	TPE HC (g/km)	Default FRnox	rHC	aPM	Mean Operating Speed m/s	aCo2	aCO	aNOx
	Observed	Predicted														
Car	109.65	85.45	0.087	94.30	318.14	0.79	2.14	0	1.02	0.17	0	0.0001	20.56	0.765635	0.022694	0.009183
Taxi	109.65	85.45	0.087	94.30	366.29	0.79	1.62	0	0.44	0.17	0	0.0001	20.56	-0.78675	0.017179	0.009183
Pickup	82.02	83.31	0.0561	70.54	318.14	1.03	0.84	0.26	0.38	0.17	0	0.0001	22.22	-2.33124	0.011909	0.016379

Small Bus	107.05	106.41	0.0675	92.06	313.44	2.27	0.57	0.08	0.17	0	0	0.0032	18.61	0.847724	0.006191	0.024657
Medium Bus	163	159	0.0583	140.18	313.44	2.27	0.57	0.08	0.17	0	0	0.0032	18.06	7.512849	0.004066	0.016193
Heavy Bus	286.9	229.86	0.073	246.73	313.44	2.77	0.7	0.13	0.42	0	0	0.0032	17.22	22.13948	0.002837	0.011227
Light Truck	170.3	130	0.0761	146.46	313.44	1.03	0.84	0.26	0.38	0.17	0	0.0032	17.22	8.267675	0.005735	0.007541
Medium Truck	205.6	170.5	0.0695	176.82	313.44	0.94	0.71	0.08	0.46	0	0	0.0032	20.00	12.49471	0.004015	0.005316
Heavy Truck	418	385.91	0.0611	359.48	313.44	0.94	0.71	0.08	0.46	0	0	0.0032	20.56	37.70118	0.001975	0.002615
Articulated Truck	477.4	477.3	0.055	410.56	313.44	0.94	0.71	0.08	0.46	0	0	0.0032	20.83	44.75044	0.001729	0.00229
Motorcycle	30	26.65	0.765	25.80	318.14	0.12	8.35	0	3.72	0	0	0.0001	18.06	-8.62857	0.323643	0.004651

Vehicle fuel consumption for good bituminous road

Vehicle Type	Fuel Consumption (FC) (L/1000 km)		=+ FC/Power
	Observed	Predicted	Total
Car	109.65	85.45	0.0870
Taxi	109.65	85.45	0.0870
Pickup	82.02	83.31	0.0561
Small Bus	107.05	106.41	0.0675
Medium Bus	163.00	159.00	0.0583
Heavy Bus	286.90	229.86	0.0730
Light Truck	170.30	130.00	0.0761
Medium Truck	205.60	170.50	0.0695
Heavy Truck	418.00	385.91	0.0611
Articulated Truck	477.40	477.30	0.0550
Motorcycle	30.00	26.65	0.0765

Source: Development of Capacity to use HDM-4 for Planning, Programming, and Budgeting: HDM-4 Configuration and Calibration Final Report (MRH)

MRH Work standards

Activity	Potholes	Units	Value
Overlay	Roughness	IRI	≥6
Overlay Crack	Total damaged area	%	≥15
Patching	Potholes	No. /Km	>10 ≤ 20
Crack Sealing	Wide Structural cracks	%	≥ 5
Reconstruction	Roughness	IRI	≥ 8

Unit Cost of Works

S/No.	Description	Units	Rate (¢)		
			Economic Unit Cost($)	Financial Unit Cost ($)	Budget Heading
1	Crack sealing	m^2	8.25	9.5	Recurrent

2	Patching	m^2	10.07	11.58	Recurrent
3.	Edge repair	m^2	7.06	8.12	Recurrent
4	Drainage	m^2	8.50	9.78	Recurrent
5	Thin overlay	m^2	62.86	72.29	Capital
6	Single Surface Dressing	m^2	6.91	7.94	Capital
7	Double Surface Dressing	m^2	8.30	9.55	Capital
8	Overlay Dense Graded Asphalt	m^2	22.60	25.99	Capital
9.	Pavement reconstruction (i) Asphaltic concrete	Km	700,000.00	805,000.00	Capital

Road Condition data for 2008

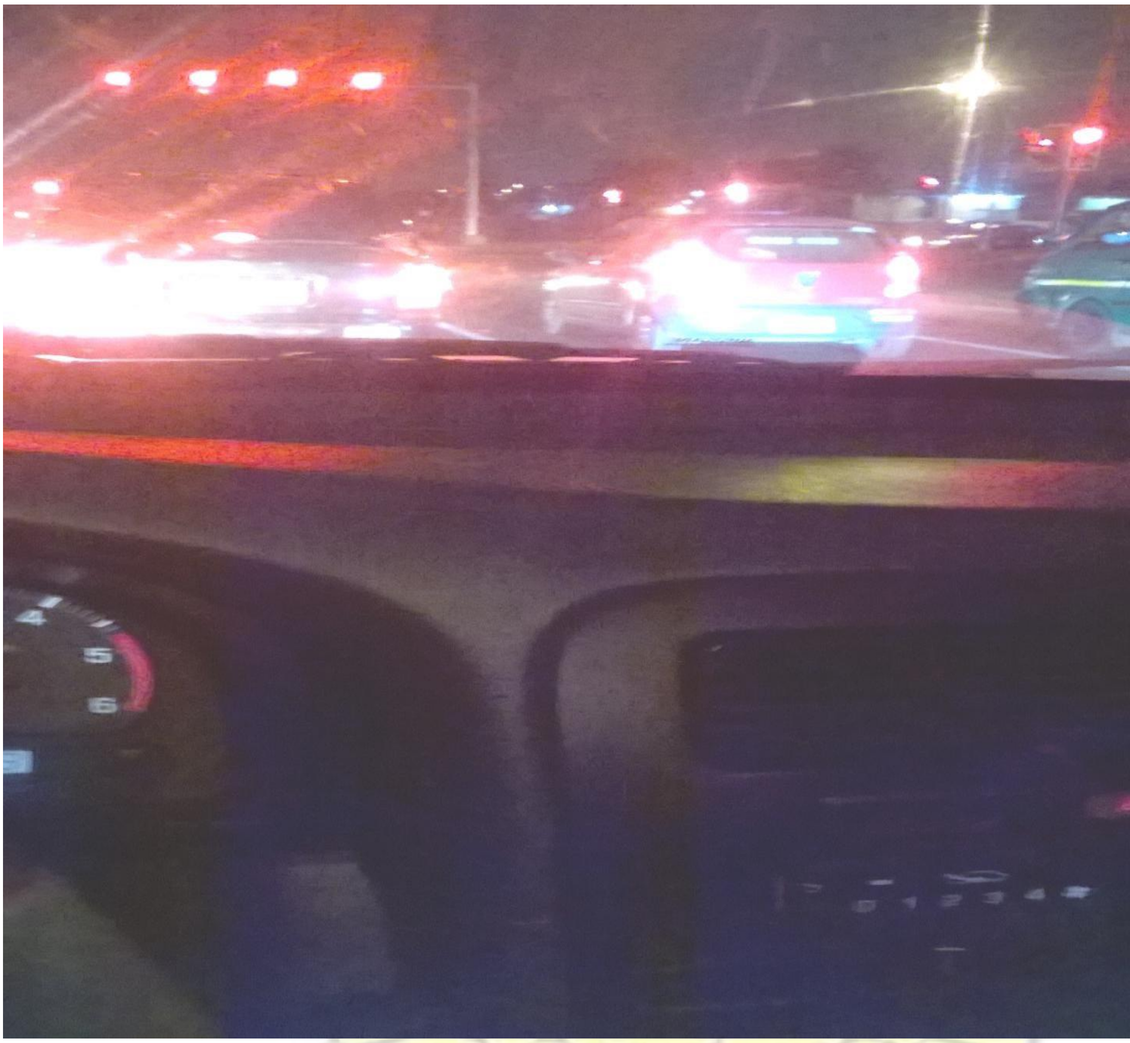
Road Defects	**Condition Year 2008**
Roughness- m/km	4
All structural cracks (%)	65
Wide Structural cracks (%)	65
Thermal cracking (%)	25
Raveling area (%)	65
No. of Potholes (No./km)	189
Edge break Area (m2/km)	0
Mean rut depth (mm)	52.5
Rut depth Standard Deviation (mm)	
Texture depth (mm)	0.5
Skid Resistance (SCRIM 50km/h)	0.4
Drainage	fair

Derivation of Structural Numbers

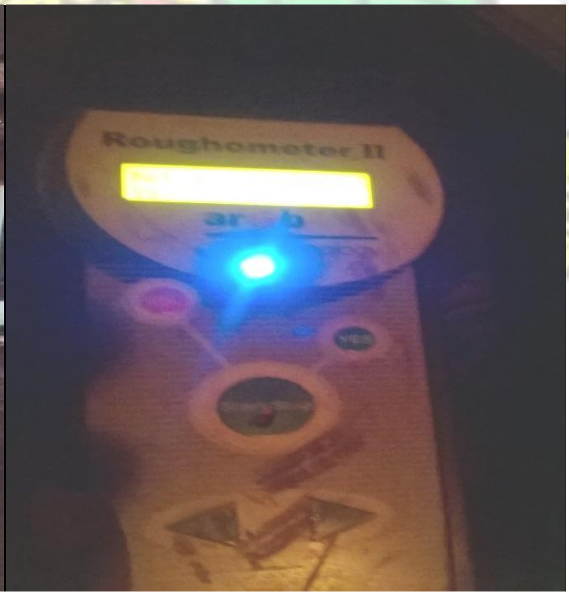
Without Project Case

Layer	**Material Description**	**Alt 1 (mm)**	**Structural layer Coefficient**	**Drainage Coefficient**	**Structural Number SN(mm)**	**Structural Number SN(inch)**
Surface Course	A/C	50	0.17	1	35.5	1.41
Binder Course	A/C	50	0.17	1		
Binder Course	A/C	50	0.17	1		
Base	Natural Gravel	100	0.05	1		
Subbase	Natural Gravel	100	0.05	1		
			Project Case			
Layer	**Material Description**	**Alt 2 (mm)**	**Structural layer Coefficient**	**Drainage Coefficient**	**Structural Number SN(mm)**	**Structural Number SN(inch)**
Wearing Course	A / C	50	0.375	1	186.875	7.00
Wearing Course	A / C	100	0.375	1		
Base	Crush rock base	225	0.275	1		
Subbase	Stabilized Natural Gravel	250	0.275	1		

APPENDIX C: INTERNATIONAL ROUGHNESS INDEX MEASUREMENTS AND RESULTS



Front view of the test vehicle



Rear of test vehicle

Roughometer II instrument

On-Road Roughness Measurement Results

Field Data Sheet

ROAD NAME: TETTEH QUARSHIE - MALLAM JUNCTION

SECTION: FROM: TETTEH QUARSHIE TO: MALLAM JUNCTION

SURVEY DATE: 2016-02-22 TIME: 23:00:42

TRAVEL DIRECTION: WEST

REFERENCE: NIL

VEHICLE: NISSAN PICK UP - GV - 477 - 14

OPERATOR: ERNEST OSEI-BONSU

COMMENTS: ASPHALTIC CONCRETE ROAD

Roughness Value

SecID	SubDist	TotDist	IRI	Speed	Event
1	0.010	0.010	11.9	17.3	
1	0.020	0.020	4.5	21.3	
1	0.030	0.030	15.4	27.5	
1	0.040	0.040	15.3	31.7	
1	0.050	0.050	8.4	35.4	
1	0.060	0.060	5.8	37.8	
1	0.070	0.070	5.0	38.5	
1	0.080	0.080	3.0	40.4	
1	0.090	0.090	1.3	42.5	
1	0.100	0.100	2.7	44.5	
1	0.110	0.110	2.8	45.4	
1	0.120	0.120	3.0	45.9	
1	0.130	0.130	3.3	46.0	
1	0.140	0.140	3.4	46.0	
1	0.150	0.150	1.6	45.2	
1	0.160	0.160	3.5	44.3	
1	0.170	0.170	1.4	43.6	
1	0.180	0.180	2.6	43.1	
1	0.190	0.190	2.9	43.2	
1	0.200	0.200	4.5	43.1	
1	0.210	0.210	3.1	43.4	
1	0.220	0.220	2.4	43.7	
1	0.230	0.230	1.7	44.2	
1	0.240	0.240	1.5	44.9	
1	0.250	0.250	1.5	45.9	
1	0.260	0.260	1.5	46.6	
1	0.270	0.270	1.3	47.4	
1	0.280	0.280	1.2	48.0	
1	0.290	0.290	2.1	48.5	
1	0.300	0.300	1.6	48.5	
1	0.310	0.310	1.5	47.5	
1	0.320	0.320	2.1	46.5	
1	0.330	0.330	2.5	45.7	
1	0.340	0.340	1.4	45.5	

Field Data Sheet

ROAD NAME: TETTEH QUARSHIE - MALLAM JUNCTION

SECTION: FROM: TETTEH QUARSHIE TO: MALLAM JUNCTION

SURVEY DATE: 2016-02-22 TIME: 23:00:42

TRAVEL DIRECTION: WEST

REFERENCE: NIL

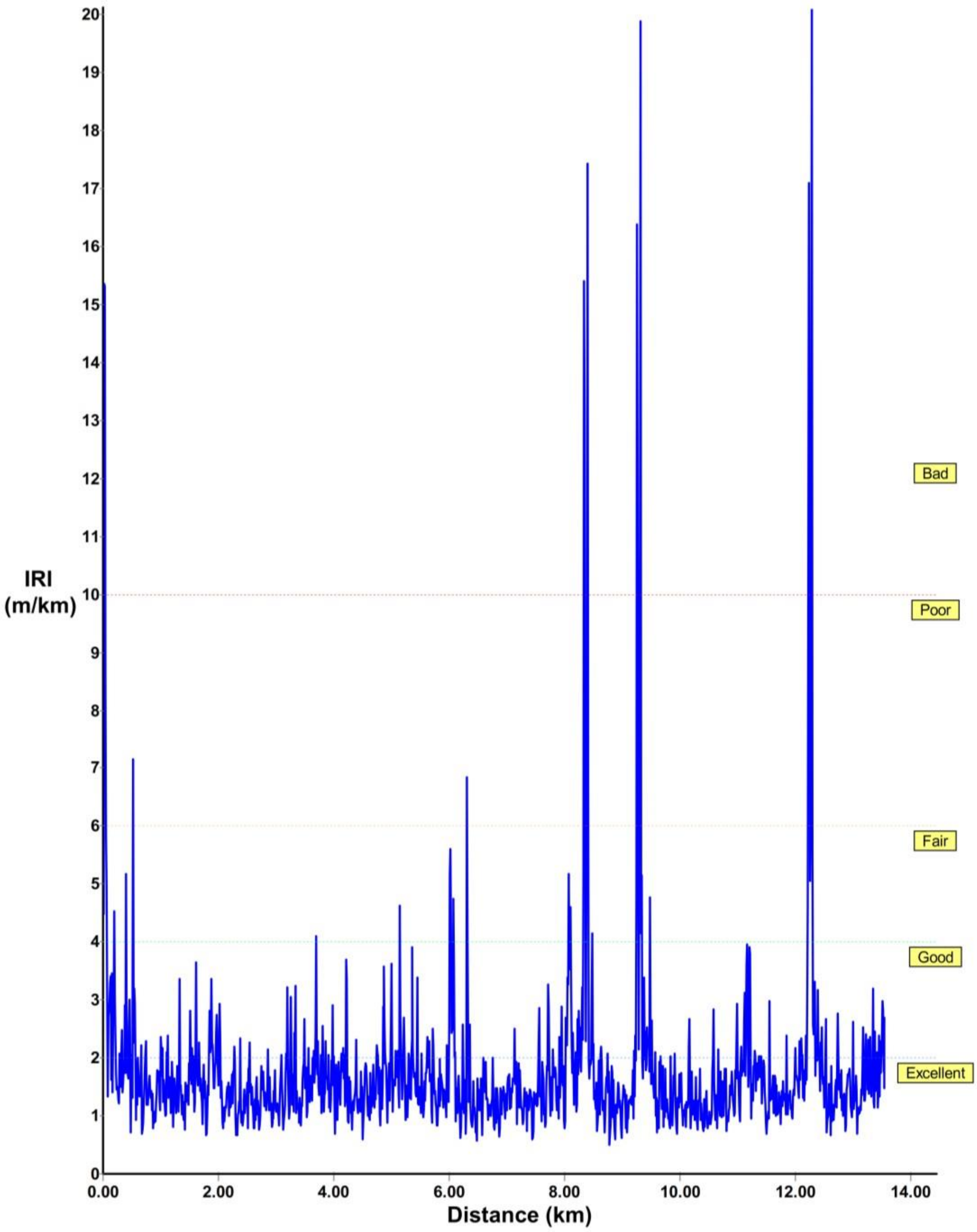
VEHICLE: NISSAN PICK UP - GV - 477 - 14

OPERATOR: ERNEST OSEI-BONSU

COMMENTS: ASPHALTIC CONCRETE ROAD

Roughness Value

SecID	SubDist	TotDist	IRI	Speed	Event
1	0.010	0.010	11.9	17.3	
1	0.020	0.020	4.5	21.3	
1	0.030	0.030	15.4	27.5	
1	0.040	0.040	15.3	31.7	
1	0.050	0.050	8.4	35.4	
1	0.060	0.060	5.8	37.8	
1	0.070	0.070	5.0	38.5	
1	0.080	0.080	3.0	40.4	
1	0.090	0.090	1.3	42.5	
1	0.100	0.100	2.7	44.5	
1	0.110	0.110	2.8	45.4	
1	0.120	0.120	3.0	45.9	
1	0.130	0.130	3.3	46.0	
1	0.140	0.140	3.4	46.0	
1	0.150	0.150	1.6	45.2	
1	0.160	0.160	3.5	44.3	
1	0.170	0.170	1.4	43.6	
1	0.180	0.180	2.6	43.1	
1	0.190	0.190	2.9	43.2	
1	0.200	0.200	4.5	43.1	
1	0.210	0.210	3.1	43.4	
1	0.220	0.220	2.4	43.7	
1	0.230	0.230	1.7	44.2	
1	0.240	0.240	1.5	44.9	
1	0.250	0.250	1.5	45.9	
1	0.260	0.260	1.5	46.6	
1	0.270	0.270	1.3	47.4	
1	0.280	0.280	1.2	48.0	
1	0.290	0.290	2.1	48.5	
1	0.300	0.300	1.6	48.5	
1	0.310	0.310	1.5	47.5	
1	0.320	0.320	2.1	46.5	
1	0.330	0.330	2.5	45.7	
1	0.340	0.340	1.4	45.5	


IRI (m/km)
Distance (km)
Bad
Poor
Fair
Good
Excellent

Field Data Sheet

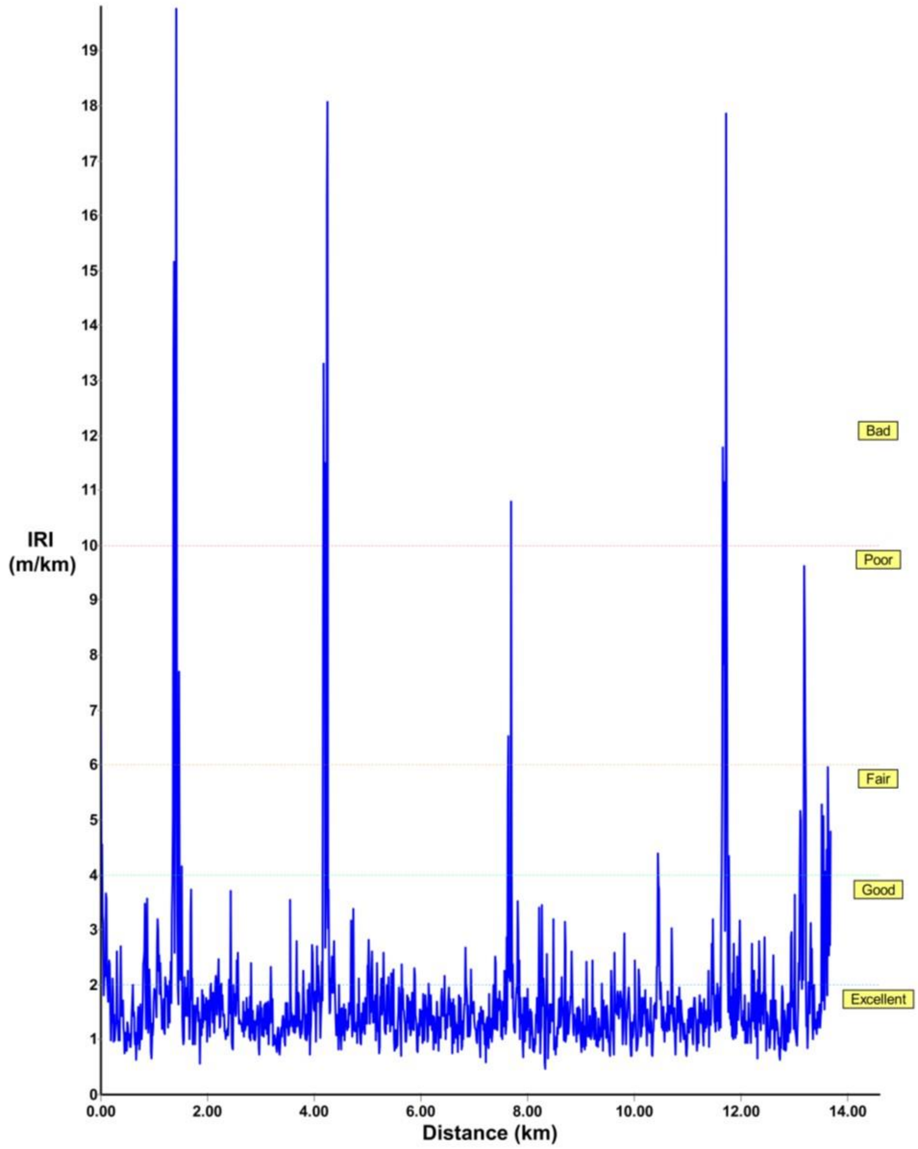
ROAD NAME:	TETTEH QUARSHIE- MALLAM JUNCTION ROAD
SECTION:	FROM: MALLAM JUNCTION TO: TETTEH QUARSHIE
SURVEY DATE:	2016-02-22 TIME: 23:26:19
TRAVEL DIRECTION:	TETTEH QUARSHIE BOUND
REFERENCE:	NIL
VEHICLE:	NISSAN PICK UP - GV - 477 - 14
OPERATOR:	ERNEST OSEI-BONSU
COMMENTS:	ASPHALTIC CONCRETE ROAD

Roughness Value

SecID	SubDist	TotDist	IRI	Speed	Event
1	0.010	0.010	6.8	37.7	
1	0.020	0.020	4.2	38.0	
1	0.030	0.030	4.6	38.6	
1	0.040	0.040	3.3	39.3	
1	0.050	0.050	3.1	39.7	
1	0.060	0.060	1.8	40.3	
1	0.070	0.070	2.1	40.7	
1	0.080	0.080	2.4	41.3	
1	0.090	0.090	2.2	41.4	
1	0.100	0.100	3.7	41.8	
1	0.110	0.110	3.6	41.8	
1	0.120	0.120	2.1	41.8	
1	0.130	0.130	2.0	41.8	
1	0.140	0.140	1.7	41.8	
1	0.150	0.150	2.2	42.6	
1	0.160	0.160	2.4	42.8	
1	0.170	0.170	2.4	42.4	
1	0.180	0.180	1.6	42.5	
1	0.190	0.190	1.0	43.4	
1	0.200	0.200	1.5	44.1	
1	0.210	0.210	1.3	45.0	
1	0.220	0.220	2.1	44.9	
1	0.230	0.230	1.8	46.6	
1	0.240	0.240	1.0	47.5	
1	0.250	0.250	1.5	48.0	
1	0.260	0.260	1.0	48.7	
1	0.270	0.270	1.2	48.8	
1	0.280	0.280	1.3	48.8	
1	0.290	0.290	1.3	48.7	
1	0.300	0.300	2.6	48.7	
1	0.310	0.310	1.4	48.6	
1	0.320	0.320	1.2	48.5	
1	0.330	0.330	1.0	48.4	
1	0.340	0.340	1.2	48.3	

1	13.069	13.069	1.3	48.5
1	13.079	13.079	1.6	48.7
1	13.089	13.089	2.4	47.6
1	13.099	13.099	2.1	47.4
1	13.109	13.109	4.0	46.4
1	13.119	13.119	5.2	45.5
1	13.129	13.129	5.0	44.2
1	13.139	13.139	2.4	43.5
1	13.149	13.149	1.9	42.9
1	13.159	13.159	3.5	42.6
1	13.169	13.169	2.1	42.4
1	13.179	13.179	4.4	42.6
1	13.189	13.189	9.6	42.9
1	13.199	13.199	8.4	43.3
1	13.209	13.209	6.4	43.5
1	13.219	13.219	5.3	45.1
1	13.229	13.229	2.1	46.2
1	13.239	13.239	1.2	47.1
1	13.249	13.249	1.5	48.1
1	13.259	13.259	0.8	48.7
1	13.269	13.269	1.2	49.3
1	13.279	13.279	2.0	49.4
1	13.289	13.289	1.5	49.6
1	13.299	13.299	1.5	49.4
1	13.309	13.309	2.5	49.0
1	13.319	13.319	3.1	48.5
1	13.329	13.329	1.9	47.1
1	13.339	13.339	2.7	47.8
1	13.349	13.349	1.3	47.5
1	13.359	13.359	1.0	47.3
1	13.369	13.369	1.4	47.2
1	13.379	13.379	2.0	47.2
1	13.389	13.389	1.2	47.2
1	13.399	13.399	1.3	47.2
1	13.409	13.409	1.4	47.1
1	13.419	13.419	1.2	46.9
1	13.429	13.429	1.1	46.9
1	13.439	13.439	1.5	46.8
1	13.449	13.449	1.2	46.9
1	13.459	13.459	1.5	47.4
1	13.469	13.469	1.5	48.2
1	13.479	13.479	1.6	48.5
1	13.489	13.489	1.2	48.5
1	13.499	13.499	1.4	47.9
1	13.509	13.509	1.5	47.0
1	13.519	13.519	5.3	46.0
1	13.529	13.529	2.8	45.1
1	13.539	13.539	1.7	44.5
1	13.549	13.549	5.1	44.0
1	13.559	13.559	3.1	43.7
1	13.569	13.569	2.4	43.5
1	13.579	13.579	1.5	43.7
1	13.589	13.589	2.1	43.8
1	13.599	13.599	4.1	43.9
1	13.609	13.609	2.5	43.9
1	13.619	13.619	4.5	43.8
1	13.629	13.629	1.8	43.3
1	13.639	13.639	6.0	42.3
1	13.649	13.649	4.8	41.3
1	13.659	13.659	2.5	39.7
1	13.669	13.669	3.2	38.3
1	13.679	13.679	2.7	36.5
1	13.688	13.688	4.8	35.4

Average Value 1.8


IRI (m/km)
Distance (km)
Bad
Poor
Fair
Good
Excellent
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00

Appendix D: International Roughness Index Prediction from the HDM-4

H D M - 4 Pavement Condition Summary

HIGHWAY DEVELOPMENT & MANAGEMENT

Study Name: **RECONSTRUCTION OF GEORGE WALKER BUSH MOTO**

Run Date: **22-10-2016**

Section: N1-016
Alternative: 3-Lane Dual Reconstruction
Sensitivity: No Sensitivity Analysis Conducted
Surface Class: Bituminous **Road Class: Primary or Trunk Width: 7.30m**
Length: 14.13km

Year	MT AADT	ESAL millions /ELANE	IRI bef. m/km	IRI Avg. m/km	All Str. Cracks %	Rave-lling %	Edge Break mm	Rut Depth	No. of Pot-holes	Struct. No. sq.m	Gravel Thick. mm	Avg. Faulting mm	Spalled Joints %	No. of Failures per km	Cracked Slabs %	Det. Cracks No/km
					Average Annual Values											
2009	28,740	3.45	16.00	10.00	65.00	18.92	10.00	50.322,365.72		1.52						
2010	30,059	3.61	16.00	10.00	65.00	18.92	10.00	50.322,365.72		1.52						
2011	31,448	3.79	16.00	10.00	32.50	9.46	5.00	25.161,182.86		4.60						

2012	32,909	3.97	2.68	2.59	0.00	0.00	0.00	2.28	0.00	7.67		
2013	34,448	4.16	2.75	2.71	0.00	0.00	0.00	2.41	0.00	7.67		
2014	36,069	4.36	2.82	2.79	0.00	0.00	0.00	2.55	0.00	7.67		
2015	37,776	4.58	2.91	2.87	1.43	0.00	0.00	2.69	0.00	7.67		
2016	39,574	4.80	3.01	2.96	4.68	0.00	0.00	2.84	0.00	7.65		
2017	41,469	5.03	3.13	3.07	10.09	0.00	0.00	2.98	0.00	7.60		
2018	43,465	5.27	3.27	3.20	17.85	0.00	0.00	3.13	0.00	7.52		
2019	45,569	5.53	3.43	3.35	28.09	0.00	0.00	3.29	0.00	7.39		
2020	47,786	5.80	3.62	3.53	40.93	0.00	0.00	3.47	0.00	7.23		
2021	50,124	6.08 1	6.00	9.81	27.74	0.00	0.00	2.11	582.98	7.65		
2022	52,588	6.37	9.19	9.09	0.00	0.00	0.00	0.68	0.00	8.28		
2023	55,187	6.68	9.40	9.30	0.68	0.00	0.00	0.82	0.00	8.28		

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2024	57,928	7.01	9.62	9.51	1.91	0.00	0.00	0.95	0.00	8.27		
2025	60,819	7.35	9.85	9.73	4.24	0.00	0.00	1.09	0.00	8.25		
2026	61,764	7.45	10.10	9.97	8.12	0.00	0.00	1.23	0.00	8.21		
2027	61,777	7.44	10.36	10.23	14.09	0.00	0.00	1.37	0.00	8.15		
2028	61,791	7.43	10.65	10.51	22.69	0.00	0.00	1.52	0.00	8.05		
2029	61,806	7.42	10.97	10.81	34.56	0.00	0.00	1.68	0.00	7.90		
2030	61,822	7.40	14.87	12.92	50.14	0.00	0.00	1.86	443.20	7.68		
2031	61,840	7.39	16.00	15.44	32.72	0.00	0.00	1.19	902.54	8.12		

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Section: N1-016
Alternative: Base Alternative
Sensitivity: No Sensitivity Analysis Conducted
Surface Class: Bituminous **Road Class:** **Primary or Trunk**
Length: 14.13km **Width:** **7.30m**

	Average Annual Values

Year	MT AADT	ESAL millions /ELANE	IRI bef. m/km	IRI Avg. m/km	All Str. Cracks %	Rave-lling %	Edge Break mm	Rut Depth	No. of Pot-holes	Struct. No. sq.m	Gravel Thick. mm	Avg. Faulting mm	Spalled Joints %	No. of Failures per km	Cracked Slabs %	Det. Cracks No/km
2009	28,740	3.45	16.00	10.00	32.50	9.46	5.00	28.93	1,182.86	1.80						
2010	30,059	3.61	14.28	13.26	0.00	0.00	0.00	7.76	0.00	2.08						
2011	31,448	3.79	16.00	15.14	0.50	0.00	0.00	7.98	0.00	2.08						
2012	32,909	3.97	16.00	16.00	1.03	0.00	0.00	8.20	0.00	2.08						
2013	34,448	4.16	16.00	16.00	1.85	0.00	0.00	8.42	0.00	2.07						
2014	36,069	4.36	16.00	16.00	3.03	0.00	0.00	8.64	0.00	2.07						
2015	37,776	4.58	16.00	16.00	4.66	0.00	0.00	8.87	0.00	2.06						
2016	39,574	4.80	16.00	16.00	6.81	0.00	0.00	9.09	0.00	2.06						
2017	41,469	5.03	16.00	16.00	9.57	0.00	0.00	9.32	0.00	2.05						
2018	43,465	5.27	16.00	16.00	7.50	0.00	0.00	9.56	0.00	2.05						
2019	45,569	5.53	16.00	15.96	3.22	0.00	0.00	9.79	0.00	2.07						
2020	47,786	5.80	16.00	16.00	4.91	2.19	0.00	10.02	0.00	2.06						
2021	50,124	6.08	16.00	16.00	7.14	6.46	0.00	10.25	0.00	2.06						
2022	52,588	6.37	16.00	16.00	4.99	7.10	0.00	6.03	0.00	2.15						
2023	55,187	6.68	16.00	14.66	0.00	0.00	0.00	1.78	0.00	2.25						
2024	57,928	7.01	16.00	16.00	0.50	0.00	0.00	2.00	0.00	2.25						
2025	60,819	7.35	16.00	16.00	1.03	0.00	0.00	2.21	0.00	2.25						
2026	61,764	7.45	16.00	16.00	1.85	0.00	0.00	2.42	0.00	2.25						
2027	61,777	7.44	16.00	16.00	3.03	0.00	0.00	2.64	0.00	2.24						
2028	61,791	7.43	16.00	16.00	4.66	0.00	0.00	2.86	0.00	2.24						
2029	61,806	7.42	16.00	16.00	6.81	0.00	0.00	3.07	0.00	2.23						
2030	61,822	7.40	16.00	16.00	9.57	0.00	0.00	3.29	0.00	2.22						
2031	61,840	7.39	16.00	16.00	7.50	0.00	0.00	3.52	0.00	2.22						

Section: N1-016
Alternative: Overlay Alternative
Sensitivity: No Sensitivity Analysis Conducted
Surface Class: Bituminous **Road Class:** **Primary or Trunk**
Length: 14.13km **Width:** **7.30m**

					Average Annual Values											
Year	MT AADT	ESAL millions /ELANE	IRI bef. m/km	IRI Avg. m/km	All Str. Cracks %	Rave-lling %	Edge Break mm	Rut Depth	No. of Pot-holes	Struct. No. sq.m	Gravel Thick. mm	Avg. Faulting mm	Spalled Joints %	No. of Failures per km	Cracked Slabs %	Det. Cracks No/km
2009	28,740	3.45	16.00	10.00	32.50	9.46	5.00	28.93	1,182.86	2.07						
2010	30,059	3.61	9.31	8.83	0.00	0.00	0.00	7.71	0.00	2.62						
2011	31,448	3.79	10.35	9.83	0.00	0.00	0.00	7.88	0.00	2.62						
2012	32,909	3.97	11.47	10.91	0.50	0.00	0.00	8.05	0.00	2.62						
2013	34,448	4.16	12.68	12.07	1.03	0.00	0.00	8.22	0.00	2.62						
2014	36,069	4.36	13.99	13.33	1.85	0.00	0.00	8.39	0.00	2.62						
2015	37,776	4.58	15.41	14.70	3.03	0.00	0.00	8.56	0.00	2.61						
2016	39,574	4.80	16.00	15.70	4.66	0.00	0.00	8.73	0.00	2.60						
2017	41,469	5.03	16.00	16.00	6.81	0.00	0.00	8.91	0.00	2.59						
2018	43,465	5.27	16.00	16.00	9.57	0.00	0.00	9.08	0.00	2.58						
2019	45,569	5.53	16.00	16.00	7.50	0.00	0.00	9.27	0.00	2.58						
2020	47,786	5.80	16.00	15.96	3.22	2.19	0.00	9.44	0.00	2.61						
2021	50,124	6.08	16.00	16.00	4.91	6.52	0.00	9.62	0.00	2.60						
2022	52,588	6.37	16.00	16.00	3.57	7.18	0.00	5.64	0.00	2.69						
2023	55,187	6.68	14.75	14.03	0.00	0.00	0.00	1.63	0.00	2.80						
2024	57,928	7.01	16.00	15.38	0.50	0.00	0.00	1.80	0.00	2.80						
2025	60,819	7.35	16.00	16.00	1.03	0.00	0.00	1.97	0.00	2.79						
2026	61,764	7.45	16.00	16.00	1.85	0.00	0.00	2.13	0.00	2.79						
2027	61,777	7.44	16.00	16.00	3.03	0.00	0.00	2.30	0.00	2.78						

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2028	61,791	7.43	16.00	16.00	4.66	0.00	0.00	2.47	0.00	2.78		
2029	61, 806	7.42	16.00	16.00	6.81	0.00	0.00	2.64	0.00	2.77		
2030	61,822	7.40	16.00	16.00	9.57	0.00	0.00	2.81	0.00	2.76		
2031	61,840	7.39	16.00	16.00	7.50	0.00	0.00	2.99	0.00	2.76		

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Appendix E Annual Emissions Predictions from the HDM-4

H D M - 4 Emissions Summary

HIGHWAY DEVELOPMENT & MANAGEMENT

Study Name: **RECONSTRUCTION OF GEORGE WALKER BUSH MOTORWAY**

Run Date: **22-10-2016**

Section: N1-016
Alternative: 3-Lane Dual Reconstruction
Sensitivity: No Sensitivity Analysis Conducted

Sect ID: N1-016 Road Class: Primary or Trunk
Length: 14.13m Width: 7.30m Rise+Fall: 15.80m/km Curvature: 12.00 deg/km

Year	Annual Emission Quantities in tonnes						
	Hydrocarbon HC	Carbon monoxide CO	Nitrous oxide NOx	Sulphur dioxide SO2	Carbon dioxide CO2	Particulates Par	Lead Pb

2009	630.28	276.23	245.75	41.01	62,313.74	139.02	0.00
2010	624.06	271.99	243.11	40.67	61,536.40	137.80	0.00
2011	651.01	281.23	253.50	42.53	63,910.57	143.99	0.00
2012	635.49	277.54	248.32	41.44	62,948.04	140.29	0.00
2013	662.85	287.16	258.87	43.32	65,394.13	146.56	0.00
2014	690.91	297.08	269.69	45.24	67,911.32	152.99	0.00
2015	715.76	306.14	279.17	46.93	70,178.01	158.66	0.00
2016	734.57	312.77	286.27	48.22	71,872.07	162.97	0.00
2017	741.03	313.84	288.60	48.72	72,321.41	164.57	0.00
2018	747.77	315.07	291.03	49.23	72,802.89	166.23	0.00
2019	754.81	316.48	293.58	49.76	73,319.07	167.96	0.00
2020	762.19	318.07	296.26	50.31	73,872.71	169.76	0.00
2021	804.08	330.14	311.26	53.25	77,113.62	179.60	0.00
2022	807.13	330.59	312.42	53.49	77,354.58	180.38	0.00
2023	815.67	332.77	315.54	54.12	78,032.60	182.42	0.00
2024	824.68	335.18	318.85	54.77	78,759.97	184.57	0.00
2025	834.10	337.81	322.32	55.45	79,532.94	186.81	0.00
2026	819.90	330.44	316.74	54.57	77,998.43	183.80	0.00
2027	813.78	326.60	314.27	54.22	77,266.26	182.57	0.00
2028	816.08	326.39	315.04	54.42	77,363.17	183.21	0.00
2029	818.49	326.27	315.85	54.63	77,475.19	183.87	0.00
2030	832.17	329.48	320.85	55.63	78,470.88	187.17	0.00
2031	848.15	333.50	326.72	56.78	79,665.54	191.00	0.00

Section: N1-016
Alternative: Base Alternative
Sensitivity: No Sensitivity Analysis Conducted

Sect ID: N1-016 Road Class: Primary or Trunk
Length: 14.13m Width: 7.30m Rise+Fall: 15.80m/km Curvature: 12.00 deg/km

Year	Annual Emission Quantities in tonnes

	Hydrocarbon HC	Carbon monoxide CO	Nitrous oxide NOx	Sulphur dioxide SO2	Carbon dioxide CO2	Particulates Par	Lead Pb
2009	630.28	276.23	245.75	41.01	62,313.74	139.02	0.00
2010	640.75	277.08	249.23	41.83	62,848.00	141.69	0.00
2011	677.69	289.35	263.29	44.38	66,007.67	150.22	0.00
2012	700.97	297.69	271.99	45.97	68,089.91	155.54	0.00
2013	730.25	307.78	283.23	47.98	70,673.91	162.27	0.00
2014	760.48	318.26	294.83	50.06	73,350.78	169.21	0.00
2015	787.57	327.95	305.14	51.91	75,790.47	175.41	0.00
2016	808.04	335.04	312.86	53.32	77,615.34	180.11	0.00
2017	814.55	336.06	315.22	53.82	78,063.76	181.74	0.00
2018	821.25	337.22	317.65	54.34	78,537.81	183.40	0.00
2019	827.91	338.45	320.08	54.84	79,020.66	185.04	0.00
2020	835.24	339.98	322.76	55.39	79,569.04	186.83	0.00
2021	842.58	341.60	325.46	55.94	80,129.59	188.62	0.00
2022	850.18	343.39	328.25	56.50	80,722.51	190.45	0.00
2023	849.39	342.75	327.94	56.47	80,664.13	190.32	0.00
2024	866.23	347.51	334.18	57.67	82,014.89	194.30	0.00
2025	874.71	349.86	337.33	58.28	82,716.99	196.32	0.00
2026	858.11	341.72	330.88	57.24	80,988.87	192.75	0.00
2027	849.97	337.25	327.68	56.75	80,096.91	191.06	0.00
2028	850.55	336.52	327.82	56.83	80,060.43	191.30	0.00
2029	851.05	335.84	327.94	56.91	80,024.38	191.51	0.00
2030	851.47	335.19	328.02	56.98	79,988.78	191.69	0.00
2031	851.80	334.58	328.08	57.03	79,953.63	191.86	0.00

Section: N1-016
Alternative: Overlay Alternative
Sensitivity: No Sensitivity Analysis Conducted

Sect ID: N1-016 Road Class: Primary or Trunk
Length: 14.13m Width: 7.30m Rise+Fall: 15.80m/km Curvature: 12.00 deg/km

Year	Annual Emission Quantities in tonnes

	Hydrocarbon HC	Carbon monoxide CO	Nitrous oxide NOx	Sulphur dioxide SO2	Carbon dioxide CO2	Particulates Par	Lead Pb
2009	630.28	276.23	245.75	41.01	62,313.74	139.02	0.00
2010	619.53	270.58	241.49	40.36	61,180.20	136.74	0.00
2011	650.98	281.22	253.49	42.52	63,908.57	143.99	0.00
2012	674.62	289.67	262.29	44.14	66,014.35	149.39	0.00
2013	709.19	301.39	275.48	46.52	69,016.34	157.36	0.00
2014	745.68	313.78	289.38	49.03	72,185.30	165.76	0.00
2015	779.96	325.63	302.33	51.39	75,188.84	173.63	0.00
2016	806.22	334.49	312.19	53.20	77,471.08	179.69	0.00
2017	814.55	336.06	315.22	53.82	78,063.76	181.74	0.00
2018	821.25	337.22	317.65	54.34	78,537.81	183.40	0.00
2019	828.14	338.52	320.16	54.86	79,039.02	185.09	0.00
2020	835.01	339.91	322.68	55.37	79,550.48	186.78	0.00
2021	842.58	341.60	325.46	55.94	80,129.59	188.62	0.00
2022	850.18	343.39	328.25	56.50	80,722.51	190.45	0.00
2023	845.43	341.56	326.47	56.20	80,351.26	189.40	0.00
2024	862.05	346.25	332.63	57.38	81,683.40	193.33	0.00
2025	874.71	349.86	337.33	58.28	82,716.99	196.32	0.00
2026	858.11	341.72	330.88	57.24	80,988.87	192.75	0.00
2027	849.97	337.25	327.68	56.75	80,096.91	191.06	0.00
2028	850.55	336.52	327.82	56.83	80,060.43	191.30	0.00
2029	851.05	335.84	327.94	56.91	80,024.38	191.51	0.00
2030	851.47	335.19	328.02	56.98	79,988.78	191.69	0.00
2031	851.80	334.58	328.08	57.03	79,953.63	191.86	0.00

Appendix F Fuel Consumption Predictions from the HDM-4 for each vehicle class in each flow periods.

Units: **Litres per 1000 vehicle-kilometres**

Section: N1-016
Alternative: 3-Lane Dual Reconstruction **Sensitivity:** No Sensitivity Analysis Conducted

Sect ID: N1-016 Road Class: Primary or Trunk
Length: 14.13 km Width: 7.30 m Rise+Fall: 15.80 m/km Curvature: 12.00 deg/km

		Period 1	**Period 2**	**Period 3**	**Period 4**
01 Car	2009	169.97	169.97	169.35	145.33
	2010	169.97	169.97	168.81	145.42
	2011	169.97	169.97	169.82	145.52
	2012	164.92	164.92	163.50	140.69
	2013	165.00	165.00	164.27	140.88
	2014	165.05	165.05	164.88	141.04
	2015	165.10	165.10	165.10	141.58
	2016	165.17	165.17	165.17	142.21
	2017	165.24	165.24	165.24	142.43
	2018	165.34	165.34	165.34	142.67
	2019	165.44	165.44	165.44	142.93
	2020	165.56	165.56	165.56	143.22
	2021	169.96	169.96	169.96	147.67
	2022	169.47	169.47	169.47	147.33
	2023	169.60	169.60	169.60	147.67
	2024	169.75	169.75	169.75	148.06
	2025	169.91	169.91	169.91	148.47
	2026	170.07	170.07	170.07	148.12

	2027	170.25	170.25	170.25	148.06
	2028	170.45	170.45	170.45	148.28
	2029	170.66	170.66	170.66	148.53
	2030	172.15	172.15	172.15	150.37
	2031	173.91	173.91	173.91	152.80
	Total	3,872.91	3,872.91	3,868.66	3,349.28
02 Taxi	2009	169.97	169.97	169.35	145.33
	2010	169.97	169.97	168.81	145.42

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		Period 1	Period 2	Period 3	Period 4
02 Taxi	2011	169.97	169.97	169.82	145.52
	2012	164.92	164.92	163.50	140.69
	2013	165.00	165.00	164.27	140.88
	2014	165.05	165.05	164.88	141.04
	2015	165.10	165.10	165.10	141.58
	2016	165.17	165.17	165.17	142.21
	2017	165.24	165.24	165.24	142.43
	2018	165.34	165.34	165.34	142.67
	2019	165.44	165.44	165.44	142.93
	2020	165.56	165.56	165.56	143.22
	2021	169.96	169.96	169.96	147.67
	2022	169.47	169.47	169.47	147.33
	2023	169.60	169.60	169.60	147.67
	2024	169.75	169.75	169.75	148.06
	2025	169.91	169.91	169.91	148.47
	2026	170.07	170.07	170.07	148.12
	2027	170.25	170.25	170.25	148.06

	2028	170.45	170.45	170.45	148.28
	2029	170.66	170.66	170.66	148.53
	2030	172.15	172.15	172.15	150.37
	2031	173.91	173.91	173.91	152.80
	Total	3,872.91	3,872.91	3,868.66	3,349.28
03 Pickups	2009	146.99	146.99	146.12	109.69
	2010	146.99	146.99	145.38	109.76
	2011	146.99	146.99	146.79	109.84
	2012	142.16	142.16	140.20	105.76
	2013	142.23	142.23	141.23	105.89
	2014	142.28	142.28	142.05	106.02
	2015	142.33	142.33	142.33	106.40
	2016	142.40	142.40	142.40	106.84
	2017	142.47	142.47	142.47	107.01
	2018	142.56	142.56	142.56	107.18
	2019	142.66	142.66	142.66	107.38
	2020	142.77	142.77	14297.77	107.60

		Period 1	Period 2	Period 3	Period 4
03 Pickups	2021	146.98	146.98	146.98	111.44
	2022	146.51	146.51	146.51	111.03
	2023	146.64	146.64	146.64	111.31
	2024	146.78	146.78	146.78	111.70
	2025	146.93	146.93	146.93	112.11
	2026	147.09	147.09	147.09	111.86
	2027	147.26	147.26	147.26	111.88
	2028	147.45	147.45	147.45	112.13
	2029	147.65	147.65	147.65	112.42

	2030	149.07	149.07	149.07	114.52
	2031	150.76	150.76	150.76	116.52
	Total	3,345.95	3,345.95	3,340.08	2,526.29
04 Small truck	2009	237.12	237.12	236.46	213.59
	2010	237.12	237.12	235.90	213.68
	2011	237.12	237.12	236.96	213.76
	2012	219.13	219.13	217.72	196.11
	2013	219.39	219.39	218.67	196.46
	2014	219.55	219.55	219.39	196.72
	2015	219.74	219.74	219.74	197.35
	2016	219.95	219.95	219.95	198.07
	2017	220.20	220.20	220.20	198.45
	2018	220.50	220.50	220.50	198.87
	2019	220.85	220.85	220.85	199.35
	2020	221.24	221.24	221.24	199.89
	2021	237.06	237.06	237.06	215.62
	2022	235.21	235.21	235.21	213.88
	2023	235.71	235.71	235.71	214.57
	2024	236.27	236.27	236.27	215.37
	2025	236.86	236.86	236.86	216.22
	2026	237.49	237.49	237.49	216.38
	2027	238.17	238.17	238.17	216.85
	2028	238.90	238.90	238.90	217.63
	2029	239.71	239.71	239.71	218.50
	2030	245.29	245.29	24598.29	224.71

		Period 1	Period 2	Period 3	Period 4
	2031	251.94	251.94	251.94	232.26

04 Small truck	**Total**	5,324.52	5,324.52	5,320.19	4,824.29
05 Medium Truck 1	2009	296.39	296.39	293.09	205.14
	2010	296.39	296.39	290.27	205.21
	2011	296.39	296.39	295.60	205.28
	2012	272.96	272.96	265.88	187.01
	2013	273.32	273.32	269.71	187.35
	2014	273.56	273.56	272.72	187.60
	2015	273.81	273.81	273.81	188.13
	2016	274.12	274.12	274.12	188.77
	2017	274.47	274.47	274.47	189.14
	2018	274.89	274.89	274.89	189.56
	2019	275.38	275.38	275.38	190.05
	2020	275.94	275.94	275.94	190.59
	2021	296.32	296.32	296.32	206.82
	2022	294.04	294.04	294.04	204.89
	2023	294.66	294.66	294.66	205.62
	2024	295.35	295.35	295.35	206.50
	2025	296.08	296.08	296.08	207.43
	2026	296.85	296.85	296.85	207.63
	2027	297.69	297.69	297.69	208.18
	2028	298.59	298.59	298.59	209.05
	2029	299.59	299.59	299.59	210.01
	2030	306.46	306.46	306.46	216.77
	2031	314.66	314.66	314.66	223.31
	Total	6,647.91	6,647.91	6,626.17	4,620.04
06 Heavy Truck 1	2009	942.85	942.85	934.79	697.11
	2010	942.85	942.85	927.92	697.43
	2011	942.85	942.85	940.92	697.77

	2012	883.33	883.33	865.74	649.16
	2013	884.24	884.24	875.28	650.24
	2014	884.84	884.84	882.76	651.09
	2015	885.50	885.50	885.50	653.22
	2016	886.27	886.27	88699.27	655.72

		Period 1	Period 2	Period 3	Period 4
06 Heavy Truck 1	2017	887.17	887.17	887.17	656.93
	2018	888.23	888.23	888.23	658.29
	2019	889.47	889.47	889.47	659.82
	2020	890.90	890.90	890.90	661.54
	2021	942.67	942.67	942.67	705.21
	2022	936.87	936.87	936.87	700.49
	2023	938.44	938.44	938.44	702.67
	2024	940.20	940.20	940.20	705.27
	2025	942.05	942.05	942.05	708.03
	2026	944.02	944.02	944.02	707.79
	2027	946.13	946.13	946.13	708.83
	2028	948.43	948.43	948.43	711.09
	2029	950.96	950.96	950.96	713.59
	2030	968.41	968.41	968.41	731.25
	2031	989.22	989.22	989.22	750.02
	Total	21,255.90	21,255.90	21,202.35	15,832.56
07 5/6 axle articulate	2009	850.97	850.97	843.69	633.10
	2010	850.97	850.97	837.49	633.36
	2011	850.97	850.97	849.23	633.63
	2012	788.06	788.06	772.36	582.56
	2013	789.02	789.02	781.02	583.59

	2014	789.65	789.65	787.80	584.39
	2015	790.35	790.35	790.35	586.20
	2016	791.16	791.16	791.16	588.33
	2017	792.12	792.12	792.12	589.47
	2018	793.24	793.24	793.24	590.77
	2019	794.55	794.55	794.55	592.24
	2020	796.06	796.06	796.06	593.90
	2021	850.78	850.78	850.78	639.44
	2022	844.65	844.65	844.65	634.41
	2023	846.31	846.31	846.31	636.48
	2024	848.17	848.17	848.17	638.95
	2025	850.12	850.12	850.12	641.58
	2026	852.21	852.21	852100.21	641.81
		Period 1	**Period 2**	**Period 3**	**Period 4**
07 5/6 axle articulate	2027	854.44	854.44	854.44	643.10
	2028	856.88	856.88	856.88	645.42
	2029	859.55	859.55	859.55	647.97
	2030	878.01	878.01	878.01	665.97
	2031	900.03	900.03	900.03	685.14
	Total	19,118.27	19,118.27	19,070.22	14,311.81
08 Small Bus	2009	196.57	196.57	195.09	149.26
	2010	196.57	196.57	193.82	149.35
	2011	196.57	196.57	196.21	149.44
	2012	187.96	187.96	184.67	141.57
	2013	188.10	188.10	186.41	141.78
	2014	188.18	188.18	187.79	141.96
	2015	188.28	188.28	188.28	142.47
	2016	188.39	188.39	188.39	143.08

	2017	188.52	188.52	188.52	143.32
	2018	188.67	188.67	188.67	143.59
	2019	188.85	188.85	188.85	143.89
	2020	189.06	189.06	189.06	144.23
	2021	196.54	196.54	196.54	151.34
	2022	195.70	195.70	195.70	150.58
	2023	195.93	195.93	195.93	151.03
	2024	196.18	196.18	196.18	151.52
	2025	196.45	196.45	196.45	152.06
	2026	196.74	196.74	196.74	151.89
	2027	197.04	197.04	197.04	152.01
	2028	197.41	197.41	197.41	152.42
	2029	197.83	197.83	197.83	152.87
	2030	200.72	200.72	200.72	156.22
	2031	204.17	204.17	204.17	160.26
	Total	4,460.43	4,460.43	4,450.47	3,416.14
10 Miduim/ Heavy Bus	2009	284.29	284.29	281.56	211.64
	2010	284.29	284.29	279.22	211.72
	2011	284.29	284.29	283.64	211.79
	2012	263.30	263.30	257101.39	194.89

		Period 1	Period 2	Period 3	Period 4
10 Miduim/ Heavy Bus	2013	263.62	263.62	260.61	195.22
	2014	263.83	263.83	263.13	195.48
	2015	264.06	264.06	264.06	196.02
	2016	264.33	264.33	264.33	196.65
	2017	264.65	264.65	264.65	197.01
	2018	265.03	265.03	265.03	197.42
	2019	265.46	265.46	265.46	197.89
	2020	265.97	265.97	265.97	198.42

	2021	284.23	284.23	284.23	213.47
	2022	282.19	282.19	282.19	211.73
	2023	282.74	282.74	282.74	212.39
	2024	283.36	283.36	283.36	213.22
	2025	284.01	284.01	284.01	214.11
	2026	284.71	284.71	284.71	214.25
	2027	285.45	285.45	285.45	214.74
	2028	286.27	286.27	286.27	215.55
	2029	287.16	287.16	287.16	216.45
	2030	293.32	293.32	293.32	222.86
	2031	300.73	300.73	300.73	229.82
	Total	6,387.29	6,387.29	6,369.22	4,782.74
11 Motorcycle	2009	24.54	24.54	24.52	23.47
	2010	24.54	24.54	24.51	23.47
	2011	24.54	24.54	24.54	23.48
	2012	23.43	23.43	23.39	22.32
	2013	23.45	23.45	23.43	22.34
	2014	23.46	23.46	23.46	22.37
	2015	23.47	23.47	23.47	22.42
	2016	23.49	23.49	23.49	22.48
	2017	23.51	23.51	23.51	22.51
	2018	23.53	23.53	23.53	22.55
	2019	23.55	23.55	23.55	22.59
	2020	23.58	23.58	23.58	22.63
	2021	24.54	24.54	24.54	23.67
	2022	24.43	24.43	24.10243	23.57
		Period 1	**Period 2**	**Period 3**	**Period 4**
11 Motorcycle	2023	24.46	24.46	24.46	23.62
	2024	24.49	24.49	24.49	23.67
	2025	24.53	24.53	24.53	23.73

	2026	24.57	24.57	24.57	23.72
	2027	24.60	24.60	24.60	23.74
	2028	24.65	24.65	24.65	23.78
	2029	24.69	24.69	24.69	23.83
	2030	25.02	25.02	25.02	24.19
	2031	25.41	25.41	25.41	24.65
	Total	556.48	556.48	556.37	534.80
Sect-Alt Total		74,842.57	74,842.57	74,672.39	57,547.23

(N.B. fuel consumption quantities are in litres per 1000 vehicle-kilometres)

Section: N1-016
Alternative: Base Alternative
Sensitivity: No Sensitivity Analysis Conducted

Sect ID: N1-016 Road Class: Primary or Trunk

Length: 14.13 km Width: 7.30 m Rise+Fall: 15.80 m/km Curvature: 12.00 deg/km

		Period 1	Period 2	Period 3	Period 4
01 Car	2009	169.97	169.97	169.35	145.33
	2010	172.39	172.39	171.33	148.23
	2011	173.71	173.71	173.68	150.06
	2012	174.31	174.31	172.95	151.11
	2013	174.31	174.31	173.61	151.24
	2014	174.31	174.31	174.15	151.37
	2015	174.31	174.31	174.31	151.89
	2016	174.31	174.31	174.31	152.50
	2017	174.31	174.31	174.31	152.66
	2018	174.31	174.31	174.31	152.83
	2019	174.28	174.28	174.28	152.97
	2020	174.31	174.31	174.31	153.20
	2021	174.31	174.31	174.31	153.40
	2022	174.31	174.31	174.31	153.61
	2023	173.38	173.38	173.38	152.34
	2024	174.31	174.31	174.31	154.07
	2025	174.31	174.31	174.31	154.32
	2026	174.31	174.31	174.31	153.75
	2027	174.31	174.31	174.31	153.46
	2028	174.31	174.31	174.31	153.46
	2029	174.31	174.31	174.31	153.46
	2030	174.31	174.31	174.31	153.46
	2031	174.31	174.31	174.31	153.46
	Total	4,001.31	4,001.31	3,997.38	3,502.18
02 Taxi	2009	169.97	169.97	169.35	145.33
	2010	172.39	172.39	171.33	148.23
	2011	173.71	173.71	173.68	150.06
	2012	174.31	174.31	172.95	151.11
	2013	174.31	174.31	173.61	151.24

		Period 1	Period 2	Period 3	Period 4
02 Taxi	2014	174.31	174.31	174.15	151.37
	2015	174.31	174.31	174.31	151.89
	2016	174.31	174.31	174.31	152.50
	2017	174.31	174.31	174.31	152.66
	2018	174.31	174.31	174.31	152.83
	2019	174.28	174.28	174.28	152.97
	2020	174.31	174.31	174.31	153.20
	2021	174.31	174.31	174.31	153.40
	2022	174.31	174.31	174.31	153.61
	2023	173.38	173.38	173.38	152.34
	2024	174.31	174.31	174.31	154.07
	2025	174.31	174.31	174.31	154.32
	2026	174.31	174.31	174.31	153.75
	2027	174.31	174.31	174.31	153.46
	2028	174.31	174.31	174.31	153.46
	2029	174.31	174.31	174.31	153.46
	2030	174.31	174.31	174.31	153.46
	2031	174.31	174.31	174.31	153.46
	Total	4,001.31	4,001.31	3,997.38	3,502.18
03 Pickups	2009	146.99	146.99	146.12	109.69
	2010	149.31	149.31	147.83	112.98
	2011	150.56	150.56	150.53	114.48
	2012	151.14	151.14	149.24	115.34
	2013	151.14	151.14	150.17	115.43
	2014	151.14	151.14	150.92	115.52
	2015	151.14	151.14	151.14	115.91

	2016	151.14	151.14	151.14	116.35
	2017	151.14	151.14	151.14	116.47
	2018	151.14	151.14	151.14	116.59
	2019	151.12	151.12	151.12	116.69
	2020	151.14	151.14	151.14	116.86
	2021	151.14	151.14	151.14	117.01
	2022	151.14	151.14	151.14	117.16
	2023	150.25	150.25	150105.25	116.11

		Period 1	Period 2	Period 3	Period 4
03 Pickups	2024	151.14	151.14	151.14	117.50
	2025	151.14	151.14	151.14	117.68
	2026	151.14	151.14	151.14	117.27
	2027	151.14	151.14	151.14	117.06
	2028	151.14	151.14	151.14	117.06
	2029	151.14	151.14	151.14	117.06
	2030	151.14	151.14	151.14	117.06
	2031	151.14	151.14	151.14	117.06
	Total	3,468.75	3,468.75	3,463.28	2,670.34
04 Small truck	2009	237.12	237.12	236.46	213.59
	2010	246.23	246.23	245.09	223.64
	2011	251.17	251.17	251.14	229.31
	2012	253.44	253.44	251.95	232.15
	2013	253.44	253.44	252.68	232.25
	2014	253.44	253.44	253.26	232.35
	2015	253.44	253.44	253.44	232.79
	2016	253.44	253.44	253.44	233.29
	2017	253.44	253.44	253.44	233.42

	2018	253.44	253.44	253.44	233.56
	2019	253.34	253.34	253.34	233.59
	2020	253.43	253.43	253.43	233.87
	2021	253.43	253.43	253.43	234.03
	2022	253.43	253.43	253.43	234.21
	2023	249.92	249.92	249.92	230.16
	2024	253.44	253.44	253.44	234.59
	2025	253.44	253.44	253.44	234.80
	2026	253.44	253.44	253.44	234.33
	2027	253.44	253.44	253.44	234.09
	2028	253.44	253.44	253.44	234.09
	2029	253.43	253.43	253.43	234.09
	2030	253.43	253.43	253.43	234.09
	2031	253.43	253.43	253.43	234.08
	Total	5,799.64	5,799.64	5,795.38	5,336.37
05 Medium	2009	296.39	296.39	293106.09	205.14

		Period 1	Period 2	Period 3	Period 4
05 Medium Truck 1	2010	307.62	307.62	301.88	216.30
	2011	313.71	313.71	313.59	221.17
	2012	316.51	316.51	309.02	223.55
	2013	316.51	316.51	312.69	223.61
	2014	316.51	316.51	315.62	223.68
	2015	316.51	316.51	316.51	223.97
	2016	316.51	316.51	316.51	224.31
	2017	316.51	316.51	316.51	224.40
	2018	316.50	316.50	316.50	224.50
	2019	316.39	316.39	316.39	224.50

	2020	316.50	316.50	316.50	224.70
	2021	316.50	316.50	316.50	224.81
	2022	316.50	316.50	316.50	224.93
	2023	312.17	312.17	312.17	221.47
	2024	316.51	316.51	316.51	225.20
	2025	316.51	316.51	316.51	225.34
	2026	316.51	316.51	316.51	225.02
	2027	316.51	316.51	316.51	224.85
	2028	316.50	316.50	316.50	224.85
	2029	316.50	316.50	316.50	224.85
	2030	316.50	316.50	316.50	224.85
	2031	316.50	316.50	316.50	224.85
	Total	7,243.38	7,243.38	7,222.02	5,130.85
06 Heavy Truck 1	2009	942.85	942.85	934.79	697.11
	2010	971.35	971.35	957.43	725.67
	2011	986.80	986.80	986.51	739.65
	2012	993.91	993.91	975.87	746.98
	2013	993.91	993.91	984.71	747.38
	2014	993.90	993.90	991.77	747.80
	2015	993.90	993.90	993.90	749.55
	2016	993.90	993.90	993.90	751.56
	2017	993.90	993.90	993.90	752.09
	2018	993.90	993.90	993.90	752.65
	2019	993.59	993.59	993107.59	752.93

		Period 1	Period 2	Period 3	Period 4
06 Heavy Truck 1	2020	993.89	993.89	993.89	753.86
	2021	993.89	993.89	993.89	754.52

	2022	993.89	993.89	993.89	755.22
	2023	982.91	982.91	982.91	745.16
	2024	993.91	993.91	993.91	756.76
	2025	993.90	993.90	993.90	757.59
	2026	993.90	993.90	993.90	755.70
	2027	993.90	993.90	993.90	754.74
	2028	993.89	993.89	993.89	754.74
	2029	993.89	993.89	993.89	754.74
	2030	993.89	993.89	993.89	754.74
	2031	993.89	993.89	993.89	754.74
	Total	22,767.66	22,767.66	22,716.02	17,215.88
07 5/6 axle articulate	2009	850.97	850.97	843.69	633.10
	2010	881.12	881.12	868.49	662.28
	2011	897.46	897.46	897.20	676.54
	2012	904.99	904.99	888.56	683.80
	2013	904.98	904.98	896.61	684.11
	2014	904.98	904.98	903.04	684.44
	2015	904.98	904.98	904.98	685.80
	2016	904.97	904.97	904.97	687.36
	2017	904.97	904.97	904.97	687.77
	2018	904.97	904.97	904.97	688.21
	2019	904.65	904.65	904.65	688.36
	2020	904.97	904.97	904.97	689.15
	2021	904.96	904.96	904.96	689.66
	2022	904.96	904.96	904.96	690.21
	2023	893.34	893.34	893.34	679.97
	2024	904.99	904.99	904.99	691.41
	2025	904.98	904.98	904.98	692.05

	2026	904.97	904.97	904.97	690.58
	2027	904.97	904.97	904.97	689.84
	2028	904.97	904.97	904.97	689.83
	2029	904.97	904.97	904108.97	689.83

		Period 1	Period 2	Period 3	Period 4
07 5/6 axle articulate	2030	904.96	904.96	904.96	689.83
	2031	904.96	904.96	904.96	689.83
	Total	20,717.04	20,717.04	20,670.13	15,733.96
08 Small Bus	2009	196.57	196.57	195.09	149.26
	2010	201.21	201.21	198.67	154.68
	2011	203.77	203.77	203.72	157.74
	2012	204.95	204.95	201.67	159.38
	2013	204.95	204.95	203.28	159.48
	2014	204.95	204.95	204.56	159.58
	2015	204.95	204.95	204.95	160.01
	2016	204.95	204.95	204.95	160.51
	2017	204.95	204.95	204.95	160.64
	2018	204.95	204.95	204.95	160.78
	2019	204.90	204.90	204.90	160.86
	2020	204.95	204.95	204.95	161.08
	2021	204.95	204.95	204.95	161.25
	2022	204.95	204.95	204.95	161.42
	2023	203.13	203.13	203.13	159.23
	2024	204.95	204.95	204.95	161.80
	2025	204.95	204.95	204.95	162.00
	2026	204.95	204.95	204.95	161.53
	2027	204.95	204.95	204.95	161.30
	2028	204.95	204.95	204.95	161.30
	2029	204.95	204.95	204.95	161.30

	2030	204.95	204.95	204.95	161.30
	2031	204.95	204.95	204.95	161.30
	Total	4,698.68	4,698.68	4,689.27	3,677.73
10 Miduim/ Heavy Bus	2009	284.29	284.29	281.56	211.64
	2010	294.35	294.35	289.60	222.02
	2011	299.80	299.80	299.70	227.24
	2012	302.63	302.63	296.43	230.04
	2013	302.62	302.62	299.47	230.12
	2014	302.62	302.62	301.89	230.20
	2015	302.62	302.62	302109.62	230.56

		Period 1	Period 2	Period 3	Period 4
10 Miduim/ Heavy Bus	2016	302.62	302.62	302.62	230.98
	2017	302.62	302.62	302.62	231.09
	2018	302.62	302.62	302.62	231.20
	2019	302.50	302.50	302.50	231.20
	2020	302.62	302.62	302.62	231.45
	2021	302.62	302.62	302.62	231.59
	2022	302.62	302.62	302.62	231.73
	2023	298.43	298.43	298.43	227.76
	2024	302.63	302.63	302.63	232.06
	2025	302.62	302.62	302.62	232.23
	2026	302.62	302.62	302.62	231.83
	2027	302.62	302.62	302.62	231.64
	2028	302.62	302.62	302.62	231.63
	2029	302.62	302.62	302.62	231.63
	2030	302.62	302.62	302.62	231.63
	2031	302.62	302.62	302.62	231.63
	Total	6,926.55	6,926.55	6,908.89	5,283.10
11 Motorcycle	2009	24.54	24.54	24.52	23.47

	2010	25.07	25.07	25.04	24.04
	2011	25.36	25.36	25.36	24.39
	2012	25.49	25.49	25.45	24.56
	2013	25.49	25.49	25.47	24.57
	2014	25.49	25.49	25.49	24.58
	2015	25.49	25.49	25.49	24.63
	2016	25.49	25.49	25.49	24.68
	2017	25.49	25.49	25.49	24.69
	2018	25.49	25.49	25.49	24.71
	2019	25.49	25.49	25.49	24.72
	2020	25.49	25.49	25.49	24.74
	2021	25.49	25.49	25.49	24.76
	2022	25.49	25.49	25.49	24.78
	2023	25.29	25.29	25.29	24.53
	2024	25.49	25.49	25.49	24.82
	2025	25.49	25.49	25.11049	24.84
		Period 1	**Period 2**	**Period 3**	**Period 4**
11 Motorcycle	2026	25.49	25.49	25.49	24.79
	2027	25.49	25.49	25.49	24.76
	2028	25.49	25.49	25.49	24.76
	2029	25.49	25.49	25.49	24.76
	2030	25.49	25.49	25.49	24.76
	2031	25.49	25.49	25.49	24.76
	Total	584.57	584.57	584.46	566.10
Sect-Alt Total		80,208.89	80,208.89	80,044.21	62,618.69

(N.B. fuel consumption quantities are in litres per 1000 vehicle-kilometres)

Section: N1-016
Alternative: Overlay Alternative
Sensitivity: No Sensitivity Analysis Conducted

Sect ID: N1-016 Road Class: Primary or Trunk
Length: 14.13 km Width: 7.30 m Rise+Fall: 15.80 m/km Curvature: 12.00 deg/km

		Period 1	Period 2	Period 3	Period 4
01 Car	2009	169.97	169.97	169.35	145.33
	2010	169.28	169.28	168.10	144.67
	2011	169.98	169.98	169.82	145.50
	2012	170.73	170.73	169.31	146.44
	2013	171.55	171.55	170.83	147.51
	2014	172.43	172.43	172.27	148.73
	2015	173.39	173.39	173.39	150.49
	2016	174.10	174.10	174.10	152.16
	2017	174.31	174.31	174.31	152.66
	2018	174.31	174.31	174.31	152.83
	2019	174.31	174.31	174.31	153.01
	2020	174.28	174.28	174.28	153.15
	2021	174.31	174.31	174.31	153.40
	2022	174.31	174.31	174.31	153.61
	2023	172.94	172.94	172.94	151.72
	2024	173.87	173.87	173.87	153.33
	2025	174.31	174.31	174.31	154.32
	2026	174.31	174.31	174.31	153.75
	2027	174.31	174.31	174.31	153.46
	2028	174.31	174.31	174.31	153.46
	2029	174.31	174.31	174.31	153.46
	2030	174.31	174.31	174.31	153.46
	2031	174.31	174.31	174.31	153.46
	Total	3,984.24	3,984.24	3,979.98	3,479.91
02 Taxi	2009	169.97	169.97	169.35	145.33
	2010	169.28	169.28	168.10	144.67
	2011	169.98	169.98	169.82	145.50
	2012	170.73	170.73	169.31	146.44
	2013	171.55	171.55	170.83	147.51

		Period 1	Period 2	Period 3	Period 4
02 Taxi	2014	172.43	172.43	172.27	148.73
	2015	173.39	173.39	173.39	150.49
	2016	174.10	174.10	174.10	152.16
	2017	174.31	174.31	174.31	152.66
	2018	174.31	174.31	174.31	152.83
	2019	174.31	174.31	174.31	153.01
	2020	174.28	174.28	174.28	153.15
	2021	174.31	174.31	174.31	153.40
	2022	174.31	174.31	174.31	153.61
	2023	172.94	172.94	172.94	151.72
	2024	173.87	173.87	173.87	153.33
	2025	174.31	174.31	174.31	154.32
	2026	174.31	174.31	174.31	153.75
	2027	174.31	174.31	174.31	153.46
	2028	174.31	174.31	174.31	153.46
	2029	174.31	174.31	174.31	153.46
	2030	174.31	174.31	174.31	153.46
	2031	174.31	174.31	174.31	153.46
	Total	3,984.24	3,984.24	3,979.98	3,479.91
03 Pickups	2009	146.99	146.99	146.12	109.69
	2010	146.33	146.33	144.68	109.10
	2011	147.00	147.00	146.78	109.79
	2012	147.72	147.72	145.74	110.84
	2013	148.50	148.50	147.50	112.03
	2014	149.35	149.35	149.12	113.35
	2015	150.26	150.26	150.26	114.75

	2016	150.94	150.94	150.94	116.07
	2017	151.14	151.14	151.14	116.47
	2018	151.14	151.14	151.14	116.59
	2019	151.14	151.14	151.14	116.72
	2020	151.12	151.12	151.12	116.83
	2021	151.14	151.14	151.14	117.01
	2022	151.14	151.14	151.14	117.16
	2023	149.83	149.83	149113.83	115.60

		Period 1	Period 2	Period 3	Period 4
03 Pickups	2024	150.72	150.72	150.72	116.90
	2025	151.14	151.14	151.14	117.68
	2026	151.14	151.14	151.14	117.27
	2027	151.14	151.14	151.14	117.06
	2028	151.14	151.14	151.14	117.06
	2029	151.14	151.14	151.14	117.06
	2030	151.14	151.14	151.14	117.06
	2031	151.14	151.14	151.14	117.06
	Total	3,452.44	3,452.44	3,446.49	2,649.15
04 Small truck	2009	237.12	237.12	236.46	213.59
	2010	234.52	234.52	233.29	210.98
	2011	237.13	237.13	236.97	213.73
	2012	239.97	239.97	238.48	216.85
	2013	243.05	243.05	242.29	220.32
	2014	246.38	246.38	246.20	224.19
	2015	249.99	249.99	249.99	228.67
	2016	252.65	252.65	252.65	232.33
	2017	253.44	253.44	253.44	233.42

	2018	253.44	253.44	253.44	233.56
	2019	253.43	253.43	253.43	233.71
	2020	253.34	253.34	253.34	233.75
	2021	253.43	253.43	253.43	234.03
	2022	253.43	253.43	253.43	234.21
	2023	248.27	248.27	248.27	228.27
	2024	251.79	251.79	251.79	232.57
	2025	253.44	253.44	253.44	234.80
	2026	253.44	253.44	253.44	234.33
	2027	253.44	253.44	253.44	234.09
	2028	253.44	253.44	253.44	234.09
	2029	253.43	253.43	253.43	234.09
	2030	253.43	253.43	253.43	234.09
	2031	253.43	253.43	253.43	234.08
	Total	5,735.43	5,735.43	5,730.95	5,263.75
05 Medium	2009	296.39	296.39	293114.09	205.14

		Period 1	Period 2	Period 3	Period 4
05 Medium Truck 1	2010	293.19	293.19	286.97	202.31
	2011	296.40	296.40	295.60	205.16
	2012	299.91	299.91	292.37	208.67
	2013	303.70	303.70	299.86	212.53
	2014	307.81	307.81	306.91	216.69
	2015	312.25	312.25	312.25	220.48
	2016	315.54	315.54	315.54	223.50
	2017	316.51	316.51	316.51	224.40
	2018	316.50	316.50	316.50	224.50
	2019	316.50	316.50	316.50	224.60

	2020	316.38	316.38	316.38	224.60
	2021	316.50	316.50	316.50	224.81
	2022	316.50	316.50	316.50	224.93
	2023	310.13	310.13	310.13	219.84
	2024	314.47	314.47	314.47	223.49
	2025	316.51	316.51	316.51	225.34
	2026	316.51	316.51	316.51	225.02
	2027	316.51	316.51	316.51	224.85
	2028	316.50	316.50	316.50	224.85
	2029	316.50	316.50	316.50	224.85
	2030	316.50	316.50	316.50	224.85
	2031	316.50	316.50	316.50	224.85
	Total	7,164.21	7,164.21	7,141.61	5,060.26
06 Heavy Truck 1	2009	942.85	942.85	934.79	697.11
	2010	934.72	934.72	919.51	690.04
	2011	942.87	942.87	940.90	697.56
	2012	951.78	951.78	933.41	706.63
	2013	961.40	961.40	952.06	716.62
	2014	971.82	971.82	969.66	727.56
	2015	983.11	983.11	983.11	739.12
	2016	991.44	991.44	991.44	749.06
	2017	993.90	993.90	993.90	752.09
	2018	993.90	993.90	993.90	752.65
	2019	993.89	993.89	993115.89	753.24

		Period 1	Period 2	Period 3	Period 4
06 Heavy Truck 1	2020	993.59	993.59	993.59	753.55
	2021	993.89	993.89	993.89	754.52

	2022	993.89	993.89	993.89	755.22
	2023	977.73	977.73	977.73	740.46
	2024	988.73	988.73	988.73	751.51
	2025	993.90	993.90	993.90	757.59
	2026	993.90	993.90	993.90	755.70
	2027	993.90	993.90	993.90	754.74
	2028	993.89	993.89	993.89	754.74
	2029	993.89	993.89	993.89	754.74
	2030	993.89	993.89	993.89	754.74
	2031	993.89	993.89	993.89	754.74
	Total	22,566.77	22,566.77	22,511.66	17,023.93
07 5/6 axle articulate	2009	850.97	850.97	843.69	633.10
	2010	842.38	842.38	828.67	625.71
	2011	850.99	850.99	849.22	633.43
	2012	860.41	860.41	843.81	642.66
	2013	870.59	870.59	862.13	652.80
	2014	881.61	881.61	879.65	663.85
	2015	893.56	893.56	893.56	675.32
	2016	902.37	902.37	902.37	684.88
	2017	904.97	904.97	904.97	687.77
	2018	904.97	904.97	904.97	688.21
	2019	904.97	904.97	904.97	688.67
	2020	904.65	904.65	904.65	688.84
	2021	904.96	904.96	904.96	689.66
	2022	904.96	904.96	904.96	690.21
	2023	887.87	887.87	887.87	675.18
	2024	899.51	899.51	899.51	686.19
	2025	904.98	904.98	904.98	692.05

	2026	904.97	904.97	904.97	690.58
	2027	904.97	904.97	904.97	689.84
	2028	904.97	904.97	904.97	689.83
	2029	904.97	904.97	904116.97	689.83

		Period 1	Period 2	Period 3	Period 4
07 5/6 axle articulate	2030	904.96	904.96	904.96	689.83
	2031	904.96	904.96	904.96	689.83
	Total	20,504.52	20,504.52	20,454.74	15,538.27
08 Small Bus	2009	196.57	196.57	195.09	149.26
	2010	195.39	195.39	192.59	147.95
	2011	196.57	196.57	196.21	149.38
	2012	197.97	197.97	194.60	151.07
	2013	199.56	199.56	197.85	152.98
	2014	201.29	201.29	200.89	155.15
	2015	203.16	203.16	203.16	157.71
	2016	204.54	204.54	204.54	159.96
	2017	204.95	204.95	204.95	160.64
	2018	204.95	204.95	204.95	160.78
	2019	204.95	204.95	204.95	160.93
	2020	204.90	204.90	204.90	161.01
	2021	204.95	204.95	204.95	161.25
	2022	204.95	204.95	204.95	161.42
	2023	202.27	202.27	202.27	158.21
	2024	204.09	204.09	204.09	160.64
	2025	204.95	204.95	204.95	162.00
	2026	204.95	204.95	204.95	161.53
	2027	204.95	204.95	204.95	161.30
	2028	204.95	204.95	204.95	161.30
	2029	204.95	204.95	204.95	161.30

	2030	204.95	204.95	204.95	161.30
	2031	204.95	204.95	204.95	161.30
	Total	4,665.71	4,665.71	4,655.59	3,638.37
10 Miduim/ Heavy Bus	2009	284.29	284.29	281.56	211.64
	2010	281.43	281.43	276.27	209.18
	2011	284.30	284.30	283.64	211.71
	2012	287.45	287.45	281.19	214.94
	2013	290.84	290.84	287.66	218.54
	2014	294.52	294.52	293.78	222.50
	2015	298.50	298.50	298117.50	226.49

		Period 1	Period 2	Period 3	Period 4
10 Miduim/ Heavy Bus	2016	301.63	301.63	301.63	230.02
	2017	302.62	302.62	302.62	231.09
	2018	302.62	302.62	302.62	231.20
	2019	302.62	302.62	302.62	231.32
	2020	302.50	302.50	302.50	231.33
	2021	302.62	302.62	302.62	231.59
	2022	302.62	302.62	302.62	231.73
	2023	296.60	296.60	296.60	226.06
	2024	300.53	300.53	300.53	230.04
	2025	302.62	302.62	302.62	232.23
	2026	302.62	302.62	302.62	231.83
	2027	302.62	302.62	302.62	231.64
	2028	302.62	302.62	302.62	231.63
	2029	302.62	302.62	302.62	231.63
	2030	302.62	302.62	302.62	231.63
	2031	302.62	302.62	302.62	231.63
	Total	6,854.03	6,854.03	6,835.30	5,211.60
11 Motorcycle	2009	24.54	24.54	24.52	23.47
	2010	24.39	24.39	24.36	23.30
	2011	24.54	24.54	24.54	23.48
	2012	24.71	24.71	24.67	23.66

	2013	24.89	24.89	24.87	23.87
	2014	25.08	25.08	25.08	24.09
	2015	25.29	25.29	25.29	24.38
	2016	25.45	25.45	25.45	24.62
	2017	25.49	25.49	25.49	24.69
	2018	25.49	25.49	25.49	24.71
	2019	25.49	25.49	25.49	24.72
	2020	25.49	25.49	25.49	24.73
	2021	25.49	25.49	25.49	24.76
	2022	25.49	25.49	25.49	24.78
	2023	25.19	25.19	25.19	24.42
	2024	25.40	25.40	25.40	24.69
	2025	25.49	25.49	25.11849	24.84
		Period 1	**Period 2**	**Period 3**	**Period 4**
11 Motorcycle	2026	25.49	25.49	25.49	24.79
	2027	25.49	25.49	25.49	24.76
	2028	25.49	25.49	25.49	24.76
	2029	25.49	25.49	25.49	24.76
	2030	25.49	25.49	25.49	24.76
	2031	25.49	25.49	25.49	24.76
	Total	580.85	580.85	580.74	561.80
Sect-Alt Total		79,492.44	79,492.44	79,317.04	61,906.95

(N.B. fuel consumption quantities are in litres per 1000 vehicle-kilometres)

Appendix G US EPA federal Emission Standards 1997

Annual Emissions and Fuel Consumption for a Passenger Car and a Light Truck.

Vehicle	Pollutant	Average Amount g/km	Average/year kg/year
Passenger Car	Hydrocarbons	1.9	34.0
	Carbon monoxide	14.3	262.7
	Oxides of nitrogen	1.0	17.7
	Carbon dioxide	225.5	3992.0
	Gasoline	88.0	1561.3
Light Truck	Hydrocarbons	2.5	57.2
	Carbon monoxide	19.9	447.7
	Oxides of nitrogen	1.2	28.1
	Carbon dioxide	338.3	7620.5
	Gasoline	123.5	2782.0

Source: EPA (1997)

Notes: 1. Values converted from g/mile and lbs/year.

2. Conversion rates of 1 gallon = 3.785 litres and a specific gravity of 0.75 for gasoline were used