



ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

**IMPACT OF ROAD GEOMETRY AND ROAD SURFACE TYPES ON
FUEL CONSUMPTION AND GREENHOUSE GAS EMISSIONS:
A CASE STUDY ON TWO GRAVEL ROADS AND THREE ASPHALT
ROADS IN DIFFERENT AREAS OF ETHIOPIA**

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Impact of Road Geometry and Surface Types on Fuel Consumption and Greenhouse Gas Emissions

The undersigned have examined the thesis entitled **IMPACT OF ROAD GEOMETRY AND ROAD SURFACE TYPES ON FUEL CONSUMPTION AND GREENHOUSE GAS EMISSIONS (A CASE STUDY ON TWO GRAVEL ROADS AND THREE ASPHALT ROADS IN DIFFERENT AREAS OF ETHIOPIA)** presented by Solomon Shiferaw, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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UNDERTAKING

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ABSTRACT

Nowadays, it is globally accepted that vehicle gas emission is a significant source of air pollution and climate change. Correspondingly, vehicle operators are interested in reducing energy consumption and accordingly fuel costs.

The paper explores the impact of road geometry and road surface types on vehicle emission and fuel consumption using the Highway Development and Management Four (HDM-4) Tool emission modeling software. The analysis was based on data acquired from three asphalt concrete (AC) and two gravel roads located in different areas of Ethiopia. In this regard, the following data were collected: Road network; Vehicle Fleet; and Work Standards in respect of improvement and maintenance. The data were entered into HDM 4 and analyzed. The results indicated that the effects of road geometry that is: rise and fall; curvature; and also vehicle speed; altitude and pavement surface types are important and should be given an emphasis on vehicle emission and fuel consumption evaluations.

In all considered road sections, the study found out that emissions and fuel consumption have a direct relationship with rise and fall. Change of curvature is also related to changes in emission and fuel consumption. At higher and lower curvatures and at lower rise and fall, both emission and fuel consumption were maximum but at some point in between the curvatures, emission and fuel consumption became minimum. At higher rise and fall, emission and fuel consumption became minimum when curvature got close to zero.

It was also found out that speed has a relationship with emission and fuel consumption. When the speed lies between 50km/hr to 70 km/hr, maximum energy saving and minimum emission were achieved. Impact of altitude on emission and fuel consumption was also investigated. Both emission and fuel consumption increased as altitude decreased.

Another finding was that emission and fuel consumption are most sensitive to road surface types. Asphalt Concrete (AC) generated most fuel savings and reduced emission compared to Double Bituminous Surface Treatment (DBST) and Gravel roads.

Impact of Road Geometry and Surface Types on Fuel Consumption and Greenhouse Gas Emissions

It is expected that the findings of this research will provide insights for policy makers when consideration of strategies for improving road design to reduce vehicle emissions and fuel consumption in Ethiopia.

Keywords: Rise and fall, Curvature, Speed, Altitude, Fuel consumption, Emission

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ACROYNMS

AC:	Asphalt Concrete
CO:	Carbon Monoxide
DAS:	Data Acquisition System
DBST:	Double Bituminous Surface Treatment
E_CO:	Carbon Monoxide Emission
E_CO ₂ :	Carbon dioxide Emission
E_HC:	Hydrocarbon Emission
E_NO _x :	Nitrous Oxide Emission
E_PAR:	Particulates Emission
E_PB:	Lead Emission
E_SO ₂ :	Sulphur dioxide Emission
ERA:	Ethiopian Road Authority
FEAT:	Fuel Efficient Automobile Test
GHG:	Greenhouse Gas
HC:	Hydrocarbon
HDM-4:	Highway Development and Management Model Four
HDVs:	Heavy Duty Vehicles
IFCO:	Instantaneous Fuel Consumption
IPCC:	Inter Governmental Panel on Climate Change
NO ₂ :	Nitrogen dioxide
NO _x :	Nitrous Oxide
PCC:	Portland Cement Concrete
PCU:	Passenger Car Unit
PEMs:	Portable Emission Measurement Systems
PID:	Photo Ionization Detection

PPM:	Parts Per Million
SO ₂ :	Sulphur dioxide
TVOC:	Total Volatile Organic Compound
VPMS:	Vehicle Performance and Emission Monitoring System

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CHAPTER ONE

INTRODUCTION

1.1 Background

Transportation activity, a key component of economic development and human welfare, is increasing around the world as economies grow. It supports the industrial and commercial base of a country, facilitates the flows of internal and external trade and allow for effective physical communications. In addition to supporting industrial production, transportation has also become an important economic sector in its own right. Within developing countries, transportation infrastructure is often seen as the key to unlocking economic growth. However, the benefits of transportation systems do not result without costs. In addition to the financial costs associated with infrastructure development, capital equipment purchases and operating costs, there are many environmental damages that result from transportation activity, including accidents, noise, land use, and pollution of air, water and land. These problems are especially acute in the most rapidly growing economies of the developing world. The damages are costs to society that are not included in the price paid by the transport users. Over 600 million people globally are exposed to hazardous level of traffic – generated pollutants (UN,1998).

Never before have highway engineers put so much effort in building in an environmentally friendly manner. In addition, the geometric design guidelines themselves need revising to accommodate the new vehicle designs and the new modes of operation proposed by green designs so as to reduce vehicle emissions and fuel consumption in road engineering works.

The Highway Development and Management (HDM-4) Tool is intended to provide a broad analysis of road management and investment alternatives mainly for developing countries. It is a computer model to simulate physical and economic conditions of highways during the analysis period for the series of alternatives and scenarios specified by the user. The HDM-4 Model can be mainly classified into two parts: Road Deterioration and Works Effects model and Road User Effects model. In the case of Road Deterioration and Works Effects model, the pavement

distress models are included. The Road User Effects models consists of energy consumption and emission effects models. In this research, the Emission Effect Model was considered for determining the amount of vehicle exhaust emissions and fuel consumption under different road geometry, vehicle speed and road surface types considering three asphalt concrete roads and two gravel roads on different areas of Ethiopia.

1.2 Statement of the problem

Highway pavement surface quality, grades, curves, wind, traffic flow rates and vehicle speed affect the fuel consumption and air contaminant emission rates for a given section of highway or a network of highways (FHWA,2001). Eventhrough the effect is significant no much effort has been done in Ethiopia in this regard.

According to the International Energy Agency (2009), Transportation accounts for about 19% of global energy use and 23% of energy related carbon dioxide (CO₂) emissions and these shares will likely rise in future. Given current trends, transport energy use and CO₂ emissions are projected to increase by nearly 50% by 2030 and more than 80% by 2050. The Intergovernmental Panel on Climate Change (IPCC), advises that, to avoid the worst impacts from climate change, global CO₂ emissions must be cut by at least 50% by 2050. To achieve this, transportation will have to play a significant role. Even with deep cuts in CO₂ from all other energy sectors, if transportation does not reduce CO₂ emissions well below current levels by 2050, it will be very difficult to meet targets such as stabilizing the concentration of greenhouse (GHG) emissions in the atmosphere at a level of 450 ppm of CO₂ equivalent.

In most developing countries of the world, vehicular growth has not been checked properly by environmental regulating authorities leading to increase in levels of pollution. Traffic emissions contribute about 50-80% of Nitrogen Oxide (NO₂) and Carbon Monoxide (CO) concentration in developing countries (Fu,2001), and (Goyal, 2006).

Vehicle pollutants cause immediate and long-term effects on the environment. The emitted gases and solid matter do cause global warming, acid rain, and harm the environment and human health. As a result, improving energy efficiency of the transportation sector including improving vehicle shape, mass, engine size, and tire quality could play a vital role in reducing fuel consumption and exhaust gas emissions. This project shows a clear pathway for achieving a

low emission and fuel consumption by identifying the effect of road geometry and surface quality on vehicular emission and fuel consumption considering three asphalt roads and two gravel roads located in different areas of Ethiopia.

1.3 Thesis Objectives

1.3.1 General Objective

The main objective of this study is to determine the impact of road geometry and road surface types on fuel consumption and greenhouse gas emissions in Ethiopia.

1.3.2 Specific objectives

The following are specific objectives of this research:-

- The impact of curvature, rise and fall, altitude and speed on fuel consumption and greenhouse gas emissions based on sample of asphalt roads located in different places of Ethiopia; and
- Understand the extent of fuel consumption and greenhouse gas emissions by operating vehicles under asphalt concrete, double bituminous surface treatment and gravel roads.

1.4 Significance of the study

The following will be among the main contributions of the study:

- The study will be useful for policy makers, transportation planners, road agencies, government, and communities for planning, identifying and designing of road networks so as to minimize greenhouse emission and fuel consumption from road transportation.
- In spite of its importance, the awareness of researches exploring the direct and indirect impact of the road transportation on emission and fuel consumption has been quite limited in Ethiopia. This study envisaged to narrow the knowledge gap in this respect.
- Since no research has been conducted in Ethiopian in this area before, the output will likely enable researchers to use the findings as a stepping-stone for further research works.

1.5 Scope of the study

The study is delimited within three Asphalt Concrete roads and two gravel roads located in different areas of Ethiopia because of unavailability of required data, and time constraints. And it is acknowledged that, the study would have been better had it covered a wider areas for more generalization.

1.6 Research Questions

- Do road geometry (rise and fall, curvature) have impact on vehicular emission and fuel consumption?
- Does vehicle speed has impact on vehicular emission and fuel consumption?
- Does altitude has impact on vehicular emission and fuel consumption?
- Do road surface types (paved and unpaved) have impact on vehicular emission and fuel consumption?

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Road characteristics such as rise and fall, curvature and road surface types have a strong influence on vehicle speed which directly affects the amount of vehicular greenhouse gas emissions and fuel consumption. The amount of emissions and fuel consumption from the transport sector is analyzed in different countries of the world to achieve significant reductions in air pollution and fuel consumption. In this review, the analysis and results of emissions and fuel consumption from different literatures are presented below.

2.2 Effect of Grade on Emission and Fuel Consumption

Tartakovsky et al., (2000) evaluated the response of vehicle emission to road slopes for roads with gradients of up to $\pm 10\%$. The experiments were carried out on road segment having: constant road slope along the segment (gradient variation not exceeding $\pm 0.5\%$); minimal curvature of the segment and sufficient length; at least two lanes and no heavy traffic; good and uniform quality of road surface. Gradient values of the segments selected for the tests are 0, 4, 8 and 10%.

The test was carried out on four passenger cars. The response of vehicle emissions to road slope was compared for the selected passenger vehicles. The vehicles were tested at a constant speed of 20, 40 and 60 km/h on each road gradient. In all experiments, car fuel consumption and emissions of CO, HC and NO_x were measured. Fuel consumption was evaluated by an accurate gravimetric method. The engine feeding and return fuel pipes were re-connected with an additional fuel pump to a special fuel tank, which was weighed in the laboratory before and after the test, with accuracy of ± 1 g. The accuracy of the fuel consumption measurement was estimated at better than 0.5%. Emitted gases during each test were collected into a special bag intended for this purpose. Immediately after the test, CO, HC and NO_x contents in the bag were

measured by gas analyzer. For uphill driving, a rise of fuel consumption and exhaust gas emission was observed as gradient increases.

For downhill driving, the fuel consumption decreases as gradient is steeper. It was found that at vehicle speeds above 40 km/h and road gradients steeper than -5% , the amount of fuel consumption and exhaust emissions shows a significant reduction. It was also observed that there is a rise of HC emissions with increase of road gradient at downhill driving.

Zhang et al., (2015) conducted a study aiming at finding the influences of road grades on CO, HC and NO_x emissions of heavy duty vehicles (HDVs) in Taiyuan Metropolitan Area, China. The road grades of the chosen network ranged 0%–4% and emissions data was collected by Portable Emission Measurement System (PEMS). As found from the research, the CO emissions increase with increasing of road grades. When the grade increases from 0% to 0.5%, the change rate of intervals is large (0.1087), when the grade increases from 2% to 2.5%, value of emission is 0.0768 and from 1.5% to 2%, the value of emission is 0.0759 and when the grade increases from 3.5% to 4%, the rate of change is the smallest (0.0063).

Similar to the CO emissions, the NO_x emissions increases with the increase of road grades. When the grade increases from 0%–0.5%, the change rate of adjacent intervals is 0.1536, in the case of the change rate of grade increase from 2.5% to 3%, the change rate of adjacent interval is 0.0771 and finally when the grade increases from 1.5% to 2%, the change rate is the 0.0015.

The variations of HC emissions are different with the increase of grade. The overall HC emissions increased by 2.2074g at 4% grade and by 1.5308 g at 0% grade. However, the variations of HC emissions within different scenarios were complicated which was reflected by both positive and negative changes. For example, the change rate is equal to 0.1523 when the grade increases from 0% to 0.5%, and the rate change is 0.1445 when the grade changes from 1% to 1.5%. On the other hand, when the grade changes from 1.5% to 2%, the change rate is negative -0.0268 , when the grade changes from 2% to 2.5% the change rate is -0.0027 and when the grade changes from 3.5% to 4% the rate is -0.0010 .

As a conclusion, CO emissions are the most sensitive to the change of road grades while the HC emissions are the least. Compared to the emissions at 0% grade, the emissions at 4% grade

increases from 39.0% to 60.6%. The CO and NO_x emissions increase with the road grades in all cases, while the variations of HC emissions in different scenarios are complicated.

Fernandez, (1997) identified the effects of road grade and other loads on vehicle exhaust emissions based on second-by-second on-board emissions measurements using an instrumented vehicle that was equipped with an on-board Data Acquisition System (DAS) that monitored engine and vehicle dynamic parameters to record driving conditions such as speed and grade, as well as emission rates measurement of total hydrocarbons and carbon monoxide. Controlled runs with predetermined speeds between 35 and 55 mph and accelerations less than 3.3 mph/second were conducted on flat terrain and on hills with grades ranging from 0 to 7%. The vehicle was a 1991 GM Chevrolet Lumina with a 3.1 liter engine. The study found that exhaust emissions of HC and CO increase significantly when driving on grades of approximately 3% or higher and speeds between 35 to 55 mph. For hydrocarbons, the increase in emissions is about 0.04 g/mile for each 1% grade increment. For carbon monoxide (CO), the increase is more dramatic: 3.0 g/mile for each 1% grade increment. For a fully occupied vehicle with four passengers on a 4.5% grade, emissions increase by 0.07 g/mile for hydrocarbons and 10.2 g/mile for CO. Air conditioning operation, at full setting, further increase emissions while driving on hills (4.5 and 6.7% grades) by 0.07 g/mile for hydrocarbons and 31.9 g/mile for CO.

2.3 The Effect of Speed on Emission and Fuel Consumption

Bokare and Maurya, (2013) conducted a study aiming at modeling the effect of speed, acceleration and deceleration on tailpipe emissions using onboard emission measurement system. To measure the speed and tailpipe emission of the test vehicle (Hyundai Santro 2009 model), two instruments were used in this study. V-Box Global Positioning System (GPS) capable of recording vehicle position and speed (data recording once a second) was used for recording vehicle speed profile and a five gas analyzer, Automotive Exhaust Monitor PEA 205, manufactured by Indus Scientific India was used for onboard measurement of tailpipe emission of test vehicle. Using this device, each second data of vehicular emissions such as Carbon Monoxide (CO, by percent of volume), Hydrocarbons (HC, by parts per million, ppm, of volume) and Oxides of Nitrogen (NO_x, by parts per million, ppm, of volume) were recorded. Both devices were installed to the test vehicle which was connected to a computer to obtain

second by second emission data. The test was done at a particular acceleration and deceleration level. The speed and emission relationships were developed at two different acceleration levels, 1.0 m/s^2 and 1.6 m/s^2 .

The result showed that tailpipe emission rate was high at lower speed. Further, increase in speed results in increase of emission rates. At first or second gear the engine exerts more power that consumes more fuel which results in lowering of speed (0-3m/s). Higher fuel consumption results in high tailpipe emissions. When the speed of vehicle increases (in second or third gear, speed 3 to 8 m/s), the power consumption of the engine reduces which results in reduction of tailpipe emission. Further, increase in speed (in fourth or fifth gear, speed above 8 m/s) effects the engine to consumes more fuel for speeding that results in increase in tailpipe emission. It is found that the emission rate was the lowest at the speed range of 3 to 8 m/s and at acceleration rate of 1 m/s^2 for all greenhouse gases.

It was also observed that at higher acceleration (1.6 m/s^2), all tailpipe emission rates (CO in %, HC and NO_x in ppm) were higher than at lower acceleration (1.0 m/s^2). This implies that tailpipe emission increases with increase in vehicle acceleration. Tailpipe emission is lower at lower acceleration and higher emission at higher acceleration. No relationship was observed between speed, deceleration and tailpipe emission. Therefore, it can be said that, tailpipe emission is not affected by deceleration.

Noland et al., (2004) found out that the relation between tailpipe emissions of CO, CO₂, NO_x and speed and acceleration. The study was conducted in central London on urban streets with speeds not exceeding about 65 km/hr. The on-board emissions measurement was done using Vehicle Performance and Emissions Monitoring System (VPEMS) which has a Mobile Unit and Master Control Center. The Mobile Unit was installed on the vehicle to take real time emission data from tailpipe and transmit the captured data to Master Control Center via Global System for Mobile(GSM) technology for storage analysis and display. The data was captured using the 1998 model Citroen Synergy minivan on a test run of one vehicle fitted with VPEMS and the following result was obtained. Figures 1 and 5 below illustrate average CO emissions versus 3km/hr speed bins and average CO₂ emissions versus 3km/hr speed bins respectively. Subsequently, Figure 2 illustrates average NO_x emissions versus 3km/hr speed bins.

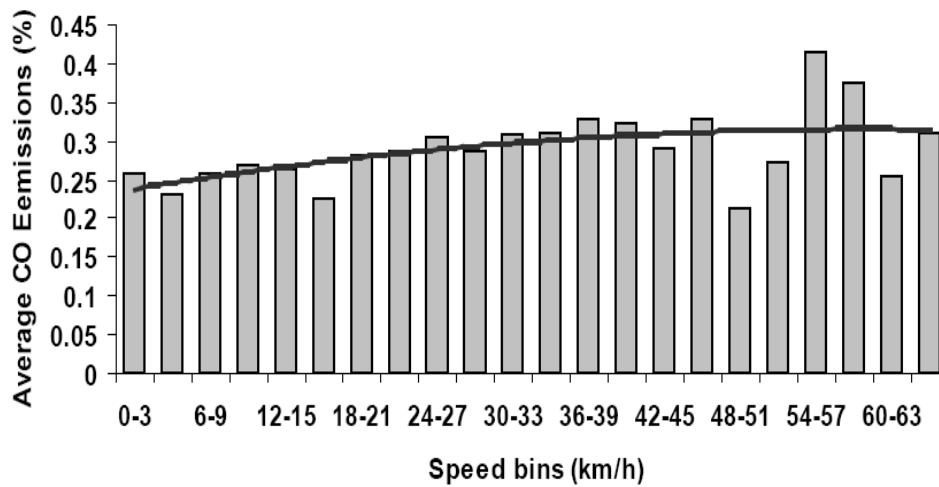


Figure 1: Average CO emissions versus 3km/hr speed bins.

Source: Noland et al., (2004)

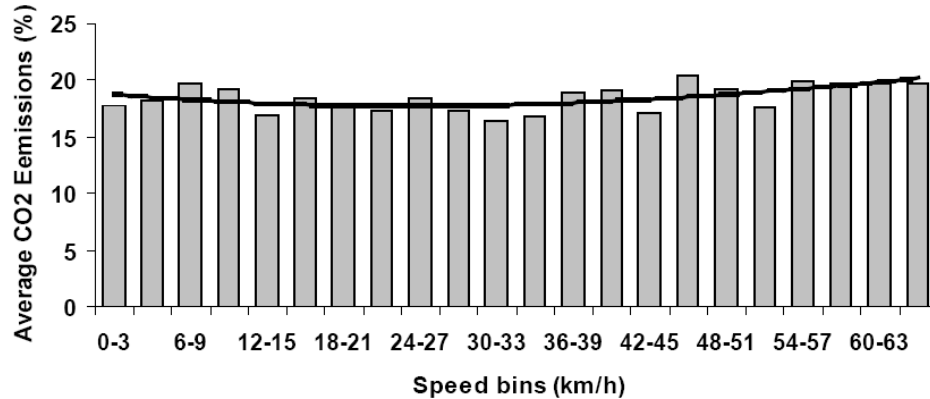


Figure 2: Average CO₂ emissions versus 3km/hr speed bins.

Source: Noland et al., (2004).

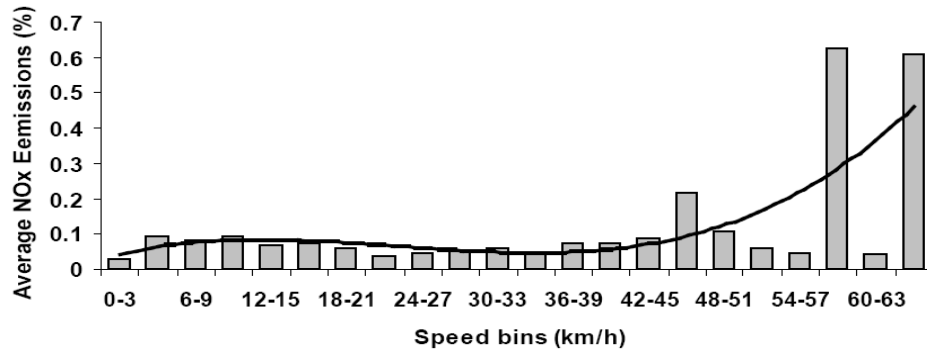


Figure 3: Average NO_x emissions versus 3km/hr speed bins.

Source: Noland et al., (2004)

As can be seen from figures 1 - 3, CO emissions increases as speeds increase while CO₂ emissions are generally flat. NO_x emissions show an upward spike around the 60 km/hr bin. Figures 4, 5 and 6 below illustrate: average CO emissions by different driving modes, average CO₂ emissions versus 3km/hr speed bins and average NO_x emissions versus 3km/hr speed bins respectively.

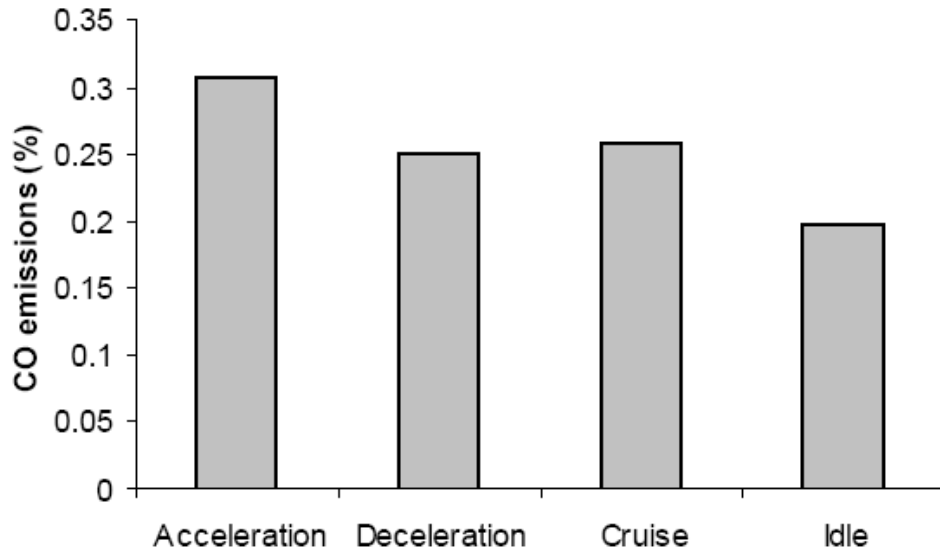


Figure 4: Average CO emissions by different driving modes.

Source: Noland et al., (2004)

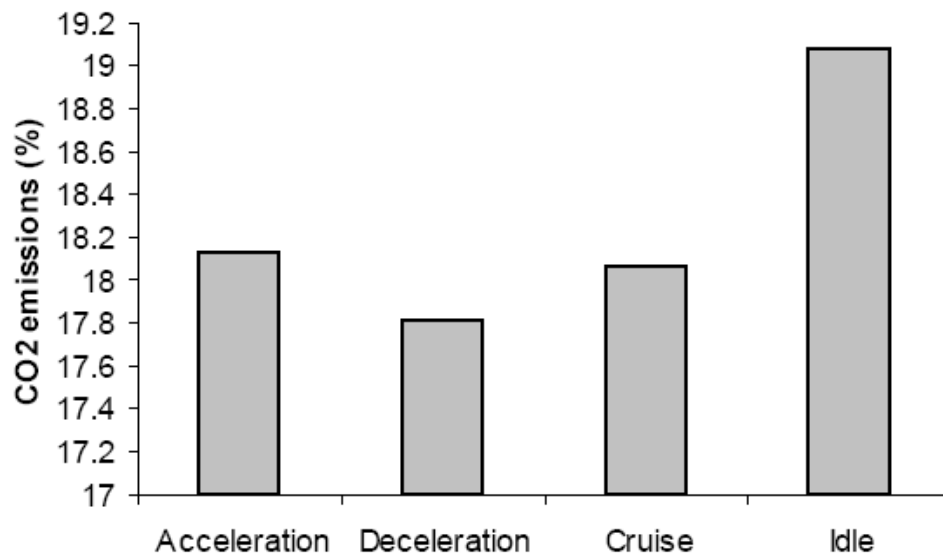


Figure 5: Average CO₂ emissions versus 3km/hr speed bins.

Source: Noland et al., (2004).

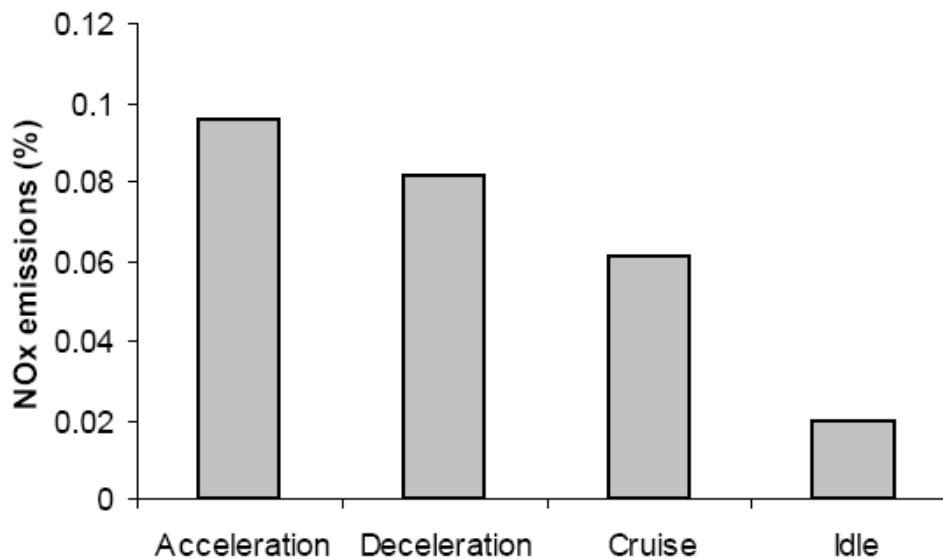


Figure 6: Average NO_x emissions versus 3km/hr speed bins.

Source: Noland et al., (2004)

The above figures shows that CO average emission is highest during acceleration modes and lowest during idling. CO₂ emission shows less variation between the various modes, but is lowest during idling. NO_x emissions is highest during accelerations and lowest during idling.

2.4 The Effect of Altitude on Emission and Fuel Consumption

Bishop et al., (2001) conducted a study to determine the relationship between altitude and emissions; the study was limited to heavy duty vehicles only. The analysis was done by remote sensing instrumentation and measurement technique (FEAT, Fuel Efficient Automobile Test). The report presents the results of remote sensing measurements of in-use heavy-duty diesel trucks collected at five different locations and elevations in the United States of America and Europe. The locations were: Anaheim, California (elevation 104 m), San Marcos, Texas (elevation 198 m), Golden, Colorado (elevation 1695 m), Dumont, France (elevation 2,530 m), and on the Gotthard route near the village of Wassen in the Canton of Uri, Switzerland (elevation 884 m). The measured ratios of CO/CO₂, HC/CO₂, and NO/CO₂ were recorded and from that grams of pollutant per kilogram of fuel burned were calculated. Figure 7 below illustrates gNO, gHC and gCO emissions/kg of fuel consumed versus altitude for five sites.

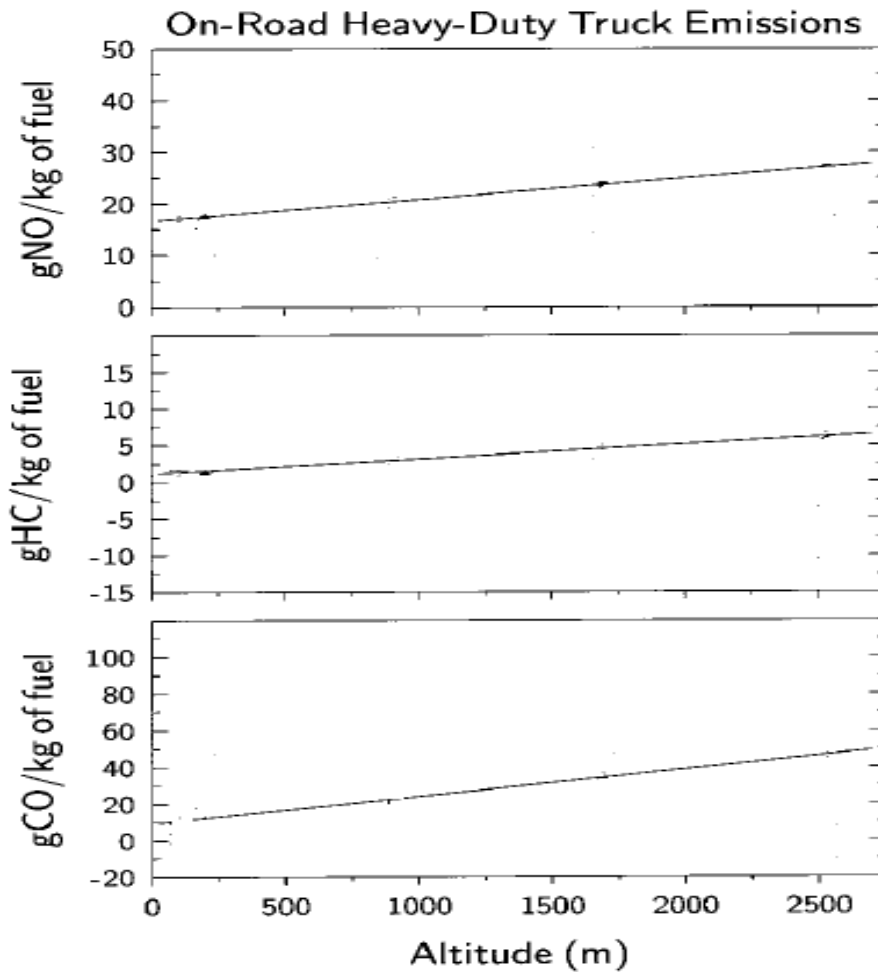


Figure 7: Plots of gNO, gHC, and gCO emissions/kg of fuel consumed versus altitude for the five sites.

Source: Bishop et al., (2001).

The above figure shows emissions of CO, HC, and NO_x increases with increasing altitude. The result for nitric oxide shows a significant increase of gNO_x/kg of fuel consumed/km with increase in altitude.

2.5 The Effect of Asphalt Concrete and Portland cement Concrete Pavement on Emission and Fuel Consumption

Ardekani, (2010) investigated the difference that exists in fuel consumption and CO₂ emissions when driving on Asphalt Concrete (AC) versus Portland Cement Concrete (PCC) pavements on a field. Two asphalt and two concrete road sections were selected for the analysis with each pair of study sections having similar gradient and roughness values. The study was conducted through field data collections using an instrumented van and it's done under constant speed and accelerating modes. Installed fuel sensors instantaneously measures the amount of fuel entering the engine and returning to the tank, with the difference between the fuel intake and the amount returned to the tank being an estimate of fuel consumed. The result shows that under both modes, the fuel consumption rate per unit distance is lower by 3% to 17% for PCC sections depending on surface conditions, crown and substructure materials and thickness. The CO₂ emissions in the PCC case were estimated using the following empirically-derived regression model (Afotey, 2008):

$$\text{CO}_2 \text{ amount in grams/sec} = 0.867 + 0.011 V + 1.172 A + 0.208 A.V$$

Where

V: vehicle speed in mph, and

A: acceleration rate in mph/second.

The percentage saving may also vary depending on the vehicle mix. The lower fuel consumption rates also results in the reduction of emission rates.

The preceding studies show the effect of road grade, speed, altitude and road surface types on emission and fuel consumption in different countries considering different methods, but in our country Ethiopia the effect has not been given much emphasis. Hence, further research is needed to address the effect of road geometry and road surface types on vehicular emission and fuel consumption. This thesis is done to analyze the effect in Ethiopia using the Highway Development and Management (HDM-4) Tool emission model considering three asphalt roads and two gravel roads in different areas of Ethiopia.

CHAPTER THREE

MATERIALS AND METHODOLOGY

3.1 General

The methodology and procedure followed in this research started with problem identification by going through different literatures and informal discussions with pertinent professionals. The analysis was done using the Highway Development and Management (HDM-4) Tool emission model.

3.2 Data Collection

3.2.1 Study Area

The selected study areas were a sample of three asphalt concrete (AC) roads and two gravel roads in different areas of Ethiopia. The sample areas include different types of terrains, climates, topography and geology. The sample asphalt roads were: Gonder-Debark (99.2km), Gedo-Nekempte (134km), and Aposto-Wendo-Negele (268.36km); and the sample gravel roads were: Debre Birhan-Ankober (42km) and Hamusit-Estie (76km).

The selected five road networks are divided into road sections depending on traffic count and terrain type that are described as follows:

- Gonder - Debark road network:
 - Section 1: Gonder - Weleka ,
 - Section 2: Weleka - Dabat, and
 - Section 3: Dabat - Debark.
- Gedo - Nekempte road network,
 - Section 1: Gedo - Bako,
 - Section 2: Bako - Nekempte,

- Aposto - Wendo - Negele road network,
 - Section 1: Aposto - Wendo - Yirba Muda,
 - Section 2: Yirba Muda - Wadera,
 - Section 3: Wadera - Negelle,
- Debrebirhan - Ankober road network,
 - Section 1: Debrebirhan - KM 16,
 - Section 2: KM 16 - Ankober, and
- Hamusit - Estie road network,

3.2.2 Method of data collection and sources

The study incorporates secondary data. It involves readily available and relevant data that were collected from pertinent organizations, institutions, agencies (governmental and private sectors). Additionally, available documents like books, manuals, thesis, past researches conducted in different countries, journals, articles and internet sources were reviewed. The input elements for HDM-4 software includes: traffic data, type and geometry of the road section, vehicle fleet, configuration, and maintenance standards. Since the existing secondary data didn't provide sufficient details on all required input data for the HDM-4 model, default settings were considered.

3.3 HDM 4 input data

Most of the HDM-4 data were obtained through examining available final feasibilities and engineering design reports which were acquired from the planning section of the Ethiopian Roads Authority (ERA).

3.3.1 The Road Networks

The network data mainly includes: speed flow pattern, climatic zone, existing geometry and condition of the road that is length, width, curvature, rise and fall, existing pavement type and thickness, roughness and traffic levels. The collected road network data for all road sections are presented in table 1 below.

Impact of Road Geometry and Surface Types on Fuel Consumption and Greenhouse Gas Emissions

Table 1: Gonder to Debark Road

	Data Description	Gondar - Weleka	Weleka - Dabat	Dabat - Debark
Definition	Road class	Secondary or Main	Secondary or Main	Secondary or Main
	Speed flow type	Two lane standard	Two lane standard	Two lane standard
	Traffic flow pattern type	Interurban	Interurban	Interurban
	AADT-2010	638	404	306
	Pavement type	Asphalt mix on granular base	Asphalt mix on granular base	Asphalt mix on granular base
	Length(km)	3.73	67.85	27.6
	Width of Carriage way(m)	7	7	7
	Shoulder(m)	2	2	2
	No. of Lane	2	2	2
	Surface class	Bituminous	Bituminous	Bituminous
	Climate zone	Humid/Tropical	Tropical Humid	Tropical Humid
	Flow direction	Two way	Two way	Two way
	Geometry	Super elevation	8%	8%
Average horizontal curvature (degree/km)		182.77	141.26	114.59
Vertical rise + fall (m/km)		28.95	27.61	21.15
Vertical rise + fall (no/km)		1.06	0.6	1.12
Speed limit (km/hr)		80	80	80
Altitude (m)		2225	2677	2726
Drain type		V shaped hard	V shaped hard	V shaped hard

Impact of Road Geometry and Surface Types on Fuel Consumption and Greenhouse Gas Emissions

Table 1: Gonder to Debark Road (Cont'd)

	Data Description	Gondar - Weleka	Weleka - Dabat	Dabat - Debark
Condition of road	Ride Quality (defaults value)	Good	Good	Good
	Surface condition (defaults value)	New	New	New
	Surface texture (defaults value)	Good	Good	Good
	Structure adequacy (good, fair and poor)	Good	Good	Good
	Total area of cracking(%)	0	0	0
	Condition at the end of year	2009	2009	2009
	Roughness(IRI-m/km)	2.5	2.5	2.5
	Raveled Area (%)	0	0	0
	Number of Potholes (No./km)	0	0	0
	Mean rut depth (mm)	0	0	0
	All Transverse Thermal Cracking (%)	0	0	0
	Wide Structural Cracking Area (%)	0	0	0
	Edge Break Area (m2/km)	0	0	0
	Texture depth (mm)	0.7	0.7	0.7
	Skid resistance (mm)	0.5	0.5	0.5
	Drainage (excellent, good, fair, poor, very poor) Default range of HDM-4	Excellent	Excellent	Excellent
Pavement	Material type	Asphalt concrete	Asphalt concrete	Asphalt concrete
	Most recent surfacing thickness(mm)	50	50	50
	Previous/old surfacing thickness(mm)	50	50	50
	Analysis Start year	2010	2010	2010
	Analysis period	20	20	20
	Last reconstruction or new construction	2009	2009	2009
	Last rehabilitation (overlay)	2009	2009	2009
	Last surfacing(resealing)	2009	2009	2009
	Last preventive treatment	2009	2009	2009

Source: Feasibility study of Gonder to Debark road by Kocks Consulting and Metaferia Consulting Engineers,(2006).

Table 2: Gedo to Nekempte Road

	Data Description	Gedo - Bako	Bako - Nekemte
Definition	Road class	Primary or Trunk	Primary or Trunk
	Speed flow type	Two lane standard	Two lane standard
	Traffic flow pattern type	Interurban	Interurban
	AADT-2011	621	608
	Pavement type	Asphalt mix on granular base	Asphalt mix on granular base
	Length(km)	58	76
	Width of Carriage way(m)	7	7
	Shoulder(m)	1.5	1.5
	No. of Lane	2	2
	Surface class	Bituminous	Bituminous
	Climate zone	Humid/Tropical	Humid/Tropical
	Flow direction	Two way	Two way
	Geometry	Super elevation	8%
Average horizontal curvature (degree/km)		126.3	263
Vertical rise + fall (m/km)		31	31
Vertical rise + fall (no/km)		2	2
Speed limit (km/hr)		80	70
Altitude(m)		2500	2300
Drainage type		V shaped hard	V shaped hard
Condition of road	Ride Quality (defaults value)	Good	Good
	Surface condition (defaults value)	New	New
	Surface texture (defaults value)	Good	Good
	Structure adequacy (good, fair and poor)	Good	Good
	Total area of cracking (%)	0	0
	Condition at the end of year	2010	2010
	Roughness(IRI-m/km)	2.5	2.5
	Raveled Area (%)	0	0
	Number of Potholes (No./km)	0	0
	Mean rut depth (mm)	0	0

Table 2: Gedo to Nekemte Road (Cont'd)

	Data Description	Gedo - Bako	Bako - Nekemte
Condition of road	All Transverse Thermal Cracking (%)	0	0
	Wide Structural Cracking Area (%)	0	0
	Edge Break Area (m ² /km)	0	0
	Texture depth (mm)	0.7	0.7
	Skid resistance (mm)	0.5	0.5
	Drainage (excellent, good, fair, poor, very poor) Default range of HDM-4	Excellent	Excellent
	Pavement	Material type	Asphalt concrete
Most recent surfacing thickness(mm)		50	50
Previous/old surfacing thickness(mm)		50	50
Analysis Start year		2011	2011
Analysis period		20	20
Last reconstruction or new construction		2010	2010
Last rehabilitation (overlay)		2010	2010
Last resurfacing (resealing)		2010	2010
Last preventive treatment		2010	2010

Source: Feasibility study of Gedo to Nekemte road by Saba Engineering, (2006).

Impact of Road Geometry and Surface Types on Fuel Consumption and Greenhouse Gas Emissions

Table 3: Aposto to Negelle Road

	Data Description	Aposto - Wendo - Yirba Muda	Yirba Muda - Wadera	Wadera - Negelle
Definition	Road class	Secondary or Main	Secondary or Main	Secondary or Main
	Speed flow type	Two lane standard	Two lane standard	Two lane standard
	Traffic flow pattern type	Interurban	Interurban	Interurban
	AADT-2010	358	312	312
	Pavement type	Asphalt mix on granular base	Asphalt mix on granular base	Asphalt mix on granular base
	Length(km)	94.1	109	65.26
	Width of Carriage way(m)	7	7	7
	Shoulder(m)	2	2	2
	No. of Lane	2	2	2
	Surface class	Bituminous	Bituminous	Bituminous
	Climate zone	Humid/Tropical	Humid/Tropical	Humid/Tropical
	Flow direction	Two way	Two way	Two way
	Geometry	Super elevation	8%	8%
Average horizontal curvature (degree/km)		134	136.5	43.5
Vertical rise + fall (m/km)		33.75	43.36	22.21
Vertical rise + fall (no/km)		1.6	1.32	1.51
Speed limit (km/hr)		70	70	80
Altitude (m)		2226	1969	1580
Drainage type		V shaped hard	V shaped hard	V shaped hard
Condition of road	Ride Quality (defaults value)	Good	Good	Good
	Surface condition (defaults value)	New	New	New
	Surface texture (defaults value)	Good	Good	Good
	Structure adequacy (good, fair and poor)	Good	Good	Good
	Total area of cracking (%)	0	0	0
	Condition at the end of year	2009	2009	2009
	Roughness(IRI-m/km)	2.5	2.5	2.5
	Raveled Area (%)	0	0	0
	Number of Potholes (No./km)	0	0	0
Mean rut depth (mm)	0	0	0	

Table 3: Aposto to Negelle Road (Cont'd)

	Data Description	Aposto - Wendo - Yirba Muda	Yirba Muda - Wadera	Wadera - Negelle
Condition of road	All Transverse Thermal Cracking (%)	0	0	0
	Wide Structural Cracking Area (%)	0	0	0
	Edge Break Area (m2/km)	0	0	0
	Texture depth (mm)	0.7	0.7	0.7
	Skid resistance (mm)	0.5	0.5	0.5
	Drainage (excellent, good, fair, poor, very poor) Default range of HDM-4	Excellent	Excellent	Excellent
	Pavement	Material type	Asphalt concrete	Asphalt concrete
Most recent surfacing thickness(mm)		50	50	50
Previous/old surfacing thickness(mm)		50	50	50
Analysis of year		2010	2010	2010
Analysis period		20	20	20
Last reconstruction or new construction		2009	2009	2009
Last rehabilitation (overlay)		2009	2009	2009
Last resurfacing (resealing)		2009	2009	2009
Last preventive treatment		2009	2009	2009

Source: Feasibility study of Aposto to Negele road by Beza Consulting Engineers, (2006).

Impact of Road Geometry and Surface Types on Fuel Consumption and Greenhouse Gas Emissions

Table 4: Debrebirhan to Ankober Road

	Data Description	Debrebirhan-Km16	Km16 - Ankober
Definition	Road class	Secondary or Main	Secondary or Main
	Speed flow type	Two lane standard	Two lane standard
	Traffic flow pattern type	Interurban	Interurban
	AADT-2012	176	176
	Pavement type	Gravel	Gravel
	Length(km)	16	26
	Width of Carriage way(m)	6.5	6.5
	Shoulder(m)	0	0
	No. of Lane	2	2
	Surface class	Unsealed	Unsealed
	Climate zone	Humid/Tropical	Humid/Tropical
	Flow direction	Two way	Two way
	Geometry	Super elevation	7%
Average horizontal curvature (degree/km)		57	193
Vertical rise + fall (m/km)		32.5	56.08
Vertical rise + fall (no/km)		4.24	3.5
Speed limit (km/hr)		40	30
Altitude(m)		2958	3090
Condition of road	Ride Quality (defaults value)	Poor	Poor
	Surface texture (defaults value)	Poor	Poor
	Structure adequacy (good, fair and poor)	Poor	Poor
	Condition at the end of year	2009	2009
	Gravel thickness(mm)	225	225
	Roughness(IRI-m/km)	30-very poor	30-very poor
Pavement	Surface material	Lateritic gravel	Lateritic gravel
	Analysis Start year	2012	2012
	Analysis period	20	20
	Sub grade material	Gravel sand mixtures with excess of fines	Gravel sand mixtures with excess of fines
	Compaction method	Mechanical	Mechanical
	Last regravell year	1998	1998

Source: Feasibility study of Debrebirhan to Ankober by Core Consulting Engineers Plc, (2011).

Table 5: Hamusit to Estie Road

	Data Description	Hamusit - Estie
Definition	Road class	Secondary or Main
	Speed flow type	Two lane standard
	Traffic flow pattern type	Interurban
	AADT-2014	298
	Pavement type	Gravel
	Length(km)	76
	Width of Carriage way(m)	6
	Shoulder(m)	0
	No. of Lane	2
	Surface class	Unsealed
	Climate zone	Humid/Tropical
	Flow pattern	Two way
	Geometry	Super elevation
Average horizontal curvature (degree/km)		55
Vertical rise + fall (m/km)		8
Vertical rise + fall (no/km)		2
Speed limit (km/hr)		70
Altitude(m)		2260
Condition of road	Ride Quality (defaults value)	Poor
	Surface texture (defaults value)	Poor
	Structure adequacy (good, fair and poor)	Poor
	Condition at the end of year	2013
	Gravel thickness (mm)	150
	Roughness(IRI-m/km)	11
	Surface material	Volcanic gravels angular
	Analysis Start year	2014
	Analysis period	20
	Subgrade material	Clays (inorganic) of medium plasticity,CI
	Compaction method	Mechanical
Last regravell year	2005	

Source: Feasibility study of Hamusit to Estie by Bahirdar University School of Civil and Water Resource Engineering, (2013).

3.3.2 Vehicle Fleet

Regarding traffic data for estimation of traffic measures on subject roads, AADTs, vehicle composition, vehicle-km, vehicle categories and traffic growth factors were determined. Available secondary data were collected from the ERA Road Planning Office. The basic characteristics of vehicle categories in this study is presented in Table 6 below.

Table 6: Vehicle classification adopted by the consultants

Vehicle category	No of axles	Vehicle types and capacities
Car	2	Small cars and taxis
Land Rovers (4WD)	2	Pick – ups, Land Rovers, Land Cruisers, Jeeps, etc.
Small Bus (SB)	2	Buses up to 27 passenger seats
Large Bus (LB)	2	Buses with passenger seats above 45
Small Truck (ST)	2	Delivery vans and light goods trucks up to 3.5 tons capacity
Medium Truck (MT)	2 or 3	Trucks with carrying capacity above 3.5 tons and below 7.5 tons
Heavy Truck (HT)	6	Trucks and tankers with carrying capacity above 7.5 tons
Truck and Trailer (TT)	4	Trucks with trailer and semi-trailer and tanker trailer

Source: ERA Geometric manual, (2002).

3.3.4 Average daily traffic(AADT) and Growth rate

In this study, the traffic have been adjusted accordingly using growth rates recommended by the Consultants. The Consultants had determined different growth rates by vehicle types during the design period. The AADT and the growth rates adopted for this study are presented in Tables 7 and 8 below.

Impact of Road Geometry and Surface Types on Fuel Consumption and Greenhouse Gas Emissions

Table 7: AADT of the project roads

Gondar - Welka Road									
Year	Car	4 WD	S/ Bus	L/ Bus	S/ Truck	M/ Truck	H/ Truck	T and T	Total
2010	89	189	38	34	74	77	98	39	638
Welka - Dabat Road									
2010	5	154	34	30	49	48	59	25	404
Dabat - Debark Road									
2010	2	104	25	31	37	36	48	23	306
Gedo - Bako Road									
2011	1	79	96	46	30	166	170	33	621
Bako - Nekempte									
2011	2	87	84	45	40	171	134	45	608
Aposto - Wendo - Yirba Muda									
2010	1	50	43	28	28	50	108	50	358
Yirba Muda - Wadera									
2010	3	46	34	22	28	46	83	50	312
Wadera - Negelle									
2010	3	46	34	22	28	46	83	50	312
Debrebirhan - Km16									
2012	1	41	34	8	1	51	28	11	176
Km 16 - Ankober									
2012	1	41	34	8	1	51	28	11	176
Hamusite - Estie									
2014	3	57	18	50	48	60	41	21	298

Source: ERA, Feasibility study of the project roads.

Table 8: Summary of traffic growth rates (%) for Gonder to Debark road

Vehicle Type	2006 - 2019	2020-2029
Car	7.9	6.8
4WD	7.9	6.8
Small bus	6.9	6.1
Large bus	6.6	5.8
Small Truck	7.2	6.1
Medium Truck	7.8	6.6
Heavy Truck	7.8	6.6
Truck Trailer	8.4	7.2

Source: Feasibility study of Gonder to Debark road by Kocks Consulting and Metaferia Consulting Engineers,(2006).

Table 9: Summary of traffic growth rates (%) for Gedo to Nekempte road

Vehicle Type	2007 - 2010	2011-2013	2014-2018	2019-2025	2026-2030
Car	5.5	6	7	6.5	6
4WD	5.5	6	7	6.5	6
Small bus	4.5	5	6	5.5	5
Large bus	4.5	5	6	5.5	5
Small Truck	4	4.5	5.5	5	4.5
Medium Truck	4	4.5	5.5	5	4.5
Heavy Truck	4	4.5	5.5	5	4.5
Truck Trailer	4	4.5	5.5	5	4.5

Source: Feasibility study of Gedo to Nekempte road by Saba Engineering, (2006).

Table 10: Summary of traffic growth rates (%) for Aposto to Negele road

Vehicle Type	Growth Rate
Car	8.4
4WD	8.4
Small bus	8.4
Large bus	7.2
Small Truck	7.2
Medium Truck	7.2
Heavy Truck	7.2
Truck Trailer	7.2

Source: Feasibility study of Aposto to Negele road by Beza Consulting Engineers, (2006).

Table 11: Summary of traffic growth rates (%) for Debrebirhan to Ankober road

Vehicle Type	2010 – 2014	2015-2024	2025-2034
Car	5.5	6.5	5.5
4WD	5.5	6.5	5.5
Small bus	5.5	6.5	5.5
Large bus	5.5	6.5	5.5
Small Truck	7.5	8.5	7.5
Medium Truck	7.5	8.5	7.5
Heavy Truck	7.5	8.5	7.5
Truck Trailer	7.5	8.5	7.5

Source: Feasibility study of Debrebirhan to Ankober by Core Consulting Engineers Plc, (2011).

Table 12: Summary of traffic growth rates (%) for Hamusit to Estie road

Vehicle Type	2014-2019	2020 - 2029	2030-2034
Car	8	9.42	8.72
4WD	8	9.42	8.72
Small bus	8	9.42	8.72
Large bus	8	9.42	8.72
Small Truck	8	9.75	9.1
Medium Truck	8	9.75	9.1
Heavy Truck	8	9.75	9.1
Truck Trailer	8	9.75	9.1

Source: Feasibility study of Hamusit to Estie by Bahirdar University School of Civil and Water Resource Engineering, (2013).

3.4 Road Improvement and Maintenance Standard

3.4.1 Road Maintenance Standard for the Asphalt Roads

For the asphalt roads, the following road maintenances were adopted for use in the analysis:

- Routine (miscellaneous) maintenance;
- Pothole Patching;
- Crack Resealing; and
- Overlay.

3.4.2 Road Improvement Standards for the Asphalt Roads

The proposed improvement of the asphalt roads considers realignment of the existing roads to get different amount of greenhouse gas emissions and fuel consumptions. By varying rises and falls, average horizontal curvatures, speed limits and altitudes, the change in greenhouse gas emissions and fuel consumptions were generated using HDM 4. Following all improvement alternatives, the maintenance types considered were the same.

3.4.3 Road Maintenance Standard for the Gravel Roads

The following maintenance standards were used in the analysis:

- **Without the Project Road**

This strategy reflects the current minimum maintenance standards which is used to keep the road at acceptable level of serviceability.

- Routine (miscellaneous) maintenance
- Resurfacing

- **With the Project Road**

The with project maintenance strategy is adopted following the implementation of upgrading of the project road. The applicable maintenance strategy of the with project case are presented below.

- Routine (miscellaneous) maintenance

- Pothole Patching
- Crack Resealing
- Overlay

3.4.4 Road Improvement Standard and Strategy for the Gravel Roads

Two improvement alternatives have been considered and each section was compared against the base-year without the study road alternative. The proposed improvement considers upgrading of the existing poor gravel road to paved standard, Asphalt Concrete (AC) as Option 1 and Double Bituminous Surface Dressing (DBST) as Option 2.

3.5 Scheduling of the Capital Expenditure

The project costs were assumed to be expended over three years of the construction period. In line with the work schedule, it was considered that investment costs would be expended as 30% in the first year, 40% in the second year and the remaining 30% in the final year of the project.

3.6 Analysis

The analyses were done using HDM-4 vehicle emission model. The Model predicts different components of vehicle exhaust emissions as a function of fuel consumption and speed. Fuel consumption is a function of vehicle speed, which in turn depends on road characteristics and the characteristics of the vehicle itself. Thus, it is possible to analyze the changes in emissions as a result of implementing different road maintenance and improvement options, or when there are major changes to the vehicle fleet using the road network. There are different kinds of pollutants that are emitted by vehicles.

3.6.1 Types of Pollutants

The following are the seven types of vehicle emissions that are generated using HDM 4:

- i. Hydrocarbon (HC)
- ii. Carbon monoxide (CO)
- iii. Nitrous Oxide (NO_x)
- iv. Sulphur dioxide (SO₂)
- v. Carbon dioxide (CO₂)

- vi. Particulates (Par)
- vii. Lead (Pb)

3.6.2 The Relationships

The quantities of different vehicular emission components were generated using the relationships together with default parameters. The relationships are presented below as acquired from the HDM 4 Manual, Volume four:

- (i) Hydrocarbon

$$E_{HC} = \frac{3.6 * Kehc0 * (a0 + a1 * Kehc1 * IFC) * (1 + 0.5 * a2 * LIFE)1000}{SPEED}$$

where

- E_HC Hydrocarbon Emission(g/veh-km);
- IFC0 Instantaneous Fuel Consumption (ml/sec);
- LIFE Vehicle service life;
- SPEED Vehicle Speed(km/hr);
- a0 to a2 Model parameters for different vehicle types;
- Kehc0 Calibration factor (default = 1.0); and
- Kehc1 Calibration factor (default = 1.0)

- (ii) Carbon monoxide

$$E_{CO} = \frac{3.6 * Kec0 * (a0 + a1 * Kec1 * IFC) * (1 + 0.5 * a2 * LIFE)1000}{SPEED}$$

where

- E_CO Carbon Monoxide Emission (g/veh-km);
- Kec0 Calibration factor (default = 1.0);
- Kec1 Calibration factor (default = 1.0); and

All other variables are as defined previously

- (iii) Nitrous oxide

$$E_{NOX} = \frac{3.6 * Kenox0 * (a0 + a1 * Kenox1 * IFC) * (1 + 0.5 * a2 * LIFE)1000}{SPEED}$$

where

E_NOX Nitrous Oxide Emission(g/veh-km);

Kenox0 Calibration factor (default = 1.0); and

Kenox1 Calibration factor (default = 1.0).

(iv) Sulphur dioxide

$$E_{SO2} = \frac{3.6 * Keso0 * a0 * a1 * IFC * 1000}{SPEED}$$

where

E_SO2: Sulphur dioxide Emission(g/veh-km); and

Keso0 Calibration factor (default = 1.0)

(v) Carbon dioxide

$$E_{CO2} = \frac{3.6 * Keco0 * a0 * IFC * 1000}{SPEED}$$

where

E_CO2 Carbon dioxide Emission (g/veh-km); and

Keco0 Calibration factor (default = 1.0).

(vi) Particulates

$$E_{PAR} = \frac{3.6 * Kepar0 * (a0 + a1 * Kepar1 * IFC) * 1000}{SPEED}$$

where

E_PAR Particulates Emission(g/veh-km);

Kepar0 Calibration factor (default = 1.0); and

Kepar1 Calibration factor (default = 1.0).

(vii) Lead

$$E_{PB} = \frac{3.6 * Kepb0 * a0 * a1 * IFC * 1000}{SPEED}$$

where

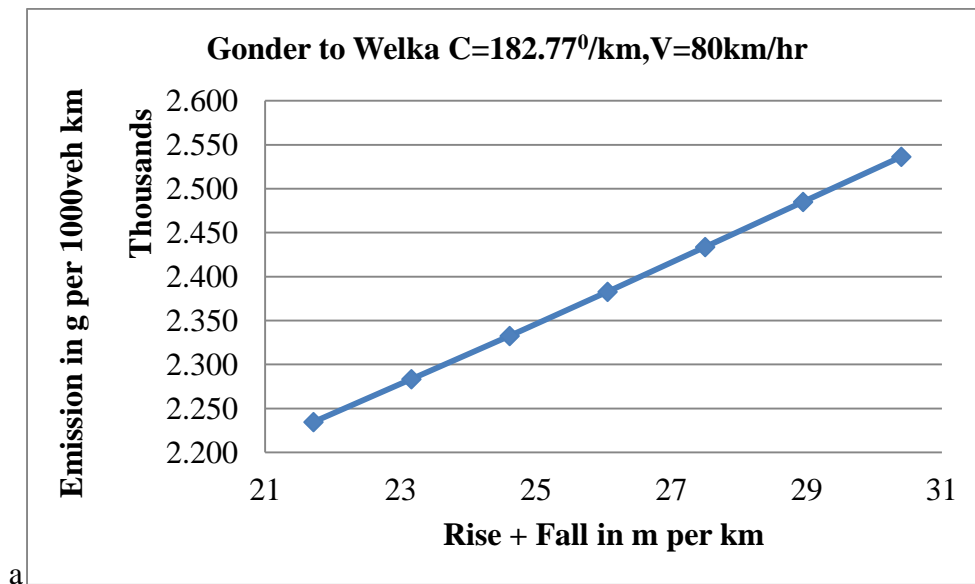
E_{PB} Lead Emission(g/veh-km); and
 $Kepb0$ Calibration factor (default = 1.0).

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 The Effect of Rise and fall on Emission and Fuel Consumption

The effect of rise and fall on vehicular greenhouse gas emission and fuel consumption for the selected study areas and sections were analyzed for 20 years and are presented in Figures 8 - 13 below.



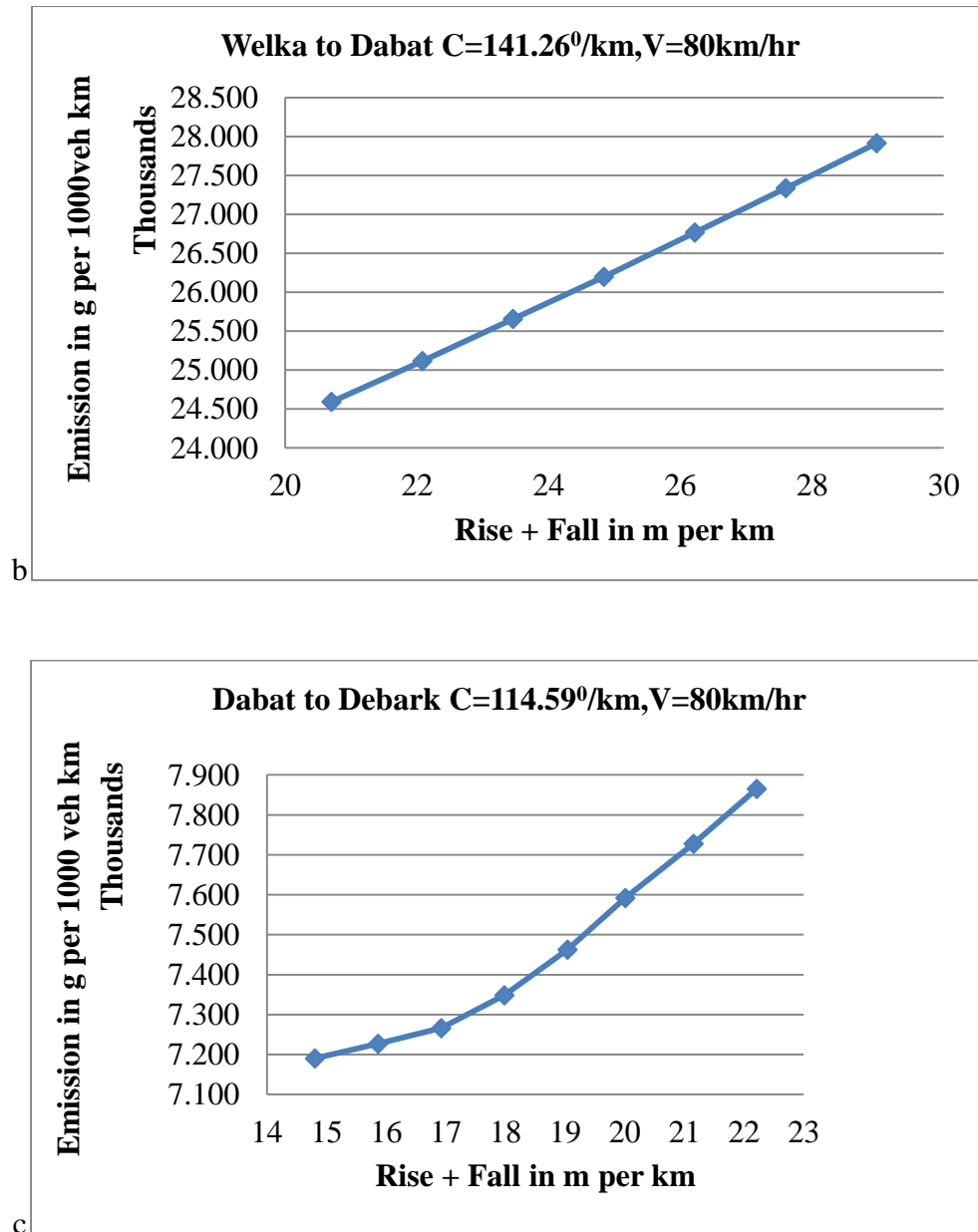


Figure 8: Emissions Vs Rise + Fall on Gonder to Debark Road

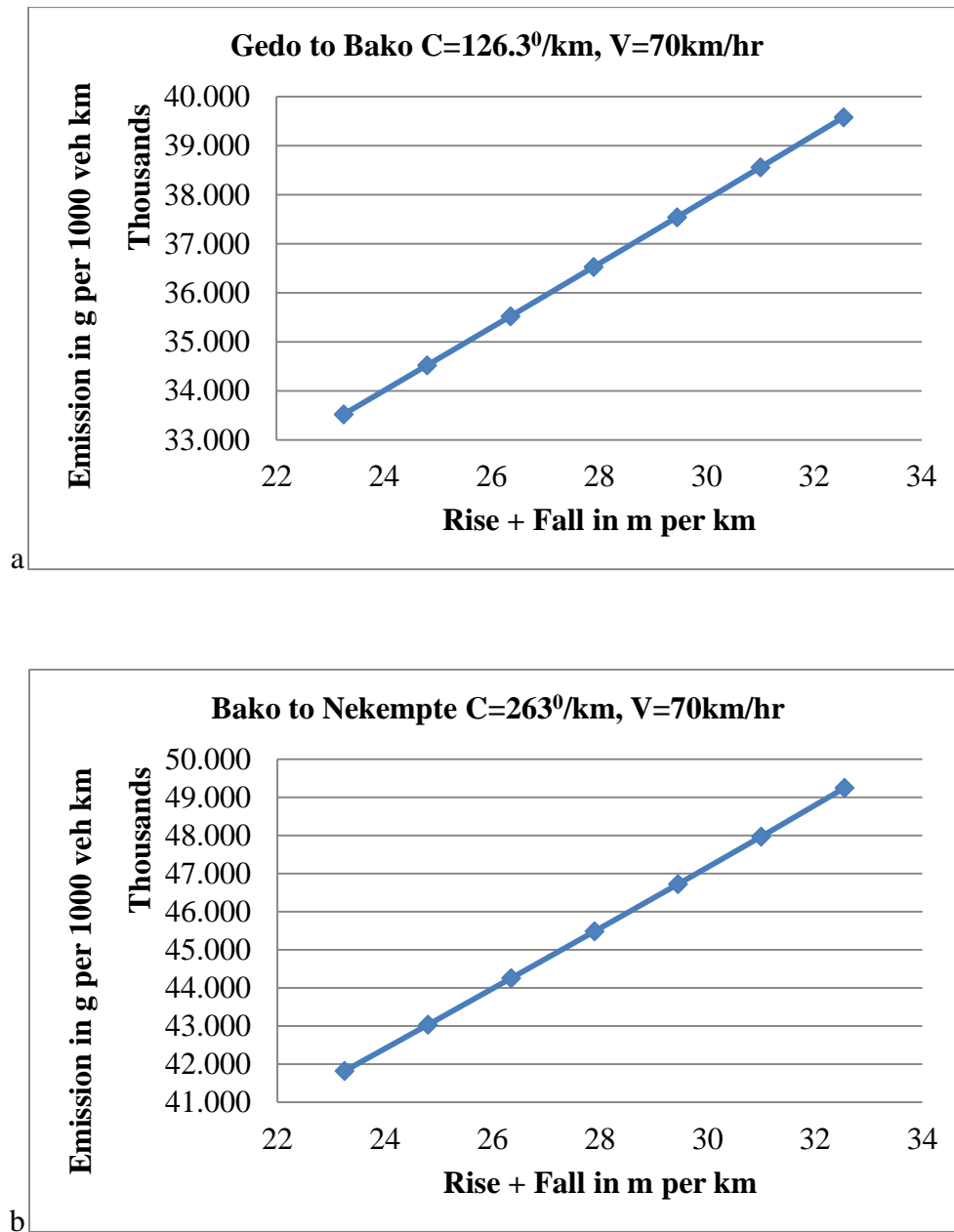
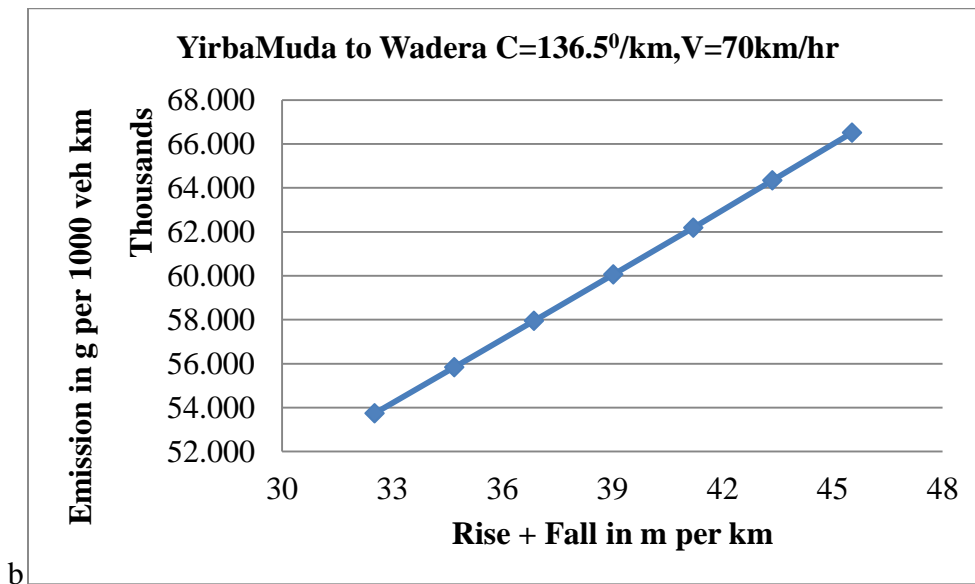
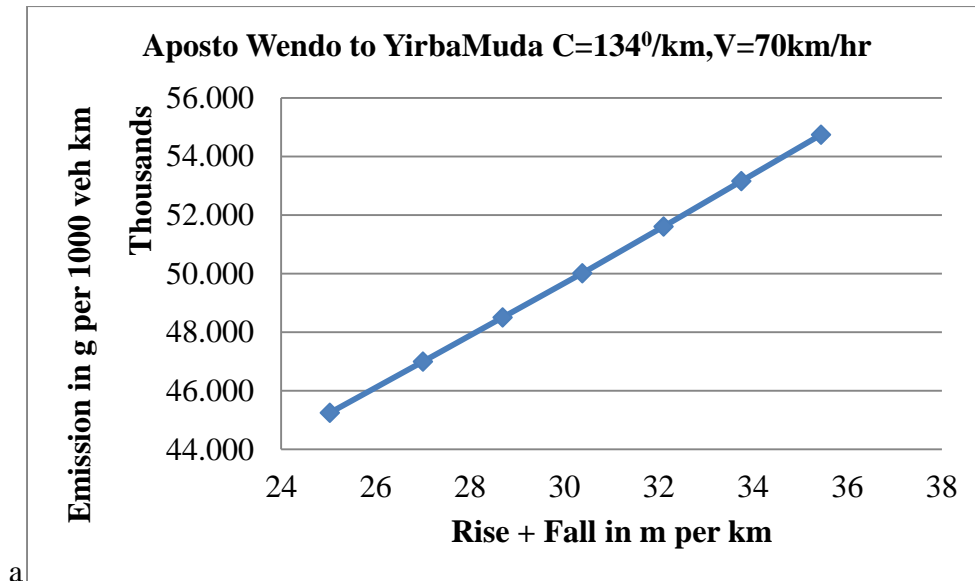


Figure 9: Emission Vs Rise + Fall on Gedo to Nekempte Road



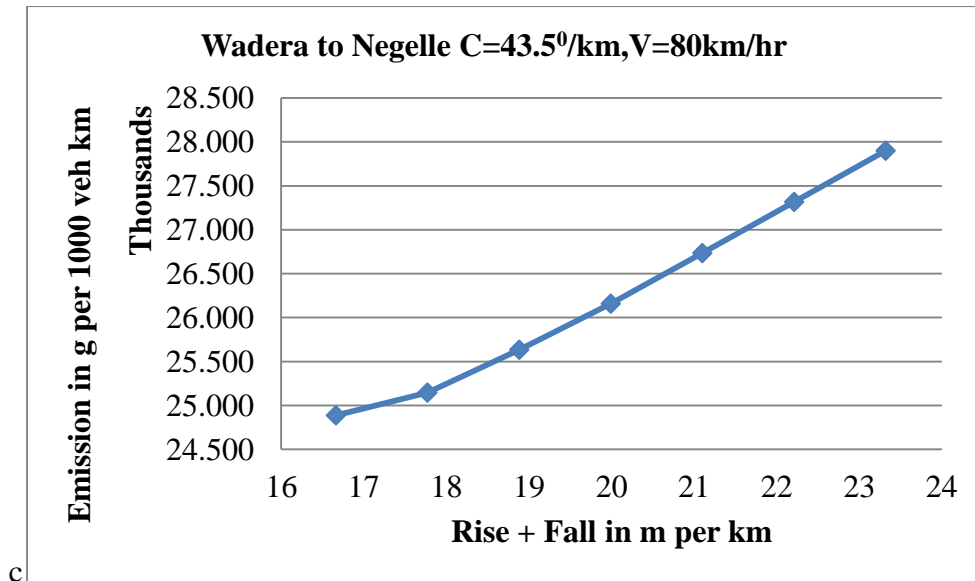
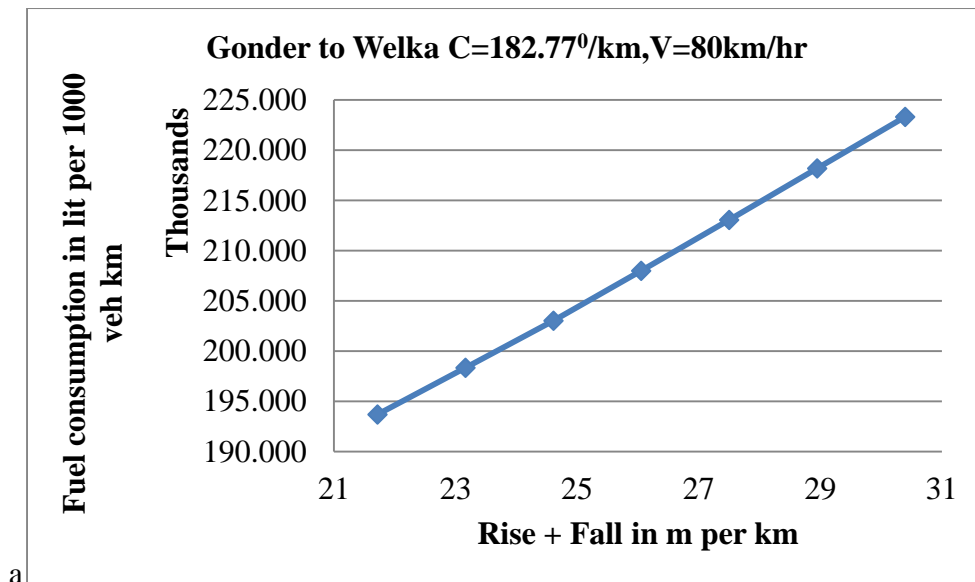


Figure 10: Emission Vs Rise + Fall on Aposto Wendo to Negelle Road



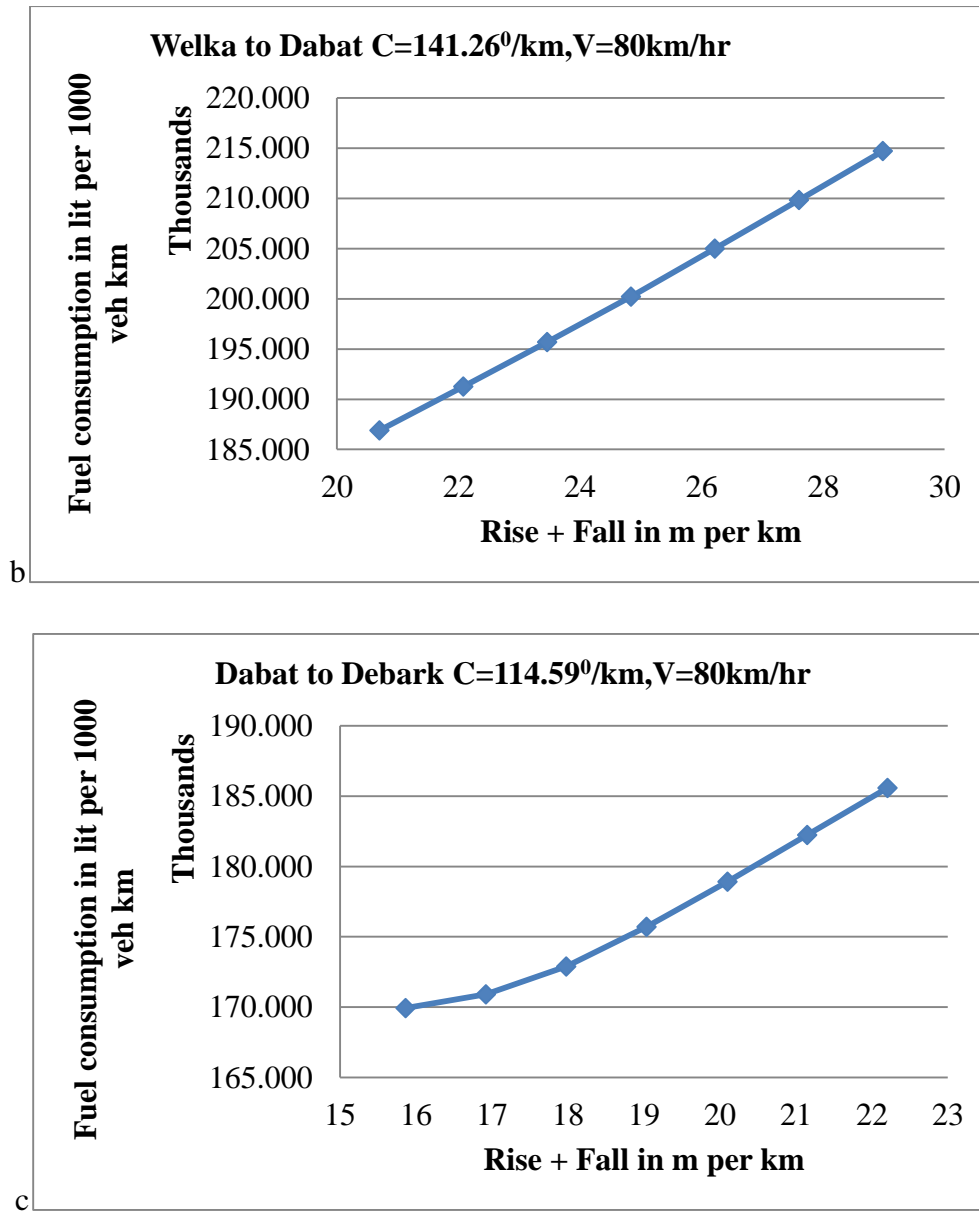


Figure 11: Fuel Consumption Vs Rise + Fall on Gonder to Debark Road

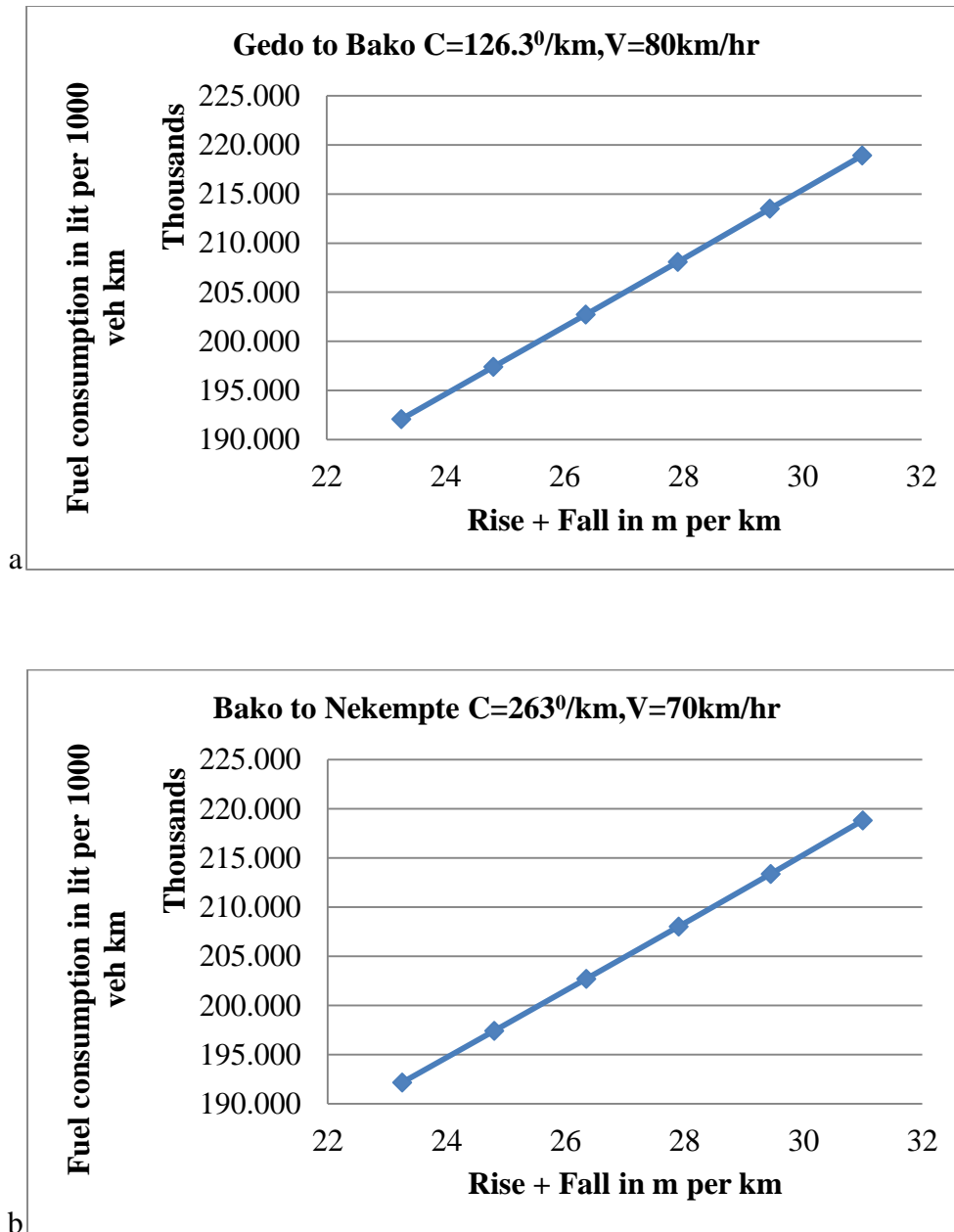
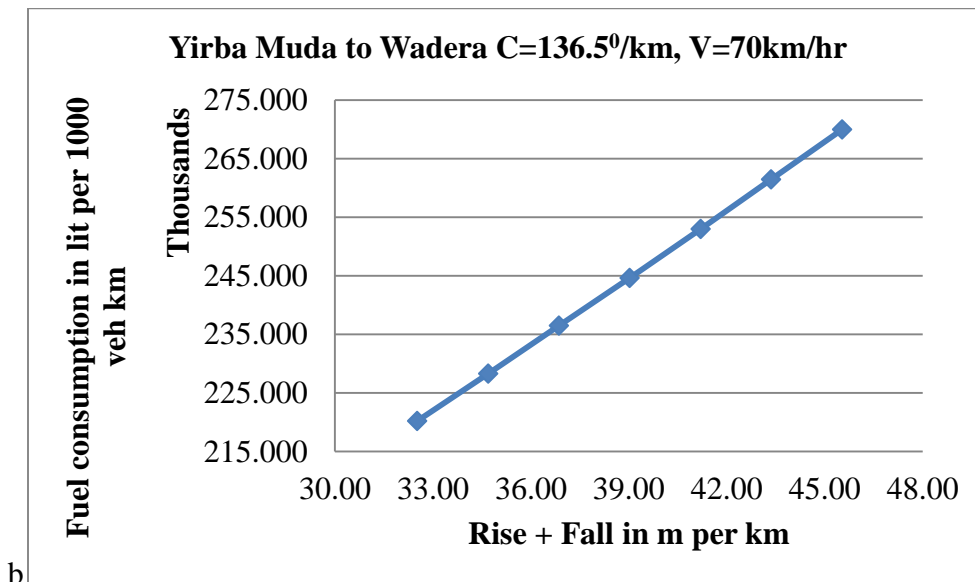
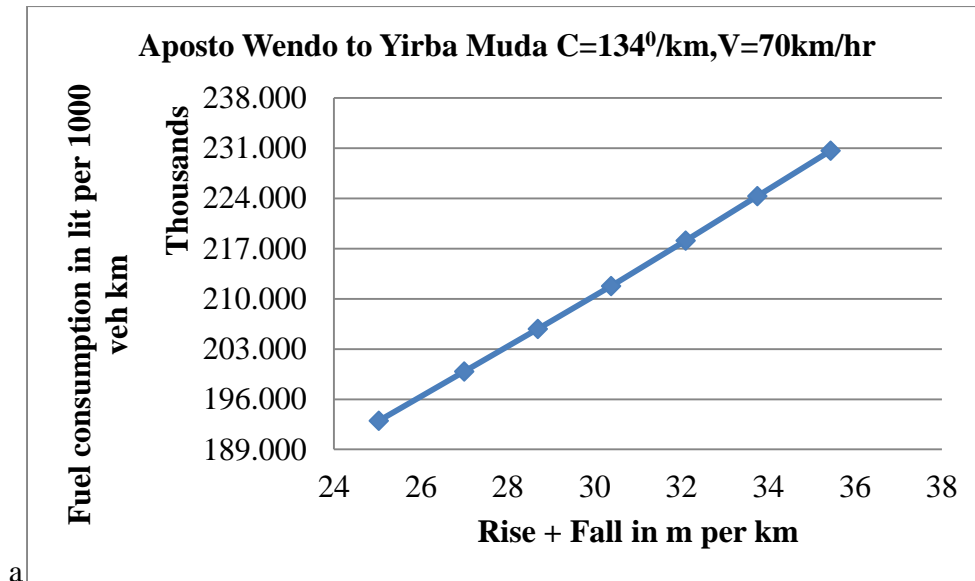


Figure 12: Fuel Consumption Vs Rise + Fall on Godo to Nekempte Road



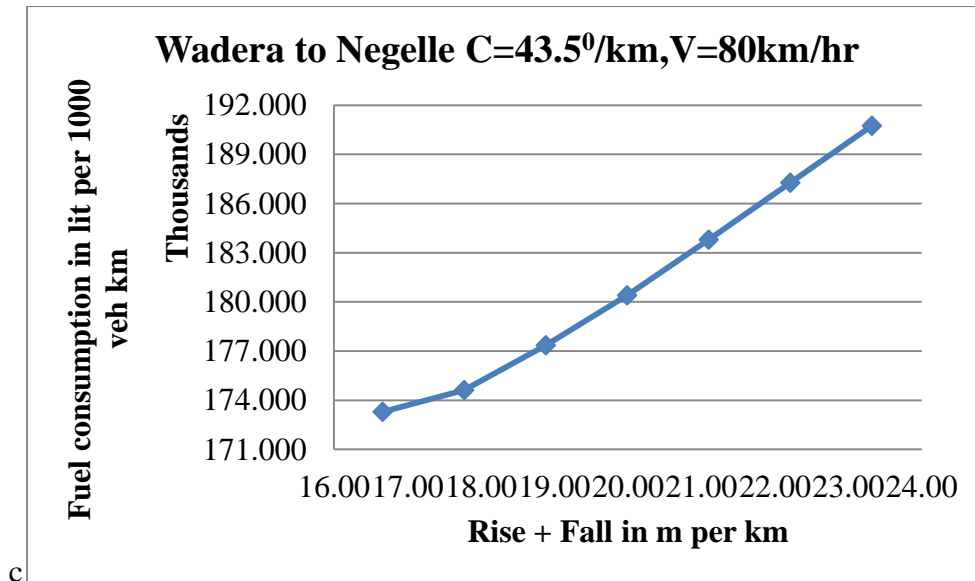
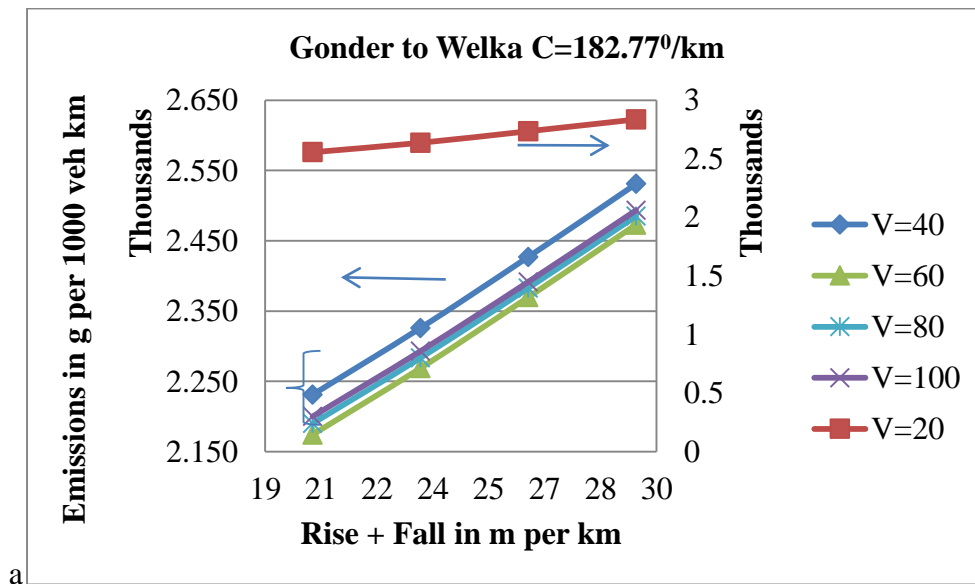


Figure 13: Fuel Consumption Vs Rise + Fall on Aposto Wendo to Negelle Road

Figures 8 - 13 show that rise + fall has an effect on vehicular greenhouse gas emission and fuel consumption. There is a direct relationship between rise + fall and emission as well as rise + fall and fuel consumption, i.e. as rise + fall increases, both emission and fuel consumption increases and as rise + fall decreases both emission and fuel consumption decreases linearly.

The effect of rise + fall on emission and fuel consumption at five different speeds was analyzed for the three study roads and the results are presented in Figures 14 - 19 below.



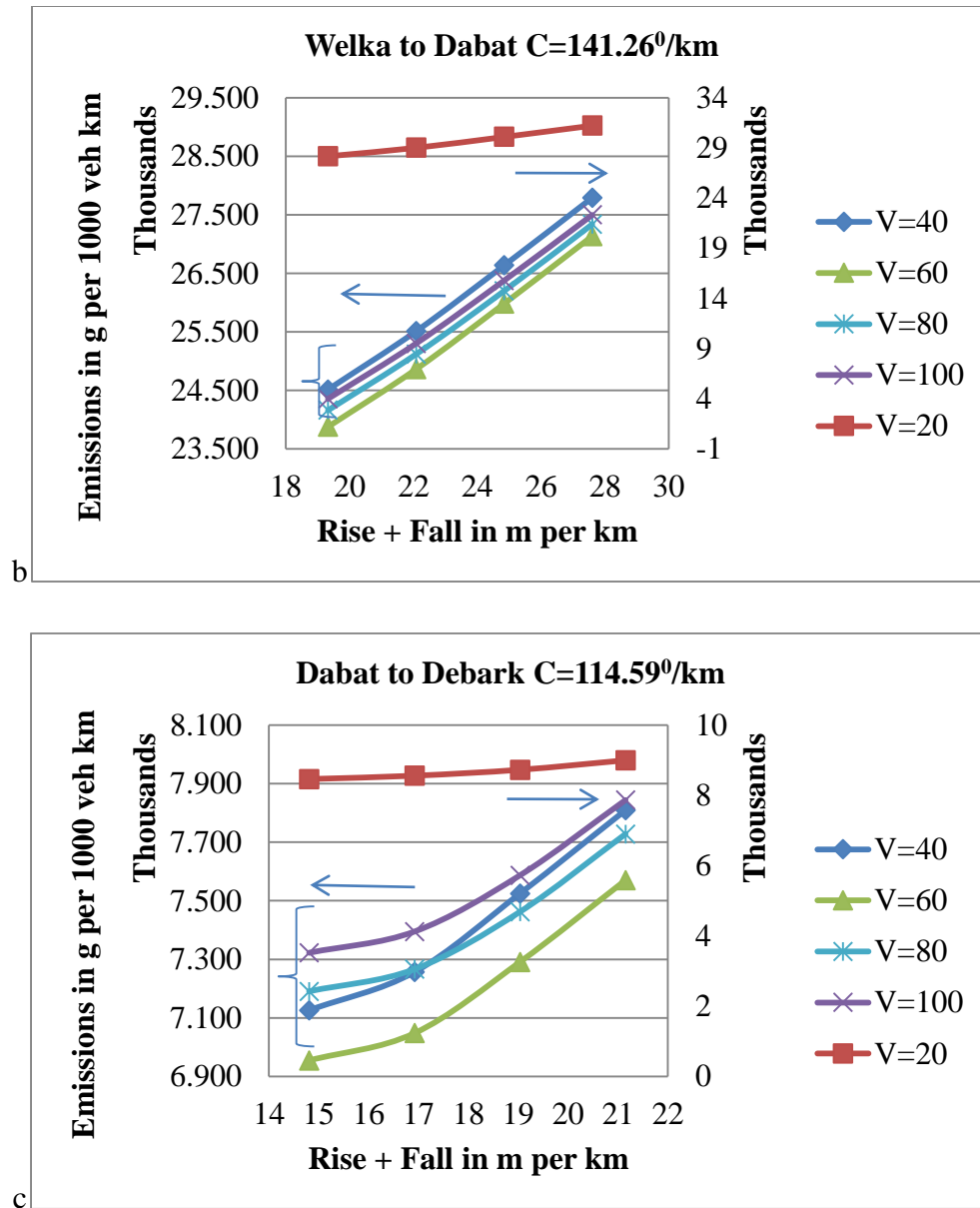


Figure 14: Emission Vs Rise + Fall at different speeds on Donder to Debarik Road

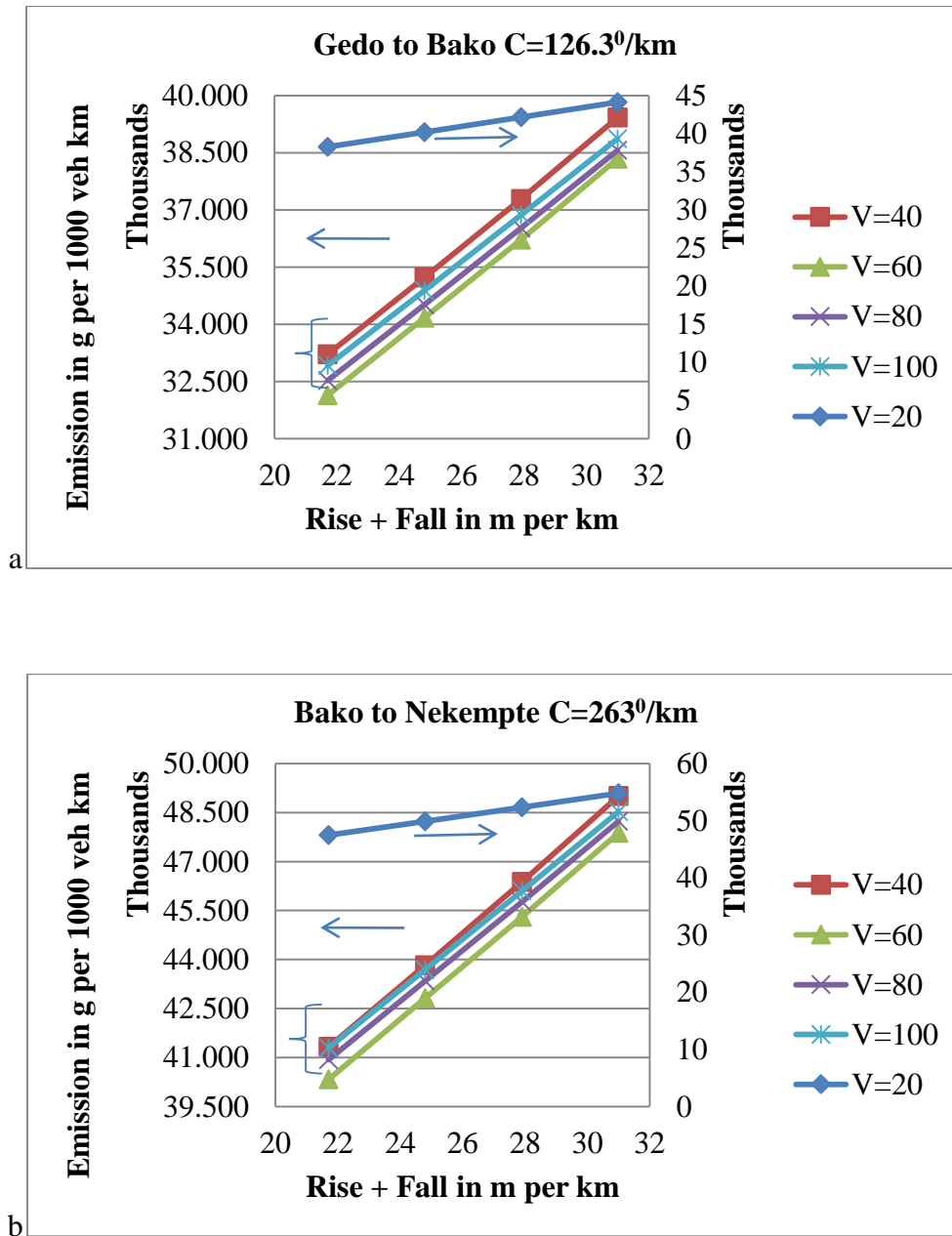
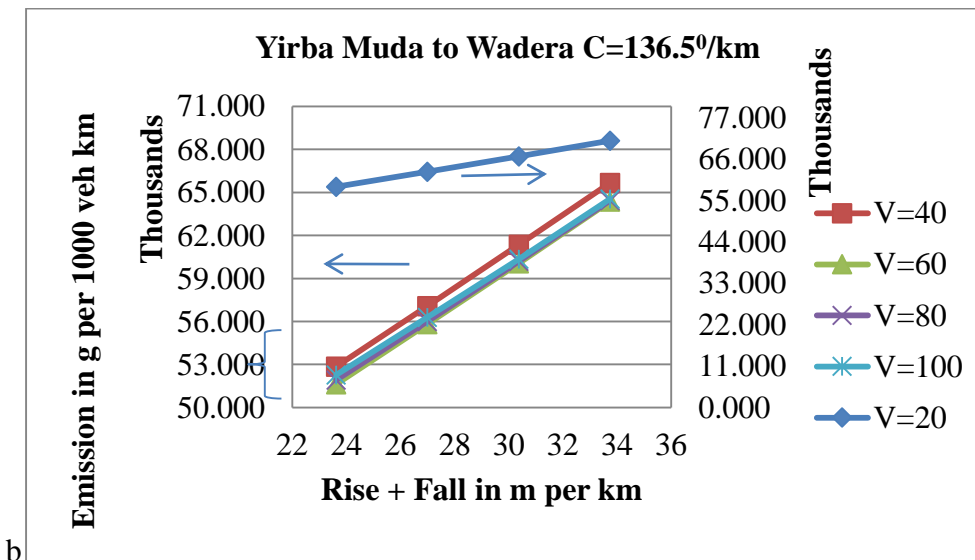
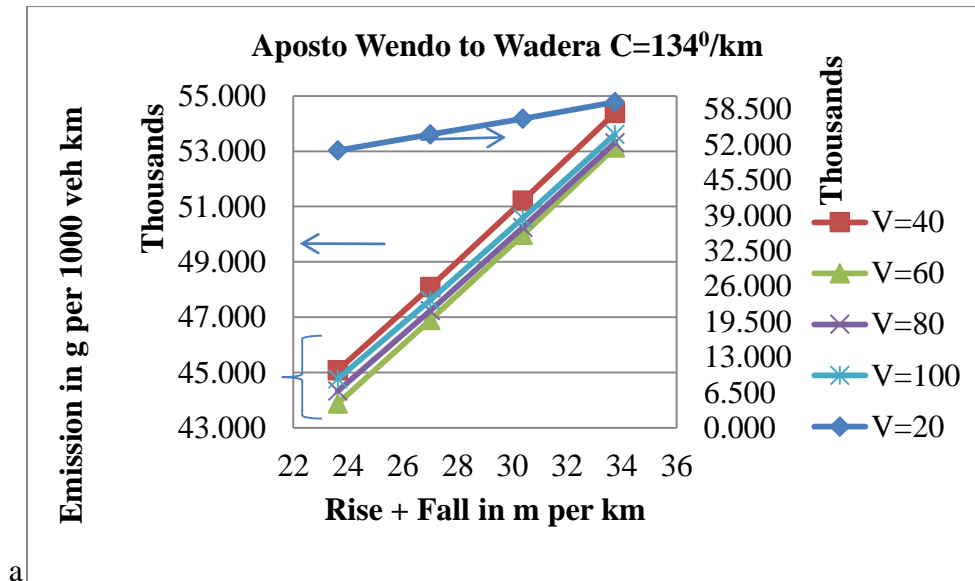


Figure 15: Emission Vs Rise + Fall at different speeds on Gedo to Nekempte Road



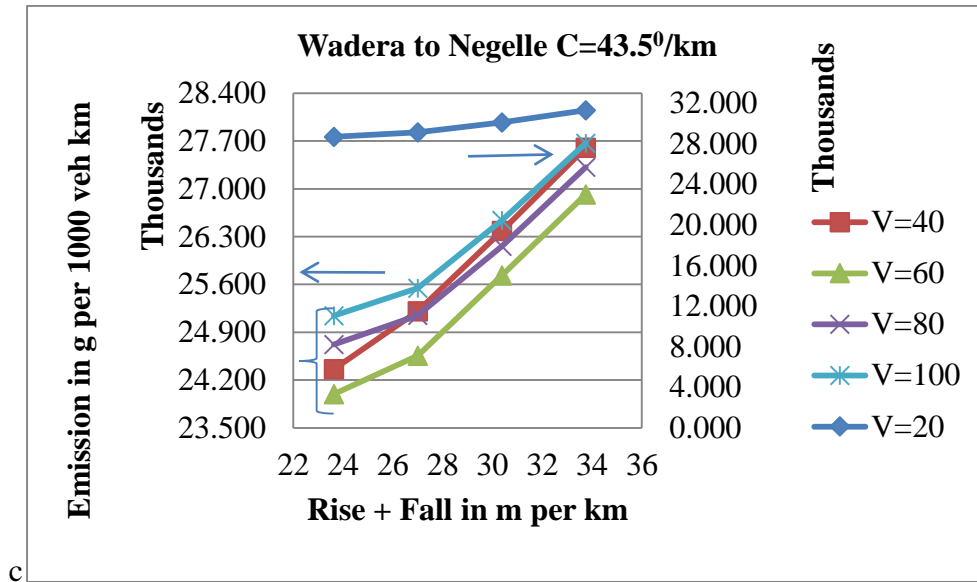
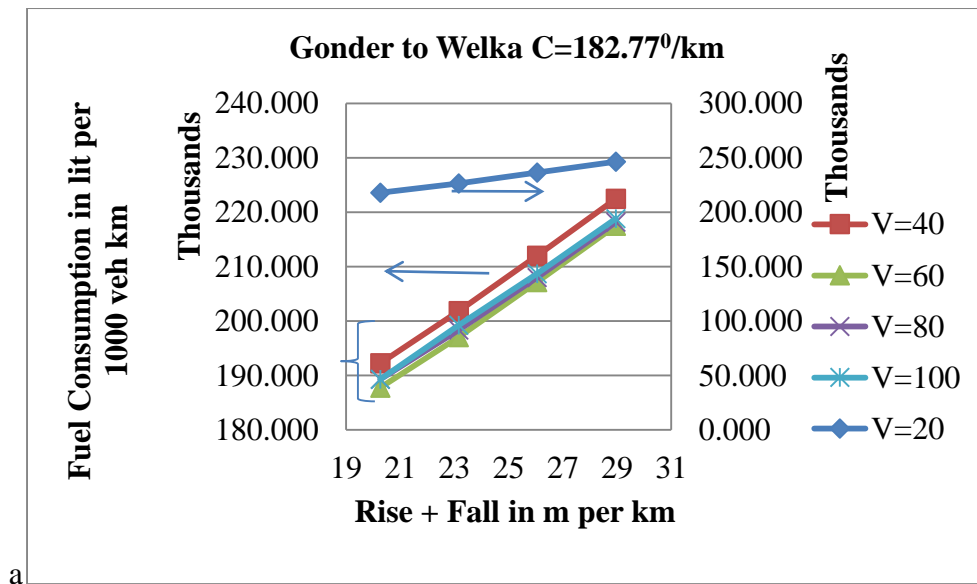


Figure 16: Emission Vs Rise + Fall at different speeds on Aposto Wendo to Negelle Road



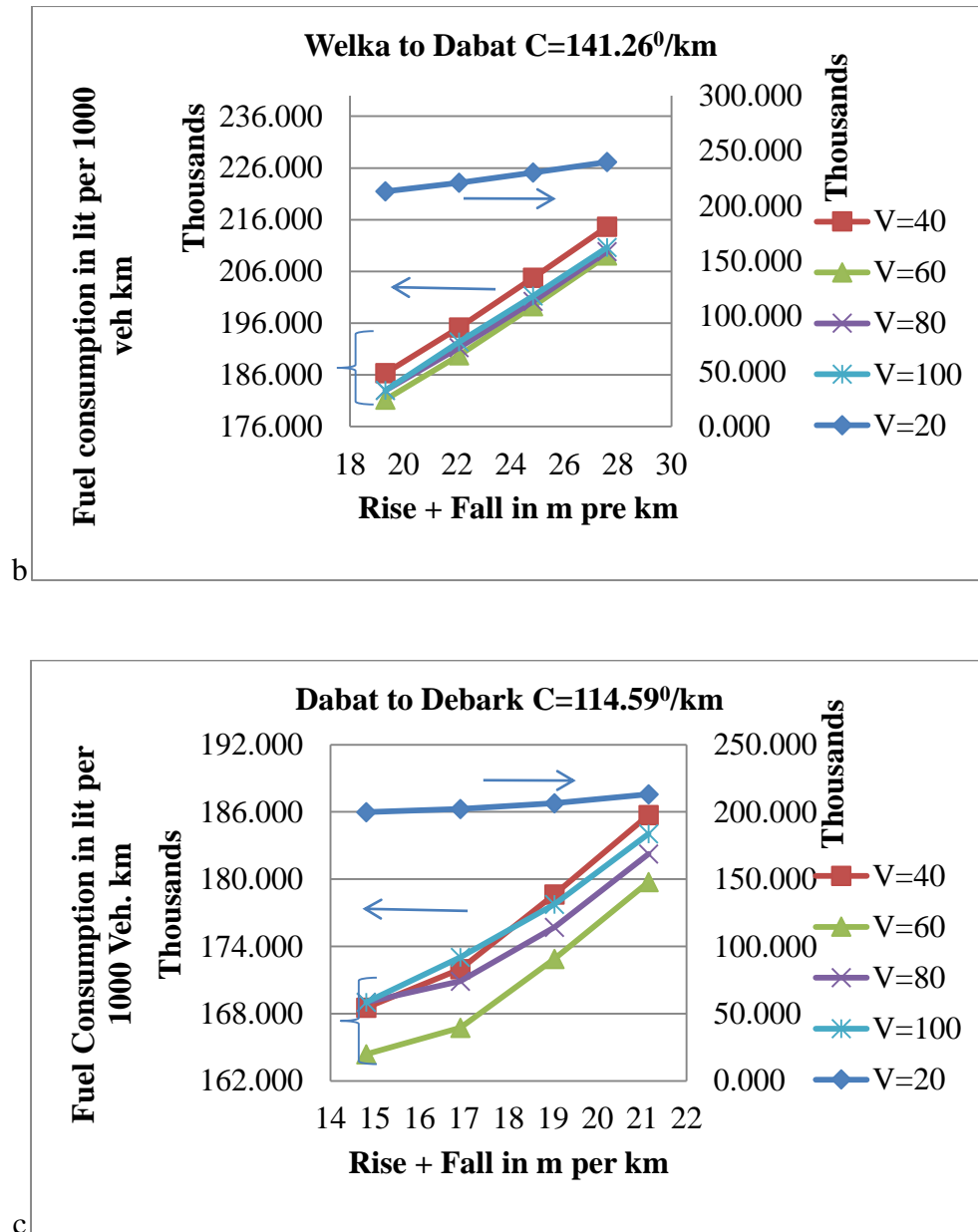


Figure 17: Fuel Consumption Vs Rise + Fall at different speeds on Gonder to Debarok Road

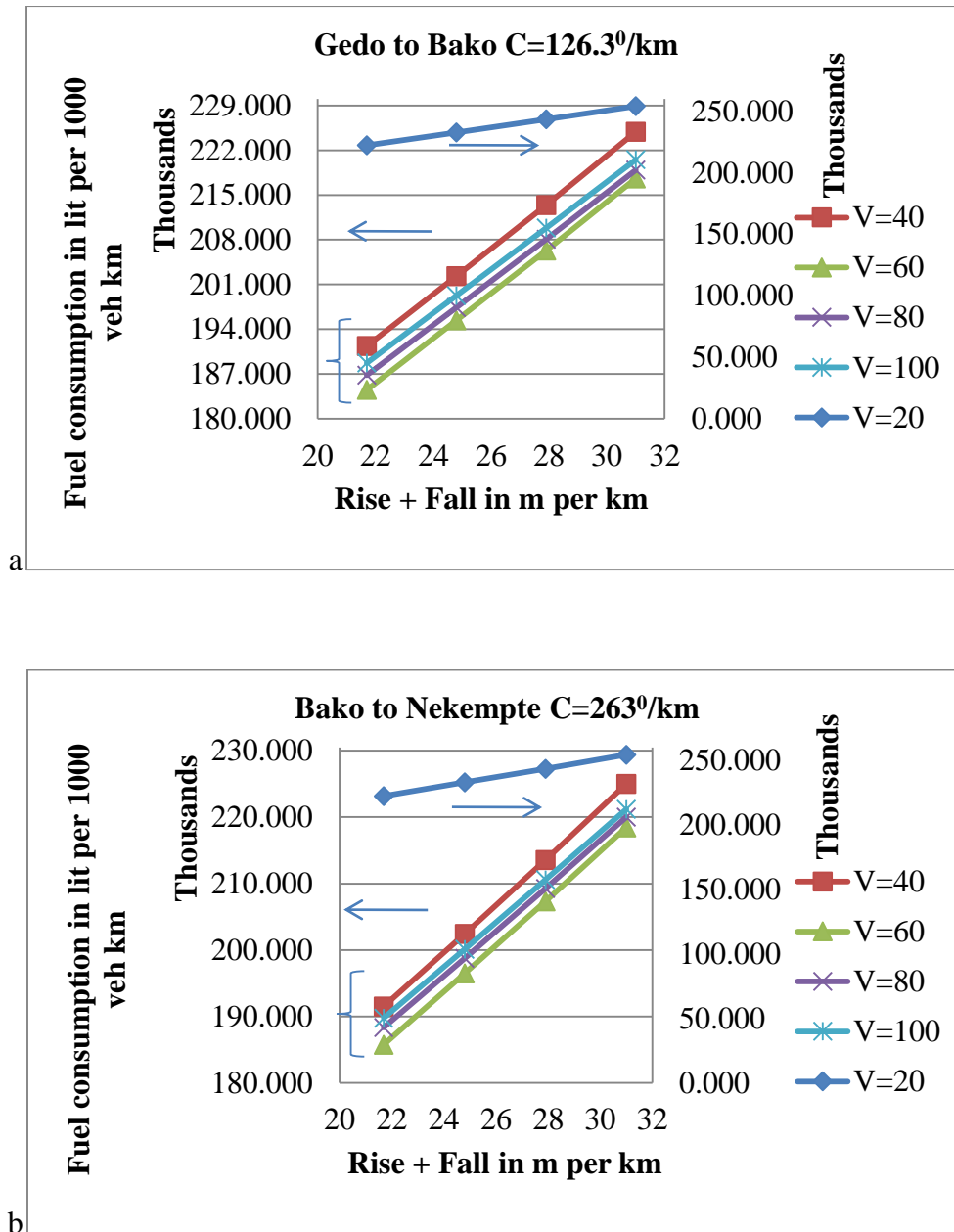
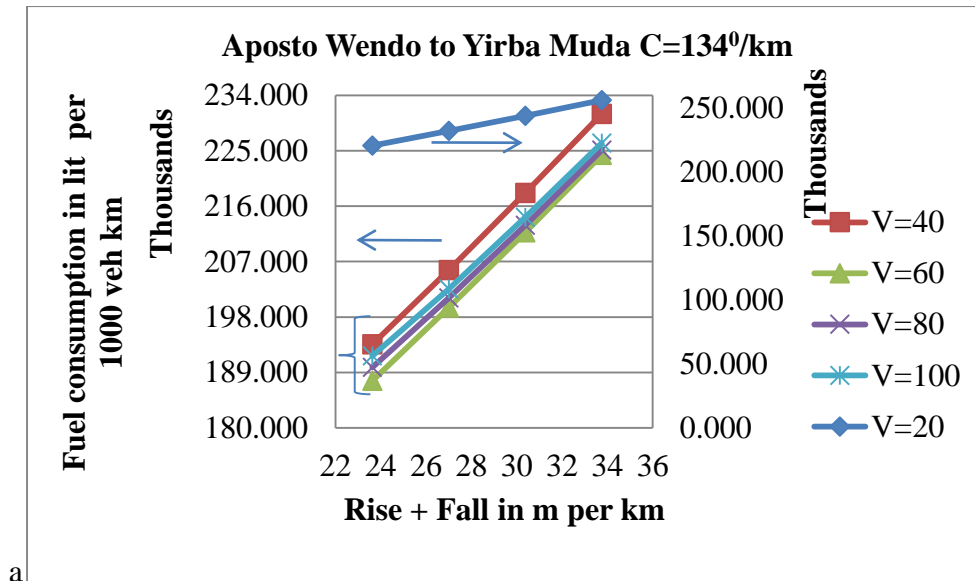
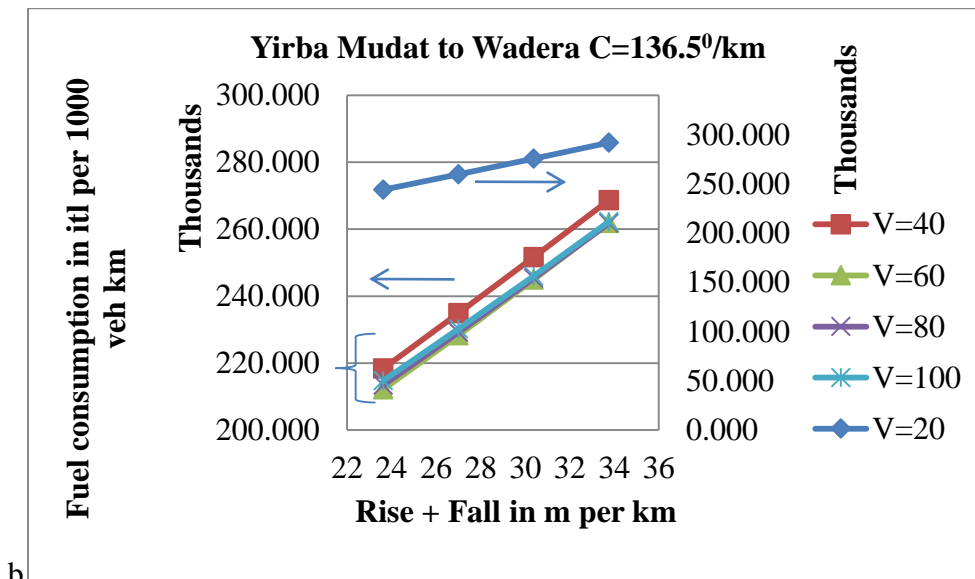


Figure 18: Fuel Consumption Vs Rise + Fall at different speeds on Gedo to Nekempte Road



a



b

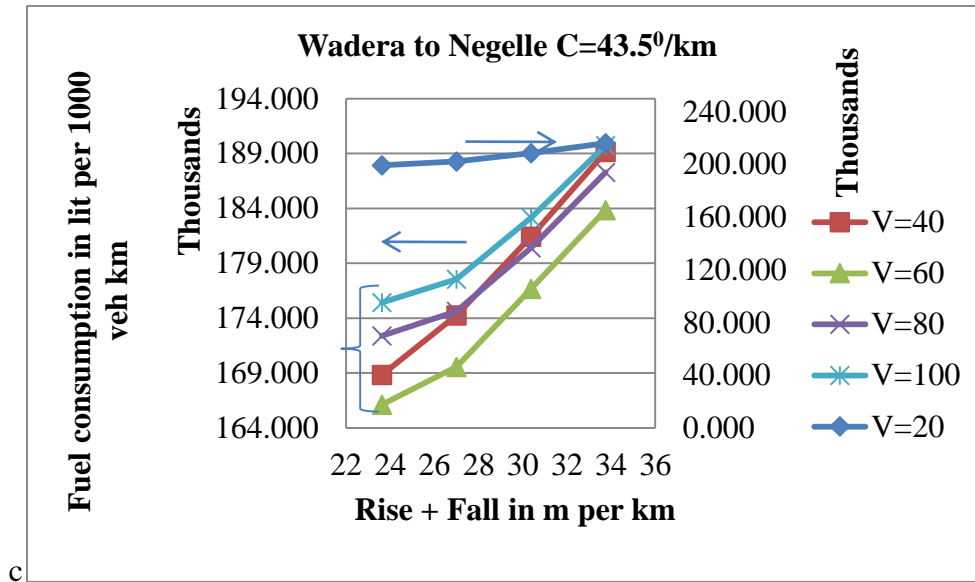


Figure 19: Fuel Consumption Vs Rise + Fall at different speeds on ApostoWendo to Yirba Muda Road

Figures 14 - 19 indicate that for all sections of the roads under study, both emission and fuel consumption became maximum and minimum when vehicles were presumed to be traversed at the speeds of 20 km/hr and 60 km/hr respectively. Excluding Dabat to Debark and Wadera to Negelle roads, emission and fuel consumption decrease as vehicle speeds was changed from 20 km/hr to 40km/hr, from 40km/hr to 100 km/hr and from 100 km/hr to 80 km/hr and became minimum when vehicles were presumed to be traversed at a speed of 60 km/hr.

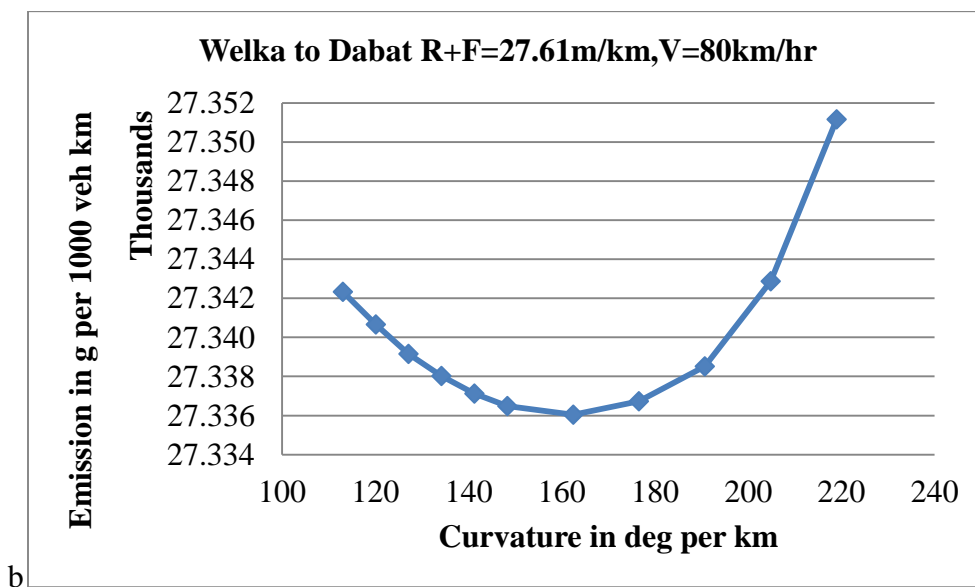
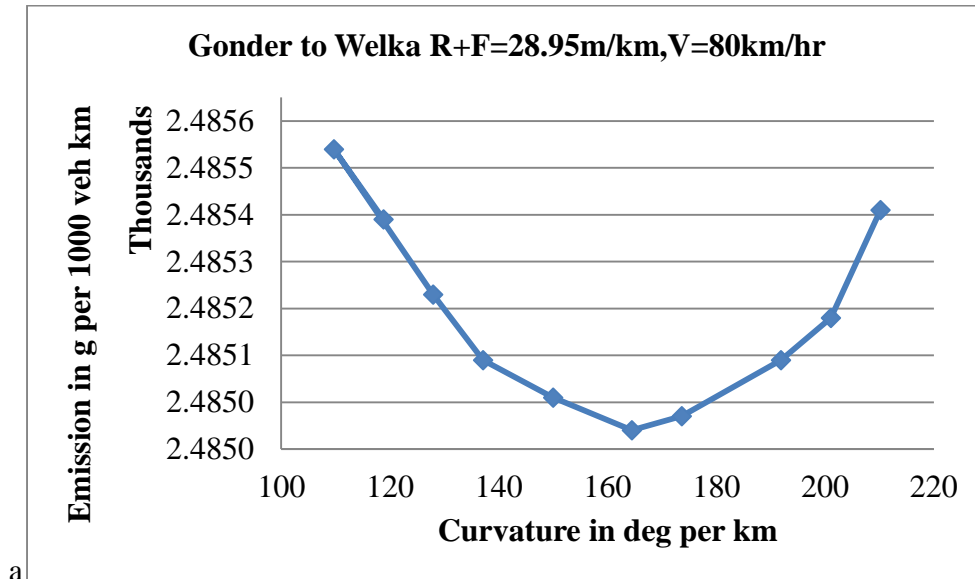
Whereas in the case of Dabat to Debark and Wadera to Negelle roads, driving at a speed of 100 km/hr results in higher emission and fuel consumption than driving at speeds of 40 km/hr and 80 km/hr when rise + fall lies below 17 m/km and 27 m/km respectively.

The lower curvature value on Wadera to Negelle road ($C=43.5^0/km$) as compared to Dabat to Debark road ($C=114.59^0/km$) results in a higher value of rise + fall value (27 m/km) for vehicles to start to consumption and emission more at 40 km/hr than 80 km/hr and 100 km/hr. This shows that as rise + fall increases, driving at a speed of 40 km/hr results in higher fuel consumption and emission than driving at a speed of 80 km/hr and 100 km/hr. This is due to the fact that when

vehicles are driven on a level road at a higher speed, the aerodynamic resistance becomes significant and results in more fuel consumption and emission.

4.2 The Effect of Curvature on Emission and Fuel Consumption

The change in emission and fuel consumption due to change in curvature are illustrated in Figures 20 - 25 below.



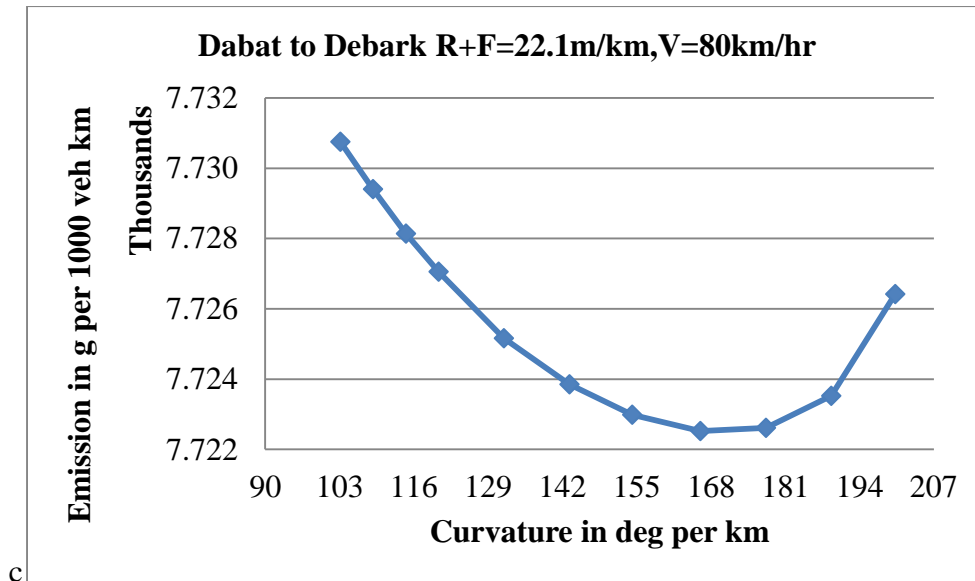
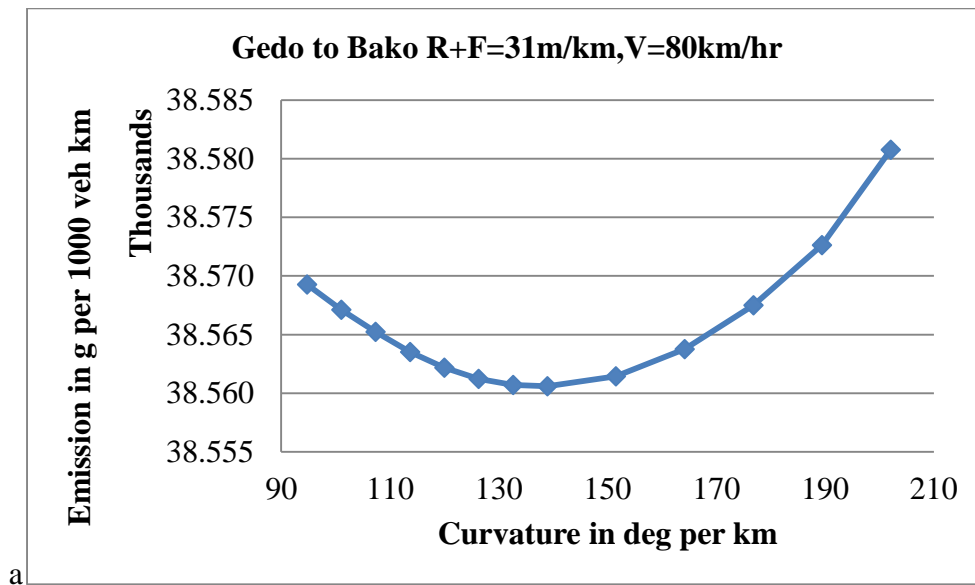


Figure 20: Emission Vs Rise + Fall on Gonder to Debark Road



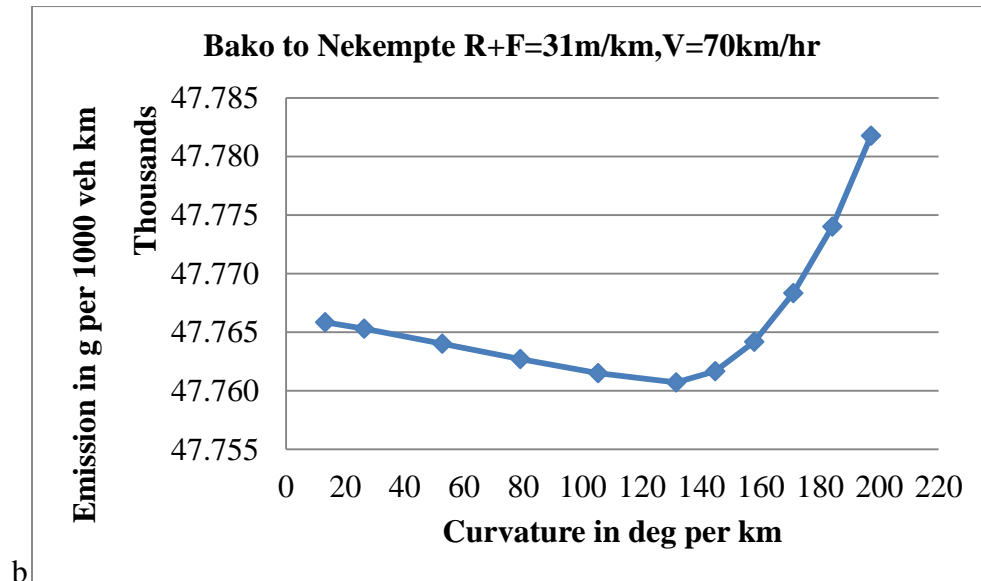
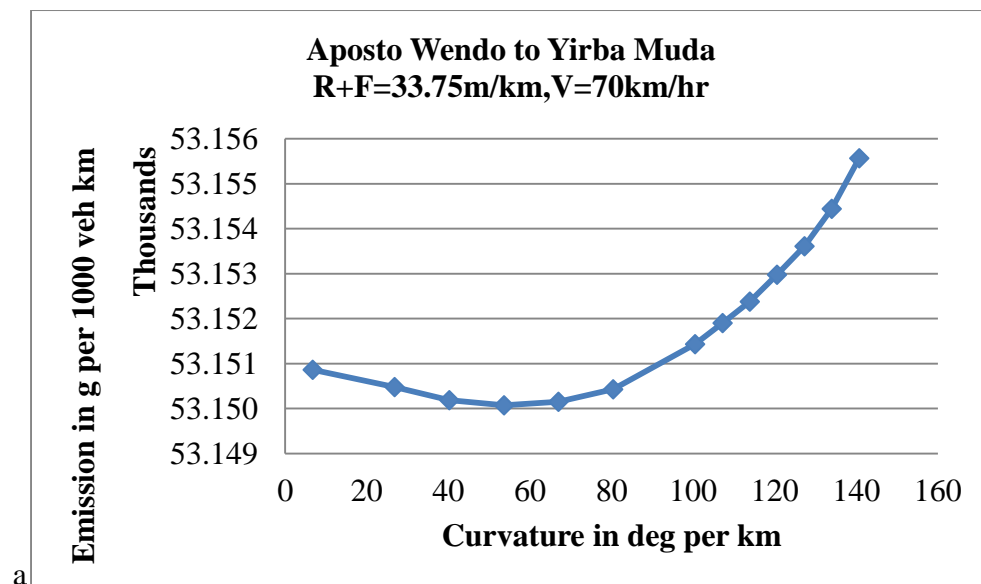
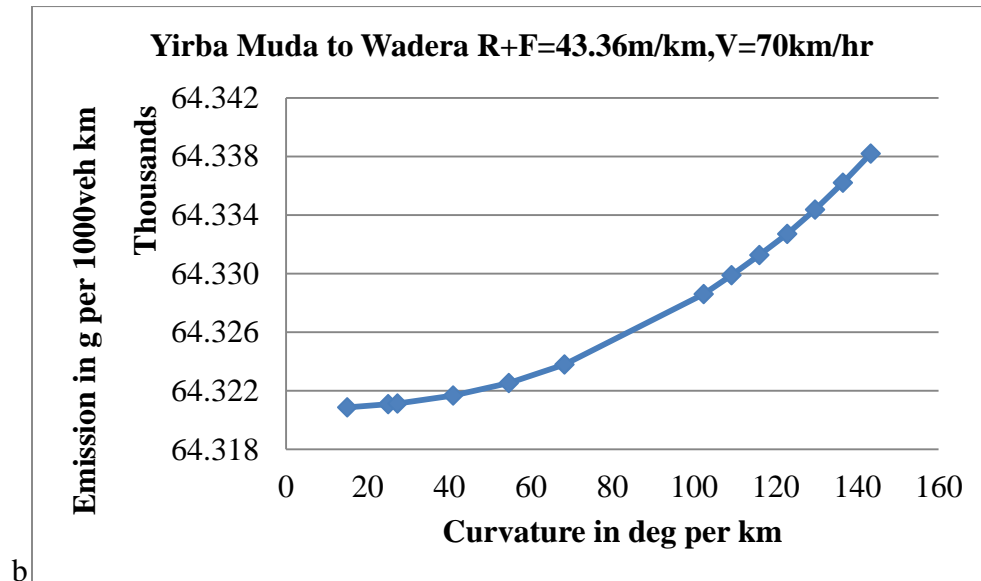
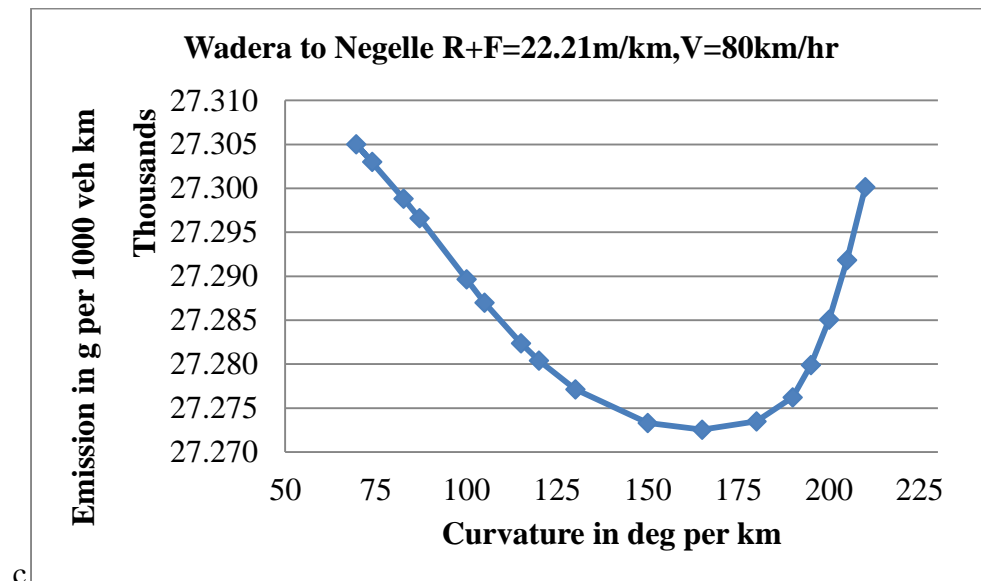


Figure 21: Emission Vs Rise + Fall on Gedo to Nekempte Road



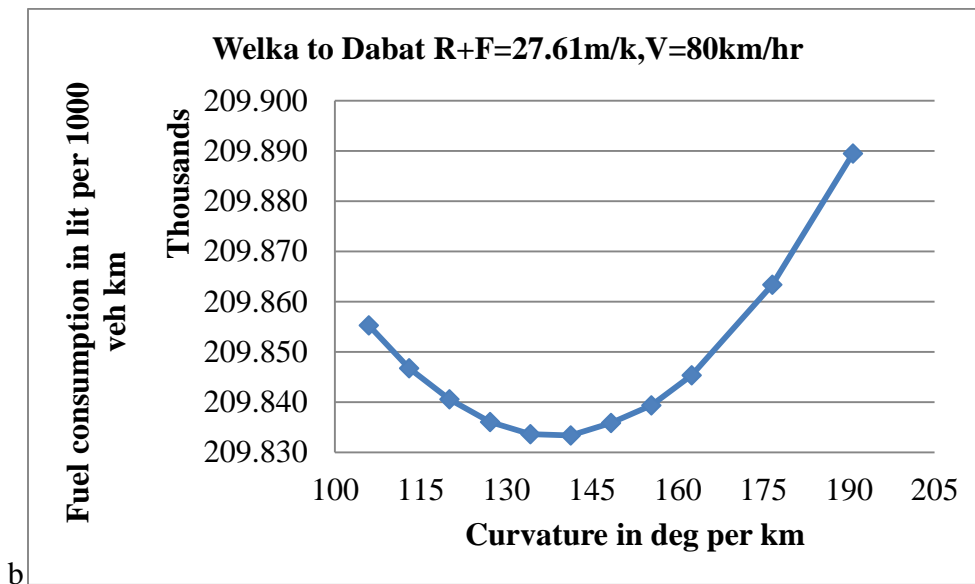
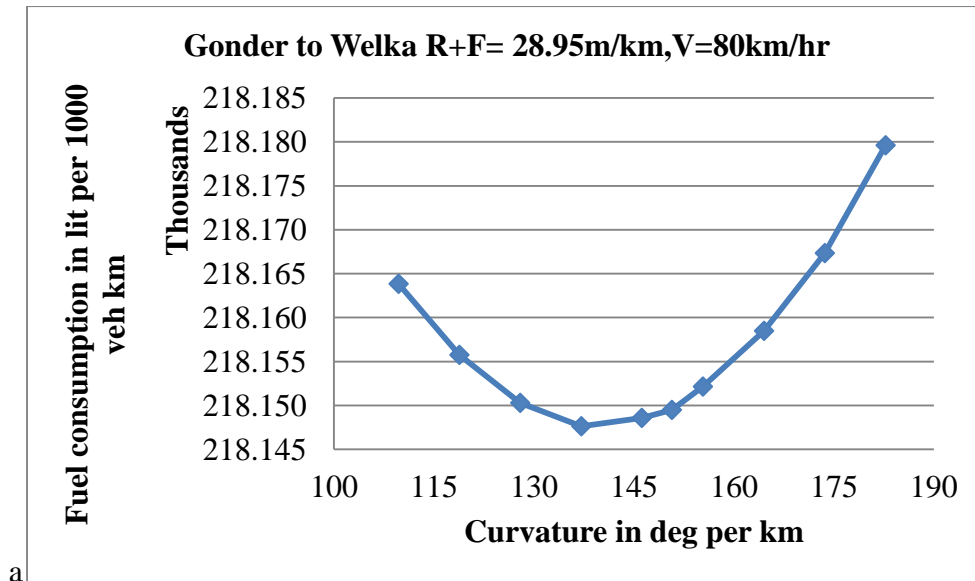


b



c

Figure 22: Emission Vs Curvature on Aposto Wendo to Negelle Road



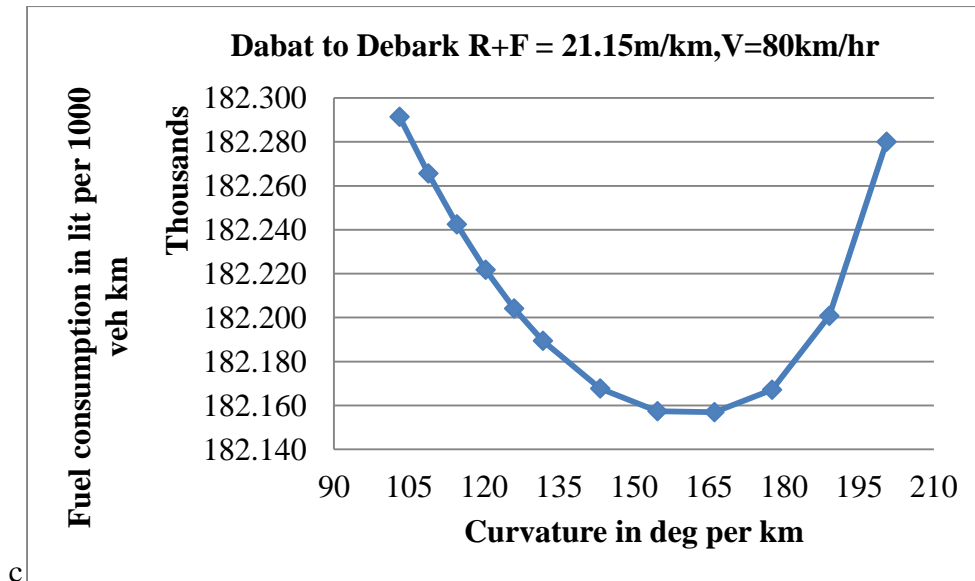
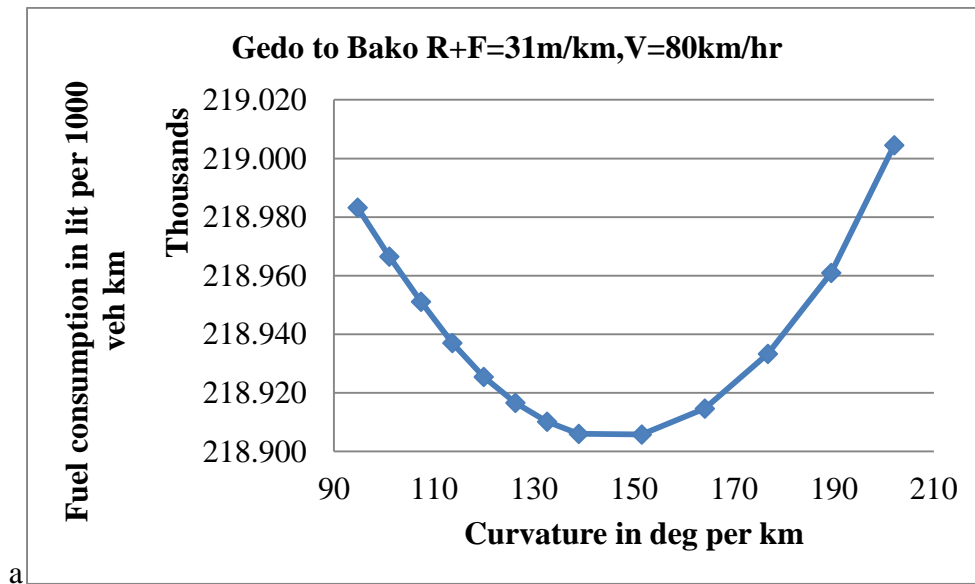


Figure 23: Fuel Consumption Vs Curvature on Gonder to Debark Road



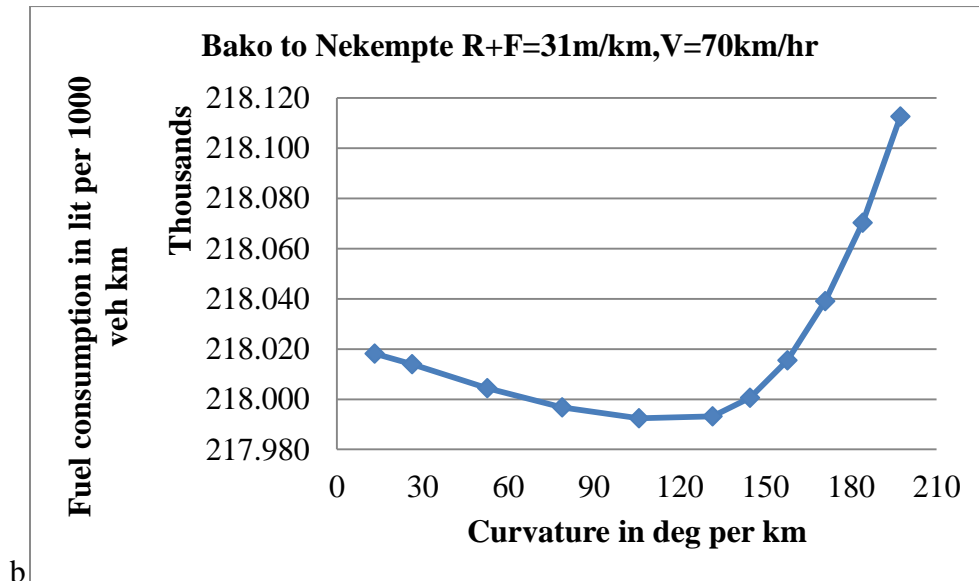
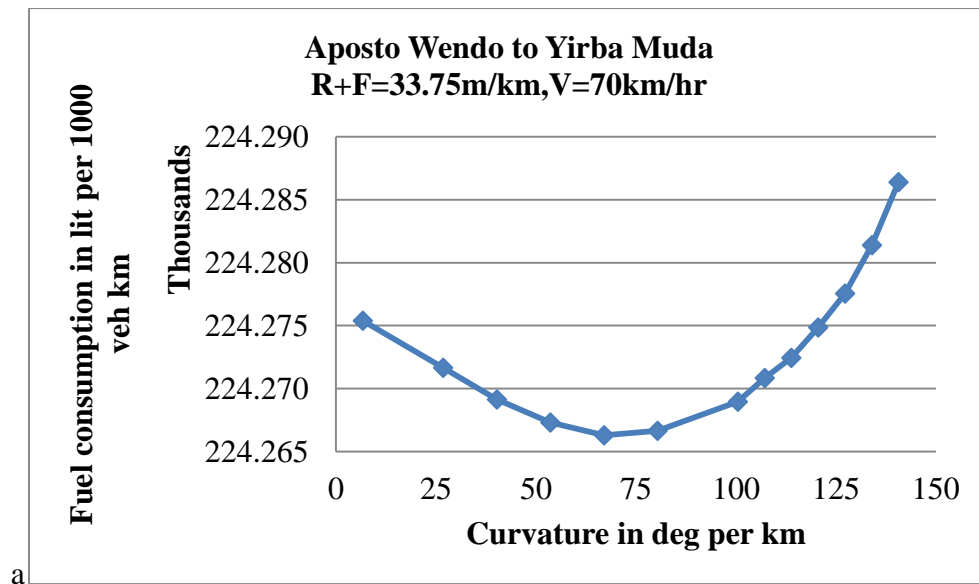


Figure 24: Fuel Consumption Vs Curvature on Gedo to Nekempte Road



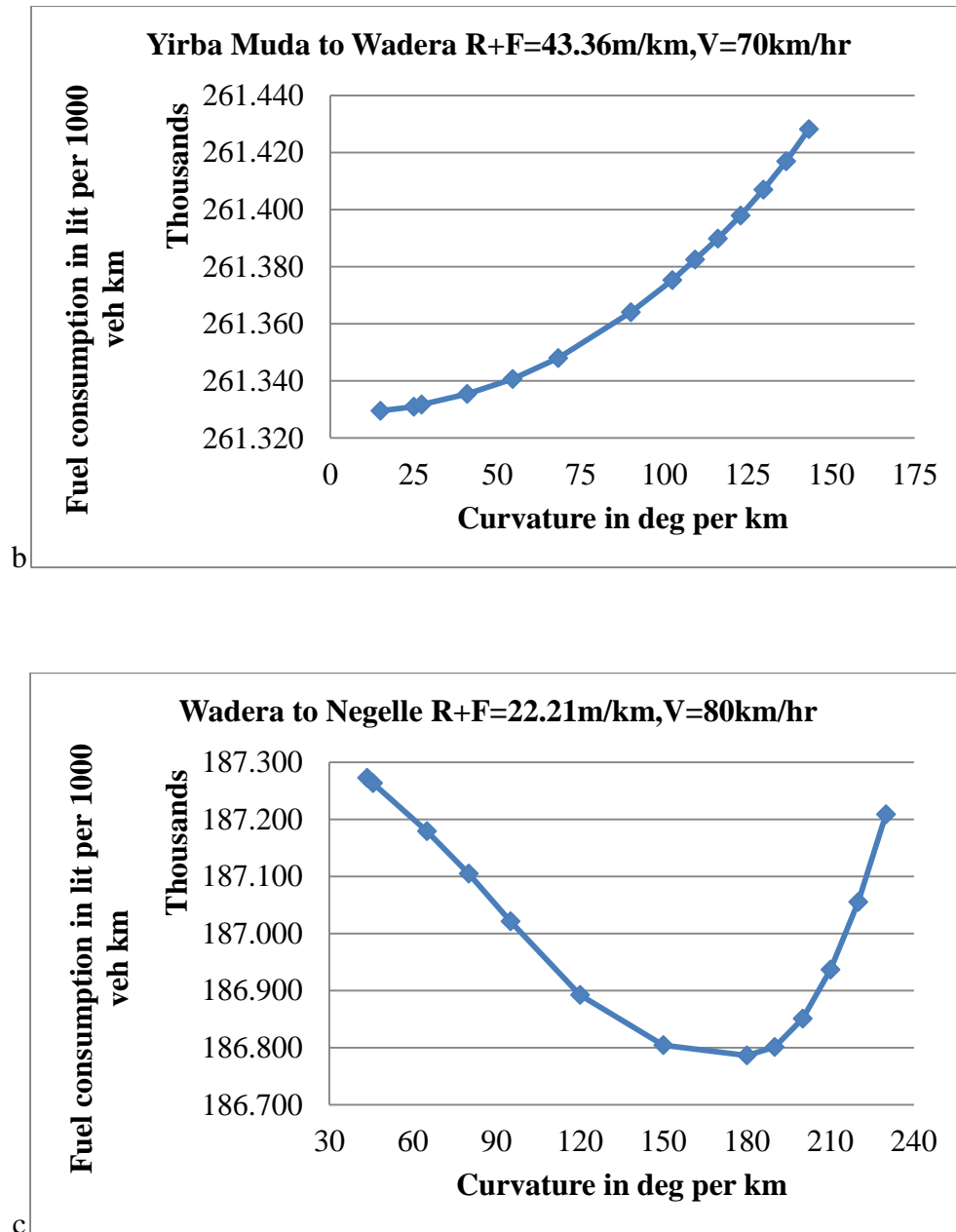


Figure 25: Fuel Consumption Vs Curvature on Aposto Wendo to Negelle Road

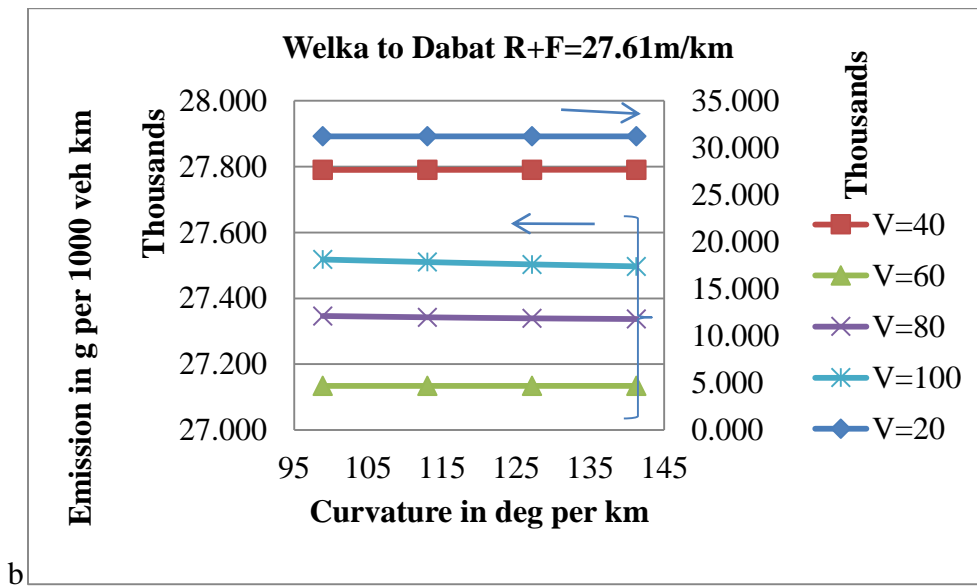
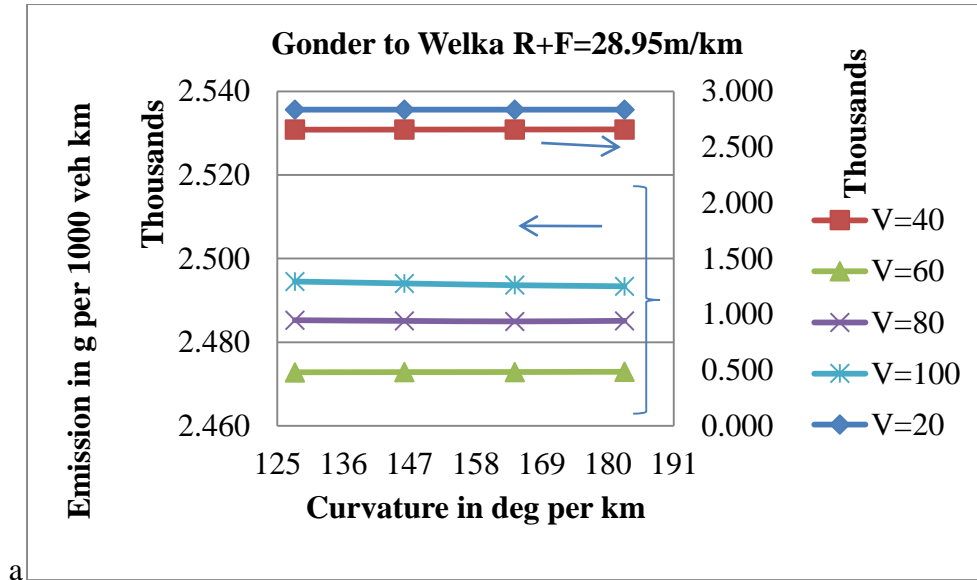
Figure 20 shows that on Gonder to Welka and Welka to Dabat roads, emission decreases as curvature increases and reaches minimum as curvature gets close to 160⁰/km and then increases as curvature increases. However, on Dabat to Debark road, emission becomes minimum when curvature gets close to 168⁰/km. This difference on curvature at which emission is at its minimum is due to the difference in rise + fall. Dabat to Debark road has lower rise + fall

(21.15m/km) compared to Gonder to Welka (28.95m/km) and Welka to Dabat roads (27.61m/km).

As shown in Figure 21, emission on Gedo to Nekempte road becomes minimum as curvature gets close to 140° /km. As explained above, the decrease in curvature at which emission is lowest is due to the difference on rise + fall values. Gedo to Bako road and Bako to Nekempte road have rise + fall of 31m/km which is greater than the rise + fall on Gonder to Debark road.

Similarly, Figure 24 shows that, on Aposto Wendo to Yirba Muda and Wadera to Negelle roads, emission becomes minimum as curvature gets close to 60° /km and 170° /km respectively; but, in the case of Yirba Mudu to Wadera road, emission becomes minimum as curvature gets close to zero. Similar to the two cases mentioned above, the difference in curvature at which emission is lowest is due to the difference in rise + fall. The Yirba Muda to Wadera road is at higher rise + fall value (43.36 m/km) than the Aposto Wendo to Yirba Muda value (33.75m/km) and Wadera to Negelle roads (22.21m/km). As can be seen in Figures 23 - 25, the variation on curvature affects fuel consumption in a similar way as it affects emission. In all cases, it was observed that as the rise + fall values increase, curvature should decrease in values in order to achieve minimum fuel consumption and emission. And the reverse is true for the two parameters, i.e. in order to attain a minimum fuel consumption and emission, increasing curvature must go together with decreasing rise + fall values. This is due to the fact that on a straight and level road, vehicles are strongly resisted by aerodynamic force and consumes more fuel and emits higher greenhouse gases.

Figures 26 - 31 illustrate the effect of curvature on emission and fuel consumption at five different speeds.



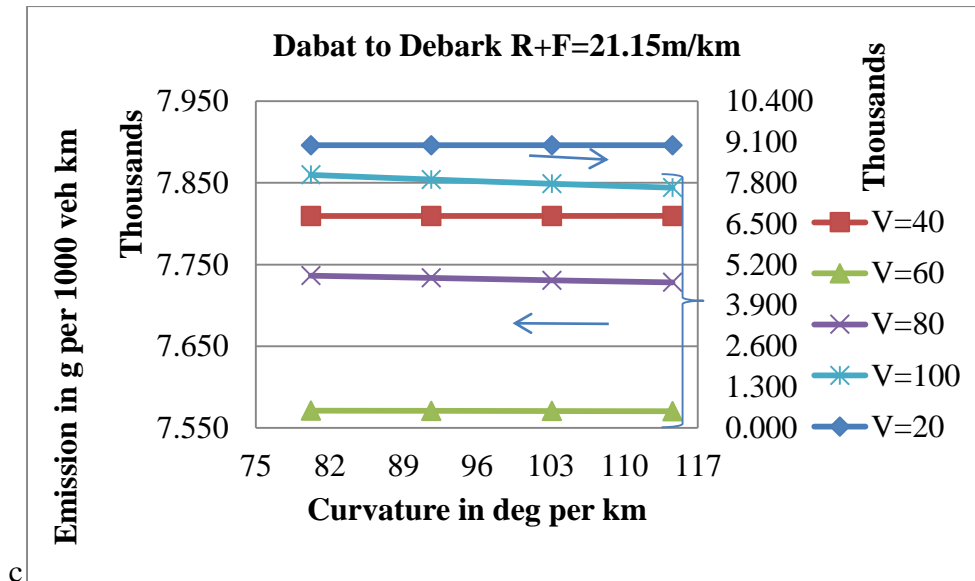
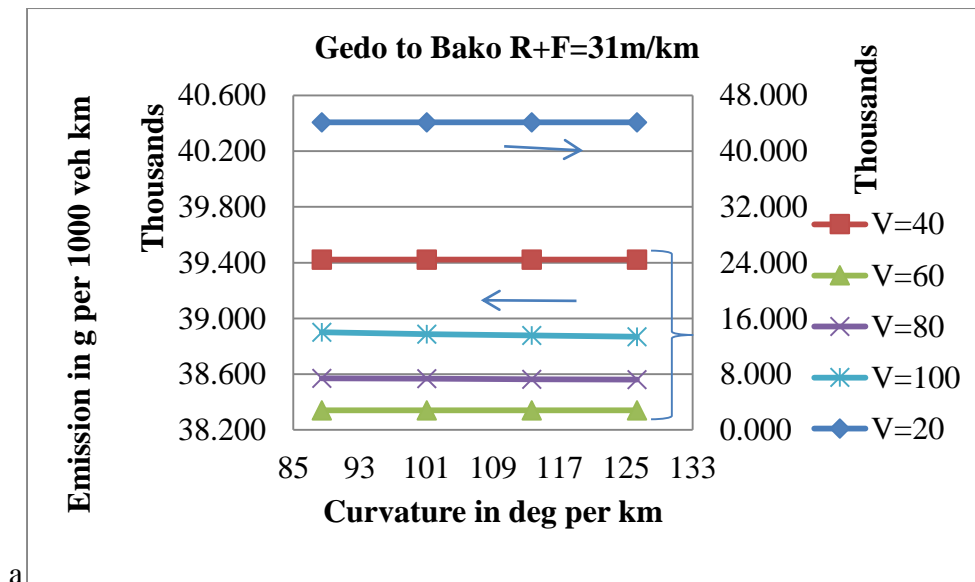


Figure 26: Emission Vs Curvature at different speeds on Gonder to Debarak Road



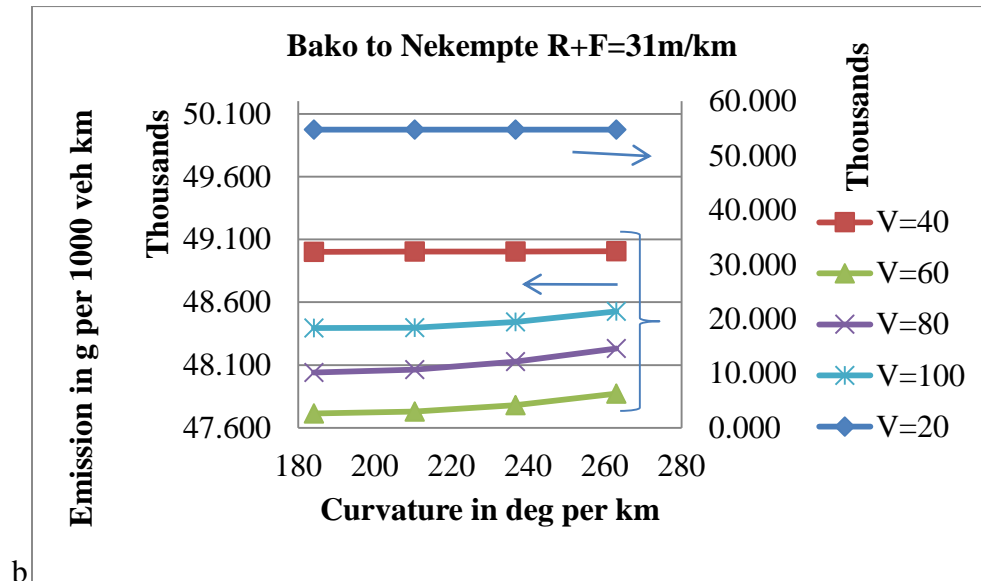
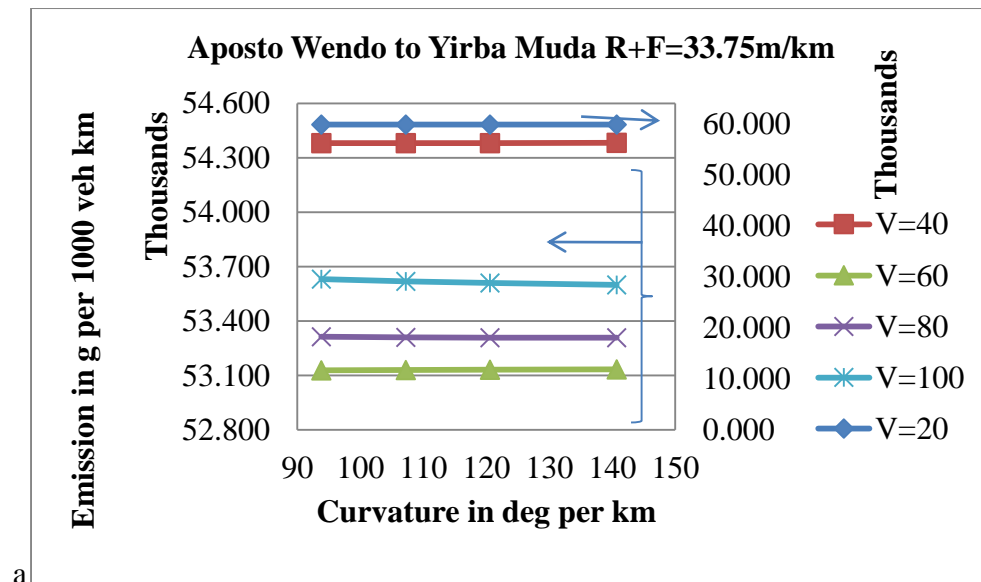


Figure 27: Emission Vs Curvature at different speeds on Gedo to Nekempte Road



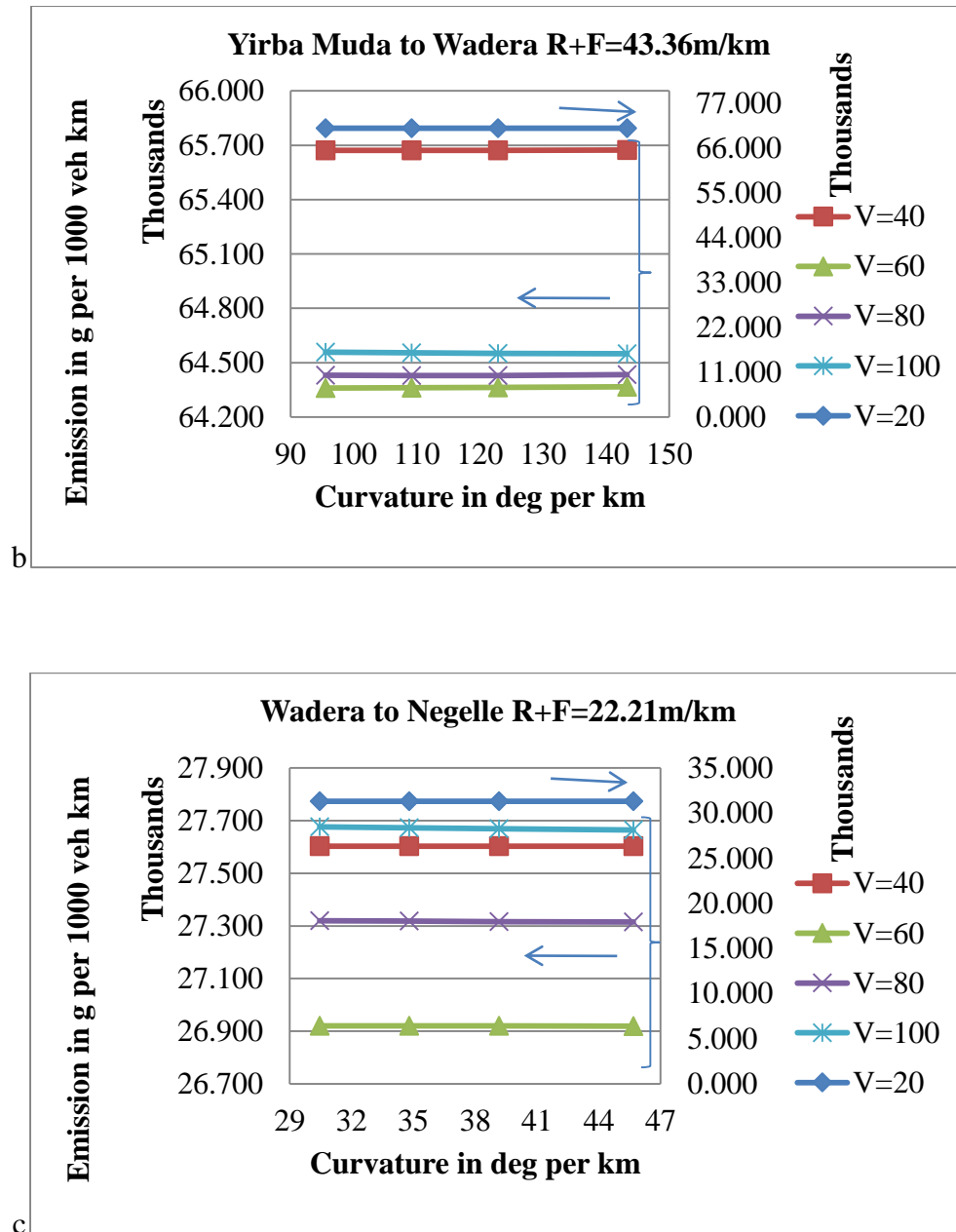
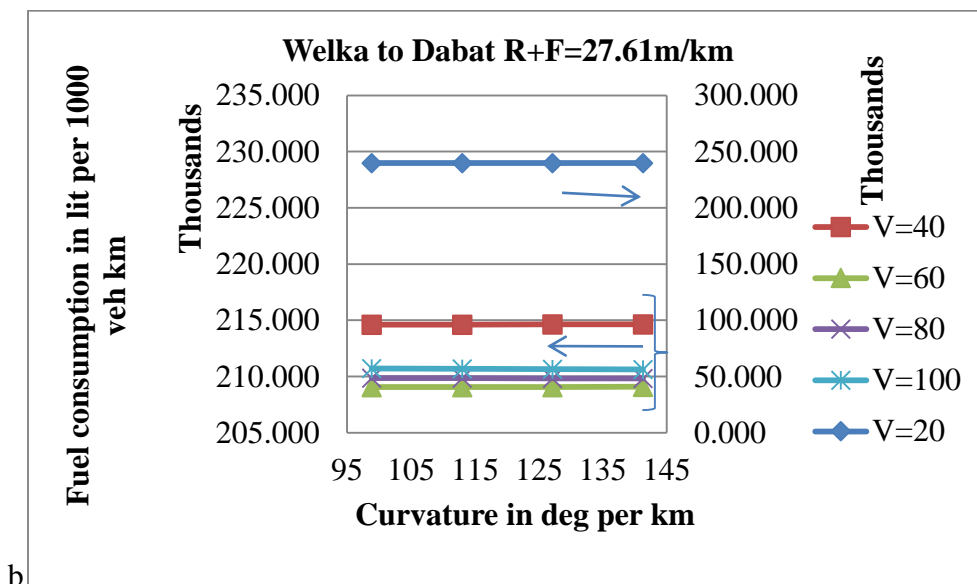
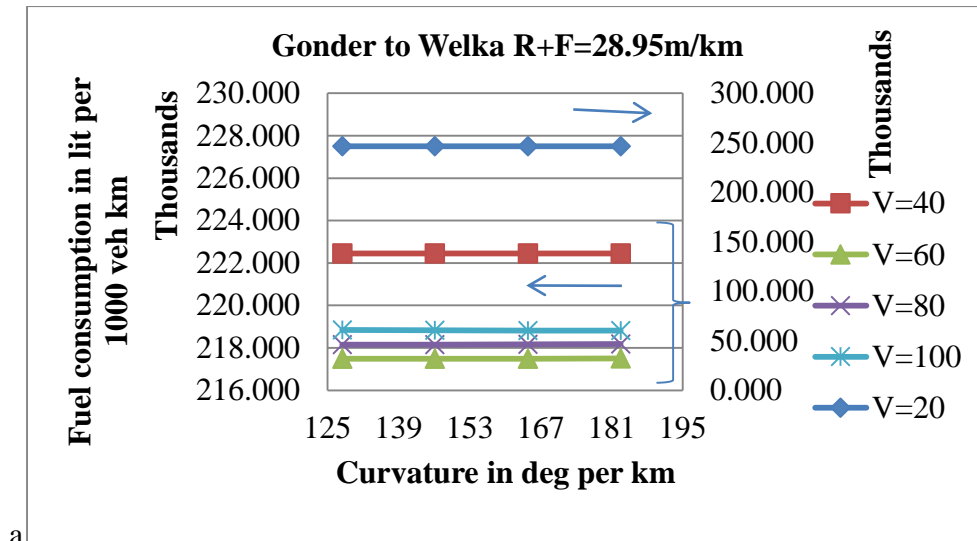


Figure 28: Emission Vs Curvature at different speeds on Aposto Wendo to Negelle Road



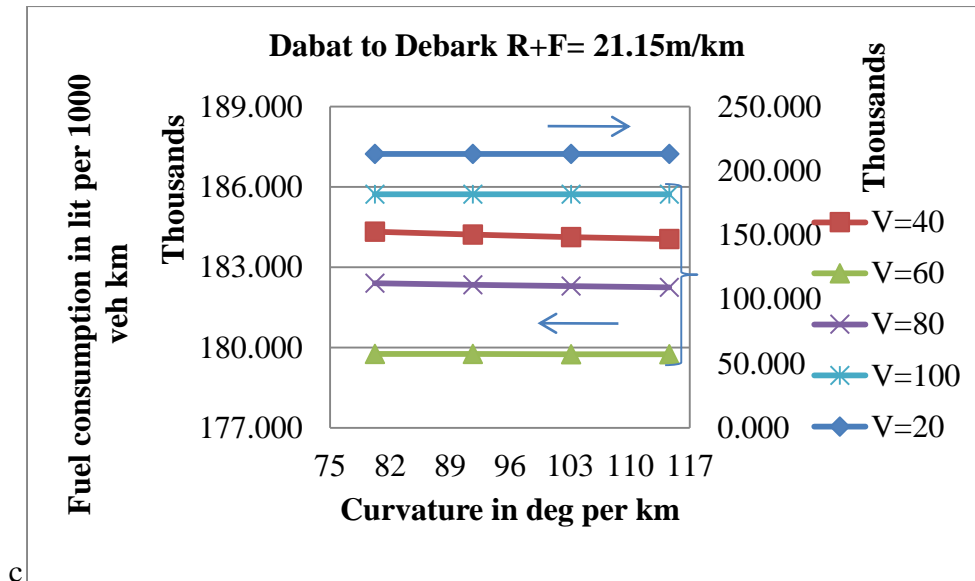
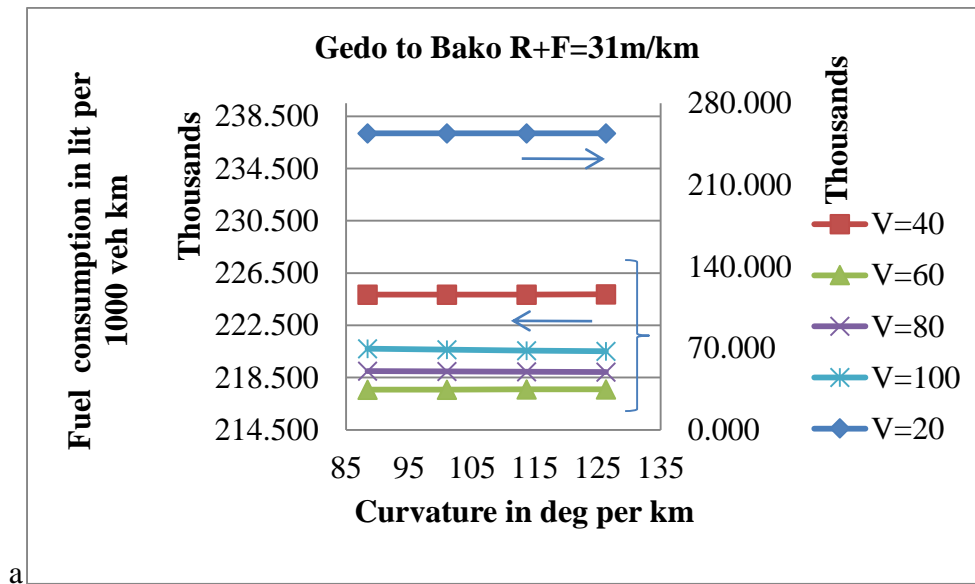


Figure 29: Fuel Consumption Vs Curvature at different speeds on Gonder to Debark Road



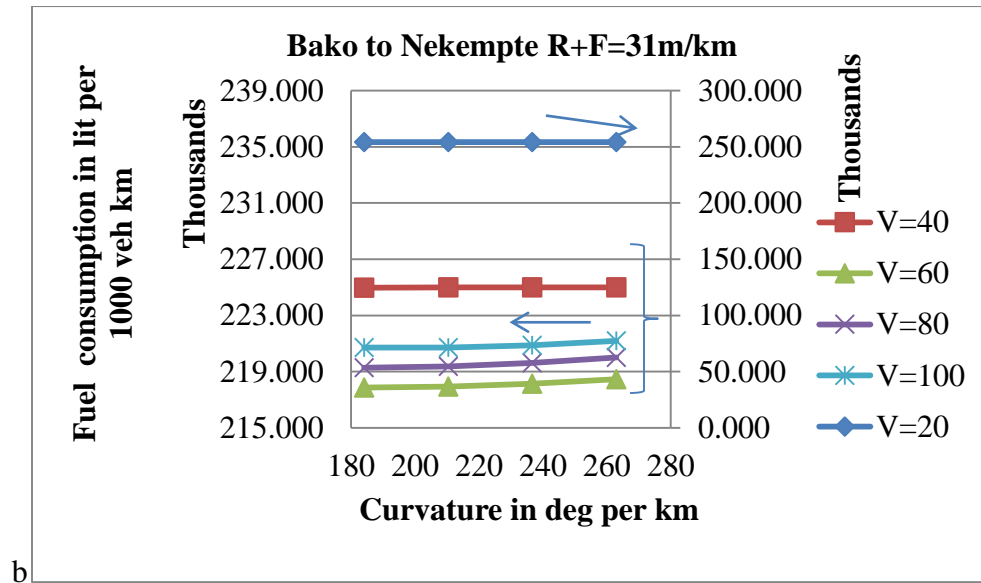
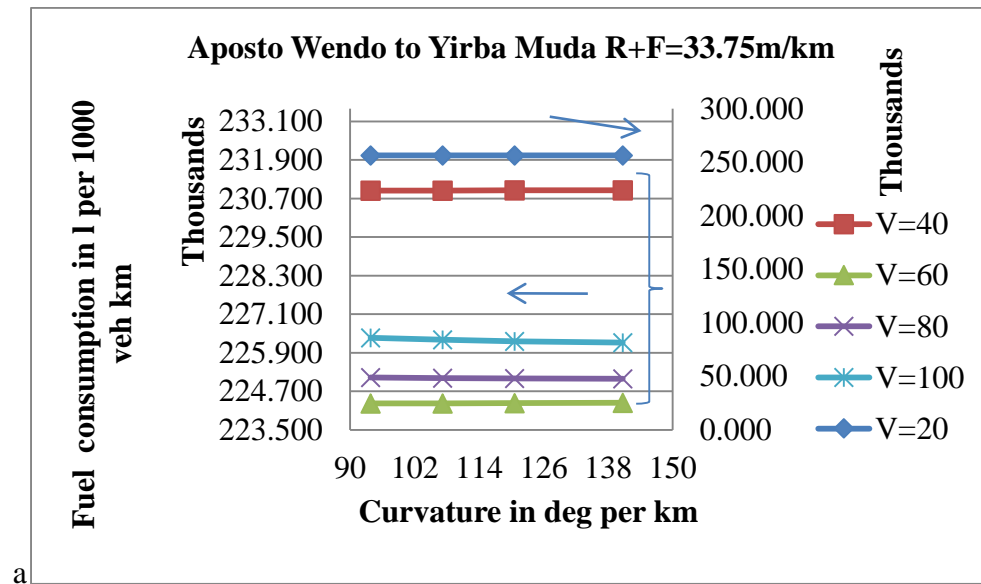


Figure 30: Fuel Consumption Vs Curvature at different speeds on Gedo to Nekempte Road



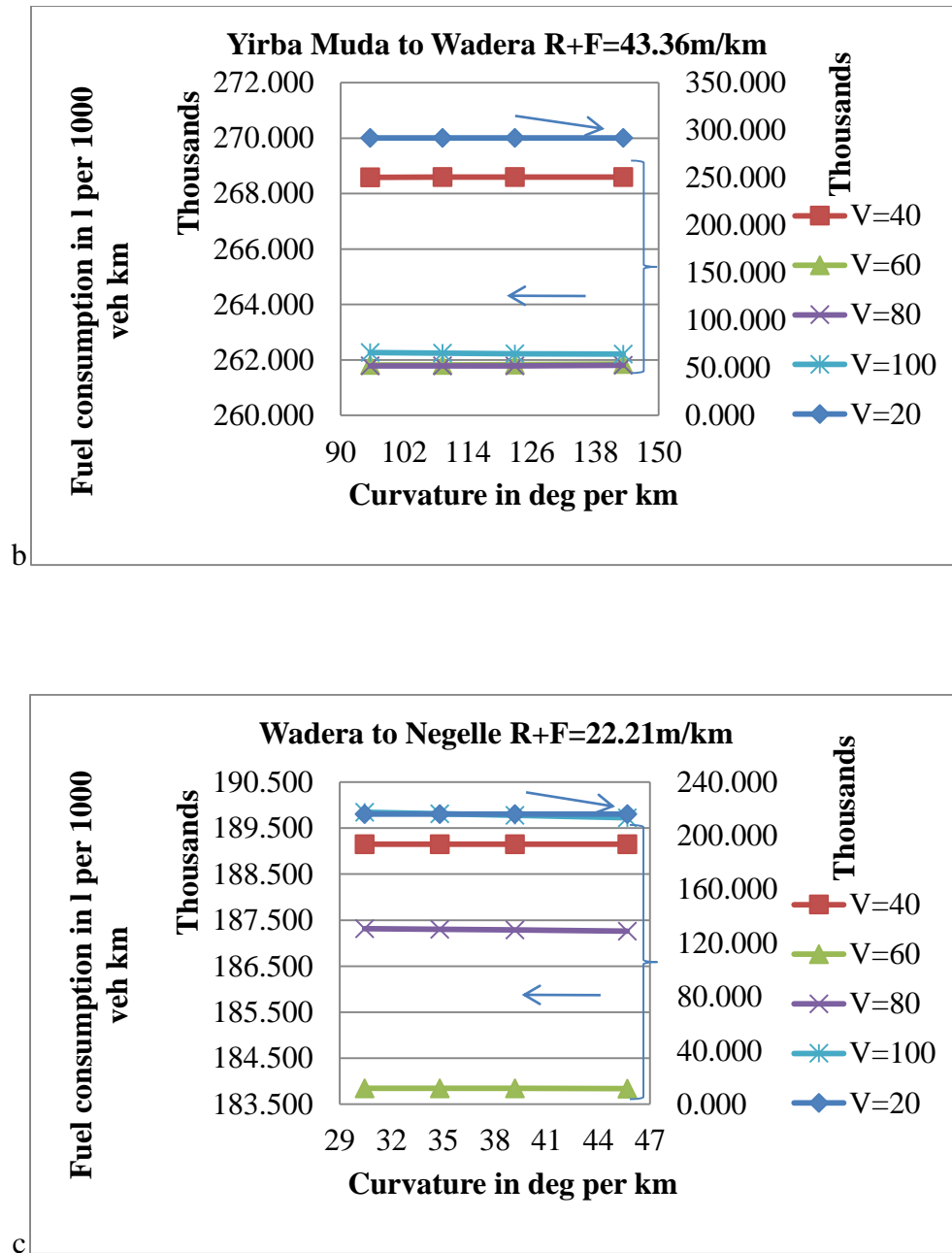


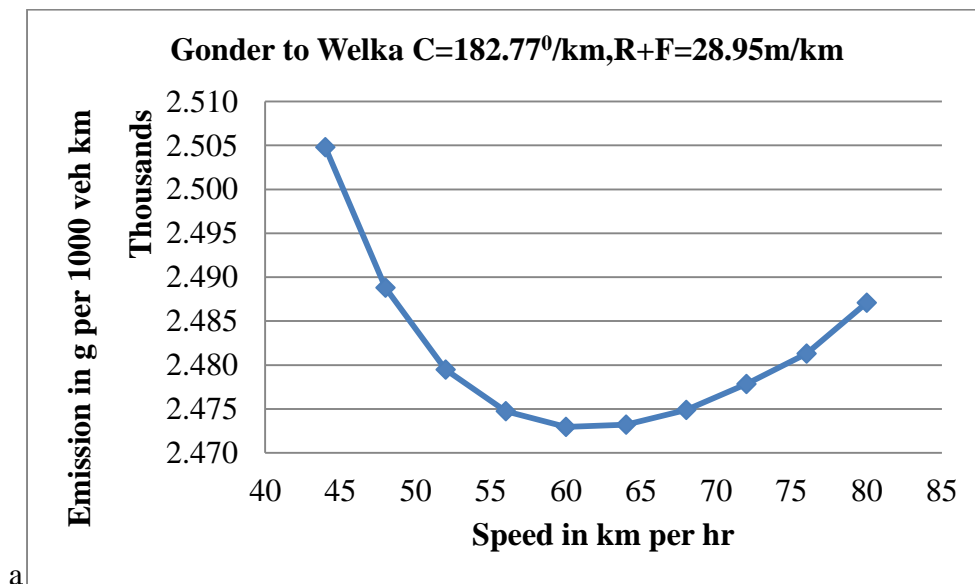
Figure 31: Fuel Consumption Vs Curvature at different speeds on Aposto Wendo to Yirba Muda Road

Figures 26 - 31 show that the rate of emission and fuel consumption varies as vehicle speed varies in accordance with curvature. For all sections of the roads under study, emission and fuel consumption are maximum at a speed of 20 km/hr and minimum at a speed of 60 km/hr. Except on Dabat to Debark and Wadera to Negelle roads, emission and fuel consumption decrease as vehicle speed changes from 40 km/h to 100 km/hr and 100 km/hr to 80 km/hr. However, on Debark to Dabat and Welka to Negelle roads, vehicles produce higher emission and consume more fuel when driven at 100 km/hr than at 40 km/hr. This is due to the fact that Dabat to Debark and Wadera to Negelle roads are with low rise + fall values (21.15 m/km and 22.21 m/km respectively) as compared to Gonder to Welka (28.95 m/km), Welka to Dabat (27.61 m/km), Gedo to Bako (31 m/km), Bako to Nekempte (31 m/km), Aposto Wendo to Yirba Muda (33.76 m/km) and Yirba Muda to Wadera (43.36m/km) roads.

On a straight and level road, vehicles consume more fuel to counteract the resisting aerodynamic force when driven at a fast speed. Therefore, to reduce emission and fuel consumption it is preferable to drive at a speed of 40 km/hr than at a speed of 100 km/hr when driving on a straight and level road.

4.3 The Effect of Speed on Emission and Fuel Consumption

Figures 32 - 37 illustrate the effect of speed on emission and fuel consumption.



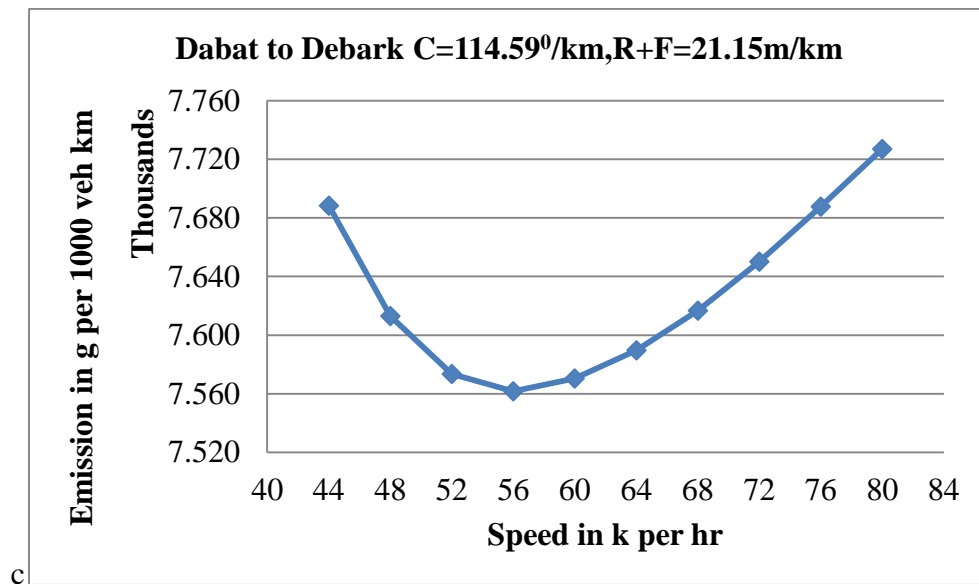
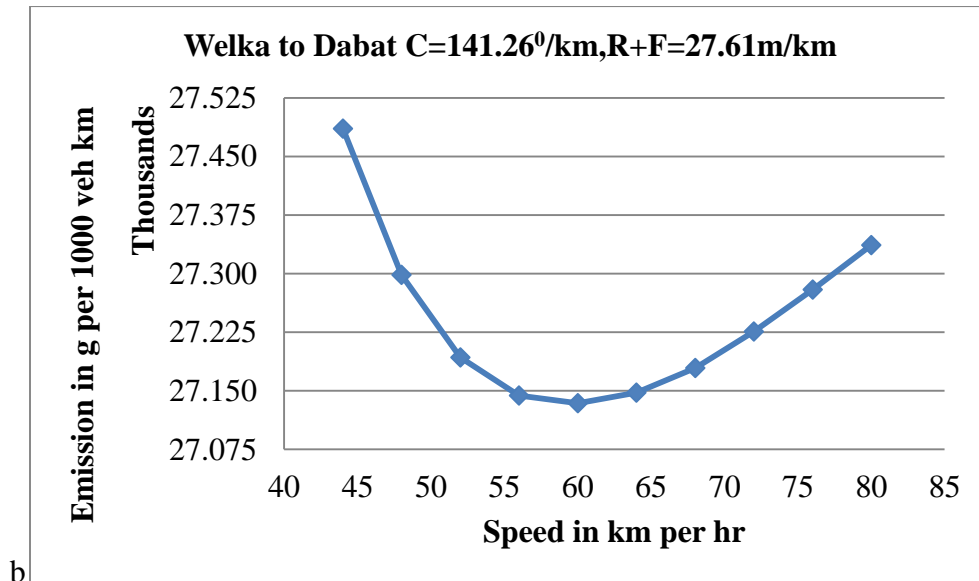


Figure 32: Emission Vs Speed on Gonder to Debark Road

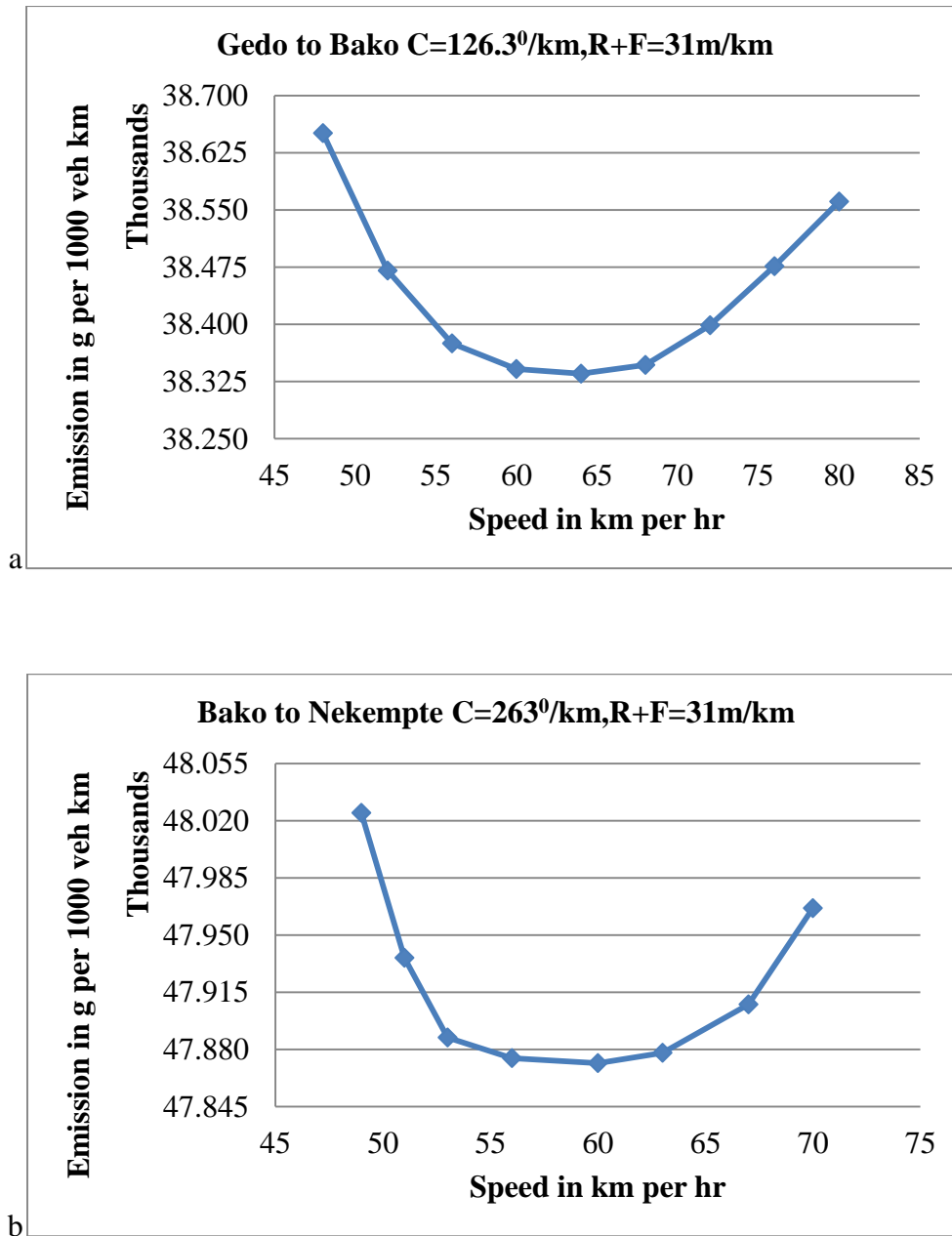
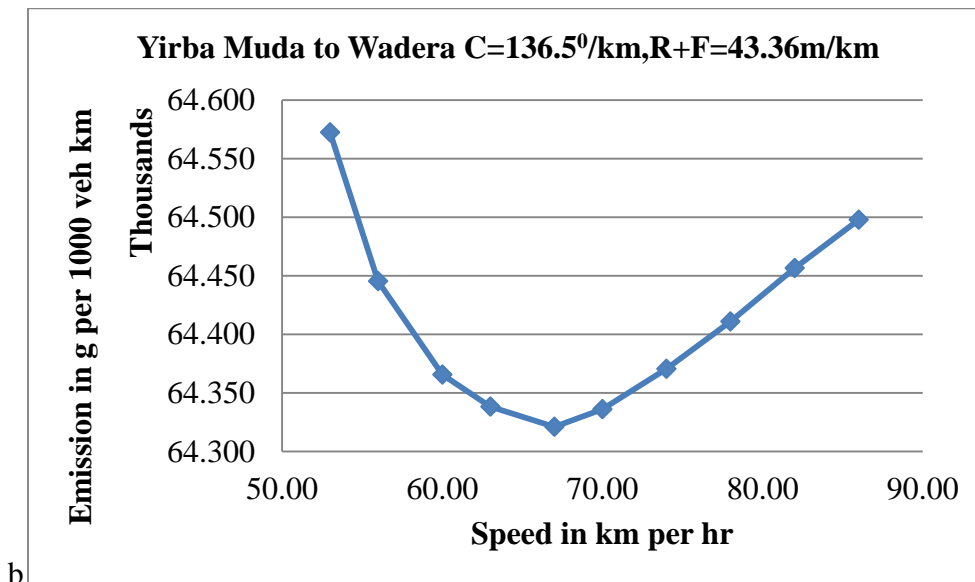
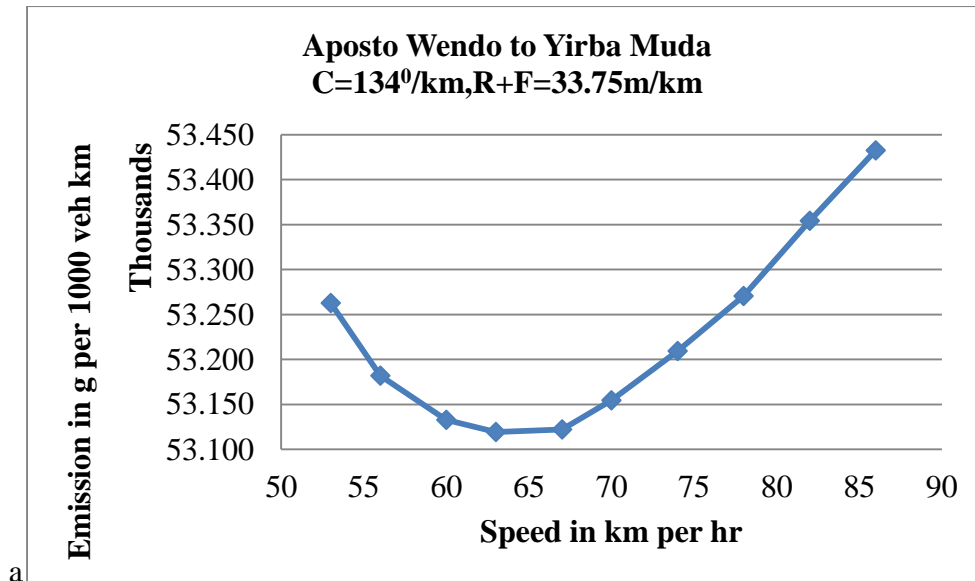


Figure 33: Emission Vs Speed on Gedo to Nekempte Road



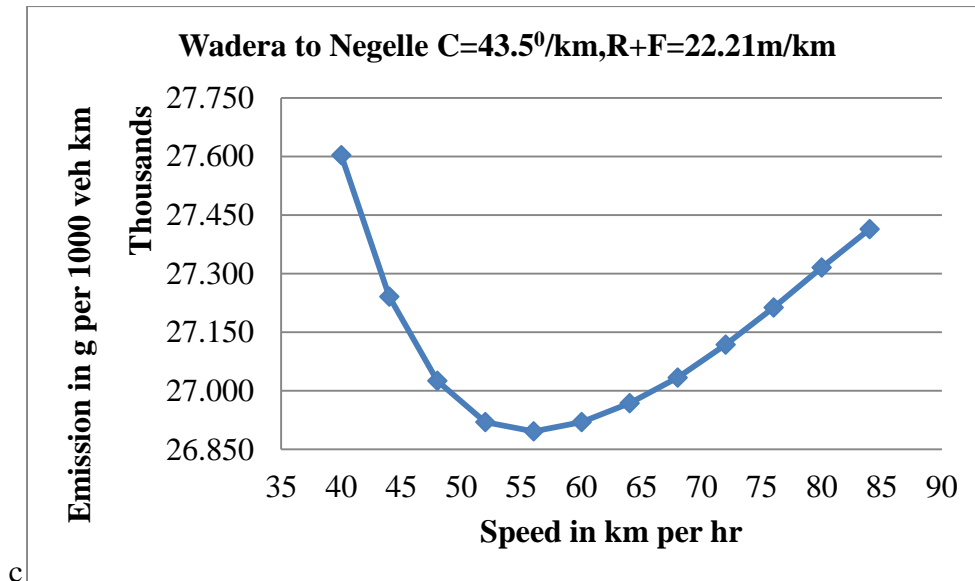
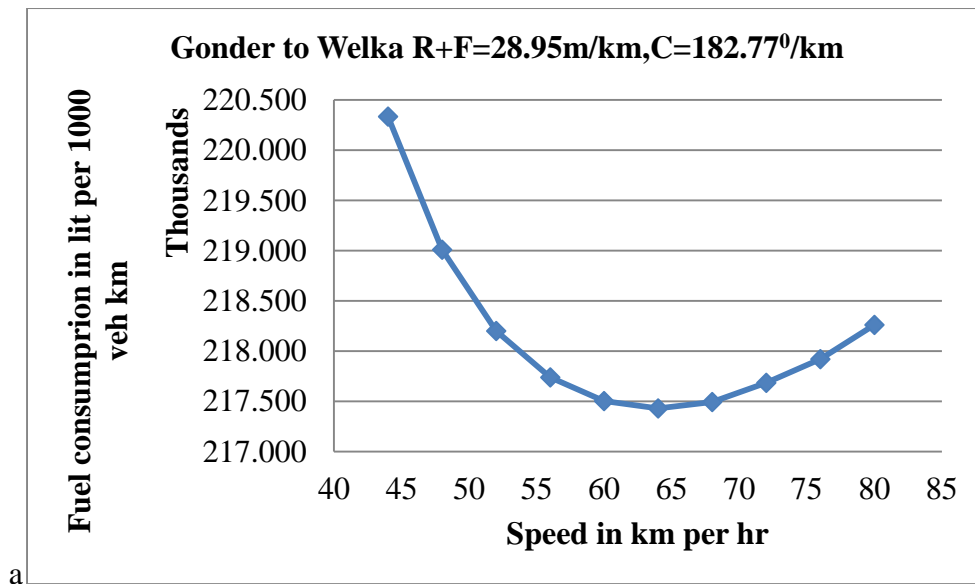


Figure 34: Emission Vs Speed on Aposto Wendo to Negelle Road



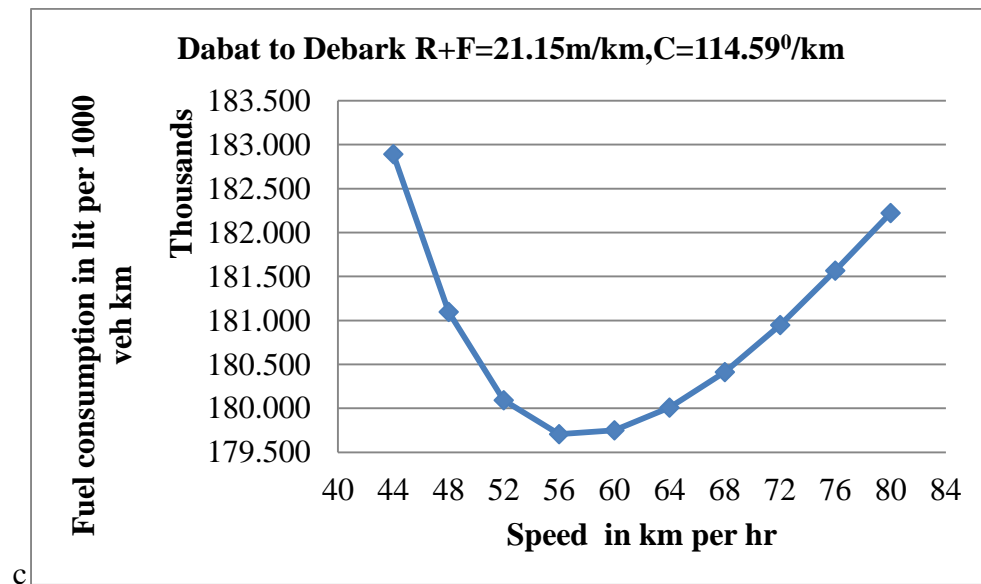
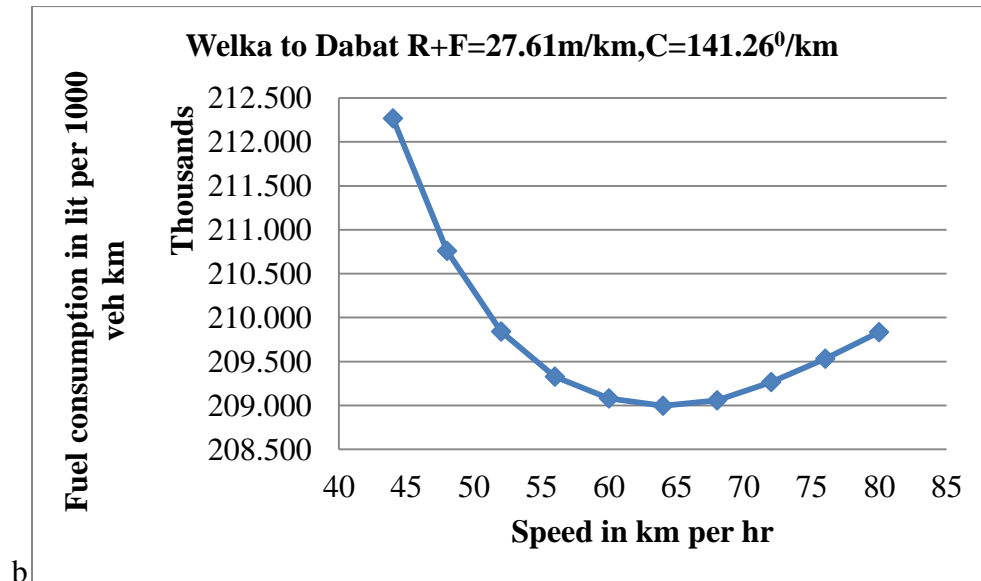


Figure 35: Fuel Consumption Vs Speed for Gonder to Debark Road

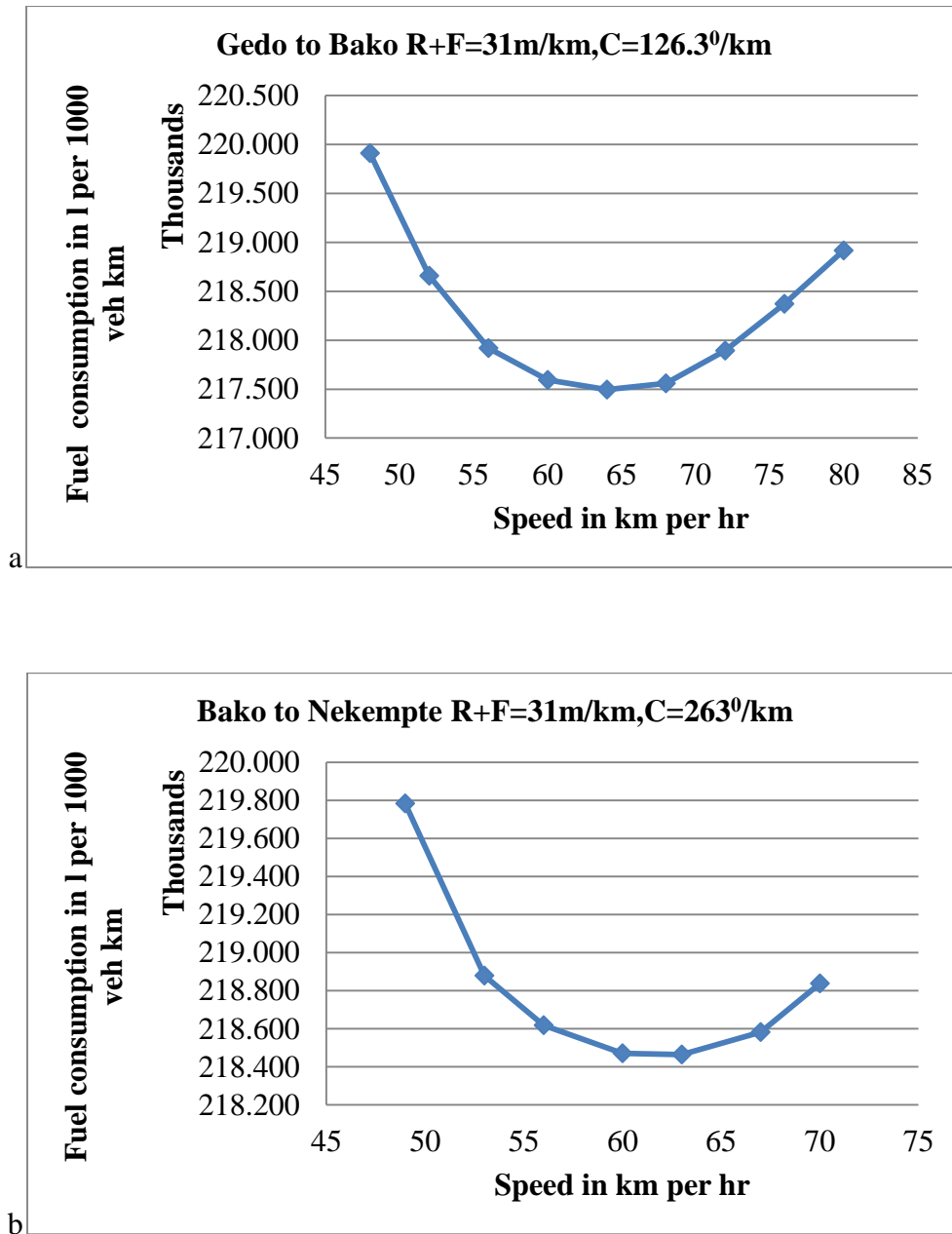
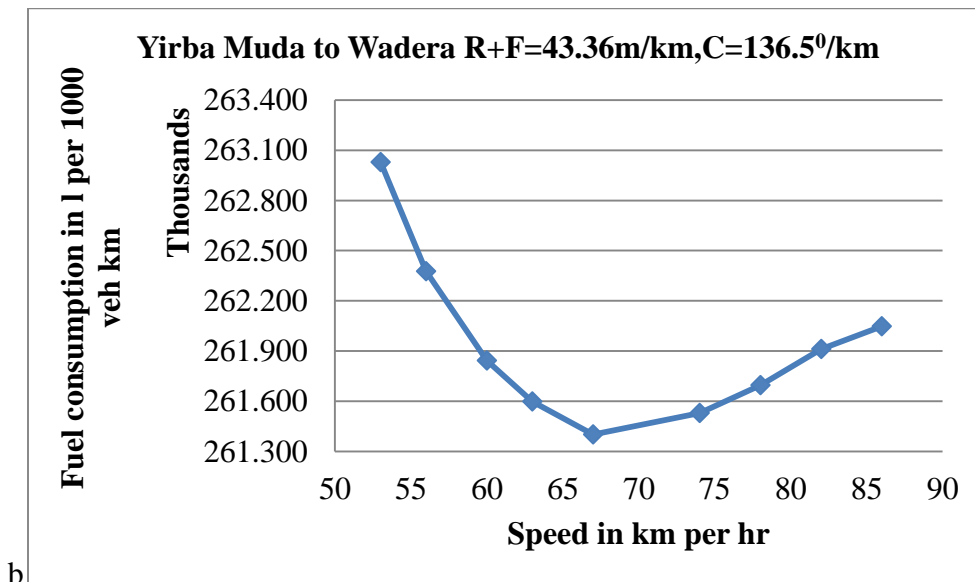
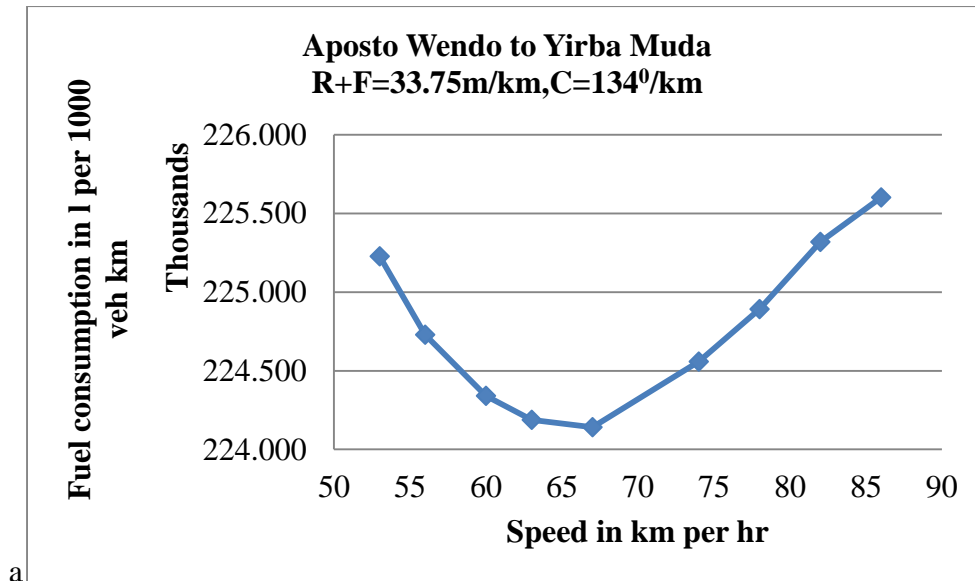


Figure 36: Fuel Consumption Vs Speed on Gedo to Nekempte Road



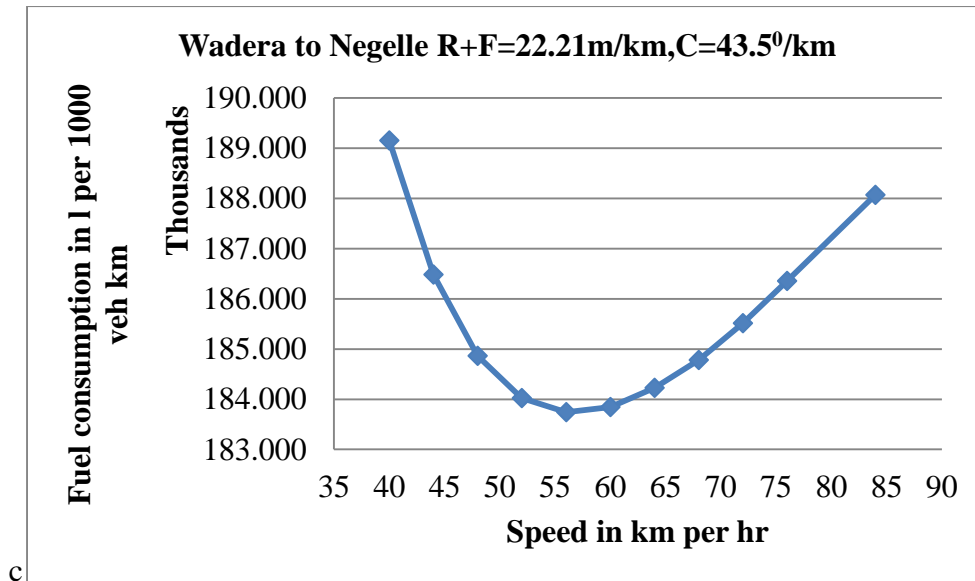
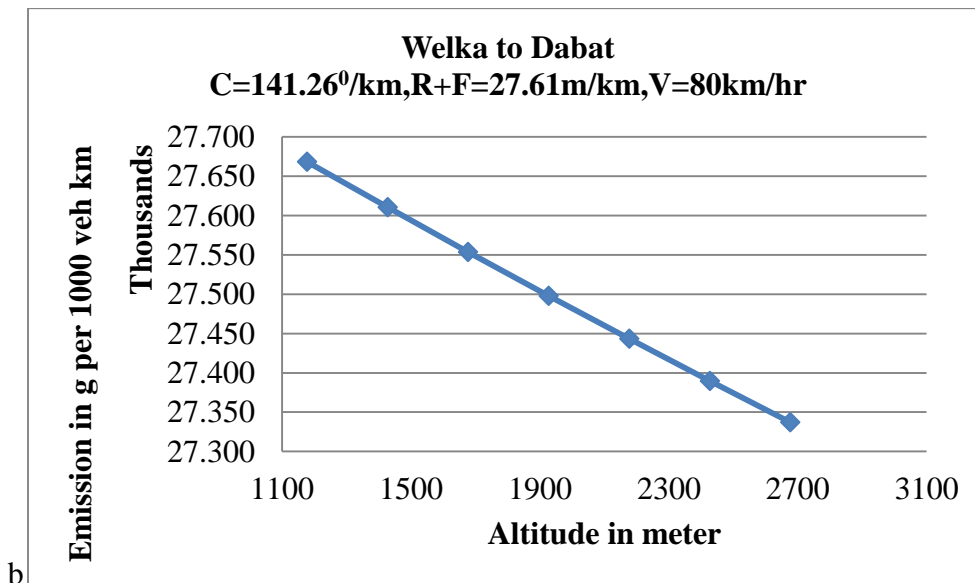
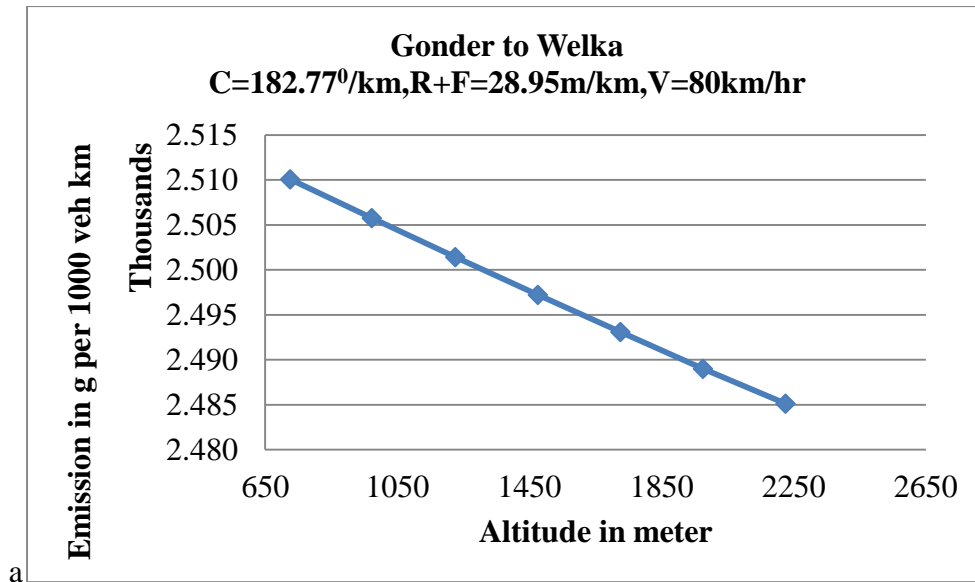


Figure 37: Fuel Consumption Vs Speed on Aposto Wendo to Negelle Road

As can be seen from figures 32 - 37 above, the relation between emission and fuel consumption with respect to speed is represented by an upward parabolic function. Both emission and fuel consumption decrease as speed increases up to a certain limit and then begin to increase as speed increases. The speed at which emission and fuel consumption is minimum lies within the speed range of 50 km/hr to 70 km/hr. As vehicles travel faster, the energy required to overcome aerodynamic drag effect increases and becomes the dominant factor in total fuel use and emission.

4.4 The Effect of Rise and fall on Emission and Fuel Consumption

The impact of altitude on emission and fuel consumption is presented in Figures.38 - 43 below.



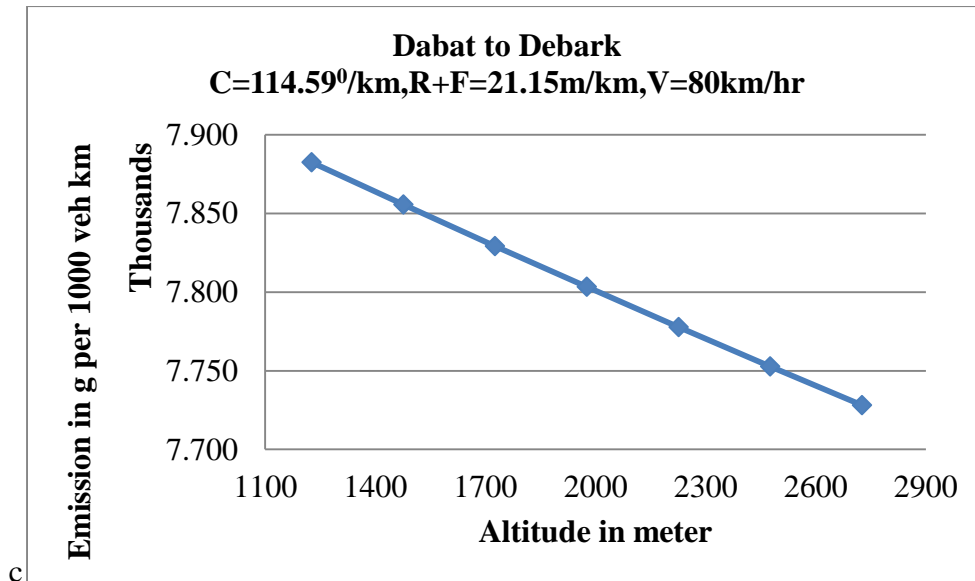
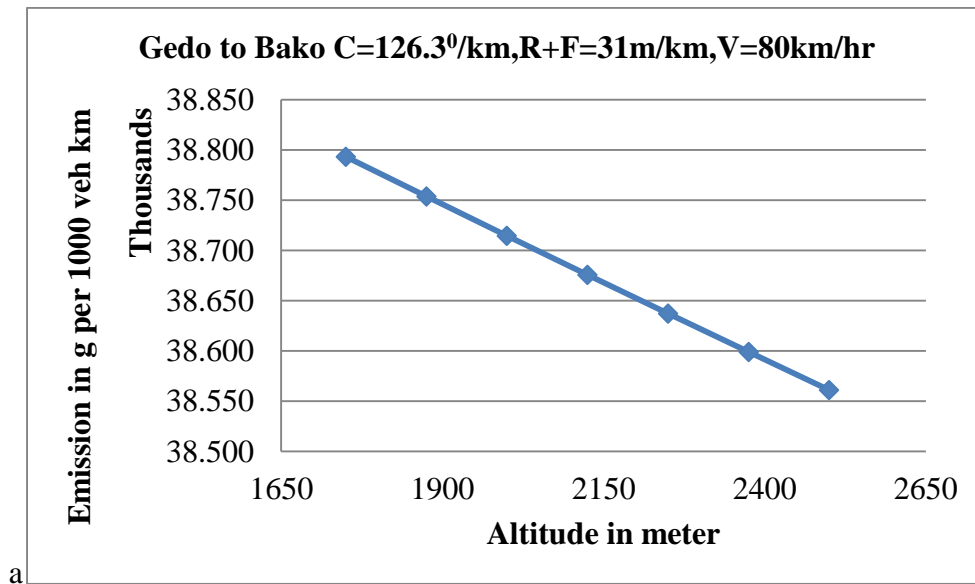


Figure 38: Emission Vs Altitude on Gonder to Debark Road



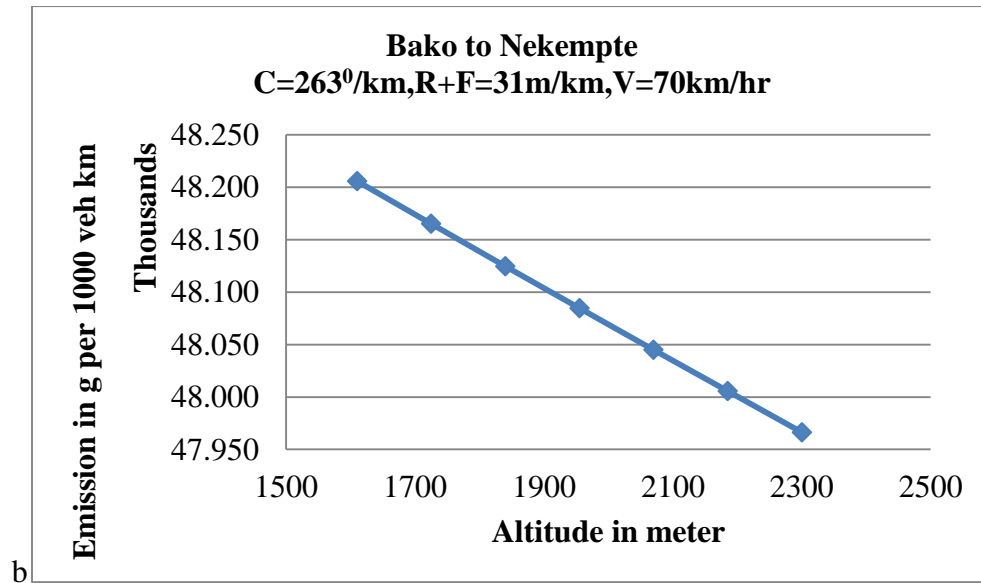
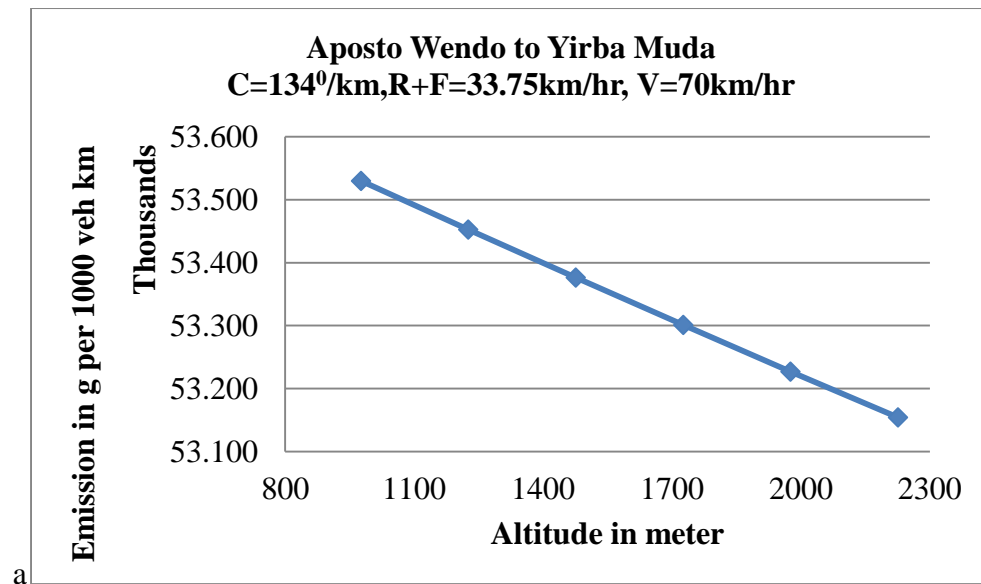


Figure 39: Emission Vs Altitude on Gedo to Nekempte Road



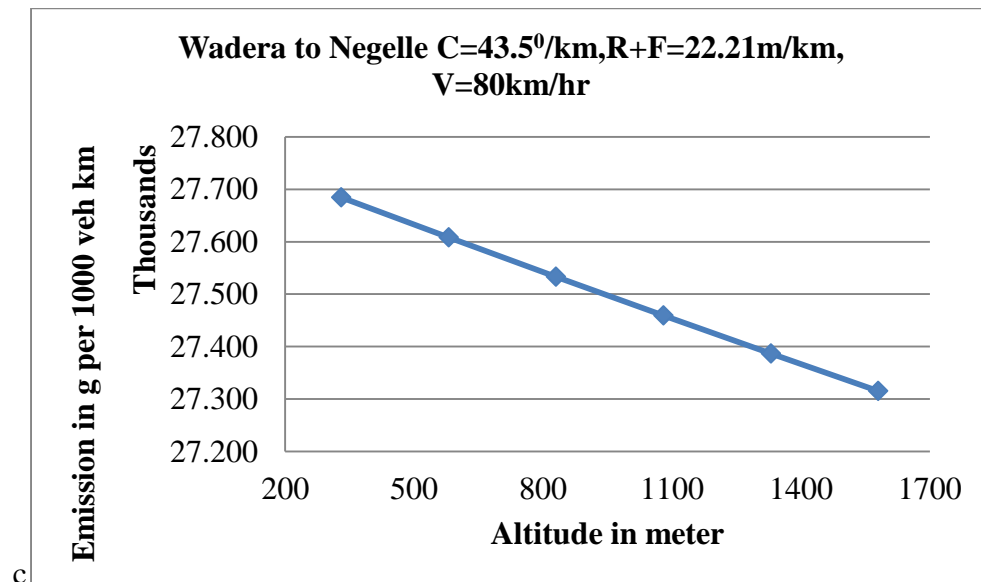
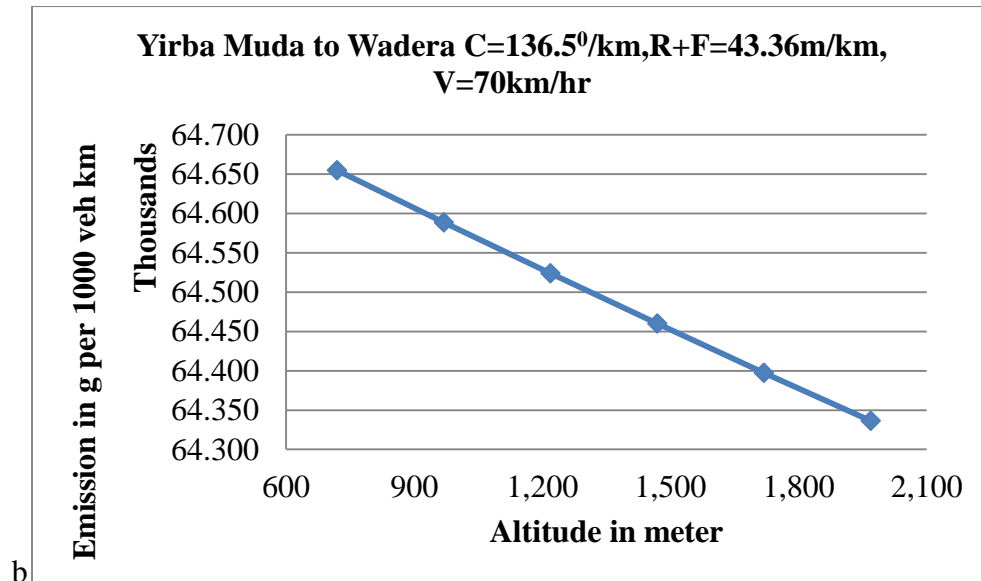
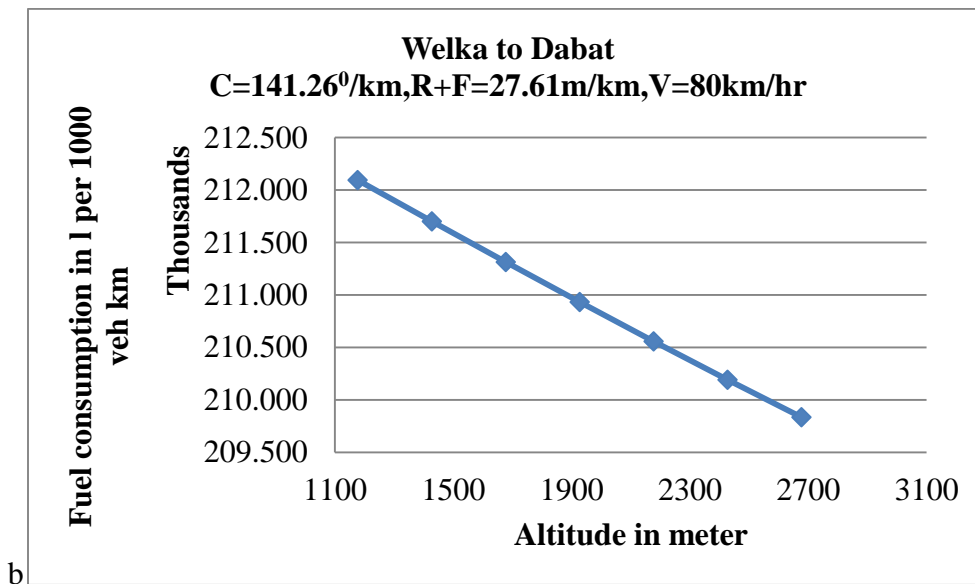
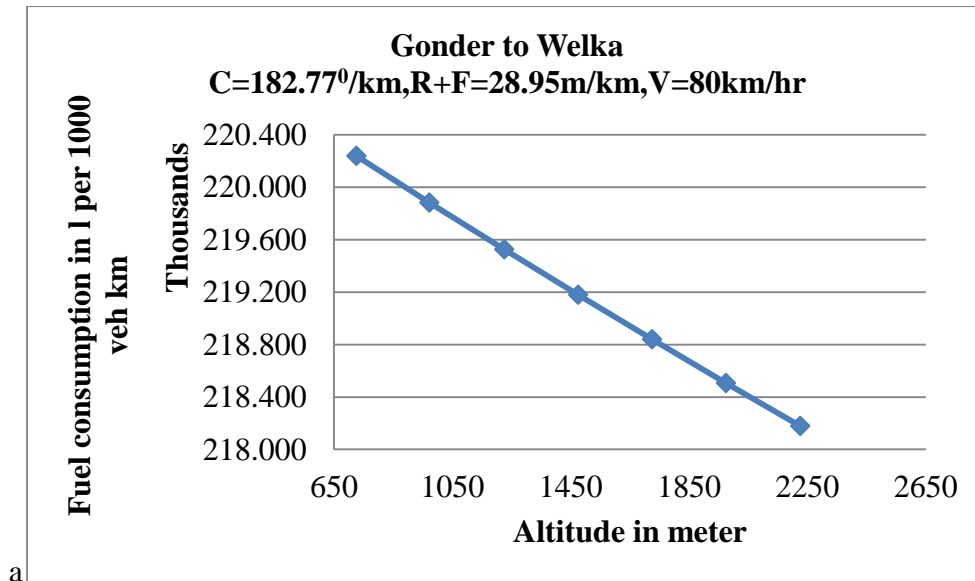


Figure 40: Emission Vs Altitude on Aposto Wendo to Negelle Road



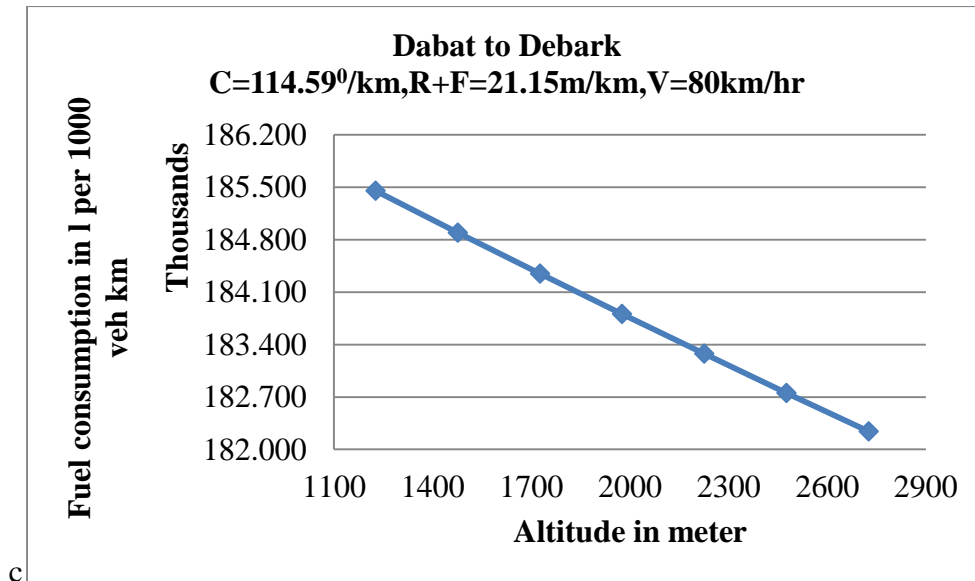
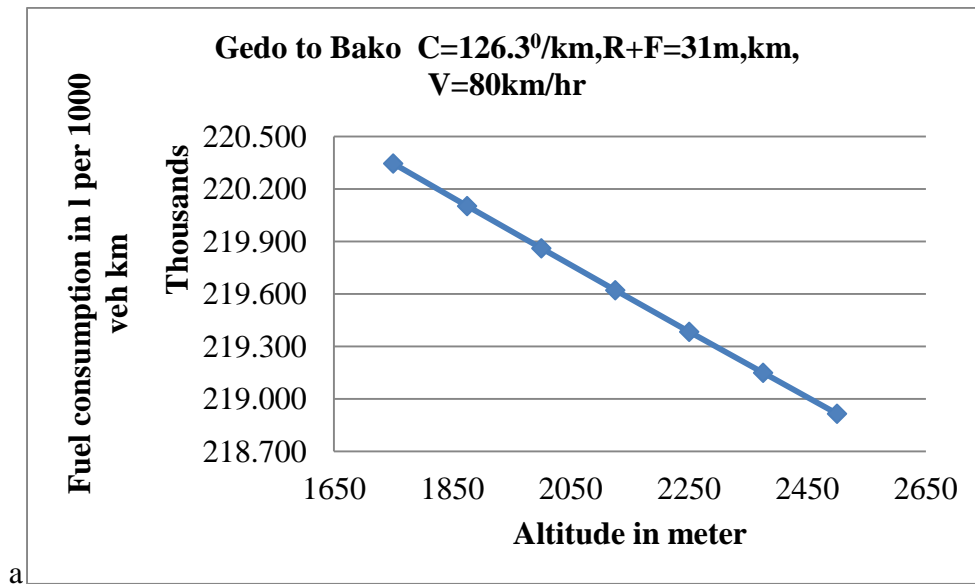


Figure 41: Fuel Consumption Vs Altitude on Gonder to Debarik Road



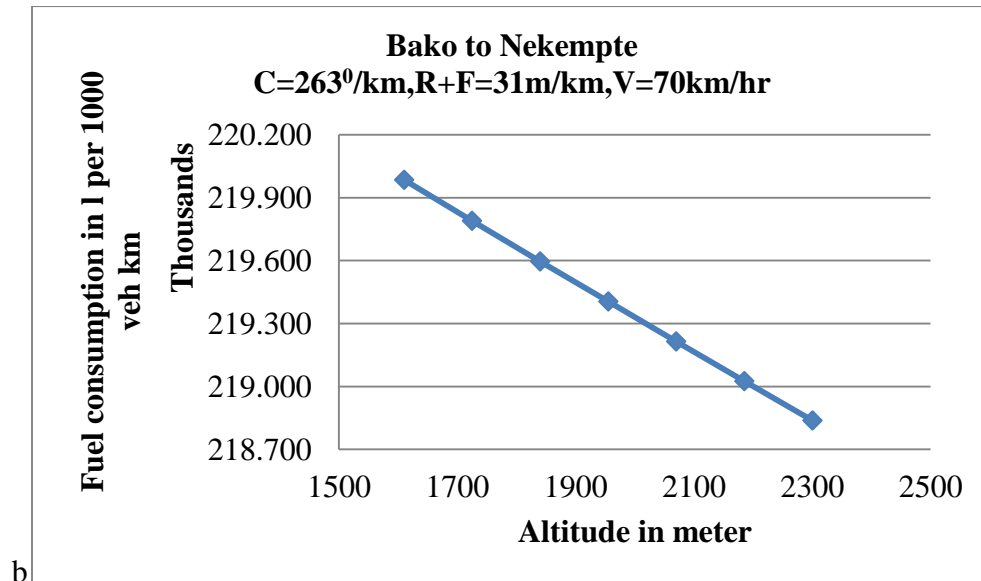
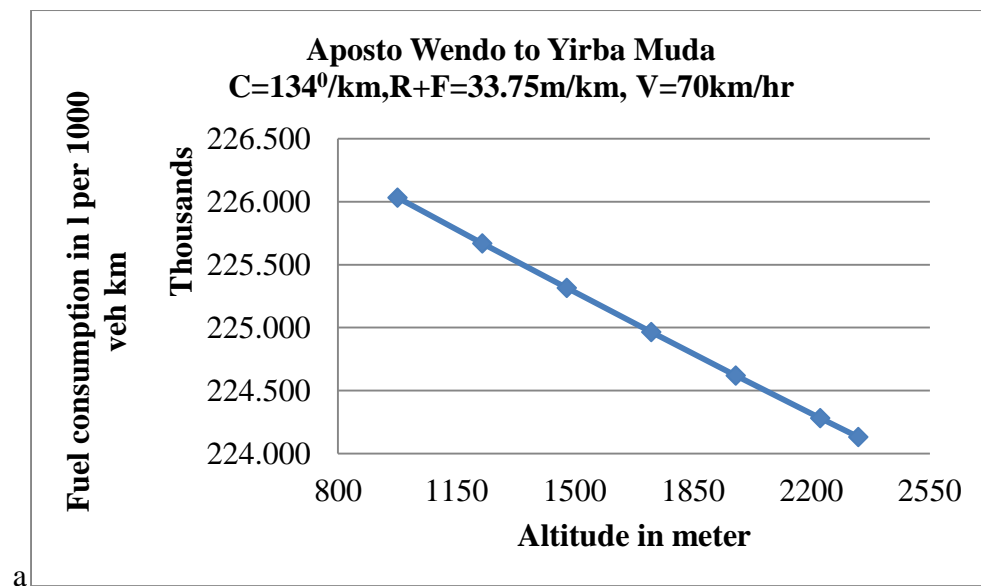


Figure 42: Fuel Consumption Vs Altitude on Gedo to Nekempte Road



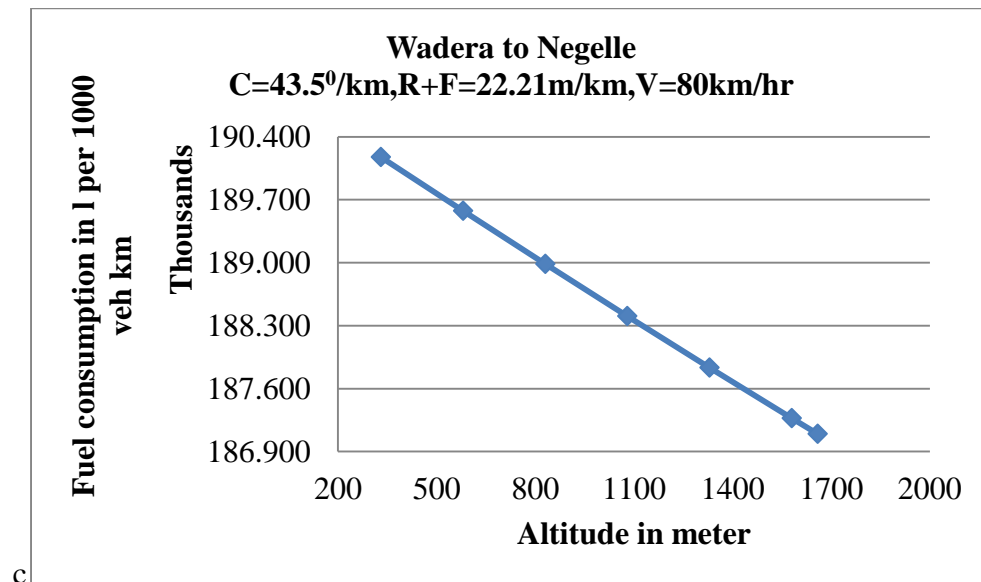
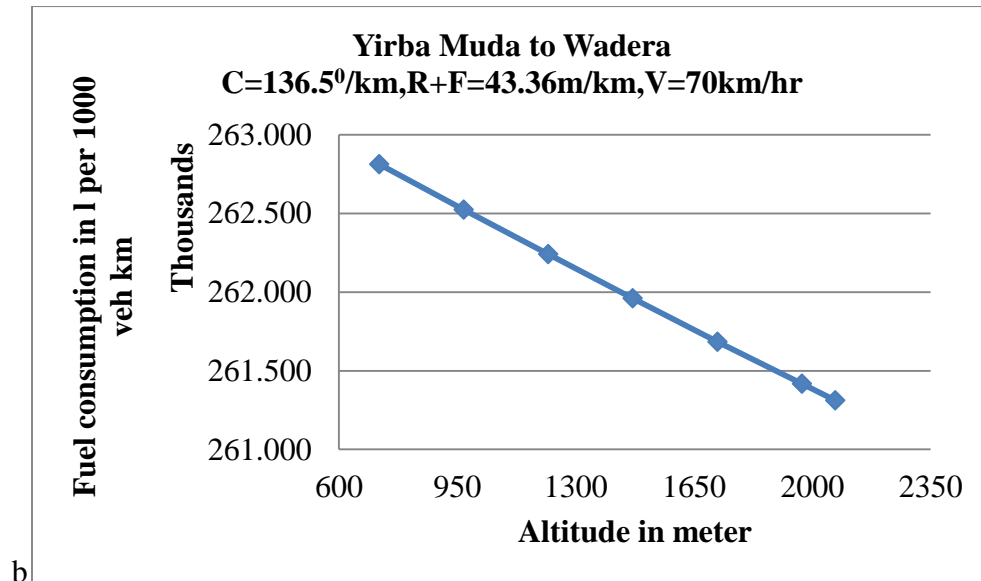


Figure 43: Fuel Consumption Vs Altitude on Aposto Wendo to Negelle Road

Figures 38 - 43 show that vehicles consume more fuel and emit higher greenhouse gases at low altitude than at high altitude. This is due to the fact that at low altitude air pressure is stronger than at high altitude so that vehicles are subjected to high aerodynamic resistance which in turn force engines to consume more fuel and emit more greenhouse gases so as to counter act the effect and traverse at a desired speed.

4.5 The Effect of Road Surface Types on Emission and Fuel Consumption

Comparison of the amount of emission and fuel consumption for gravel, double surface treatment (DBST) and Asphalt concrete (AC) roads was performed. In this regard, the results obtained are presented in Figures 44 - 47 below.

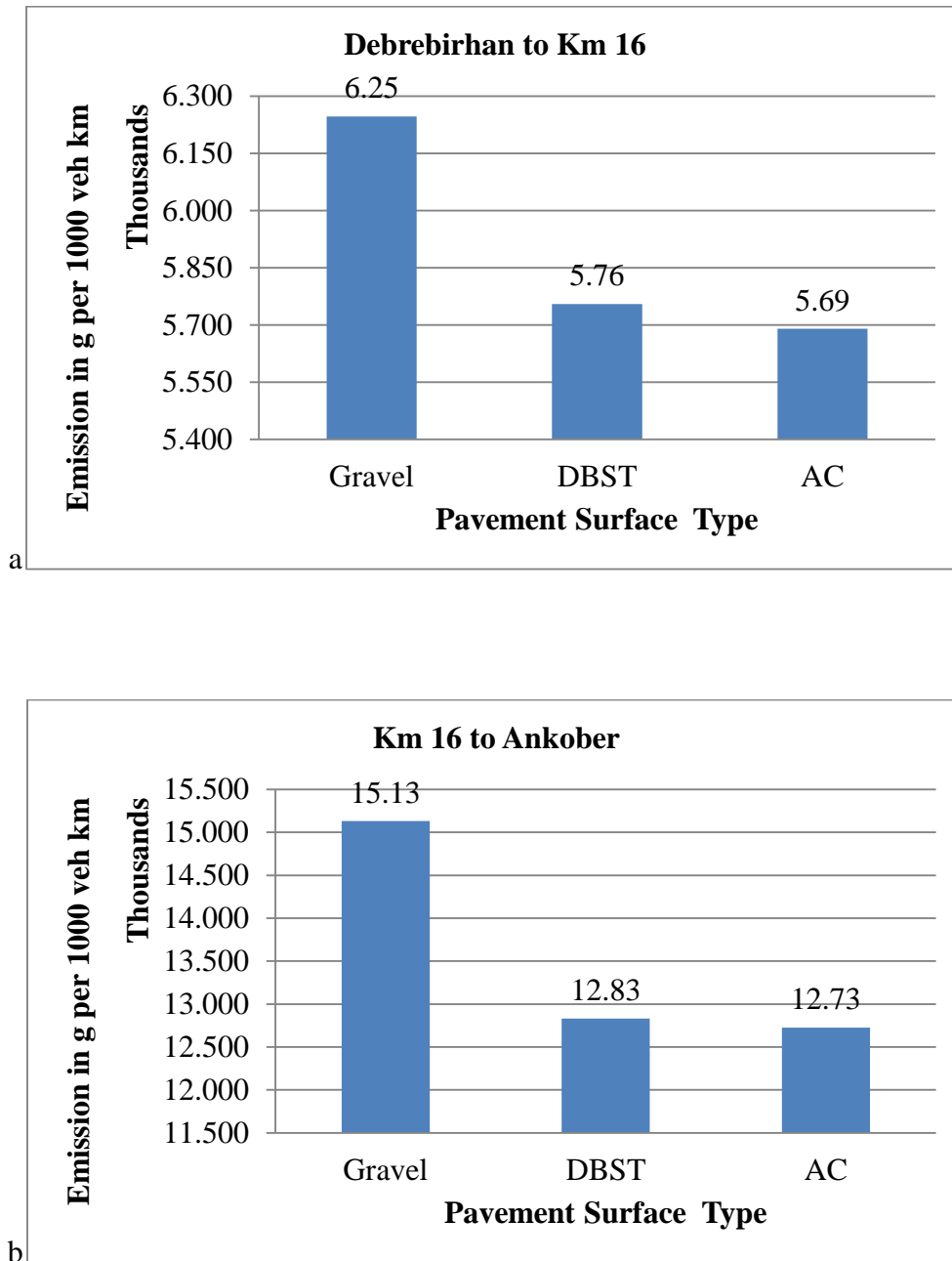


Figure 44: Emission Vs Pavement Surface type on Debrebirhan to Ankober Road

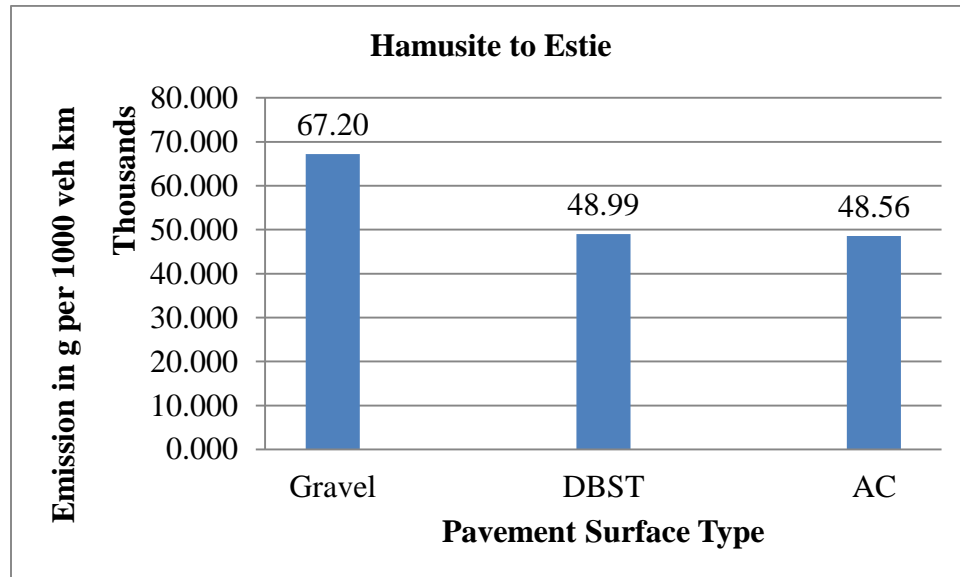
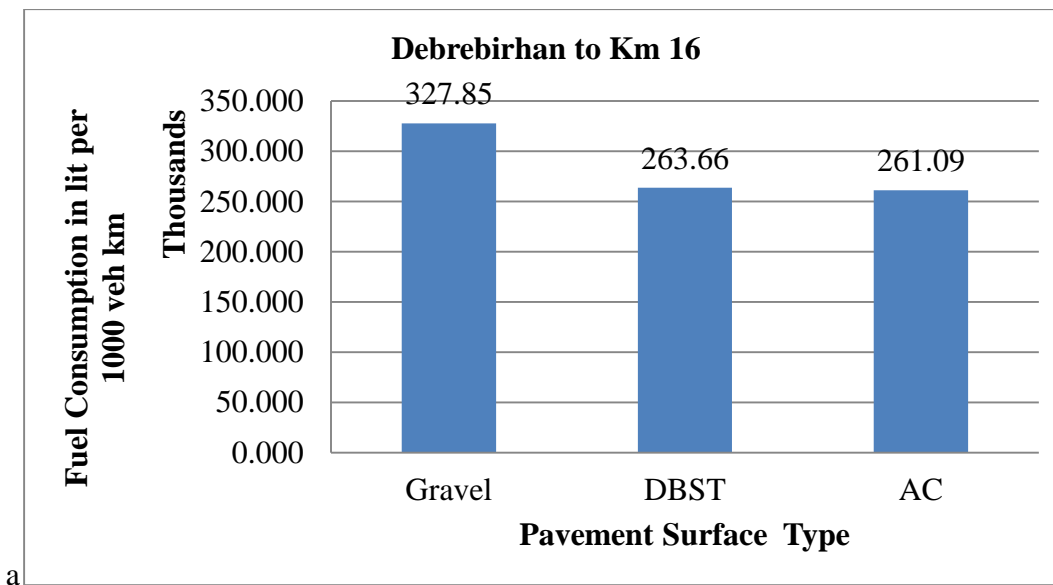


Figure 45: Emission Vs Pavement Surface type on Hamisite to Estie Road



a

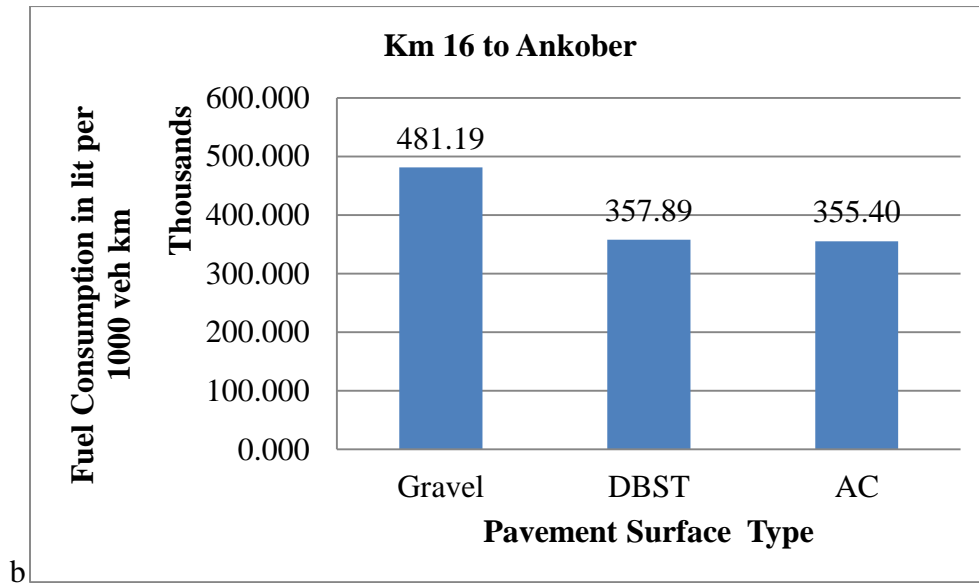


Figure 46: Fuel Consumption Vs Pavement Surface type on Debrebirhan to Ankober Road

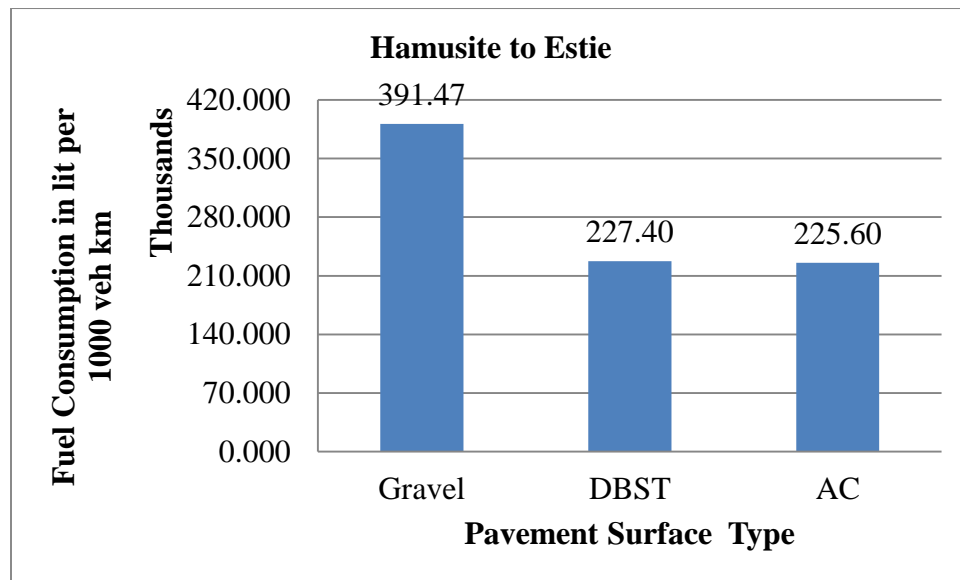


Figure 47: Fuel Consumption Vs Pavement Surface type on Hamusite to Estie Road

Table 13: Reduction on emission and fuel consumption when pavement is upgraded from Gravel to DBST

Road Section	Upgrading from Gravel to DBST			
	Reduction on emission		Reduction on fuel consumption	
	In gram per 1000 veh km	In Percent	In liter per 1000 veh km	In Percent
Debrebirhan to Km 16	490.00	7.84%	64,170.00	19.60%
Km 16 to Ankober	2,300.00	15.20%	123,300.00	25.60%
Hamusite to Estie	18,210.00	27.10%	164,070.00	41.90%

Table 14: Reduction on emission and fuel consumption when pavement is upgraded from Gravel to AC

Road Section	Upgrading from Gravel to AC			
	Reduction on emission		Reduction on fuel consumption	
	In gram per 1000 veh km	In Percent	In liter per 1000 veh km	In Percent
Debrebirhan to Km 16	560.00	8.96%	66,740.00	20.40%
Km 16 to Ankober	2,400.00	15.90%	125,790.00	26.10%
Hamusite to Estie	18,640.00	27.70%	165,800.00	42.40%

Figures 44 - 47 and Tables 13 - 14 show that the amount of emission and fuel consumption increase as the road surface quality decreases. The total amount of reduction on emission over the analysis period as the pavement surface is upgraded from Gravel to AC is greater than Gravel to DBST. Similarly, there is a great reduction in total fuel consumption throughout the analysis period as the pavement is upgraded from Gravel to DBST or AC. The reduction is more when the upgrading is from Gravel to AC than Gravel to DBST.

In view of the above, it is apparent that saving in fuel consumption and subsequent reduction in emission is associated with surface quality of a road. As surface quality decreases, vehicles consume more fuel and emit higher greenhouse gases in order to counteract the effect of highly resisting friction force; but, as the quality increases, friction is less so vehicles can traverse with less resistance at lower fuel consumption and emission.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Analyses were carried out regarding the effect of Rise + fall, Curvature, Speed, Altitude and Road surface types (Gravel, DBST, AC) on greenhouse gas emission and fuel consumption on the selected three Asphalt Concrete (AC) roads namely; Gonder to Debark (99.2 km), Gedo to Nekempte (134 km) and Aposto Wendo to Negelle (268.36 km) and similarly on two Gravel roads namely; Debrebirhan to Ankober (42 km) and Hamusit to Estie (76 km). Based on the results of the analyses, the following conclusions have been arrived at:

- Change on Rise + fall, Curvature, Speed, Altitude and Road surface types change the amount of vehicular greenhouse gas emission and fuel consumption.
- As rise + fall increases, both emission and fuel consumption increase. In all cases the maximum and minimum emission and fuel consumption occur at a speed of 20 km/hr and 60 km/hr respectively.
- The analysis of road curvature demonstrates that at a higher value of rise + fall, both emission and fuel consumption decrease as curvature decreases and reach to its minimum value as curvature gets close to zero. However at a lower rise + fall, both emission and fuel consumption decrease as curvature increases and reach to a certain minimum value, and then starts to increase as curvature increases. This means that, the relationship is described by an upward parabolic curve.
- The results of the analysis demonstrates that greenhouse gas emission and fuel consumption are optimum when vehicles are driven within a speed range of 50 km/hr to 70 km/hr. Decrease or increase in vehicle speed outside this optimum range results in considerable increase in vehicle greenhouse gas emission and fuel consumption.
- Altitude is inversely related to both emission and fuel consumption.
- Better road quality vitally reduces emission and fuel consumption. The reduction is greater when pavement is upgraded from gravel to AC than gravel to DBST. The lowest emission and fuel consumption was obtained for an AC road and the highest was for gravel road.

5.2 Recommendations

Based on the above conclusions, the following recommendations are forwarded for minimizing emission and fuel consumption:

- It is noticed that by varying rise + fall and curvature, there is a possibility of minimizing emission and fuel consumption; therefore, road engineers should see all possible combinations during design period.
- On a straight and level road, it's preferable to drive at a speed of 40 km/hr than at 100 km/hr; but, when the rise + fall increases driving at a speed of 100 km/hr is better than 40 km/hr.
- On a level road it's preferable to provide curvature up to some certain limit, but on a severely undulating road curvature should get close to zero.
- Speed limit should lay in the range of 50 km/hr to 70 km/hr.
- During route selection, it's preferable to choose a route that passes through reasonably high altitude than low altitude.
- AC road results in reduction of emission and fuel consumption as compared to DBST and gravel roads; therefore, the long-term reduction of emission and fuel consumption have to be compared with the construction cost of AC, DBST and gravel roads.
- The ERA geometric design manual should include design guidelines to reduce vehicle greenhouse gas emission and fuel consumption in Ethiopia.

5.3 Future Study

- The effect of rise + fall, curvature, speed, altitude and road surface types on emission and fuel consumption were evaluated using the HDM-4 software based upon the data collected in the selected five study areas. In this regard, assessment of the effects should be extended to other locations using others methods for more generalized conclusions.
- Besides the factors considered in this research, more factors, such as super elevation, traffic flow pattern and climatic zone be considered in a larger scale in order to satisfy the multiple requirements of protecting the environment (limiting greenhouse gas emission), saving energy, reducing traffic noise and ensuring driving safety and comfort.

- In this research, only fuel consumption was considered out of road users cost components. Therefore, future studies should consider construction, maintenance and other road users cost components.
- Beside individual parameter comparisons, further studies should be done to develop a model that relates the parameters.

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APPENDIX A: Fuel consumption

Uphill segment instantaneous fuel consumption

For the uphill segment, the instantaneous fuel consumption for each vehicle type k during traffic flow period p is giving by:

$$IFC_{kpu} = \text{Max}[\text{IDLE_FUEL}_k, \text{ZETA}_{kpu} * \text{PTOT}_{kpu} * (1 + d\text{FUEL}_{kpu})] \quad \dots(\text{A.1})$$

Where

IFC_{kpu} instantaneous fuel consumption for vehicle type k during traffic flow period p (ml/s)

IDLE_FUEL_k idle rate of fuel consumption of vehicle type k (ml/s)

ZETA_{kpu} Uphill fuel-to-power efficiency factory of vehicle type k (ml/k W/s)

PTOT_{kpu} Uphill total power requirement for steady-state motion (kW)

$d\text{FUEL}_{kpu}$ additional fuel consumption factor sue to vehicle speed-change cycles (that is, accelerations and decelerations)

The expression steady-state implies that speed-change cycles are not considered. Thus, the steady-state instantaneous fuel consumption for the uphill segment is calculated using

Equation A.1 above with the value of $d\text{FUEL}$ set to zero.

Downhill segment instantaneous fuel consumption

For the downhill segment, the instantaneous fuel consumption for each vehicle type k during traffic flow period p is given by:

$$IFC_{kpd} = \text{Max}[\text{IDLE_FUEL}_k, \text{ZETA}_{kpd} * \text{PTOT}_{kpd} * (1 + d\text{FUEL}_{kpd})] \quad \dots(\text{A.2})$$

Where

IFC_{kpd}	instantaneous fuel consumption of vehicle type k during traffic flow period p (ml/s)
$IDLE_FUEL_k$	idle rate of fuel consumption of vehicle type k (ml/s)
$ZETA_{kpd}$	downhill fuel-to-power efficiency factor of vehicle type k (ml/k W/s)
$PTOT_{kpd}$	downhill total power requirement for steady-state motion (kW)
$dFUEL_{kpd}$	additional fuel consumption factor due to vehicle speed-change cycles

The steady-state instantaneous fuel consumption for the downhill segment is calculated using equation A.2 above with the value of $dFUEL$ set to zero.

One-way traffic flow

For the analysis of one-way traffic flow, the instantaneous fuel consumption is calculated as follows:

- For uphill segments
 IFC_{kpu} is calculated using Equation A.1 above
- For downhill segments
 IFC_{kpd} is calculated using Equation A.2 above

Power requirements

The total power requirements of the engine comprise the tractive power needed to overcome forces opposing motion and the power to overcome engine drag and run vehicle accessories. These are calculated separately for the uphill segment and the downhill segment.

Tractive power

At any instant of vehicle movement along a road section, the tractive power may be positive, negative or zero depending upon the road vehicle characteristics. The tractive power required for each vehicle type k during traffic flow period p (PTR) is given by the expression:

$$PTR_{kp} = \left[\frac{FTR_{kp} * V_{kp}}{100} \right] \quad \dots(A.3)$$

Where:

PTR_{kp} tractive power for vehicle type k during traffic flow period p (kW)

FTR_{kp} total resistance to steady-state motion experienced by vehicle type k during traffic flow period p (N)

V_{kp} Speed of vehicle type k during traffic flow period p (m/s)

- **For calculating the tractive power (PTR_{kpu}) for the uphill segment**
Use $V_{kp} = V_{U_{kp}}$, and FTR_{kpu} is given by Equation A.4 below.
- **For calculating the tractive power (PTR_{kpd}) for the downhill segment**
Use $V_{kp} = V_{D_{kp}}$, and FTR_{kpd} is given by Equation A.5 below.

The total resistance to steady-state motion comprises aerodynamic resistance, gradient resistance, rolling resistance, and curvature resistance. Inertial resistance is considered only under the regime of speed change cycles. The total resistance to steady state motion is calculated as follows:

- For the uphill segment
 $FTR_{kpu} = FA_u + FG_u + FR_u + FCV_u \quad \dots(A.4)$

- For the downhill segment
 $FTR_{kpd} = FA_d + FG_d + FR_d + FCV_d \quad \dots(A.5)$

Where:

FA aerodynamic resistance to motion (N)

FG gradient resistance to motion (N)

FR rolling resistance to motion (N)

FCV curvature resistance to motion (N)

The subscripts u and d denote the uphill and downhill segments, respectively.

The components of total resistance to steady state motion are calculated as given below:

- **Aerodynamic resistance**

The aerodynamic resistance to motion is calculated as:

$$FA = 0.5 * RHO * CD_{mult} * CD * AF * V_{kp}^2 \quad \dots(A.6)$$

All the parameters are as defined previously.

The default parameter values to calculate aerodynamic resistance for each vehicle type are given in Table A2

- **Gradient resistance**

The gradient resistance to motion is calculated separately for the uphill and downhill segments using the following experience:

$$FG = WGT_{OPER} * g * GR \quad \dots(A.7)$$

Where:

All the parameters are as previously defined.

For the uphill segment FG_u use the positive value of GR , and for the downhill segment FG_d use the negative value of GR

- **Rolling resistance**

The rolling resistance to motion is calculated as:

$$FR = FCLM * CR2 * (b11 * NUM_WHEELS + CR1 * b12 * WGT_{OPER} + CR1 * b13 * V_{kp}^2) \quad \dots(A.8)$$

All the parameters are as defined previously.

The default parameter values to calculate rolling resistance for each vehicle type are given in Table A2

- **Curvature resistance**

The curvature resistance to motion is calculated as follows:

$$FCV = \left\{ \frac{\left(\text{MAX} \left[0, \left(\frac{WGT_{OPER} * V_{kp}^2}{R} - WGT_{OPER} * g * e \right) \right] * 2 \right)}{[NUM_WHEELS * CS / 1000]} \right\} \quad \dots(A.9)$$

Where:

e superelevation of the road (as a fraction)

CS cornering stiffness of the tyres

The cornering stiffness is calculated as:

$$CS = Kcs * [CS_a0 + \frac{CS_a1 * WGT_OPER}{NUM_WHEELS} + CS_a2 * (\frac{WGT_OPER}{NUM_WHEELS})^2] \quad \dots(A.10)$$

Where:

Kcs tyre stiffness factor

CS_a0 to model parameters

CS_a2

All the other parameters are as previously defined.

Table A1: gives the parameter values for the cornering stiffness model.

Table A1: Cornering stiffness model parameters

Coefficient	WGT_PER <=2500kg		WGT_OPER > 2500 kg	
	Bias	Radial	Bias	Radial
CS_a0	30	43	8.8	0
CS_a1	0	0	0.088	0.0913
CS_a2	0	0	-0.0000225	-0.0000114
Kcs	1	1	1	1

Source: NDLI (1995)

Inertial resistance

The inertial resistance is not included in the total tractive power steady-state motion.

The internal resistance is calculated as follows:

$$FI = WGT_OPER * EMRAT * ACC \quad \dots(A.11)$$

The parameter EMRAT is calculated as:

$$EEMRAT_a0 + EMRAT_a1 * \text{atan} \left(MRAT = \left(\frac{EMRAT_a2}{V_{kp}^3} \right) \right) \quad \dots(A.12)$$

Where:

EMRAT_a0 to inertial resistance parameters

EMRAT_a2

ACC vehicle acceleration in m/s²

Note that the inertial resistance to motion is considered to be zero under steady-state conditions.

The default parameter values to calculate inertial resistance for each vehicle type are given in

Table A2

Engine and accessories power

The total power required for overcoming engine drag and running vehicle accessories

(PENGACCS) by each vehicle type is calculated as a function of the engine speed and vehicle speed:

$$PENGACCS_{kp} = K_{pea} * PRAT_k * [PACCS_{a1} + \frac{(PACCS_{a0} - PACCS_{a1}) * (RPM_{kp} - RPM_{IDLE})}{(RPM_{100} - RPM_{IDLE})}] \quad \dots(A.13)$$

Where:

PENGACCS_{kp} total engine and accessories power of vehicle type *k* during traffic flow period *p* (kW)

K_{pea} calibration factor for total engine and accessories power (default 1.0)

PRAT_k the maximum rated engine power of vehicle type *k* (kW)

RPM_{kp} engine speed (rev/min)

RPM_IDLE idle engine speed (rev/min)

RPM100 the engine speed calculated at 100km/h (rev/min)

PACCS_{a0} the ratio of engine and accessory drag to rated engine power when travelling at 100 km/h

PACCS_{a1} a model parameter

The parameter PACCS_a1 is related to the idle fuel consumption rate. It is calculated from the user-supplied value for IDLE-FUEL as follows:

$$a = ZETAB * EHP * K_{pea}^2 * PRAT * \frac{(100 - PCTPENG)}{100}$$

$$b = ZETAB * K_{pea} * PRAT$$

$$c = IDLE_FUEL$$

$$PACCS_a1 = \frac{(-b + \sqrt{b^2 - 4ac})}{2a} \quad \dots(A.14)$$

Where:

ZETAB base fuel-to-power efficiency factor (ml/kW/s) see Table 2

EHP decrease in engine efficiency when producing higher power

PCTPENG percentage of the total engine and accessories power produced from the engine
(default = 80)

The engine speed (RPM) depends upon the vehicle speed, and it is calculated using Equations 5.15 below to 5.17 below with $V_{kp} = V_{U_{kp}}$ for the uphill segment and $V_{kp} = V_{D_{kp}}$ for the downhill segment:

- If $V_{kp} \leq 5.6$ m/s

$$RPM_{kp} = RPM_a0 + 5.6 * RPM_a1 + 31.36 * RPM_a2 \quad \dots (5.15)$$

- If $V_{kp} \leq RPM_a3$

$$RPM_{kp} = RPM_a0 + RPM_a1 * V_{kp} + RPM_a2 * V_{kp}^2 \quad \dots (A.16)$$

- If $V_{kp} > RPM_a3$

$$RPM_{kp} = \frac{(RPM_a0 + RPM_a1 * V_{kp} + RPM_a2 * V_{kp}^2 + RPM_a3 * V_{kp}^3) * V_{kp}}{RPM_a3} \quad \dots(A.17)$$

The engine speed RPM100 at 100 km/h is calculated as follows:

If $27.8 \leq \text{RPM}_{a3}$

$$\text{RPM}_{100} = \text{RPM}_{a0} + \text{RPM}_{a1} * 27.8 + \text{RPM}_{a2} * 27.8^2 \quad \dots(\text{A.18})$$

Else

$$\text{RPM}_{100} = \frac{(\text{RPM}_{a0} + \text{RPM}_{a1} * \text{RPM}_{a3} + \text{RPM}_{a2} * \text{RPM}_{a3}^2) * 27.8}{\text{RPM}_{a3}} \quad \dots(\text{A.19})$$

The values for the above model are given in Table A2.

Total power requirement

The total power requirement of the engine (PTOT) is calculated depending on whether or not the total tractive power is negative as follows:

If $\text{PTR}_{kp} \geq 0$

$$\text{PTOT}_{kp} = \left(\frac{\text{PTR}_{kp}}{\text{EDT}} + \text{PENGACCS}_{kp} \right) \quad \dots(\text{A.20})$$

else

$$\text{PTOT}_{kp} = (\text{PTR}_{kp} * \text{EDT} + \text{PENGACCS}_{kp}) \quad \dots(\text{A.21})$$

Where:

PTOT_{kp} total power requirement for steady-state motion by vehicle type k during traffic

flow period p (kW)

PTR_{kp} total tractive power of vehicle type k during traffic flow period p (k W)

EDT drivetrain efficiency

Table A2: Default fuel model parameters

Vehicle number	Engine speed model parameters				Idle engine speed	Idle fuel rate	Base fuel efficiency	Decrease in efficiency	Rated engine power	Efficiency of the drivetrain	Engine and Accessories Power	
	RPM_a0	RPM_a1	RPM_a2	RPM_a3	RPM_IDLE	IDLE_FUEL	AETAB	EHP	PRAT	EDT	PACCS_a0	PCTPENG
	RPM	RPM/(m/s)	RPM/(m/s) ²	m/s	RPM	l/s	l/k W/s		kW			
1	2790	94.0	2.83	21	800	0.12	0.067	0.25	15	0.95	0.20	80
2	2280	17	0.83	42	800	0.25	0.067	0.25	60	0.90	0.20	80
3	2280	17	0.83	42	800	0.36	0.067	0.25	70	0.90	0.20	80
4	1709	7.16	0.99	42	800	0.48	0.067	0.25	90	0.90	0.20	80
5	2490	-30.4	2.25	34	800	0.48	0.067	0.25	6	0.90	0.20	80
6	2574	-27.8	2.46	32	800	0.37	0.067	0.25	55	0.90	0.20	80
7	2490	-30.4	2.25	34	800	0.48	0.057	0.10	60	0.90	0.20	80
8	1214	17.6	2.32	22	500	0.37	0.057	0.10	75	0.86	0.20	80
9	1214	17.6	2.32	22	500	0.37	0.057	0.10	100	0.86	0.20	80
10	1167	-24.0	1.76	22	500	1.12	0.056	0.10	280	0.86	0.20	80

Table A2: Default fuel model parameters (Cont'd)

Vehicle number	Engine speed model parameters				Idle engine speed	Idle fuel rate	Base fuel efficiency	Decrease in efficiency	Rated engine power	Efficiency of the drivetrain	Engine and Accessories Power	
	RPM_a0	RPM_a1	RPM_a2	RPM_a3	RPM_IDLE	IDLE_FUEL	AETAB	EHP		RPM_a0	RPM_a1	RPM_a2
	RPM	RPM/(m/s)	RPM/(m/s) ²	m/s	RPM	MI/s	MI/k W/s			RPM	RPM/(m/s)	RPM/(m/s) ²
11	1167	-24.0	1.76	22	500	1.12	0.055	0.10	300	0.86	0.20	80
12	2490	-30.4	2.25	34	800	0.48	0.067	0.25	60	0.90	0.20	80
13	1214	17.6	2.32	22	500	0.37	0.057	0.10	75	0.86	0.20	80
14	1214	17.6	2.32	22	500	0.37	0.057	0.10	100	0.86	0.20	80
15	1167	-24.0	1.76	22	500	1.12	0.057	0.10	130	0.86	0.20	80
16	1167	-24.0	1.76	22	500	1.12	0.057	0.10	150	0.86	0.20	80

Source: Bennett and Greenwood, (1996)

Efficiency factor

The fuel-to-power efficiency factor ZETA relates instantaneous fuel consumption to the total power requirement of the engine as expressed by Equations A.1 above and A.2 above. For each vehicle type and for each traffic flow period ZETA is calculated separately for the uphill segment and the downhill segment as given below.

Uphill segment efficiency factor

$$ZETA_{kpu} = ZETAB * \left\{ 1 + EHP * \left[\frac{PTOT_{kpu} - PCTPENG * PENGACCS_{kpu}/100}{PRAT_k} \right] \right\}$$

...(A.22)

Downhill segment efficiency factor

$$ZETA_{kpd} = ZETAB * \left\{ 1 + EHP * \left[\frac{PTOT_{kpd} - PCTPENG * PENGACCS_{kpu}/100}{PRAT_k} \right] \right\}$$

...(A.23)

All the other parameters are as previously defined.

The values for the above model are given in Table A2

Additional fuel consumption

Fuel –acceleration simulation model

The additional fuel consumption due to vehicle speed-change cycle effects is estimated using a simulation model called ACCFUEL. This model is described in detail by Bennett (1996c). the model computes the additional fuel consumption, tyre consumption and spare parts consumption as described in this document. High magnitudes of total acceleration noise lead to high consumption of fuel, tyres and spare parts.

The method is as follows:

1. The user runs a calibration routine external to HDM-4 (that is, ACCFUEL) which generates a matrix of values for dFUEL as a function of mean speed and acceleration noise, for each vehicle type.
2. These matrices are read in HSM-4. A default set of matrices for the standard vehicle types is contained within HDM_4. Values of dFUEL are linearly interpolated for intermediate speeds and acceleration noise, and applied in the analyses.

Mean speeds and acceleration noise

The mean speeds (km/h) that are used for determining the corresponding values of dFUEL for the uphill and downhill segments are given as follows:

- For uphill segments

The mean speed for each vehicle type k and traffic flow period p is given by:

$$SU_{kp} = 3.6 * YU_{kp} \quad \dots(A.24)$$

- For downhill segments

The mean speed for each vehicle type k and traffic flow period p is given by:

$$SD_{kp} = 3.6 * VD_{kp} \quad \dots(A.25)$$

The total acceleration noise (σa_{kp}) for each vehicle type k and for each traffic flow period p used for determining dFUEL is calculated as described in Section 4.6

Fuel consumption per 1000 vehicle-km

The specific fuel consumption (ml) per vehicle-kilometer on the road section is calculated from the expression:

$$SFC_{kp} = 500 \left[\frac{IFC_{kpu}}{VU_{kp}} + \frac{IFC_{kpd}}{VD_{kp}} \right] \quad \dots(A.26)$$

Where:

SFC_{kp} specific fuel consumption (ml/km)

IFC_{kpu}	instantaneous fuel consumption for uphill travel (ml/s)
VU_{kp}	uphill speed (m/s) of vehicle type k in traffic flow period p
IFC_{kpd}	instantaneous fuel consumption for downhill travel (ml/s)
VD_{kp}	downhill speed (m/s) of vehicles type k in flow period p

For one-way traffic, the specific fuel consumption is calculated as follows:

- For uphill segments

$$SFC_{kp} = \frac{1000 * IFC_{kpu}}{VU_{kp}} \quad \dots(A.27)$$

- For downhill segments

$$SFC_{kp} = \frac{1000 * IFC_{kpd}}{VU_{kd}} \quad \dots(A.28)$$

The fuel consumption (litres per 100 vehicle-kilometers) is thus given by the expression:

$$FC_{kp} = SFC_{kp} * FUELBIAS \quad \dots(A.29)$$

Where:

FC_{kp} Fuel consumption of vehicle k in traffic flow period p (1/100 veh-km)

$FUELBIAS$ Fuel adjustment factor to account for the bias introduced through the use of the time mean speed instead of the space mean speed

The traffic stream is comprised of vehicles travelling at different speeds and, thus, different fuel consumption rates. Since fuel consumption is non-linear with speed, the mean fuel consumption does not correspond to the fuel consumption at the mean speed. The fuel adjustment factor ($FUELBIAS$) is therefore applied to correct the bias introduced to the analysis through the use of the mean speed instead of individual vehicle speeds. It is given by the following expression:

$$FUELBIAS = \text{MAX} (dFUEL, 1.000 - 0.0182 * COV + 0.7319 * COV^2) \quad \dots(A.30)$$

Annual average fuel consumption

The annual average fuel consumption in litres per 1000 vehicle-kilometers of each vehicle type is required for reporting purposes, and it is calculated as follows:

$$FC_{kav} = \frac{\sum_{p=1}^n HR_{YR_p} * HV_p * FC_{kp}}{\sum_{p=1}^n HR_{YR_p} * HV_p} \quad \dots(A.31)$$

Table A3: Model parameters for CO₂, Particulates and Pb emissions

Veh N°	Vehicle type	CO ₂	Particulates		Pb	
		a0	a0 (x10 ⁻⁴)	a1 (x10 ⁻⁴)	a0	a1
1	Motorcycle	2.36	0.000	0.000	0.15	7.5
2	Small car	2.36	0.455	0.436	0.15	7.5
3	Medium car	2.36	0.455	0.436	0.15	7.5
4	Large car	2.36	0.455	0.436	0.15	7.5
5	Light deliver vehicle	2.36	-1.440	2.550	0.15	7.5
6	Light goods vehicle	2.36	-1.440	2.550	0.15	7.5
7	Four wheel drive	2.61	-1.440	2.550	0.00	0.0
8	Light truck	2.61	-1.440	2.550	0.00	0.0
9	Medium truck	2.61	-11.900	18.400	0.00	0.0
10	Heavy truck	2.61	-11.900	18.400	0.00	0.0
11	Articulated truck	2.61	60.300	5.330	0.00	0.0
12	Mini-bus	2.36	0.455	0.436	0.15	7.5
13	Light bus	2.61	-1.440	2.550	0.00	0.0
14	Medium bus	2.61	-11.900	18.400	0.00	0.0
15	Heavy bus	2.61	-11.900	18.400	0.00	0.0
16	Coach	2.61	-11.900	18.400	0.00	0.0

Source: Hammerstorm, (1995)

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Where:

FC_{kav} annual average fuel consumption of vehicle type k (km/h)

HR_{YR_p} the number of hours in traffic flow period p

HV_p the hourly traffic flow in period p expressed as a proportion of AADT

FC_{kp} fuel consumption of vehicle type k during traffic flow period p

Table A4: Model parameters for NO_x and SO_2 emissions

Veh N°	Vehicle type	NO _x			SO ₂	
		a0 (x 10 ⁻²)	a0 (x10 ⁻²)	a1 (x10 ⁻²)	a0	a1 (x 10 ⁻³)
1	Motorcycle	0.00	0.25	2	0.012	15.0
2	Small car	-3.92	4.92	2	0.012	15.0
3	Medium car	-3.92	4.92	2	0.012	15.0
4	Large car	-3.92	4.92	2	0.012	15.0
5	Light deliver vehicle	-3.92	6.01	2	0.012	15.0
6	Light goods vehicle	-3.92	6.01	2	0.012	15.0
7	Four wheel drive	-3.92	6.01	0	0.031	16.6
8	Light truck	-3.92	6.01	0	0.031	16.6
9	Medium truck	1.39	2.90	0	0.031	16.6
10	Heavy truck	1.39	2.90	0	0.031	16.6
11	Articulated truck	13.70	2.94	0	0.031	16.6
12	Mini-bus	-3.92	4.92	2	0.012	15.0
13	Light bus	-2.93	6.01	0	0.031	16.6
14	Medium bus	1.39	2.90	0	0.031	16.6
15	Heavy bus	1.39	2.90	0	0.031	16.6
16	Coach	1.39	2.90	0	0.031	16.6

Source: Hammerstrom (1995)

Impact of Road Geometry and Surface Types on Fuel Consumption and Greenhouse Gas Emissions

Table A5: Model parameters for HC and CO emissions

Veh N°	Vehicle type	HC			CO		
		a0 (x 10 ⁻²)	a1 (x10 ⁻²)	a2 (x10 ⁻²)	a0 (x 10 ⁻²)	a1 (x10 ⁻²)	a2 (x10 ⁻²)
1	Motorcycle	0.000	21.0000	7	0.000	66.500	6
2	Small car	-0.866	2.4400	7	-3.020	18.500	6
3	Medium car	-0.866	2.4400	7	-3.020	18.500	6
4	Large car	-0.866	2.4400	7	-3.020	18.500	6
5	Light deliver vehicle	-3.510	5.6000	7	-21.400	36.400	6
6	Light goods vehicle	-3.510	5.6000	7	-21.400	36.400	6
7	Four wheel drive	-3.510	5.6000	0	-21.400	36.400	6
8	Light truck	-3.510	5.6000	0	-21.400	36.400	6
9	Medium truck	2.400	-0.0439	0	2.020	0.049	0
10	Heavy truck	2.400	-0.0439	0	2.020	0.049	0
11	Articulated truck	2.810	0.0446	0	-0.715	0-.107	0
12	Mini-bus	-0.866	2.4400	7	-3.020	18.500	6
13	Light bus	-3.510	5.6000	0	-21.400	36.400	0
14	Medium bus	2.400	-0.0439	0	2.020	0.949	0
15	Heavy bus	2.400	-0.0439	0	2.020	0.949	0
16	Coach	2.400	-0.0439	0	2.020	0.949	0

Source: Hammerstrom (1995)

APPENDIX B: Emission quantities

For each section option, the quantities of emissions by vehicle type k and traffic flow period p were calculated using the following expression:

$$EYR_{i_{kp}} = T_{pk} * L_j * EMI_{i_{kp}} * 10^{-9}$$

where:

- $EYR_{i_{kp}}$ the annual quantity of emission component i from vehicle type k in the traffic flow period p (tones);
- T_{pk} the annual traffic volume of vehicle type k in the traffic flow period p (vehicle per year);
- L_j length of the road section under investment option j (km);
- $EMI_{i_{kp}}$ the average quantity of emission component i (g/1000 veh-km), from vehicle type k during traffic flow period p

The value of the average quantities of emission ($EMI_{i_{kp}}$) was obtained using the following expression:

$$EMI_{i_{kp}} = 500(Ei_{kpu} + Ei_{kpd})$$

where:

- Ei_{kpu} the quantities of emission components i (g/veh-km) for the uphill trip on the section.

It is calculated using the respective equations for each emission component using the following parameters.

- IFC taken as IFC_{kup} -the instantaneous fuel consumption (ml/s) for the uphill road section
- SPEED taken as SU_{kp} (km/h)
- Ei_{kpd} the quantities of emission component i (g/veh-km) for the downhill trip on the section.

It is calculated using the respective equations for each emission component using the following parameters:

- IFC taken as IFC_{kpd} - the instantaneous fuel consumption (ml/s) for the uphill

road section

SPEED taken as SU_{kp} (km/h)

The annual average quantities of vehicle emissions (by component i) per 1000 vehicle-kilometers is given by the following expression:

$$EAVi_k = \frac{\sum_{p=0}^n HRYR_p * HV_p * EMi_{kp}}{\sum_{p=1}^n HRYR_p * HV_p}$$

where:

$EAVi_k$ annual average quantity of emission component i by vehicle type k (g/1000veh-km);

$HRYP$ the number of hours in traffic flow period p ;and

HV_p the hourly traffic flow in period p expressed as a proportion of AADT.

The annual quantities of emissiona (by component i) for each vehicle type k using the road section under investment option j was calculated using the following expression:

$$EYRi_{jk} = \sum_{p=1}^n EYRi_{kp}$$

where:

$EYRi_{jk}$ the annual quantities of emission of component i by vehicle type k for section option j (tonnes)

The total annual quantities of emission (by component i) for all vehicle using the road section were calculated using the following expression:

$$EYRi_j = \sum_k \sum_{p=1}^n EYRi_{kp}$$

where:

$EYRi_j$ the annual quantities of emission of component i (tonnes), for section option j .

