4-2018

Assessment of Carbon Emissions of Road Projects and Development of a Framework for Carbon Footprint Calculation of Roads in the City Of Abu Dhabi

Mohammed H. H. Alzard

UAEU

جامعة الإمارات العربية المتحدة
United Arab Emirates University

United Arab Emirates University

College of Engineering

Department of Civil and Environmental Engineering

ASSESSMENT OF CARBON EMISSIONS OF ROAD PROJECTS AND DEVELOPMENT OF A FRAMEWORK FOR CARBON FOOTPRINT CALCULATION OF ROADS IN THE CITY OF ABU DHABI

Mohammed H. H. Alzard

This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Civil Engineering

Under the Supervision of Prof. Munjed Maraqa

April 2018

Declaration of Original Work

I, Mohammed H. H. Alzard, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Assessment of Carbon Emissions of Road Projects and Development of a Framework for Carbon Footprint Calculation of Roads in the City of Abu Dhabi*" hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Prof. Munjed Maraqa, in the College of Engineering at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Approval of the Master Thesis

This Master Thesis is approved by the following Examining Committee Members:

1) Advisor (Committee Chair): Munjed A. Maraqa
   Title: Professor
   Department of Civil and Environmental Engineering
   College of Engineering
   Signature ______________________ Date 22/5/2018

2) Member: Yasser E. Hawas
   Title: Professor
   Department of Civil and Environmental Engineering
   College of Engineering
   Signature ______________________ Date 22/5/2018

3) Member: Brian Lamb
   Title: Professor
   Department of Civil and Environmental Engineering
   Institution: Washington State University, United States of America
   Signature ______________________ Date 20/5/2018

This Master Thesis is accepted by:

Dean of the College of Engineering: Professor Sabah Alkass

Signature ____________________ Date 28/5/2018

for Dean of the College of Graduate Studies: Professor Nagi T. Wakim

Signature Ali Hassan ____________________ Date 28/5/2018

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Advisory Committee

1) Advisor: Munjed A. Maraqa

Title: Professor

Department of Civil and Environmental Engineering

College of Engineering

2) Co-advisor: Rezaul Kabir Chowdhury

Title: Senior Lecturer

Department of Civil Engineering & Surveying

School of Civil Engineering and Surveying, University of Southern Queensland

Abstract

Climate change has become a global issue affecting the environment and human health. Transportation is a major contributor of greenhouse gases (GHG) emissions, with road transport being responsible for more than half of these emissions. The main objective of this thesis was to estimate the carbon footprint associated with road projects in the city of Abu Dhabi following a comprehensive approach that considers all activities within the life cycle of roads. Three cases were considered including, Al Rahba City internal road network, the upgrading of Al Salam Street, and the widening of the Eastern Corniche Road. A carbon footprint estimation model (referred to as RoadCO_2) was developed to estimate GHG emissions of the three road cases. The model considers emissions from all phases of road projects and reports emissions in terms of carbon dioxide equivalent (CO_2eq). The methodology suggested by the Intergovernmental Panel on Climate Change (IPCC) was adopted in constructing the model. Results revealed that the total emissions from the construction of the investigated road cases are about 43, 292, and 16 thousand tons CO_2eq, respectively. Equipment used in construction contributed about 70%, 15% and 21% of the total emissions of the construction phase, respectively. The rest of the emissions during the construction phase originated from the use of construction materials and their associated transport. Upgrading of Al Salam Street project produced the highest emissions from construction materials due to the construction of a tunnel. Annual total emissions during the operation phase of Al Salam Street was estimated to be over 108 thousand tons CO_2eq/yr, whereas emissions during the operation phase for Al Rahba City internal roads were about 15 thousand tons CO_2eq/yr, and those for the Corniche Road were 91 thousand tons CO_2eq/yr. For the three cases, emissions were generated mainly during the operation phase (94% or more), with the main contributor being vehicle movement, followed to a lesser extent by street lighting.

Keywords: Carbon footprint, Greenhouse gases, Road projects.

Title and Abstract (in Arabic)

تقييم انبعاثات الكربون من مشاريع الطرق و تطوير إطار مفاهيمي لحساب البصمة الكربونية للطرق في مدينة أبوظبي

الملخص

أصبح التغير المناخي قضية عالمية تؤثر على البيئة وصحة الإنسان. يعتبر قطاع المواصلات أحد أكبر القطاعات المساهمة في انبعاثات الغازات الدفيئة، وتعتبر الطرق مسؤولة عن أكثر من نصف هذه الانبعاثات. الهدف من هذه الأطروحة هو تقدير البصمة الكربونية المرتبطة بثلاث مشاريع طرق في مدينة أبوظبي وذلك باتباع نهج شامل يراعي كامل دورة حياتها. شملت هذه المشاريع بناء شبكة طرق داخلية لمدينة الرحبة، تطوير شارع السلام، وتوسيع شارع الكورنيش الشرقي. في هذه الدراسة، تم تطوير نموذج لتقدير انبعاثات الغازات الدفيئة الناتجة عن مشاريع الطرق الثلاث المختارة على امتداد دورة حياتها بمراحلها المختلفة يدعى ($RoadCO_2$). يعتمد هذا النموذج على المنهجية المقترحة من قبل الهيئة الحكومية الدولية المعنية بتغير المناخ (IPCC)، كما يعتمد أيضاً على مزيج من عوامل الانبعاثات التي توفرها الهيئة وبعض عوامل الانبعاثات المحلية. أظهرت النتائج أن مجموع الانبعاثات الكلي لمرحلة البناء لهذه الطرق قد بلغ حوالي 43، 292، 16 ألف طن من ثاني أكسيد الكربون مكافئ، على التوالي. ساهمت الآلات المستخدمة في البناء في حوالي 70%، 15%، و20%، على التوالي، من مجمل الانبعاثات الكربونية الكلية لمرحلة البناء في حين أن المواد المستخدمة ساهمت في الباقي. أكثر الانبعاثات الكربونية لمشروع تطوير شارع السلام كانت بسبب استخدام كميات كبيرة من المواد لبناء النفق في هذا الشارع. بلغ مجموع الانبعاثات السنوية الناتجة خلال مرحلة التشغيل لشارع السلام 108 ألف طن ثاني أكسيد الكربون-مكافئ لكل سنة، في حين أن مرحلة التشغيل للطرق الداخلية لمدينة الرحبة ساهمت بما يقارب 15 ألف طن ثاني أكسيد الكربون-مكافئ لكل سنة. أما عن مرحلة التشغيل لشارع الكورنيش الشرقي، فقد ساهمت بـ 91 ألف طن ثاني أكسيد الكربون-مكافئ سنة. مرحلة التشغيل ساهمت بما يقارب 94% أو أكثر من اجمالي الانبعاثات الكربونية للطرق الثلاث المدروسة. الحركة المرورية هي أكبر مشارك في هذه الانبعاثات يليها إنارة الطريق.

مفاهيم البحث الرئيسية: البصمة الكربونية، انبعاثات الغازات الدفيئة، مشاريع الطرق.

Acknowledgements

First and foremost, I would like to thank my family who has been unbelievably supportive through the course of my graduate work. My mother and my father, you always had faith in me and kept on pushing me to reach the skies, and for that I will be forever thankful. To my brothers and sister, thank you for being there for me.

Special thanks to both Professor Munjed Maraqa and Dr. Rezaul Chowdhury, whose enthusiasm and continued support and guidance throughout my graduate studies, made this possible. Thanks are also extended to Dr. Timur Mauga and Dr. Francisco Albuquerque at the Department of Civil and Environmental Engineering for their feedback and guidance. Special thanks also go to both Professor Yasser Hawas and Professor Brian Lamb for their constructive comments on an earlier version of this thesis.

I would like to recognize the members of the Roadway, Transportation and Traffic Safety Research Center (RTTSRC) at the UAE University and say thank you for your support and guidance. Special thanks go in this regard to Mr. Mohamed Sherif who assisted in developing the code for the RoadCO_2 model.

My special thanks are extended to Abu Dhabi Municipality (ADM) for providing me with both the fund (grant number 21R021-Abu Dhabi City Municipality 283/2015) and data to carry on this study.

Dedication

To my beloved parents. May your souls rest in peace.

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List of Abbreviations

ADB	Asian Development Bank
ADM	Abu Dhabi City Municipality
ADNOC	Abu Dhabi National Oil Company
ADSRRS	Abu Dhabi Sustainable Road Rating System
ADUPC	Abu Dhabi Urban Planning Council
BMS	Bridge Management System
BOQ	Bill of Quantities
BTU	British Thermal Unit
CDWMP	Construction & Demolition Waste Management Plan
CFET	Carbon Footprint Estimation Tool
CH_4	Methane
CHANGER	Calculator for Harmonized Assessment and Normalization of Greenhouse-Gas Emissions
CIA	The Central Intelligence Agency
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide Equivalent
COP	Certificate of Performance
DBIS	Department for Business Innovation and Skills
DC	District Cooling
DFT	Department for Transport
DMA	Department of Municipal Affairs
DOT	Department of Transport
EA	Environmental Assessment

EAD	Environmental Agency of Abu Dhabi
EAPA	European Asphalt Pavement Association
EC	European Commission
EcoTransIT	The Ecological Transport Information Tool
EEA	European Environment Agency
EHS	Environment, Health and Safety
EIA	Environmental Impact Assessment
EMEP	The European Monitoring and Evaluation Program
EMP	Environmental Management Plan
EMS	Environmental Management System
GCC	Gulf Cooperation Council
GFA	Gross Floor Area
GGBFS	Ground Granulated Blast-Furnace Slag
GHG	Greenhouse gases
GPS	Global Positioning System
GRCPs	Green Road Construction Practices
GREET	The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
GRP	Glass Reinforced Pipes
GWP	Global Warming Potential
HFC	Hydrofluorocarbons
HGV	Heavy Goods Vehicles
HMA	Hot-Mix Asphalt
HOV	High Occupancy Vehicle
HPS	High Pressure Sodium

ICCT	International Council on Clean Transportation
IDE	Integrated Development Environment
IEA	International Energy Agency
IEE	Intelligent Energy Europe
IFEU	Institut Für Energieund Umweltforschung
INVEST	Infrastructure Voluntary Evaluation Sustainability Tool
IPCC	Intergovernmental Panel on Climate Change
IRF	The International Road Federation
IRID	Internal Road and Infrastructure Directorate
ISSRC	International Sustainable System Research Center
ITF	International Transport Forum
ITS	Intelligent Transportation System
IVE	International Vehicle Emissions
L	Liters
LDV	Light Duty Vehicles
LED	Light Emitting Diode
LNG	Liquefied Natural Gas
MH	Metal Halide
MMS	Maintenance Management System
MOVES	The EPA's Motor Vehicle Emission Simulator
MSE	Mechanically-Stabilized Earth
MVC	Model-View-Controller
MVEI	Motor Vehicle Emission Inventory
N_2O	Nitrous Oxide

O&M	Operation and Maintenance
OWM	Operational Waste Management
PC	Portland Cement
PFC	Per Fluorinated Compounds
PMS	Pavement Management System
PSI	Present Serviceability Indices
RCP	Reinforced Concrete Pipes
REAP	Resources and Energy Analysis Program
RTTSRC	The Roadway, Transportation and Traffic Safety Research Center
SASO	Saudi Standards, Metrology and Quality Organization
SCAD	Statistics Centre - Abu Dhabi
SF_6	Sulfur Hexafluoride
SUV	Sports Utility Vehicles
TAGG	Transport Authorities Greenhouse Group
TDM	Travel Demand Management
TRB	Transportation Research Board
TSE	Treated Sewerage Effluent
UAE	United Arab Emirates
UAEU	United Arab Emirates University
UI	User Interface
UK DEFRA	United Kingdom Department for Environment Food and Rural Affairs
UME	Utilities-ME
UNDP	United Nations Development Program
UOM	Units of Measurements

UPC	Urban Planning Council
USEPA	United States Environmental Protection Agency
USFHA	United States Federal Highway Administration
VMS	Variable Message Signs
WB	World Bank
WMO	World Meteorological Organization
WRI	World Resource Institute

Chapter 1: Introduction

1.1 Background

Global energy consumption and carbon dioxide (CO_2) emission rates are increasing dramatically. Continued CO_2 and other greenhouse gas (GHG) emissions are of a major concern to climate change. While several factors affect CO_2 and other GHG emissions, energy consumption from fossil fuels and the level of economic activity are probably the most important factors. The United Arab Emirates (UAE) has one of the world's highest per capita energy consumption rate. From 1980 to 2011, the total primary energy consumption in the country increased from 0.27 to 3.68 quadrillion BTU (Mundi, 2016).

Due to the growing concern regarding climate change and sustainable development, the UAE government has launched various initiatives aimed at identifying alternative means for producing power. The country is taking steps to reduce carbon emissions through major initiatives in both the Abu Dhabi and Dubai emirates (Gulfnews, 2014). The emirate of Abu Dhabi, for instance, has committed to invest more than $15 billion in renewable energy programs. The Masdar Initiative in Abu Dhabi, which focuses on the development and commercialization of technologies in renewable energy, energy efficiency, carbon management, water reuse and desalination, reflects twin commitments to the global environment and diversification of the UAE economy (Masdar, 2016). Furthermore, the UAE government through its major electricity suppliers, is encouraging sustainable energy consumption among its residents. In 2013, the United Nations aided Dubai in developing 5 projects that will reduce about 1.3 million tons of carbon dioxide emissions by 2021 (UNDP, 2013).

According to the Asian Development Bank (ADB, 2010a), the transportation sector is one of the major contributors to global climate change in Asia through emissions of CO_2 and other GHGs. However, GHG emissions from the UAE's transportation sector has not received sufficient attention yet. About 23% of energy-related CO_2 emission is produced by the transportation sector (ADB, 2010a). Most of these emissions are due to vehicle travel. Nonetheless, roadway construction and maintenance have a significant contribution of CO_2 emissions besides energy. Despite its numerous social and economic benefits, road development may negatively affect the environment by damaging ecosystems and ruining productive agricultural lands. It may also disrupt the socio-cultural practices of local communities including demographic changes, accelerated urbanization, and introduction of diseases from air pollution.

One of the major strategies utilized in decreasing air pollution is to reduce carbon footprint emissions, which can be defined as the total amount of CO_2 and other GHGs emitted over the full life cycle of a product or service (ADB, 2010a). As such, carbon footprint should be calculated for the entire life cycle of a road project. In this context, carbon emissions produced by road projects can be due to (1) embodied carbon in construction materials consumed, (2) fuel consumption in which carbon is released during the process of extraction up until the distribution of the finished product, (3) removal of vegetation in which new trees are planted along roads, and (4) usage of machinery and vehicles (ADB, 2010a).

On the other hand, the International Road Federation (IRF) has found that lowering fuel consumption by improving traffic fluidity and reducing traffic congestion is an effective way to reduce GHG emissions produced by the road sector. The impact of driving behavior and vehicle maintenance on fuel consumption and

GHG emission have also been found to be significant. Under-inflated tires have been found to increase fuel consumption by 1% per 3 psi tire pressure drop, full power air conditioning has been found to cause a 20% to 25% increase in GHG emissions; and eco-driving and decreasing average vehicle speeds have been found to reduce fuel consumption by 5 to 10% (DEFRA, 2007). Studies suggest, however, that reducing carbon footprint produced by road projects has a price. There needs to be a balance between improving environmental conditions and keeping costs at reasonable levels; raising the importance of the concept of sustainability. Pears (2004) notes that the concept of sustainability shifts the focus from short term, individual win-lose behavior towards longer-term, community benefit that includes environmental factors. Lumb et al. (2000) suggests five principles to define sustainability: 1) precautionary principles, 2) equity, 3) management of natural resources and capital, 4) management of bio-diversity, and 5) economic and social wellbeing.

For sustainability assessment of road projects, one has to consider the whole life cycle of the project. From an engineering or planning perspective, road project development generally follows a well-defined process which includes pre-feasibility and feasibility studies, preliminary design, detailed design, and construction. This is followed by operation and maintenance (O&M) of the completed project. Depending on the nature of the project, consultation with various government agencies, the public, or both, may be an essential component during early stages of the process. It is important to synchronize environmental impact studies with the project development process. Ideally, from a sustainable development perspective, the environmental assessment (EA) and project development processes should be conducted concurrently. The EA document needs to be completed by the feasibility stage of the engineering project, and the implementation of the mitigation plan should be tied in contractual documents, since they are most pertinent to road projects.

1.2 Motivation

Little attention was given to sustainable development in the UAE in the past. However, this behavior has significantly changed in the last decade. The government of the UAE is paying a lot of attention nowadays to sustainability and climate change. In 2015, the government created a new ministry called Ministry of Climate Change and Environment. Such attention has also transferred from the federal to the local level, with each emirate setting initiatives and establishing key performance indicators for sustainable development in different sectors. Although the effort is still at its early stage with the main focus of identifying the gaps, it is expected that progress will move forward and reach an acceptable stage in the coming 20 years with the will and support of the government. One of the aspects that the government is undertaking is to strengthen research collaboration among entities to provide practical solutions for sustainable development.

In January 2015, the Infrastructure Coordination and Services Department within the Infrastructure and Municipal Asset Sector of the Abu Dhabi City Municipality (ADM) invited the Roadway, Transportation and Traffic Safety Research Center (RTTSRC) at the UAE University to submit a research proposal regarding carbon footprint calculation and sustainability issues in road projects in the Emirate of Abu Dhabi. The RTTSRC responded to ADM invitation and submitted a proposal entitled “Assessing the carbon footprint of road projects and related sustainability initiatives in Abu Dhabi”. On November 24, 2015, the UAE University signed a contractual agreement with ADM to execute the project. The project aimed at providing means to make road projects in the city of Abu Dhabi more environmentally sustainable. The project was concluded on February 28, 2018.

This study is part of the ADM funded project. It attempts to answer several questions that are related to the level of sustainability of road projects in Abu Dhabi city by considering three road cases. These questions are: How much GHG emissions road projects emit during their lifecycle in the city of Abu Dhabi? What is the contribution of each activity involved in the different phases of the road lifecycle?

1.3 Objectives

This study is part of the UAE University/ADM project. The study aimed at providing a holistic approach for calculating the carbon footprint during the entire life cycle of road projects, covering road construction, operation, maintenance and rehabilitation phases. The specific objectives of the study were:

[1] Conduct a state-of-the-art review of studies covering environmental sustainability related issues in road projects;

[2] Develop a model to calculate GHG emissions produced by road projects; and

[3] Use the model to investigate the GHG emissions of three road projects in Abu Dhabi city throughout the entire project's life-cycle.

1.4 Scope of Work

This work is intended to improve sustainability issues of road construction and operation in the city of Abu Dhabi. Specific scopes of the project are:

- Review of carbon footprint and GHG emissions produced by road projects;
- Development of a framework for carbon footprint calculation during the road life cycle;

- Estimation of the carbon footprint produced by road projects during different stages of their life cycle.

To carry out this work, a thorough review of sustainability initiatives and environmental impact assessment studies in the emirate of Abu Dhabi was conducted. Furthermore, the current road development practices in the city of Abu Dhabi, as well as the engineering design and materials, and their alternatives in road development projects were studied.

Three road cases were studied. Input data for these cases were obtained from or through ADM. In cases where information was partly missing, information was collected from the field or reasonable assumptions were made. Due to absence of UAE-specific emission factors, emission factors used in the carbon footprint calculation were mainly based on those reported by the International Panel of Climate Change (IPCC). Estimation of local emission factors was beyond the scope of work of this study. Similarly, data on vehicle fuel efficiency in the emirate are not available and as such data were obtained from published reports.

The developed model estimates CO_2 emissions from road projects based on estimate of quantities by the road contractors. The model could as well be used to determine emissions based on actual values if available. The model, however, is not designed in its current form to determine emissions based on road design values. Nonetheless, this could be conducted in the future with another module that could be added to the model. Another limitation of the developed model is that it estimates emissions from vehicle movement based on average vehicle speed.

1.5 Thesis Structure

This thesis contains 5 chapters. Chapter 1 provides a description of the project including project background, motivation, objectives, and scope of work. Chapter 2 provides an extensive literature review which covers GHG emissions, carbon footprint associated with road projects, existing assessment tools, comparison of country-specific emission levels, and mitigation measures to reduce carbon emissions during road life cycle. The chapter also includes a review of road design, construction, operation and maintenance practices in Abu Dhabi, in addition to reviewing sustainable roads initiatives in Abu Dhabi emirate. Chapter 2, in fact, laid down the foundation for the intended work and was helpful in emphasizing the need for developing a holistic framework to assess the carbon footprint of road projects.

Chapter 3 explains in detail the development of the web-based RoadCO_2 Model. This model estimates CO_2 emissions for the whole life cycle of a road which includes pre-construction, construction, operation, maintenance, and rehabilitation phases. Utilization of the development model for estimation CO_2 emissions was explored for different case studies in Abu Dhabi city. The explored cases differ in their posted speed limit as well as their road infrastructure such as pavement, sidewalks, utilities, road furniture, etc. They include an urban street, an urban road and a highway. Chapter 5 concludes the study and provides recommendations for future work.

Chapter 2: Review of Literature and Sustainable Road Initiatives in Abu Dhabi

2.1 Introduction

Due to the continued GHG emissions from anthropogenic and natural activities, climate change has become a major global concern (Sing and Edwards, 2017). According to the IPCC (2006), climate change is defined as "any change in climate over time, whether due to natural variability or as a result of human activity." It is caused by continued GHG emissions since they trap heat around the earth's surface, leading to an increase in global warming (IPCC, 2006; IPCC, 2014; Sowunmi et al., 2015; United Nations, 1998).

The World Meteorological Organization (WMO, 2017) indicated in its latest statement on the state of global climate that warming continued in 2016 with a new temperature record of about 1.1 °C above the pre-industrial period. The statement also added that CO_2 reached new highs at 400 ppm in the atmosphere at the end of 2015. Global sea-ice extent dropped at an unprecedented anomaly of more than 4 million km2 below average. Meanwhile, global sea levels rose strongly, with the early 2016 values making new records.

Almost all of the world's transportation energy comes from burning of diesel and gasoline. Road transportation (i.e., motorized vehicles), more specifically, has produced the majority of these emissions (Sperling and Cannon, 2010). However, vehicle operation is not the only source of carbon footprint produced by road projects. Road projects produce carbon footprint even before they become operational. Road construction involves activities that produce significant amounts of GHG emissions such as excavation, as well as material and labor transportation. Road maintenance and rehabilitation are also responsible for GHG emissions, as road works are carried out to bring deteriorated infrastructure to desirable quality standards (ADB, 2010b; Egis, 2010; Angelopoulou et al., 2009). Therefore, in order to assess the impact of road transportation in terms of carbon footprint production, a full life cycle analysis approach is advised (Dilger et al., 2013).

In the UAE, energy consumption and GHG emission levels are among the highest in the world. Major contributors to these high levels may be associated with the country's significant oil and gas consumption, high standard of living, harsh weather which demands cooling, highly subsidized energy costs, and rapid economic growth associated with infrastructure development. From 1980 to 2013, the total primary energy consumption of the UAE reached about 4 quadrillion BTU with an increase of 2.14% from 2012 (Mundi, 2016). In 2014, the UAE total energy consumption was about 7,770 kg of oil equivalent per capita (World Bank, 2014). The transportation sector in particular has been found to be one of the main carbon footprint producers over the last century, with almost 15% of energy related CO_2 equivalent emissions coming from this sector. Out of UAE's total GHG emissions produced by the transportation sector, about 63% is related to road transport. CO_2 accounted for more than 98% of emissions while the reaming 2% consisted of the remaining GHGs. (Hill et al., 2012; SCAD, 2014). This high percentage may be attributed to a number of contributing factors such as high vehicular ownership and ridership levels, inexpensive fuel, as well as to a relatively lengthy highway network in the country, in terms of number of kilometers of paved travel lane per area of land mass (CIA, 2016). Abu Dhabi's main road (freeways) network, as per 2015 data, is estimated to be 2708 km long, while the secondary (urban) road length is 18,965 km of lanes (SCAD, 2016).

2.2 Greenhouse Gas Emissions

GHGs are gases that trap heat in the atmosphere, creating the "greenhouse effect", and are produced by a number of human activities such as electricity production, industry, transportation, waste treatment, and agriculture (IPCC, 2014a). According to the Kyoto Protocol, six GHGs are identified: Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC), perfluorinated compounds (PFC), and sulfur hexafluoride (SF_6) (IPCC, 2014b; Sowunmi et al., 2015; United Nations, 1998). Each one of these gases can stay in the atmosphere for different periods of time, ranging from a few years to thousands of years (USEPA, 2016). Combustion of fossil fuels has been the major source of CO_2 emissions, whereas agricultural activities have been the major sources of CH_4 and N_2O. Industrial processes and refrigeration have been the major source of HFC, PFC, and SF_6 (IPCC, 2014a). CO_2, however, has been found to be the most predominant gas emitted, often accounting for over 60% of the total direct GHG emissions (Sperling and Cannon, 2010). Predominance of CO_2 often leads to quantification of GHG emissions in terms of carbon dioxide equivalent (CO_2eq) (Galli et al., 2011; Dilger et al., 2013). CO_2eq is a relative scale that compares the warming potential of a gas with the same mass of carbon dioxide. CO_2eq of a GHG is estimated by multiplying the amount of the GHG by its global warming potential (GWP), which is a measure of how much a given mass of a GHG is estimated to contribute to global warming (Dilger et al., 2013).

Global CO_2 emissions are expected to grow from 26 billion tons to 39 billion tons between 2004 and 2025, resulting in an average annualized increase of 2% (ADB, 2010b). Indeed, global emissions from fossil fuels have increased by 90% since 1900 (Galli et al., 2011). Figure 2.1A shows emissions (in terms of CO_2eq) from two sectors (oil and gas, as well as water and electricity sectors) from 2005 to 2013 in the Emirate of Abu Dhabi. Figure 2.1B shows emissions from energy, industrial processing, agriculture, and waste sectors in the emirate for the year 2012. It can be observed that there has been a steady increase in GHG emissions in the Emirate of Abu Dhabi for the past many years. As population grows in the emirate, its demand for energy increases leading to an escalation in emissions. However, while GHG emissions increased by 30% in less than 10 years (i.e., from 2005 to 2013), population increased by a staggering 70%. The fact that population growth significantly outpaced emissions growth may reflect the UAE government's commitment in pursuing measures to reduce energy consumption (World Bank, 2014; UAEG20, 2012; UME, 2014).

Carbon footprint has been a commonly used term to describe the total amount of GHGs or CO_2eq emitted by a product or service over its entire life cycle. Carbon footprint can be estimated at the national, sector, household, or individual levels. The present form of carbon footprint may be viewed as a hybrid, as the concept of carbon footprint has been used over several decades, but known differently as a life cycle impact category indicator GWP (Pandey et al., 2010). When only CO_2 is included, the unit is kg CO_2. When other GHGs are included the unit is kg CO_2eq, expressing the mass of CO_2eq based on a 100 years GWP (Galli et al., 2012).

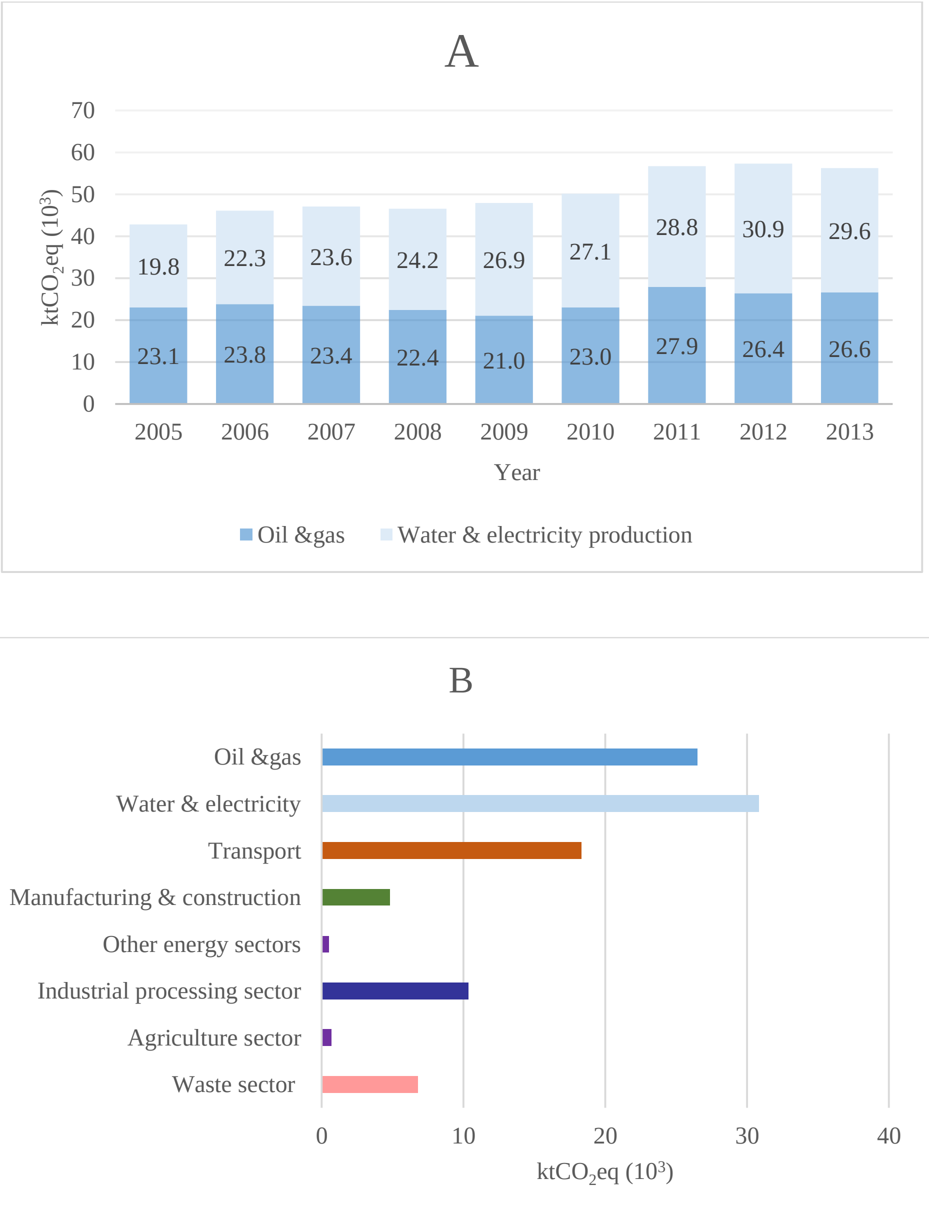


Figure 2.1: Emissions produced in Abu Dhabi Emirate in CO_2eq (A) CO_2eq emissions produced during 2005-2013 and (b) CO_2eq emissions produced in Abu Dhabi emirate for the year 2012 (ADNOC, 2009; SCAD, 2014)

2.3 Carbon Footprint Associated with Road Projects

The transportation sector is one of major contributors of GHG emissions worldwide. Almost 15% of the global GHG and over 20% of energy-related CO_2 emissions are produced by the transportation sector. The larger portion of these emissions is produced during the road operation phase due to vehicle exhaust (ADB, 2010b). However, sources of GHG emissions in the road sector also include those coming from construction materials, machinery use, removal of vegetation, as well as transportation of labor, equipment, and materials as shown in Table 2.1 (ADB, 2010b).

Table 2.1: Sources of GHG emissions during the life cycle of a road project (ADB, 2010a)

	Road Project Stage		
Sources of Emissions	Construction	Maintenance	Operation
Materials	Embodied carbon		Not applicable
Machinery use	Direct GHG emissions		
Transportation			
Vegetation removal	Sequestration potential lost		
Road use	Not applicable		Direct GHG emissions

In recent years, over 50% of global primary oil consumption has been used to meet over 90% of the total transport energy demand, with bio-fuels supplying only 2%, electricity 15%, and natural gas and other fuels 3%. More specifically, about 72% of the total direct and indirect GHGs emissions of the transportation sector originate from road transport (Huang et al., 2013). Hence, given the relevance of road transport to GHG emissions globally, quantifying emissions produced during the life cycle of a road project, as well as finding ways to mitigate them, is crucial. However, the combination of different GHG emission sources pertinent to various phases of a road project's life cycle may make carbon footprint estimation of a road project an overwhelming task. Such a task often requires extensive and detailed quantification of material items such as cement, steel, aggregate, and bitumen, as well as hours of machinery use, fuel consumption, and vegetation removal (ADB, 2010b; Barandica et al., 2013; EAPA and, Eurobitume, 2004).

2.3.1 Road Construction and Maintenance

As shown in Table 2.1, sources of carbon emissions during road construction and maintenance include construction materials, fuel consumed by construction machinery as well as by material and labor transport, and removal of vegetation (Egis, 2010). Some of the activities that contribute to GHG emissions during road construction/maintenance include site clearing, sub-grade preparation, production and transport of construction materials, operation of construction machinery, etc.

Previous studies have estimated that road construction/maintenance accounts for only a small proportion of the total GHG emissions produced throughout a road project's life cycle (Park et al., 2003; DBIS, 2010). For example, a study by Park et al. (2003) concluded that construction contributed to less than 2 to 5% of the total life-cycle emission of a road project. The study involved an analysis of a four-lane, 1-km long highway in the Republic of Korea. The authors found that the total non-operating emissions were mostly associated with four phases: manufacturing of construction materials, construction, maintenance/repair, and demolition/recycling. It was estimated that 57% of the total non-operating emissions were produced through manufacturing of construction materials. Other studies confirm that sourcing and manufacturing, in general, account for the largest portion of construction-related CO_2 emissions, suggesting that more effort in reducing materials' embodied carbon is necessary (Barandica et al., 2013). Emissions produced in the maintenance and repair stages were also relatively high, accounting for as much as 40% of total non-operating emissions. Construction accounted for 2% and demolition only 1% (DBIS, 2010).

Another study (EAPA and Eurobitume, 2004) found that earthwork activity contributed to the majority of the emissions produced during the road construction stage, accounting for 60 to 85% of the total emissions. In this case, earthwork included extraction, supply, internal transport of earth material, and disruption of environmental systems. Use of off-road machinery, however, accounted for most of total emissions, followed by construction material-related emissions and disruption of environmental systems. Emissions from transport vehicles had little contribution to total GHG emissions produced during road construction (EAPA and Eurobitume, 2004). Road structures and furniture have been found to contribute to almost 50% of the total emissions produced during construction of expressway facilities. To a lesser extent, pavement, culverts, and earthwork also presented meaningful contributions to GHG emissions. Pavement was the main contributor of GHG emissions during construction of lower-class road facilities (Angelopoulou et al., 2009). Fabrication and extraction of construction materials have been found to represent the main GHG contributors. On the other hand, aggregate and base materials, cement, bitumen, and steel reinforcement have been found to be the construction materials used in largest quantities (Egis, 2010).

Despite its relatively low overall contribution to GHG emissions, road construction and rehabilitation may still offer ways to minimize loss of resources, reduce waste generation, and enable the recycling of materials. In fact, recent research has indicated that the potential to reduce CO_2 emissions produced by road construction and maintenance is substantial (Keijzer et al., 2015).

Other key issues that have been raised as contributing factors to GHG emissions during road construction/maintenance are: use of older machinery, under-designed drainage systems resulting in high maintenance requirements, pavement life-shortening due to overloading, deficiency of suitable materials, inappropriate compaction equipment and procedures, cement produced in older plants translating into higher emissions per ton of cement produced, and excessive use of road furniture such as steel and concrete roadside barriers which have been found to contribute to as much as 5% of the total GHG emissions produced during construction of expressway facilities (Angelopoulou et al., 2009).

Another important consideration is the selection of pavement type. Concrete pavements have been found to produce significantly higher amounts of GHG emissions as compared to asphalt pavements, especially when cold-mix asphalt is chosen over hot-mix asphalt (HMA). HMA has been found to be more pollutant than warm-mix asphalt (Angelopoulou et al., 2009). The mixture mixing phase has been found to generate the largest amount of GHG emissions during asphalt pavement construction, accounting for 54% of the total, whereas raw material production has been found to account for 43% of total GHG emissions. For construction of asphalt mixture courses, the use of efficient equipment for laying, mixing, and transporting have been recommended to decrease the GHG emissions (Ma et al., 2016).

2.3.2 Road Operation

Road operation is the single, largest contributing stage to GHG emissions during the entire life-cycle of a road project. This may be attributed to the fact that roads are usually operated for decades, often carrying significant amounts of daily traffic. Another factor contributing to intense GHG emission production related to road operation is the fact that large majority of the world’s current vehicle fleet is powered by petroleum-derived products such as gasoline and diesel which have been recognized as unclean sources of energy (Casper, 2010). Indeed, approximately 80% of all transportation-related CO_2 emissions in the United States is produced by cars and trucks (ITF, 2010). Moreover, a significant increase in the vehicle fleet, especially by a large increase in the number of light-duty vehicles and trucks, may increase CO_2 emissions from transportation in Asian countries from three to five fold by 2030 as compared to emissions levels back in 2000 (ADB, 2010a). In China, CO_2 emissions from fuel combustion experienced 172% growth between 1990 and 2007. Passenger road transport accounts for approximately 30% of China's total road sector CO_2 emissions while heavy trucks account for approximately 40% (Marland et al., 2008).

Undeniably, CO_2 emissions produced by fuel combustion have experienced an exponential-like growth globally as shown in Table 2.2 (ITF, 2010). For instance, in the Emirate of Abu Dhabi, part of the UAE, four types of fuel are generally consumed in the transport sector. These types are gasoline, diesel, natural gas, and jet kerosene. These fuel types produce a total GHG emissions of over 18 Gg CO_2eq annually.

Table 2.2: Global, U.S., and India CO_2 emissions by fossil fuel combustion (ITF, 2010)

Year	**Emissions (million tons CO_2 per year)**		
	Global	**India**	**U.S.**
1750	3	0	0
1800	8	0	0.07
1850	54	0.03	5
1900	534	3	180
1950	1,630	5	692
1970	4,075	14	1,152
1980	5,297	26	1,263
1990	6,096	50	1,314
1998	6,608	79	1,487

The amount of GHG emissions produced by road and aviation transport sub-sectors in the Emirate of Abu Dhabi is shown in Table 2.3 (EAD, 2012). As indicated above, roads contribute about 63% of the direct GHG emissions in the transport sector, of which more than 98% is attributed to CO_2 emissions produced by fuel combustion.

Table 2.3: GHG emissions from roads and aviation in the emirate of Abu Dhabi (EAD, 2012)

	Roads		Aviation		Total
Emissions	**Gg CO_2eq**	**%**	**Gg CO_2eq**	**%**	**Gg CO_2eq**
Total GHG	11,736	63	6,774	37	18,547
CO_2	11,549	63	6,735	37	18,322
CH_4	15	92	1.4	8	17
N_2O	171	82	37	18	209

But it is not just fuel combustion that plays a role in the production of GHG emissions. As indicated in Table 2.1, loss of carbon sequestration potential due to vegetation removal is also a major contributing factor to GHG emissions during not only the road construction and maintenance stages, but also during the road operation stage due to its longer duration in the road life cycle.

Carbon sequestration potential lost has been referred to as CO_2 that would have been removed from the atmosphere, in the road project's entire life cycle (i.e., construction, operation, and maintenance), had vegetation not been removed. This occurs since vegetation often needs to be cut and removed to give way to a road project (Lal, 2008; Le Quéré et al., 2013). Most of the times, removed vegetation is replanted alongside the road which will lead to counterbalance the loss due to removal.

2.4 Carbon Footprint Assessment Tools

A number of carbon-footprint-related assessment tools have been developed over the years. The Resources and Energy Analysis Program (REAP) and HDM-4 can be used to investigate the impact road transport policies have on fuel consumption and environmental damage (Paul, 2008; HDM Global, 2016). The Greenhouse Gas Protocol has been used as a GHG emission accounting tool. It calculates emissions from personal vehicles, public transport, and mobile machinery. However, its emission factors may not be the most suitable for certain countries (WRI, 2001).

The Ecological Transport Information Tool Worldwide (EcoTransIT World) is a web-based software tool for assessing environmental impacts of transporting freight by various transport modes. The tool allows a user to input parameters such as transport mode (e.g., road, rail, water, or air), vehicle type, and emission factors (IFEU Heidelberg et al., 2014). The Motor Vehicle Emission Simulator (MOVES) estimates emissions from cars and trucks under different user-defined vehicle operating characteristics and road types (USEPA, 2016). The Motor Vehicle Emission Inventory (MVEI) model was developed by the California Air Resources Board and is used to evaluate pollutants released by road transport networks at several regional levels. While other GHGs (CH_4 and N_2O) still need to be included in this model, MVEI can be a practical tool for evaluating different scenarios and performing sensitivity analysis (El-Fadel and Bou-Zeid, 1999). Other traffic simulators, such as SIDRA and Synchro, allow the user to estimate both fuel consumption and the GHG emissions caused by the vehicles using the roads.

COPERT 4 and VERSIT+ were developed to predict emissions from road vehicles based on a set of statistical models (Smit et al., 2007; Ntziachristos et al., 2009). COPERT has most frequently been used in European countries such as Spain, Denmark, and Sweden (Berkowicz et al., 2006; Burón et al., 2004; Ekström et al., 2004). However, both COPERT III and IV have been found to under-estimate emissions (Berkowicz et al., 2006). MOBILE 6.2 was developed using recent vehicle emission testing data, and it can report emission rates in grams of pollutant per vehicle-mile traveled (USEPA, 2003). The GHG, regulated emissions, and energy-use in transportation model (GREET) was developed to evaluate energy and emission impacts of various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis. For a given vehicle and fuel system, GREET separately calculates consumption of total energy and CO_2 emissions (Wang et al., 2007). The International Vehicle Emissions Model (IVE) was designed to estimate emissions from motor vehicles. It predicts local air pollutants, toxic pollutants and GHG emissions. The emission prediction process of the IVE Model starts with a base emission rate, and a series of correction factors such as fuel quality and driving behavior are then applied to estimate the amount of pollution from a variety of vehicle types (ISSRC, 2008).

The Calculator for Harmonized Assessment and Normalization of Greenhouse-Gas Emissions (CHANGER) was released in 2009, and it enables an estimation of carbon footprint of road construction activities. CHANGER estimates GHG emissions produced by each road construction activity and materials taken into consideration. CHANGER considers three GHGs (i.e., CO_2, CH_4, and N_2O) and converts them all into a CO_2eq. However, CHANGER does not account for emissions produced either by road maintenance or operation stages; neither does it account for CO_2 sequestration potentially lost (Huang et al., 2013).

CO2NSTRUCT was developed in Spain and considers a life-cycle assessment approach for road transport infrastructure in evaluating GHG emissions. It makes use of a relatively large dataset of construction materials and machinery, energy sources, electricity mixes, and transport vehicles. However, just like CHANGER, CO2NSTRUCT also does not take the operational stage of a road project into account. In addition, it uses emission factors based on Spanish conditions (Fernández-Sánchez et al., 2015). ROADEO is also a software tool developed for quantifying GHG emissions produced by road projects and assessing alternative construction practices to limit GHG emissions (World Bank, 2010).

Carbon Gauge is another tool that can be used to estimate GHG emissions produced by road projects. The tool was developed by the Transport Authorities Greenhouse Group Australia and New Zealand (Dilger et al., 2013). The tool provides a means of estimating GHG emissions produced by major road activities throughout entire project life-cycle phases such as construction, operation, and maintenance. The tool is a Microsoft Excel macro-enabled spreadsheet. It is a tool for use in case of scoping where estimates or actual data are not available since it lists a comprehensive default values for road works. However, it does not include emissions from traffic during the operation phase. Other limitations include not accounting for sequestration, irrigation requirements of road trees/plants, and other activities such as sewage, water, and telecommunication works.

In the United States, a Carbon Footprint Estimation Tool (CFET) was developed for the estimation of emissions from road projects (Melanta et al., 2012). The tool was developed to help include emissions from transport infrastructure development projects into the decision making for future sustainability road projects. CEFT estimates emissions from all major processes observed on a construction project site including those associated with the used material and equipment. The tool also accounts for loss of CO_2 sequestration due to deforestation. However, it does not account for estimation of emitted GHGs during the operation phase. The CFET tool has the ability to estimate emissions from cement, asphalt, fertilizer, chemicals, and steel but it does not include emissions from materials such as plastic or HDPE. Other limitations of the tool are its inability to estimate emissions from sewerage works, telecommunication works, waste generated during construction, and the transport of extra materials (not used) from the site.

In the United Kingdom, the Highways England (2015) developed the Carbon Tool for estimation of GHG emissions from the construction and maintenance phase of road projects. The tool is comprehensive in terms of the data entry as it was developed after consultation with the local contractors. The tool estimates emissions for materials, waste, and consumed electricity. However, sequestration, stormwater drainage, and sewerage works are not included in the estimation of emissions. Additional limitations of the tool include inability to account for emissions from mobility of traffic during the operation phase or during detouring.

2.5 Comparison of Country-Specific Emissions Level

China, the United States, India, Russian Federation, Japan, Germany, the United Kingdom, and France have been found to be major emitters, in terms of CO_2 emissions, between 1970 and 2012. Emissions produced by China surpassed those of the United States in 2007, making China the world's largest CO_2 emitter. In 2012, China's emissions were almost equivalent to those produced by the United States and the European Union combined. While emissions from developed economies in the European Union have either stabilized or decreased over the last 4 decades, emissions from developing countries such as China and India have grown exponentially (Liu, 2015).

Table 2.4 presents a comparison among seven countries/states in regards to their emission levels in terms of CO_2eq. The United States, the United Kingdom and Russia may represent developed countries with more mature economies and, therefore, slower annualized economic growth. On the other hand, China and India may represent developing countries with emerging, faster growing economies. Saudi Arabia and the Emirate of Abu Dhabi also represent emerging, faster growing economies. However, Saudi Arabia and the Emirate of Abu Dhabi possess distinct socio-economic characteristics, enjoying very high vehicle ownership and ridership levels.

Table 2.4 shows the amount of emissions roads contribute in relation to the whole transport sector. For instance, in the Emirate of Abu Dhabi, emissions produced by road transportation accounted for 63% of the emissions produced by the transport sector as a whole. Table 2.4 also shows emissions normalized by each country's land mass area and road network length. In China, the normalized emissions by land mass area (in terms of 10^3 km^2) and by road network length (in terms 10^3 km of road) are 0.029 and 0.061 Mt CO_2eq which are considerably lower than those from the United States (i.e., 0.155 and 0.232 Mt CO_2eq, respectively). Normalizing emissions is important in order to draw meaningful conclusions about emission levels from different countries/states.

Table 2.4: Comparison of annual emission rates among countries

Country/ State	**Roads only (Mt CO_2eq)**	**Roads % Out of total trans. emissions**	**Area (10^3 km^2)[a]**	**Network length (10^3 km)[a]**	**Emission rate (Mt CO_2eq/10^3 km^2)**	**Emission rate (Mt CO_2eq/10^3 km road)**	**Ratio (Area)[b]**	**Ratio (km-road)[c]**
Abu Dhabi	12[d]	63[d]	67[e]	21[e]	0.179	0.571	1	1
Saudi Arabia	88[f]	84[f]	2,149	221	0.041	0.398	4.36	1.43
India	110[g]	83[g]	3,287	4,699	0.033	0.023	5.42	24.8
Russia	120[f]	35[f]	17,098	1,283	0.007	0.093	25.57	6.13
China	280[f]	57[f]	9,596	4,577	0.029	0.061	6.17	9.36
UK	119[f]	69[f]	243	394	0.489	0.302	0.36	1.89
US	1,528[h]	78[h]	9,833	6,586	0.155	0.232	1.15	2.46

(a) Obtained from CIA (2015)
(b) Ratio (Area) = Abu Dhabi Emission rate (Mt CO_2eq/10^3 km^2)/Country's Emission rate (Mt CO_2eq/10^3 km^2)
(c) Ratio (km road) = Abu Dhabi Emission rate (Mt CO_2eq/10^3 km)/Country's Emission rate (Mt CO_2eq/10^3 km)
(d) Obtained from EAD (2007)
(e) Obtained from SCAD (2016)
(f) Obtained from ITF (2013)
(g) Obtained from MoEF (2007)
(h) Obtained from EPA (2013)

The importance of normalizing emissions can be seen when looking at the figures for the Emirate of Abu Dhabi. That is, the total emissions produced by the road sector in the Emirate of Abu Dhabi is only approximately 12 Mt CO_2eq. However, once emissions are normalized in terms of number of kilometers of road, the Emirate of Abu Dhabi appears to present the largest GHG emission rate. The two right-most columns of Table 2.4 show the ratios in terms of Mt CO_2eq produced per area of land and kilometer of road, respectively, between the Emirate of Abu Dhabi and other countries listed in the table. For instance, the ratio of 9.36 indicates that the emission levels in the Emirate of Abu Dhabi, in terms of Mt CO_2eq per km of road, are over 9 times higher than those in China. This is a striking figure. That is, even though the absolute amount of emissions produced by road transport in the Emirate of Abu Dhabi is significantly lower than that produced in China (i.e., 12 vs. 280 Mt CO_2eq), road network length in the Emirate of Abu Dhabi is significantly shorter than in China (i.e., 21,402 vs. 4,577,300 km). The difference in road transportation emission levels between China and the Emirate of Abu Dhabi probably stems from the fact that even though they both are usually categorized as “emerging” economies, they have different socio-economic characteristics, including different vehicle ownership and ridership levels, as well as different vehicle fleet distribution (Shahbandari, 2015; Sambidge, 2010). That is, not only the number of vehicles and kilometers traveled per capita is higher in the Emirate due to its higher income per capita and cheaper fuel, but also its proportion of guzzler vehicles such as sport utility vehicles (SUVs) is higher.

Comparisons can also be made by dividing the road network length by the land mass area of each country/state. This would be an indicator as to how extensive the road network in each country is as a function of its land mass. Higher emission levels may also be associated with a more extensive road network system. If the lengths of road networks of India and the Emirate of Abu Dhabi are divided by their land masses, the resulting ratios are 1.42 and 22, respectively. This would indicate that the Emirate of Abu Dhabi has a lot more roads built per squared-kilometer of land. However, road network length does not take the number of lanes per kilometer of built road into account. That is, a significant portion of rural roads in the emirate are 5-, 6-, and even 7-lane roads in each direction, whereas there is a significant portion of 2-lane undivided roads in rural parts of India. Also, one would need to consider that most roads in the Emirate of Abu Dhabi are paved, whereas a large portion of roads in India are unpaved. This would also have an impact on emission levels, as paved roads usually not only carry higher traffic volumes which yield higher absolute amount of emissions, but they also carry faster traveling vehicles which translates into higher emission rates in terms of CO_2eq per vehicle-km traveled.

2.6 Mitigation Measures

A number of mitigation measures and initiatives have been proposed and/or implemented over the years as a means to reduce GHG emissions produced by road transportation. These measures include travel demand management, use of low-carbon or carbon-free fuels, advancement in vehicle technology, ecological driving, adoption of greener road construction practices, and implementation of traffic engineering principles. These measures are discussed as follows.

2.6.1 Travel Demand Management (TDM)

TDM intends to limit the number of vehicles traveling on a specified road, even at particular times of the day. Thus, TDM may adopt measures which have the potential to not only shift road users to less carbon-emitting travel modes such as public transit and cycling, but also to spread vehicular travel over both space and time (Ortúzar and Willumsen, 2011).

2.6.1.1 Mode-Shifting TDM Measures

Urban planning focused on non-motorized transportation may contribute more to city design based on a mixed-land-use approach so that people are less dependent on cars due to shortened travel distances. This means planning cities more based on a traditional neighborhood concept rather than on a sub-urban sprawl one (Speck, 2013; Frumkin et al., 2004).

Road space reallocation may also impact vehicular travel demand by shifting road users from driving their private vehicles to more environmental-friendly travel modes such as cycling, walking, and public transit. Creation of exclusive bike paths and bus lanes, as well as the improvements of pedestrian realms, all enhance attractiveness of transit and active transport (NACTO, 2013; UPC, 2017). At the same time, automobiles become less attractive due to less road space translating into lower traveling speeds, higher travel times, and more vehicular congestion, if drivers do not make the shift to alternate modes. Real-world experiments have shown that designing cities in a more cycling-oriented fashion often translates into a higher share of travelers biking rather than driving. The city of Freiburg, in Germany, has significantly increased walking, cycling and public transit while reducing per capita automobiles between 1990 and 2006 during which the city experienced rising income. The city made transit and active transport more attractive through a combination of tram and bus network improvements, walking and cycling improvements, and supportive land-use policies. It was observed that per capita, pollution emissions declined by 13%, significantly below the German average (Pucher and Buehler, 2009). The German city of Berlin also experienced a significant shift from cars to bikes due to road space reallocation (Strompen et al., 2012). After the implementation of the rapid transit system TransMilenio, the city of Bogota in Colombia has experienced a significant reduction in CO_2 emissions. The TransMilenio project required major road space reallocation as buses travel in exclusive lanes ensuring attractive travel times as compared to their vehicle counterparts which travel under more congested road conditions. As a result, a significant number of Bogota residents have shifted from traveling in their private vehicles to riding TransMilenio, while GHG emissions have decreased significantly in the process (Strompen et al., 2012; Hook et al., 2010). Overall, road space reallocation may significantly reduce vehicular trips if implemented in parallel with urban planning which places the needed emphasis on non-motorized transport so that the average trip lengths are reduced. Research in the United Kingdom shows that a quarter of all car trips made are actually under two miles in length, and as many as 80% of journeys could be completed using an alternative mode of transport (Mackett, 2000; Stradling, 2003).

Congestion pricing, parking charges and limited parking supply, as well as taxes may all have a mode-shifting effect. Congestion pricing applications have been found to produce meaningful reductions in GHG emissions in London, Singapore, Hong Kong, Stockholm, and California (Pike, 2010). Limited parking supply and parking charges may reduce GHG emissions by discouraging motorists from driving their private vehicles to certain areas (Shoup, 2011). Video-based conferencing calls have also been investigated as a means to decrease vehicle use altogether by enabling people to work from home and, therefore, diminishing their need to commute. However, evidence shows that the number of people working from home may be too low (DFT, 2003).

Lastly, motorists may be subject to taxation as a means to discourage low efficiency vehicles and promote high-efficiency ones, or encourage them to shift travel modes altogether (Davis et al., 1995). Car labeling has been used as a means to persuade consumers to opt for more fuel-efficient vehicles (Liu et al., 2016; Haq and Weiss, 2016). Fuel taxes may also be an option. It has been found that a 10% increase in fuel prices usually results in a 1 to 3% decline in travel (Anable and Boardman, 2005). However, taxation schemes are often unpopular, unless the revenue is clearly reinvested appropriately (Lyons et al., 2004). Plus, it has been argued that certain population groups, such as young families, may be especially disfavor of taxation schemes since they tend to be more dependent on motor vehicles (Ryley, 2006). Therefore, it is essential that successful tax policies are sustainable both socially and environmentally (Button and Nijkamp, 1997).

2.6.1.2 Route and Departure Time Shifting TDM Measures

TDM measures intending to spread vehicles over a network may accomplish this by attracting motorists to take alternative routes over congested ones, while TDM measures intending to spread vehicular demand more evenly throughout the day may accomplish this by helping motorists choose less congested times to travel.

Intelligent Transportation Systems (ITS) technologies have been used as TDM measures with the aim to help motorists choose the optimal routes in terms of minimal travel times. Congestion pricing may be considered an ITS technology which may be used to optimize system travel time as motorists may choose an alternative, charge-free route instead of driving through toll roads (Palma and Lindsey, 2009). However, it has been argued that because congestion pricing has commonly been adopted in parallel with other TDM measures, it may be difficult to infer the real impact of congestion pricing (Givoni, 2012). Distance-based charging systems using Global Positioning System (GPS) technology have been proposed as an attempt to mitigate congestion and its consequences such as air pollution. In these cases, motorists are charged as they travel depending on the route taken and the time of day. Their aim is to encourage motorists to adjust journey route and/or departure time based on congestion levels since higher charges would apply to more congested routes (Mitchell, 2005). However, some argue that these systems may be difficult and expensive to introduce and would offer no significant carbon reductions (Anable and Boardman, 2005). Variable message signs (VMS) is also an ITS technology application which works as an advanced traffic guidance system providing real-time traffic information in urban road networks to help drivers choose routes with lower traffic volumes. In doing so, vehicles are distributed in a road network in a way that the overall performance of the traffic system is improved in terms of less congestion and, potentially, less pollution (Emmerink et al., 1996).

Staggered work arrival and departure schedules have also long been mentioned in the literature as a means to reduce congestion by flattening the travel demand peaks primarily associated with work arrival and departure times (TRB, 1980). Due to its congestion relief benefit, staggered work arrival and departure schedules have the potential to decrease GHG emissions from road transport at a low cost, or no cost at all, as long as GHG emissions reductions by lower congestion levels are not completely offset by increased electricity consumption due to longer workplace usage (i.e., provided the electricity production is not pollutant-free).

2.6.2 Low Carbon and Carbon Free Fuels

Replacing lower fuel-efficiency vehicles with higher fuel-efficiency ones may yield considerable reduction in GHG emissions in the road transport arena. Initiatives targeting the fuel economy of light-duty vehicles have been put in place in Saudi Arabia and aim to increase Saudi Arabia’s fuel economy by 4% by 2020 (SASO, 2015). However, besides improving vehicles’ fuel efficiency, making use of renewable and alternative fuel sources on a larger scale may also prove to be an effective measure to reduce GHG emissions from road transport (Lutsey and Sperling, 2008; Maniatopoulos et al., 2015; Yedla et al., 2005; Hawkins et al., 2013; Yan et al., 2013; Liu, 2006; Yan and Crookes, 2009; Yang et al., 2009). Electricity and hydrogen may all yield significant reductions in GHG emissions as compared to fossil fuels (Maniatopoulos et al., 2015). Natural gas, biodiesel, and ethanol have also been proposed as alternatives to petroleum-derived gasoline and diesel (Yedla et al., 2005).

Switching from conventional to environmental-friendly fuels, particularly by private vehicles, has been proposed as a potential mitigation measure against GHG emissions produced by road transport (European Commission, 2010; Greater London Authority, 2009; IEA, 2009; US Department of Energy, 2011). However, it has been argued that there may be a number of factors to consider before favoring electricity over fossil fuels. First, even though electric vehicles produce zero emission at the tailpipe, their production tends to generate higher emissions as compared to the production of conventional vehicles. Thus, a life-cycle analysis approach is needed when comparing these two fuel options. Second, assumptions about battery and vehicle lifetimes need to be taken into consideration, for benefits from electricity-powered vehicles tend to be more substantial as battery and vehicle lifetimes are extended. Third, electric vehicles may not present real benefits over conventional ones if the source of electricity is unclean such as coal- or petroleum-powered plants (Hawkins et al., 2013). As a zero-GHG-emitting source of energy, however, hydrogen has the potential to significantly reduce GHG emissions from road transport. Even though it is a carbon-free energy source, hydrogen may require major infrastructure investments before it is widely used to fuel road transport. That is, advances in hydrogen storage and transport capabilities, as well as expansion in the number of fueling stations available, may need to be addressed (Johansson, 2003; Khare and Sharma, 2003; DFT, 2004).

Different from electricity and hydrogen which are not naturally occurring, and thus require production, natural gas is not only naturally available, but it also produces less GHG emissions than petroleum-derived gasoline and diesel due to its lower carbon content. However, due to lack of proper infrastructure to market natural gas to final consumers, its market share has remained small - around 2%. Nonetheless, natural gas has been seen as the fuel type which can bring the greatest benefit to the road sector in terms of GHG reductions in the short- to intermediate-term. Large-scale conversion of light- and heavy-duty trucks into natural gas could significantly reduce GHG emissions from the road sector within the next few years or decades while other cleaner energy sources become more technically and economically viable (Le Fevre, 2014).

Biodiesel and ethanol are biofuels which can be produced from recycled vegetable oils and sugar plants. They have been used to a larger extent in Brazil where a significant number of vehicles run on a fuel mix containing at least a 5% content of these fuels (U.S. Department of Energy, 2007). Biodiesel has been found to produce significantly lower emissions as compared to its fossil-based counterparts such as diesel and gasoline, as well as compared to other alternate fuels such as natural gas and corn-based ethanol (Robinson, 2015; Black, 2001). In addition, biodiesel may be considered a more sustainable fuel as plants take up CO_2 from the atmosphere before it is released when the fuel is processed. However, biodiesel production may require significant amounts of energy, while energy yield may vary considerably depending on the crop (Johansson, 2003). Second, large-scale biodiesel production may take up large land areas that could, otherwise, be used for food production for an ever growing world population (Black, 2001). Lastly, but not least importantly, the cost of biofuel production may not be competitive with the cost of fossil-fuel production (DFT, 2004). Ethanol, on the other hand, has largely been used as an alternative fuel to petroleum-derived transportation fuel. However, uncertainty levels remain high in regards to the net GHG effect of ethanol, particularly when used in a low-level blend with gasoline (Yan et al., 2013; Yan and Crookes, 2009).

2.6.3 Vehicle Technology

Technological advances in vehicle engineering have steadily been capable of decreasing the GHG emissions a vehicle emits (DFT, 2004). Hybrid vehicles using both gasoline and electricity, which have been found to be more fuel efficient than their conventional counterparts, appear to be the compromise between fully-powered electric vehicles using electricity from clean energy sources and conventional, fully fossil fuel powered vehicles (Lovins and Cramer, 2004). Fuel cell technology is one of the latest vehicle combustion innovations. This technology allows vehicles to run on hydrogen which is a carbon-free energy source. Fuel cells enable hydrogen-run-vehicles to run for longer and be filled up faster than their purely electric counterparts (Khare and Sharma, 2003; DFT, 2004; Le Fevre, 2014).

Emphasis has also been placed on reducing vehicle weight and drag so that power requirements are less, translating to lower fuel consumption and GHG emissions. Other advancements in high efficiency lightening, more efficient transmissions, light-weighting, aerodynamic improvements, and more efficient air-conditioning systems have also all contributed to vehicles achieving lower GHG emission rates (Ortmeyer and Pillay, 2001; Rahman et al., 2017). Advancements such as these have been found to produce GHG emission reductions of up to 30% (Maniatopoulos et al., 2015).

2.6.4 Ecological Driving

Ecological driving, or eco-driving, fosters driving behavior and maintenance practices which reduce vehicle fuel consumption and, therefore, GHG emissions. Some of the behavior and practices supported by eco-driving are traveling at speed limits, accelerating smoothly, coasting to stops, not idling for too long, eliminating unnecessary weight, keeping tires properly inflated, as well as changing oil and air filters regularly (Shaheen et al., 2012). Research conducted in Europe and North America have compared the fuel consumption of drivers before and after taking an eco-driving course, and it was found that changes in driving behavior and vehicle maintenance practices may indeed result in significant average fuel consumption reduction (Johansson, 1999; IEE, 2009). Providing real-time feedback to eco-drivers, in terms of recommended speeds, has also proven to substantially reduce average fuel consumption (Barth and Boriboonsomsin, 2008; Boriboonsomsin et al., 2011).

2.6.5 Greener Road Construction Practices (GRCP)

GRCPs include procedures and technologies capable of reducing GHG emissions produced by road construction activities. GRCPs have targeted construction material type and processing, transporting activities, as well as efficient operation of heavy machinery to reduce emissions during the construction stage (IRF, 2009; IRF, 2013).

The use of blast furnace slag, a by-product of iron and steel, has been favored over cement to reduce CO_2 emissions during production of road concrete. Use of blast furnace slag has proven not only to reduce CO_2 emissions due to lower cement consumption, but also to lower CO_2 emissions by recycling industrial waste, and thus reduce the overall environmental load. Low carbon, non-cement soil pavements utilizing industrial by-products and inorganic binder, as well as low carbon soil pavements utilizing polymer concrete have also been proposed as GRCPs. It was found that these technologies reduce emissions from road construction, although their costs have not been taken into account. Hence, further analyses may be required to investigate whether these GRCPs are cost-effective (Baek et al., 2015). Other GRCPs have been proposed by practitioners such as the use of warm mix asphalt, faster pavement compaction, earthwork balancing, recycled aggregates, environmentally sound road marking products, more fuel efficient and/or biofuel-powered road construction machinery, regionally available materials, long-life pavement, as well as provision of environmental training to construction personnel (Green Roads, 2011).

2.6.6 Traffic Engineering

Traffic engineering measures such as high-occupancy-vehicle (HOV) lanes, ramp metering, signal timing optimization, enforcement of speed limits, and incident management have been used to not only improve traffic flow, but also to reduce GHG emissions from traffic operations. These measures differ from highway capacity expansion measures which tend to improve operations in the short-term but suffer from the negative effects of induced travel demand in the long run (Noland, 2001; Barth and Boriboonsomsin, 2009).

HOV lanes may reduce fuel consumption by encouraging colleagues to carpool and share trips to work (Ortmeyer and Pillay, 2001). Ramp metering has been shown to effectively reduce CO_2 emissions (Arnold, 1998). Even though emissions from merging vehicles may increase with ramp metering adoption, this may be offset by avoiding unstable conditions within the heavy, faster-moving traffic on freeways. Signal coordination has also been shown to positively impact GHG emission rates by eliminating the constant need for acceleration and breaking and, instead, creating smoother traffic flow (De Coensel and Botteldooren, 2011; Frey et al., 2001; De Coensel et al., 2012). Enforcing speed limits may help reduce fuel consumption. Optimum fuel consumption has been found to be within the 50-70 km/h range (H. Wang et al., 2008). However, a considerable decrease in the traveling speed due to congestion may increase emissions (Y. Wang et al., 2008). Traffic incident management systems have been used to detect and rapidly remove disabled vehicles so that traffic delays are minimized (Barth and Boriboonsomsin, 2009).

2.7 Road Design, Construction, Operation, and Maintenance in Abu Dhabi

2.7.1 Management of Road Projects in Abu Dhabi

ADM through its Municipal Infrastructure and Assets Sector is responsible for the administration of design, construction, maintenance, operation, maintenance, specifications and practices of engineering projects. The Abu Dhabi Emirate has a set of roadway design manuals including a manual related to pavement design (DMAT, 2016a), another related to road geometric design (DMAT, 2016b), a third one related to road structures design (DMAT, 2016c), a fourth one related traffic control devices (DMAT, 2016d), and a fifth one related to lighting (DMAT, 2016e). In addition, ADM has a consultant procedure manual for design consultancy services (ADM, 2014a) and another one about standard specifications (ADM, 2014b).

2.7.2 Road Construction in Abu Dhabi

Road construction starts with contractors' mobilization, and proceeds with preparation of the site. Preparation of a site depends whether or not the site is new or reconstructed. For the latter site planning involves preparation of detour routes, which may be new or existing, erection of temporary works, protection or relocation of existing utilities, demolition of existing structures, clearance of debris, and appropriate disposal of the debris. On new sites, after mobilization, the contractor marks the limits of the site and clears it of unwanted materials.

After clearance of the site and construction of proposed utilities, earthwork is prepared for the sub-grade. Layers follow, thereafter, comprising the road pavement: sub-base course, base course, binder course, and wearing course. At locations with deep valleys and at interchanges, concrete is used for the construction of bridges and grade-separated ramps.

Surfaces of highways should be built according to design geometrics. Such geometrics are divided into three elements: cross section, horizontal alignment, and vertical alignment. Features of the first element include the number of lanes, medians, shoulders, sidewalks, bicycle lanes, roadside parking, cross slope, side slope, utility corridors, landscape, roadside area, public realm, etc. Standard dimensions of these features are presented in the Abu Dhabi Emirate Road Geometric Design Manual (DMAT, 2016b). Features of horizontal alignments are horizontal curves, super elevation, and horizontal tangents and roadside clearance for sight distance, while those of vertical alignments are vertical curves and vertical tangents (grades). All geometric features are related to traffic emissions depending on the interaction between traffic and the features.

2.7.3 Road Operation Service in Abu Dhabi

2.7.3.1 Traffic Control

This service is intended to optimize the flow of traffic at intersections. Optimization of traffic at signalized intersections is accomplished by implementation of optimal signal timings and coordination. At un-signalized intersections, traffic flow is optimized by installation of appropriate signs such as stop signs, yield signs, or no sign at all. As far as traffic control is concerned, energy to run the signals and the traffic management center may be the major contributor to traffic control related carbon footprint.

2.7.3.2 Traffic Flow Monitoring

Traffic data is collected from many locations for highway planning, design and maintenance, traffic control, economic analyses, safety analyses, public information, and legislation, for example. There are two types of equipment utilized in data collection: temporary and permanent counters. The permanent counters continuously consume electrical energy; hence they contribute to carbon footprint production. Carbon footprint for counters running on solar energy are resulting from manufacturing of the installations (embedded carbon).

2.7.3.3 Incidence Management

This involves the detection or reception of information at the location of a non-recurrent incident and includes the response, attendance, and clearance of the incident. Detection may be through automated ITS or other means such as phone calls from drivers or patrol teams. Response teams include police officers, civil defense officers, medical personnel, and others. For recurrent incidents, police officers respond to sites for manual control of traffic.

2.7.3.4 Traffic Surveillance

Cameras are installed for surveillance purposes. These purposes include but are not limited to detection of traffic incidents, traffic violations, criminal activities, as well as tracking subjects of interest. These cameras, along with their connected computers, continuously consume electricity.

2.7.3.5 Traveler Information

Dissemination of information to travelers is carried out via variable message signs (VMS) regarding downstream traffic conditions. The information may be used by some travelers to select alternative routes in order to avoid congestion, bad weather, and work zones. Other forms of information dissemination include TVs and radios.

2.7.4 Road Maintenance Works in Abu Dhabi

Section IV-5 of the Standard Specifications Manual (ADM, 2014b) addresses repairs to rectify structural failures, grade lines, drainage, and preparation of pavement surfaces for seal coats and overlays. Procedures are presented for the repair of innumerous items such as potholes, deep patches, skin patches, utility cuts, cracks, curbs, tiles, and manholes. However, the manual does not specify the frequency of these repairs nor the severity of distresses (trigger values) at which specific repairs should be carried out.

Section IV-6 of the manual (ADM, 2014b) addresses cold in-situ asphalt recycling, using foamed bitumen and cement. It is a rehabilitation technique that uses existing pavement materials to produce a stabilized sub-base or base course for new surfacing. An equipment cuts pavement to a design depth and pulverizes the cut material; then, foamed bitumen, stabilizing agent, filler (cement), and other additives are charged into the pulverized materials, mixed, spread, and finally compacted into a stabilized sub-base or base. Sub-section 402.03 (b & c) presents traffic based criteria for the decision on whether or not cold in-situ recycling should be undertaken.

DMAT (2016a) indicates that pavements in Abu Dhabi Emirate are mainly hot mix asphalt (HMA). The manual emphasized, however, that warm mix asphalt (WMA) is a more sustainable alternative to HMA with quality and effectiveness that match those of HMA. An additional benefit is that lower temperatures ensure that WMA paved roads are more quickly available for use by traffic, which is a significant benefit when time schedules are tight or in case of a need for reducing project duration. The manual does not specify the condition of pavement at which rehabilitation is necessary. However, terminal present serviceability indices (PSI) presented in Table 4.2 of the manual (DMAT, 2016a) may be taken as pavement condition at which rehabilitation or reconstruction is needed.

2.7.5 Road Construction Materials and Equipment Use in Abu Dhabi

ADM Standard Specification Manual (ADM, 2014b) specifies highway materials and equipment by pavement layer as presented below.

2.7.5.1 Sub-Grade

Sub-grade is the foundation of the pavement structure. It is formed by cutting and filling to grade-line. Section II-7, part 207.04(b), stipulates that materials for sub-grade may be the existing soil if that soil can achieve a consistent CBR of 10% when compacted to 95% maximum density. If not, the in-situ soil is removed and replaced with stronger soil imported from borrow pits that meet the load bearing requirement. The material would then be placed in layers not exceeding a thickness of 15 cm in loose form 206.02 (d).

Existing load-bearing sub-grades (206.05(a)) with CBR less than 5% when compacted to a maximum dry density of 95% for a minimum depth of 45 cm should also be replaced. Existing sub-grades with CBR greater than 5% but less than 10% when compacted to a maximum dry density of 95% for a minimum depth of 30 cm should also be replaced. Sources of replacement materials may be project-specific. Classification of borrow materials is presented in Table 202.05, with at least a CBR of 25%. Water used for compaction should be clean.

Earthwork equipment (section II-1) used for sub-grade preparation includes rotary cultivators, water sprinklers, bulldozers, motor graders, shovel tractors, and rollers/compactors. The extent to which these equipment contribute to carbon footprint production depends on each equipment's fuel consumption and operation duration.

2.7.5.2 Geotextile Fabrics

Geotextile fabrics are laid on prepared sub-grade and other locations to restrain soil movement, to provide for drainage, and/or to prevent soil erosion (sub-section 207.05a). The fabrics are of "non-woven type produced from long chain polymeric filaments or yarns such as polypropylene, polyethylene, polyester, polyamide, or polyvinyl-chloride and formed into a stable network such that the filaments or yarns retain their relative position to each other when subjected to the proposed use within the limits of the physical characteristics required.

2.7.5.3 Geo-Grids

Sub-section 3.7 of the Pavement Design Manual (DMAT, 2016a) presents guidance on use of geo-grids. Geo-grids are open grid meshes made of polymer materials used to reinforce or stabilize soils, aggregates, and asphalt concrete.

2.7.5.4 Sub-Base Course

Sub-base is the pavement layer directly above the sub-grade. Sub-bases are constructed from granular materials consisting in blends of fine and coarse aggregates that meet gradation presented in Table 302.05 of the ADM Standard Specifications (ADM, 2014b). The table presents gradation classes A, B, and C, and states that class B is to be used when no specification is made. Sub-base materials should be compacted in layers not exceeding 15 cm when in compacted form. Compaction is to achieve a relative density of 98% of maximum dry density. The CBR value of sub-base materials should be at least 65%. Thicknesses for sub-bases are a function of CBR material, traffic demand, and environmental factors.

When recycled (i.e., secondary) aggregates are to be used, they should be in accordance with DMA Circular number 57/2012. These aggregates come from recycled construction or demolition waste produced in Abu Dhabi. Gradation of the materials should conform to ASTM D2940.

2.7.5.5 Base Course

Specifications for sub-base materials also apply here, except those regarding recycled aggregate. Recycled aggregates for bases should have a different gradation than sub-bases. Minimum CBR for base courses is not specified. Thicknesses for bases are a function of CBR material, traffic demand, and environmental factors.

Equipment for construction of sub-bases and bases (Section III-1) includes aggregate crusher (and conveyors), loaders, hauling trucks, spreaders, travel mixers, central mixers, screens for asphalt mixing plants, and rollers. The extent to which these equipment contribute to carbon footprints depends on each equipment’s fuel consumption and operation period.

2.7.5.6 Flexible Surface/Wearing Course

This layer is constructed with a flexible concrete made by mixing fine aggregates, course aggregates, and filler, while using asphalt as a binding agent. Fine aggregates may be obtained from pits or crushed sand that have sand equivalents of at least 30 and 45, respectively. Coarse aggregates consist of crushed natural stone and gravel. Two refinery asphalt penetration grades, 40-50 and 60-70, are used. Other properties of the asphalt binders are presented in Table 400.10 (ADM, 2014b). Liquid asphalt used in asphalt works is MC-70. Emulsions are CSS 1h cationic emulsified asphalt in accordance with AASHTO M208 or SS 1h anionic emulsified asphalt in accordance with AASHTO M140.

The gradation of aggregates differs according to the type of pavement layer as per Table 402.03 (ADM, 2014b). A minimum of 40% of fine aggregates used should be of crushed rock. The optimum content of asphalt binder is determined using the Marshall method. Lab specimens prepared should pass all criteria presented in Table 402.04 of Standard Specifications (ADM, 2014b). The two binder grades 40-50 and 60-70 are to be used for base course, binder course, and wearing course according to highway classification and traffic levels as shown in Table 402.04 (ADM, 2014b). Thicknesses of the courses depend on material properties, traffic loading, and environmental factors.

Before mixing for construction, the asphalt binder should be heated to a temperature that yields a viscosity in the range of 150-300 mm^2/s (equivalent to 75-150s of Saybolt-Furol test). Once mixing is complete and the mixes are being emptied, the temperature of the mixes should not exceed 165 ^oC for grade 60-70 and 170 ^oC for grade 40-50. Mixes delivered to sites should be between temperatures of 120 ^oC and 160 ^oC. The mix should be spread into layers not exceeding 5 cm of thickness unless otherwise authorized. Compaction is conducted by steel-wheeled rollers and pneumatic-tired rollers at speeds not exceeding 4.8 and 8 kph, respectively, or at speeds approved by the engineer.

A prime coat of MC-70 liquid asphalt should then be applied to an absorbent sub-base or road-base prior to placing asphalt concrete. The coat should be applied at rates between 0.25-0.5 kg/m^2, at temperatures ranging between 60 and 85 ^oC.

A tack coat of asphalt emulsion (CSS-1h or SS-1h) is applied at a rate not exceeding 0.5 kg/m^2 onto an asphalt base, an existing asphalt, or a cement concrete surface in order to provide a bond between the existing surface and the next layer of asphalt concrete.

Equipment used for construction of asphaltic courses (Section III-1) include asphalt mixing plant, cold feed system, drier, dust collector, screens, hot bins, bitumen equipment, weigh box hopper, scales and meters, pugmill mixer, hauling equipment, spreader/paver, rollers, power broom, power blower, and asphalt distributor (for prime coat and tack coat). Again, the extent to which these equipment contribute to carbon footprints depends on each equipment's fuel consumption and operation period.

2.7.5.7 Concrete

Concrete is to be composed of cement (sub-section 501.03(a)), aggregates (501.04, 501.05), water (501.06), reinforcement (501.07), and admixtures (501.08). Cement and water contents are presented in Table 502.02 by class of concrete (ADM, 2014b).

2.7.5.8 Paints

The paint type depends on the type of base surface used. For kerbs, alkyd resin or a modified acrylic is used. As per Part 2, Section 200, item 209.01, concrete kerbs may be left unpainted if no specific mention of color. For pavements, white and yellow reflective thermoplastic striping material, or MMA cold plastic road markings based on Methyl Methacrylate resin are used. For metal surfaces, the following list of paints are used:

- Vinyl paint system (sub 1201.09c): consists of vinyl wash primer, vinyl intermediate coat, third, fourth, and finish coats are same as the intermediate coat.
- Epoxy-polyamide paint system (sub 1201.09d): consists of prime coat, intermediate, third, and finish coats.
- Inorganic zinc silicate system (sub 1201.09e): consists of prime coat on bare (un-galvanized) or galvanized steel surfaces, second coat, intermediate coat of epoxy polyamide, and finish coat of aliphatic polyurethane acrylic paint.

2.7.5.9 Adhesives

There are two packages of adhesives used for pavement markers. Package A consists of epoxy resin, titanium dioxide, and talc (sub-section 903.05), while Package B consists of n-aminoethyl piperazine, phenol, carbon black, talc, and resin grade asbestos.

2.7.5.10 Materials for Drainage

Section 7.0 of the Pavement Design Manual (DMAT, 2016a) provides designers of guidance for the design of a road drainage system. For detailed design requirements and criteria, the manual refers designers to Chapters 3 and 4 of the DMAT Storm Water and Subsurface Drainage Manual. The manual suggests use of glass reinforced pipes (GRP) for construction of stormwater drainage systems and that the sizes of the pipes be limited to a maximum of 500 mm in diameter. For pipe sizes greater than 500 mm in diameter, contractors are limited to using reinforced concrete pipes (RCP) only. The manual has also issued guidance on drainage accessories such as manhole covers, catch basin covers, inlet covers, and curb inlet gratings, to name a few. The accessories are to be of ductile iron.

2.7.6 Road Furniture Used in Abu Dhabi

2.7.6.1 Lighting

Part 1, Section A, subsection 1.1 (a) of the Abu Dhabi Emirate Lighting Manual (DMAT, 2016e) spells out that it is a statutory requirement to use LED lights or other equally sustainable luminaire technology. Subsection 1.1(j) indicates that pole heights, pole spacing, and pole arrangement requirements vary by road category and area. Table 4.3 presents such information on page P1-SA-22 in the manual (DMAT, 2016e). Pole height and spacing is a function of functional class of a road. The manual (DMAT, 2016e) also supersedes the design manual (ADM, 2014c) by specifying LED as sole lights to be used. Part 1, section E of the manual (DMAT, 2016e) allows solar options to be considered for projects. The section lays down requirements solar options should comply with.

2.7.6.2 Signals

The Manual on Uniform Traffic Control Devices (DMAT, 2016d) directs designers to the “Traffic Signals and Electronic Warning and Information Systems Manual.”

2.7.6.3 Pedestrian Facilities

Pedestrian facilities are sidewalks, zebra crossings, pedestrian bridges (overpasses), and pedestrian subways (underpasses). Sidewalks are spaces reserved for pedestrian outside the roadway. The spaces are paved with slip-resistant materials (normally tiles or interlocking bricks) to a longitudinal slope of 6% and a minimum cross slope of 1.5% and a maximum of 3%. Sidewalk widths are in the range of 2-4 m following highway contextual classification as shown in Table 13-1 of the Road Geometric Design Manual (DMAT, 2016b)

Overpasses and underpasses are provided where there is a high pedestrian demand to cross a section of highway operating as an uninterrupted flow facility such as freeways, expressways, and arterials.

The Road Geometric Design Manual (DMAT, 2016b), section 13.2.3.6 specifies that benches and other furniture be beyond boundaries of pedestrian space. Section 16.9.2.8 suggests that inclusion of specific pedestrian shelters be determined on a case-by-case basis.

2.7.6.4 Safety Barriers

The Road Geometric Design Manual (DMAT, 2016b) presents a few types of barriers that are used in Abu Dhabi, but refers the reader to the Abu Dhabi Roadside Design Guide for in-depth guidance.

2.7.6.5 Landscape

Roadsides and medians are planted with lawn and trees for most divided highways. These plants are irrigated. Landscaping, irrigation, and maintenance of plants contribute to carbon footprint, though the plants may offset the footprint due to carbon sequestration of the plants.

2.8 Sustainable Road Initiatives

2.8.1 Abu Dhabi Sustainable Road Rating System (ADSRRS)

The Abu Dhabi Department of Municipal Affairs (DMA) identifies best practices for applying sustainable policies and measures to road projects through the ADSRRS, along with clarifying the appropriate guidelines to be followed. As the ADSRRS is an initial start in developing a comprehensive rating system for road projects, it can then be used over time to score performance in applying sustainable best practices to projects. This system was developed through a series of steps that include decisions made by the DMA regarding technical rating system design choices, where each decision-making step was based upon the review of technical information provided in the technical deliverables (CH2MHILL, 2015). Key features of the ADSRRS are: (1) it applies to the entire cross-section for road projects, which means the entire context of the transportation system for roadways, (2) as the DMA is the initial developer and owner of the ADSRRS, various related rating systems are developed, and as transportation guidelines are updated, further integration and updates will be necessary, and (3) the ADDSRRS version 1.0 has pre-scoped credits that will apply to certain types of road projects. Moreover, the ADSRRS is designed as a weighted system, in which points are earned in a graduated manner in most credits. The goal of weighing is to make the point value for each credit corresponds with its potential to affect sustainability in terms of span, duration and magnitude of the impact. Larger weights are assigned to credits that are likely to have largest impacts in sustainability of most projects, indicating their relative impact to sustainability. Appendix A contains the 44 subcategories of the ADSRRS along with weighting of credits/points and their requirements (CH2MHILL, 2015).

2.8.2 Estidama

Abu Dhabi initiated “Estidama”, which means ‘sustainability’ in Arabic, in order to transform the Abu Dhabi city into a model of sustainable urbanization. Its aim is to create more sustainable communities, cities and global enterprises, as well as to balance the four pillars of Estidama which are environment, economy, culture and society. Plan 2030 and other Urban Planning Council (UPC) policies such as the Development Code were incorporated into the creation of Estidama. It is the first program of its kind that is tailored to the Middle East. In the immediate term, Estidama is focused on the rapidly changing built environment. It is in this area that the UPC is making significant strides to influence projects under design, development or construction within the Emirate of Abu Dhabi. One of Estidama’s key initiatives is the Pearl Rating System which aims at addressing sustainability of a given development throughout its lifecycle from design through construction to operation. The Pearl Rating System provides design guidance and detailed requirements for rating a project’s potential performance in relation to the four pillars of Estidama (Appendix A) (ADUPC, 2010).

2.9 Existing Environmental Impact Assessment (EIA) Guidelines in Abu Dhabi

The Environment Agency – Abu Dhabi (EAD) published guidelines for conducting EIA in the Abu Dhabi Emirate. It defines an EIA report as a comprehensive document that serves as a planning tool to guide evaluation of environmental impacts and potential mitigation and monitoring efforts associated with a proposed project within the Abu Dhabi Emirate. The EIA should be within the context of Abu Dhabi Emirate laws and the jurisdiction of the EAD.

The EIA report supports the goals of environmental protection and sustainable development along with integrating environmental protection and economic decisions. It also predicts environmental, social, and economic consequences of a proposed activity and evaluate plans to mitigate any other impacts resulting from the proposed activity. Findings and recommendations of the EIA should be documented clearly and briefly in the EIA report. The report should provide any important technical details, especially those regarding baseline data. The usefulness of an EIA report is measured by how well potential problems are foreseen, evaluated, and addressed with adequate and straightforward measures and proposed actions. An EIA report should not make recommendations, decisions, or conclusions about the appropriateness or approval of the proposed project (EAD, 2010).

According to the EAD guidelines (2010), the proponent of the proposed project is responsible for preparing and submitting an EIA report. The EIA report should be executed by an approved and registered consultant (from EAD) operating within the Abu Dhabi Emirate. EAD provides an up to date list of its approved and registered consultants. This list can be obtained from EAD's website. To make things easier, EAD provides project proponents with a checklist that contains all components and criteria to be included in the EIA report. These components and criteria should be adequately addressed within the EIA report.

Chapter 3: RoadCO$_2$ Model Development

3.1 Introduction

A comprehensive understanding of trends and patterns associated with relevant activities is required to make assessment of GHG emissions and to be able to find an appropriate solution. With the high emissions rate and the cross-boundary effect of GHGs, both national and international initiatives are being launched to reduce and mitigate the effect of these emitted gases.

Transportation sector is one of the fastest growing main contributors to global climate change. Globally, it produced about 7.0 GtCO$_2$eq of direct GHG emissions (including non-CO$_2$ gases) in 2010, which accounts for more than 23% of energy-related CO$_2$ and other GHG emissions (IPCC, 2014). Roads accounted for almost 72% (5.116 GtCO$_2$eq) of the total direct and indirect GHGs emissions of the transportation sector. In the same year, Abu Dhabi's transport sector contributed about 0.018 GtCO$_2$eq of which 63% was road-related emissions (EAD, 2016). Despite these huge quantities, carbon emission inventory and reduction of GHG emissions from the road sector has not received much attention in the emirate, and in the country as a whole, even though several initiatives are observed in reducing carbon emissions through wise use of energy and renewable energy production.

As a result of the international efforts to estimate the GHG emissions, serval methodologies to calculate the carbon footprint were developed and successfully used. These methodologies consist of standards and standard-like guidelines that are widely accepted and used (VTT, 2011). In this study, a thorough review was conducted of the developed methods and the way they were utilized in the calculation of carbon footprint emissions from road projects. As a result of the knowledge gained in the field, a comprehensive carbon footprint estimation model for road projects was developed to fulfil the purpose of the study. The model is referred to here as RoadCO_2. The model provides a common approach to estimating GHG emissions from road projects.

Adopting a life-cycle approach to determine the total amount of GHG emissions produced during the full life-cycle of a road project may be an overwhelming effort. Ideally, road engineers would be able to access analytical tools capable of handily estimating quantities of GHG emissions based on design input. As indicated in Chapter 2, a number of software tools have been specifically developed for estimating GHG emissions of road projects. However, these tools do not cover all phases of a road project (i.e., construction, operation, maintenance, and rehabilitation). Meanwhile, these tools vary considerably in terms of their level of details, coverage and scope. Among these models are the Carbon Gauge (Dilger et al., 2013), CHANGER (IRF, 2009), CO2NSTRUCT (Fernández-Sánchez et al., 2015), Carbon Tool (Highways England, 2015), and the Carbon Footprint Estimation Tool (CFET) (Melanta et al., 2013). Table 3.1 shows a comparison between the scope of RoadCO_2 and other carbon footprint calculation tools. It should also be indicated that the above mentioned models use emission factors from different sources, some of which are country-specific. For example, Carbon Gauge (Dilger et al., 2013) uses emission factors that are specific to Australia and New Zealand, CO2NSTRUST (Barandica et al., 2013) uses the European Environmental Agency emission factors called EMEP-EEA, Carbon Tool (Highways England, 2015) uses emission factors developed by the UK Department of Environment, Food and Rural Affairs (UK DEFRA), CFET (Melanta et al., 2013) uses the US EPA AP-42 emission factors, and CHANGER (IRF, 2009) uses the IPCC recommended emission factors.

This chapter details the development of the RoadCO_2 model. The model is intended to estimate the carbon footprint of road projects along its life cycle. Road life cycle includes several phases, namely pre-construction, construction, operation, maintenance, and rehabilitation. GHGs are emitted in every single phase whether in a direct or an indirect way. RoadCO_2 accounts for all the possible sources of GHG emissions during the full life cycle of the road.

RoadCO_2 can be utilized in various ways and by different entities. Regulatory authorities can use the model for planning, if design data were available, screening and sustainability evaluation of road projects. Consultants and contractors can also use the model for planning and screening purposes. The model can also be utilized by academic institutes and research centers for comparison, sensitivity analysis, and designing guidelines.

Table 3.1: Comparison between the scope of $RoadCO_2$ and other carbon footprint calculation tools

Tool	Road phase and activities																											
	Pre-Construction			Construction										Operation						Maintenance						Rehabilitation		
	Design	Ground investigations	Demolition & site clearance	Sewerage works	Water works	Stormwater works	Road works	Irrigation works	Telecommunication works	Electrical works	Landscaping and street furnishing	Labor transportation	Detouring	Vehicle movement	Traffic signals	Road lighting	Irrigation	Sequestration	Stormwater pumping	Road related works*	Lighting	Irrigation	Traffic signals	Cleaning	Detouring	Road related works*	Detouring	Labor transportation
Carbon Gauge	√	√	√	X	X	√	√	X	X	X	√	X	X	X	√	√	X	X	X	√	√	√	√	√	√	√	√	√
CO2NSTRUCT	√	√	√	√	√	√	√	√	√	√	√	X	X	X	X	X	X	√	X	√	√	√	√	√	X	X	X	X
CHANGER	√	√	√	√	√	√	√	√	√	√	√	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Carbon Tool	√	√	√	√	√	√	√	√	√	√	√	X	X	X	X	X	X	X	X	√	√	√	√	√	√	√	√	√
CFET	X	√	X	X	X	X	√	X	X	X	√	√	X	X	X	X	X	√	X	X	X	X	X	X	X	X	X	X
MOVES	X	X	X	X	X	X	X	X	X	X	X	X	X	√	X	X	X	X	X	X	X	X	X	X	X	X	X	X
COPERT 4	X	X	X	X	X	X	X	X	X	X	X	X	X	√	X	X	X	X	X	X	X	X	X	X	X	X	X	X
MVEI	X	X	X	X	X	X	X	X	X	X	X	X	X	√	X	X	X	X	X	X	X	X	X	X	X	X	X	X
$RoadCO_2$	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√

*Road related works include sewerage, stormwater network, water network, pavement, street lighting, telecommunication, and landscaping and street furnishing

3.2 RoadCO$_2$ Conceptual Framework

3.2.1 Approach

RoadCO$_2$ was developed to estimate the total GHG emissions from the full life cycle of roads. While the model was specifically developed to serve ADM, it could be used to estimate the carbon footprint emission of projects by other entities within the country or elsewhere. The general approach used in developing the model framework is shown in Figure 3.1.

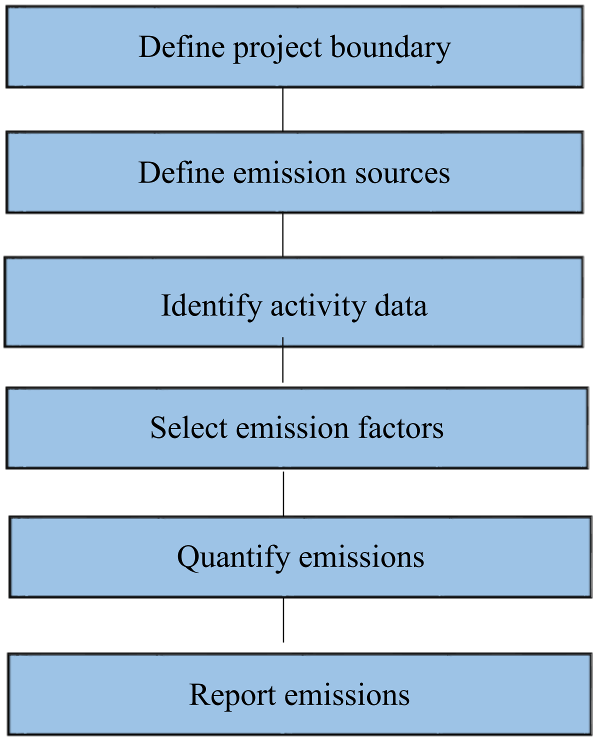


Figure 3.1: General approach for developing RoadCO$_2$

The first step of creating the framework was to define the project's boundaries and to recognize the need to account for all possible sources of direct and indirect GHG emissions during the life cycle of the road (pre-construction, construction, operation, maintenance, and rehabilitation). The boundary is an imaginary line around the emission sources and activities that are included in the GHG assessment (see Figure 3.2). In here, the assessment boundary of a road project is considered to be all of the GHG emissions from activities over which the designers, constructors and operators have control, which could be within and outside the physical boundary of the project. Thus, defining boundaries help in determining which activities to be considered and which emission/sink sources to be used.

After defining the project boundary and emission sources, activities need to be identified. An activity is defined as any action that gives rise to a source/sink of GHGs. It should be realized that some activities could involve more than one GHG emission source (Dilger et al., 2013). An activity data is then multiplied by the corresponding emission factor to estimate the emissions from that activity. Emissions are then summed up to determine the total emissions associated with the project. The following discussion will reveal more about the boundaries considered in RoadCO$_2$.

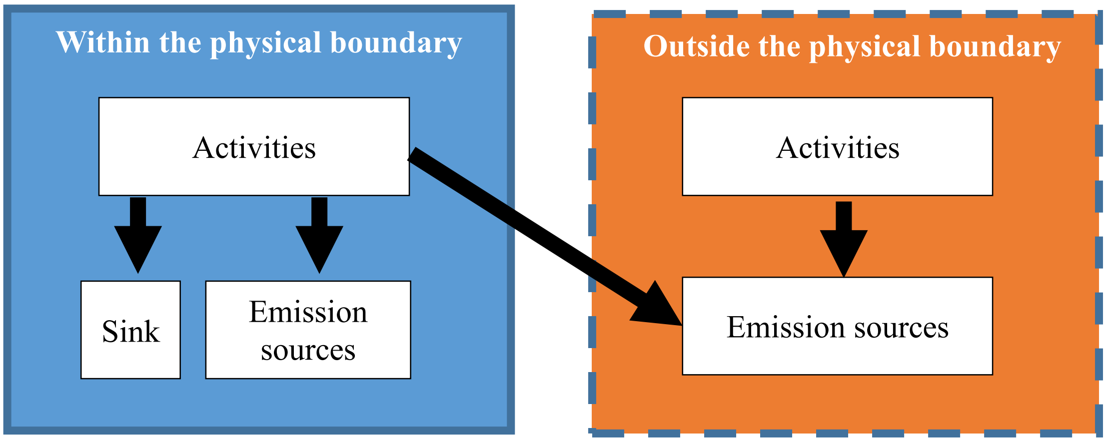


Figure 3.2: Overview of RoadCO$_2$ boundaries

During the road phases (pre-construction, construction, operation, maintenance, and rehabilitation phases), most of the direct emissions are caused by combustion of fossil fuels and other forms of energy consumption such as electricity.

These energy sources, among others, are used at the full extent of the road life cycle. On the other hand, pre-construction, construction, maintenance, and rehabilitation phases use different types of construction machinery and vehicles. Direct GHG emissions results from the combustion of fossil fuels in the engines. Another source of GHG emission in the previous phases is the use of construction materials. While these materials might not emit GHGs on-site, but their production and transport to the site does contribute to GHG emissions. Their emissions are accounted for in RoadCO_2 as indirect (embodied) emissions.

The road operation phase involves the movement of motorized vehicles that emit GHGs due to combustion of fuel. It also involves the use of electricity to power lights, traffic signals, and operate irrigation and stormwater pumping systems. The operation phase also involves sequestration of GHG emissions by vegetation within the road physical boundary. These direct GHG emissions are included in the estimation of carbon footprint of road projects. Figure 3.3 shows a summary of all possible direct and indirect GHG emissions that are considered in the model. It should be noted that different activities are expressed in different units of measurements (UOM) that are consistent with the way their corresponding emission factors are expressed in.

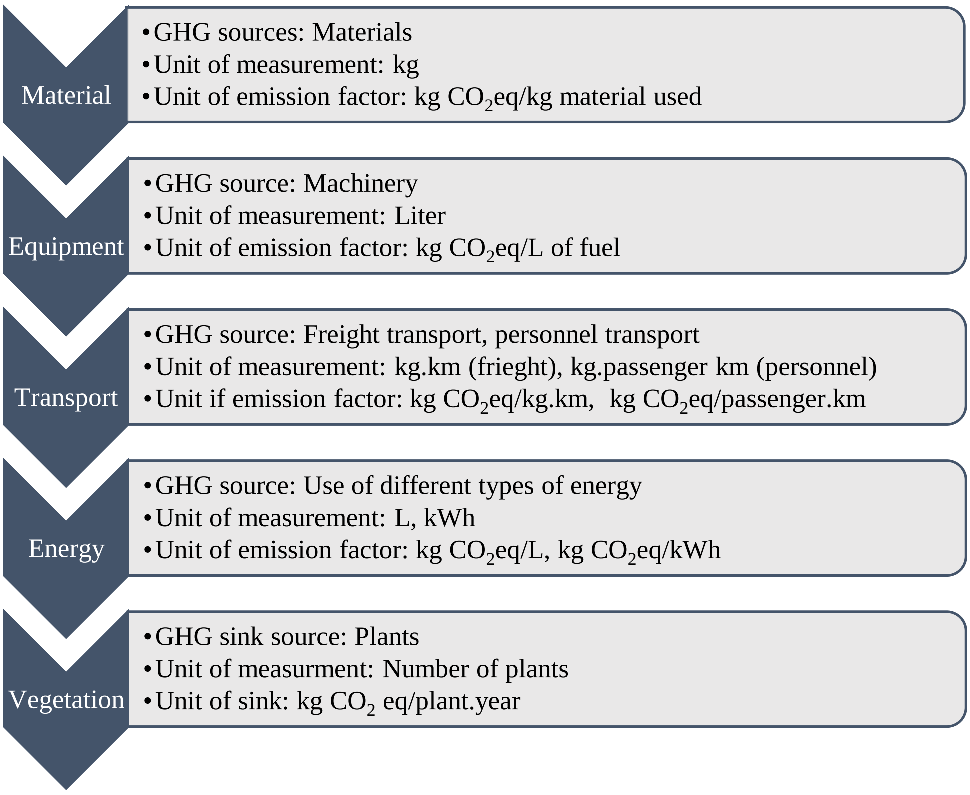


Figure 3.3: Direct and indirect GHG emissions sources considered in RoadCO_2

3.2.2 Road Phases and Activities

Activities involved in road projects must be identified so that GHG emissions can be quantified. To determine which activities to include in the model, a careful study of ADM standard specifications was conducted since the model is tailored to the emirate of Abu Dhabi. In addition to that, several tools were reviewed to determine if additional activities should be included. RoadCO_2 calculates the GHG emissions over the whole life cycle of the road. This includes pre-construction, construction, operation, maintenance, and rehabilitations phases. These phases are different in nature, so as the activities associated with them.

Pre-construction phase involves the design stage and other activities carried out prior to construction. Activity information for some items of this phase includes those listed in the ADM conventional Bill of Quantities (BOQ) and those associated with the loss of vegetation. Whilst the design of a road can greatly impact on its emissions, the actual GHG emissions associated with design activities are likely to be very small and are, therefore, generally considered not significant. Thus, GHG emissions associated with design activities can generally be excluded from a GHG assessment of a road project (Dilger et al., 2013). Some of the BOQ items involved in the pre-construction phase include ground investigations, establishment of site offices and laboratories, clearing the area, etc.

The construction phase includes more BOQ items than the pre-construction phase. These items cover most of the work that is conducted on site. Some of the BOQ items involved in the construction phase include earthwork, pavement works, utilities work, etc. In addition, the construction phase includes detouring of traffic and labor transportation.

The operation phase is considered to be post construction and includes activities that are required on a continuous basis for the functioning of the road. The operation phase extends over the road service lifetime, usually taken between 30-50 years. This phase contains four main GHG emissions contributors and one GHG sink. Traffic movement, traffic signals, road lights, irrigation, and stormwater pumping are contributors to emissions, while plants along the road are considered as a source of a GHG sink or removal.

Maintenance is considered to be post construction and includes activities that are intermittently required to keep the road assets at the required standard. Maintenance in this study refers to minor planned/routine or reactive work. Maintenance work could be related to road, lighting, irrigation, and cleaning. These works have their own set of BOQ items. In addition to that, emissions during the maintenance phase could include emissions from detouring.

Rehabilitation is considered to be post construction and includes major activities that are conducted to keep the road assets at the required standard. Rehabilitation is thus a major planned maintenance work. These works might include resurfacing, or reconstruction of the whole road segment. Rehabilitation is usually accompanied by detouring of traffic. Figure 3.4 shows the categorized activities that are included in each phase of the road life cycle. All these activities are included in RoadCO$_2$.

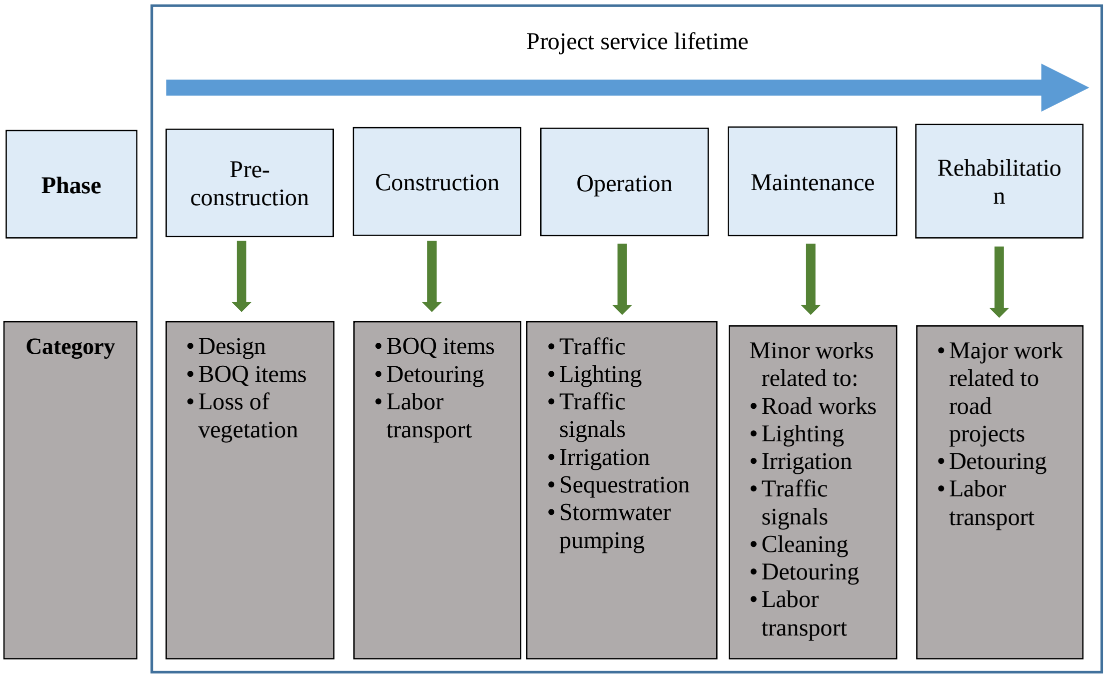


Figure 3.4: Categorized activities included in RoadCO$_2$

3.3 RoadCO$_2$ Model Methodology

The RoadCO$_2$ model follows the methodology proposed by the IPCC 2006. This methodological approach combines information on the extent to which the human activity takes place with coefficients which quantify the emissions or removals per unit activity. Road life cycle involves different activities in each of its main phases. Equation 3.1 shows the general mathematical form used by $RoadCO_2$ for estimation of carbon footprint emissions.

$$Emissions = \sum_{i=1}^{n} AD_i \; x \; EF_i \tag{3.1}$$

Where AD_i is the activity data associated with activity i and EF_i is the emission factor associated with activity i.

$RoadCO_2$ was created based on a huge database that contains many factors contributing to GHG emissions of the road project over its respective life cycle. The database contains the emission factors of 156 types of materials commonly used in construction of infrastructure projects, 3 types of fuels widely used in Abu Dhabi and their emission factors, 27 different kinds of both freight and personnel transportation mode, and the grid electricity. It also contains information needed for the indirect GHG emissions calculations. These are construction equipment fuel consumption rates, road vehicle fuel consumption rates, plants irrigation rates, electricity consumption rates for different types of road lights, and sequestration rates. It should be emphasized that $RoadCO_2$ is a holistic model with a database that covers almost all activities that emit GHGs. Meanwhile, users can enter their own activities values in case it is not available in the model database.

The IPCC national greenhouse inventories guidelines provide a generalized decision tree for selecting tiers used in GHG calculations (see Figure 3.5). The decision tree was used to decide which tier would be appropriate to adopt in the development of the $RoadCO_2$ model. Since the model uses estimates of quantities based on data provided in the BOQs and due to the lack of UAE-specific emission factors, the IPCC Tier 1 approach was used. The model mainly uses emission factors reported by the IPCC. Values for the emission factors include those for processing materials, fuel consumption, transportation, waste treatment, water consumption, and electricity generation (see Appendix B). Nevertheless, the model has a flexibility of being updated in future with local data to ensure more precise results.

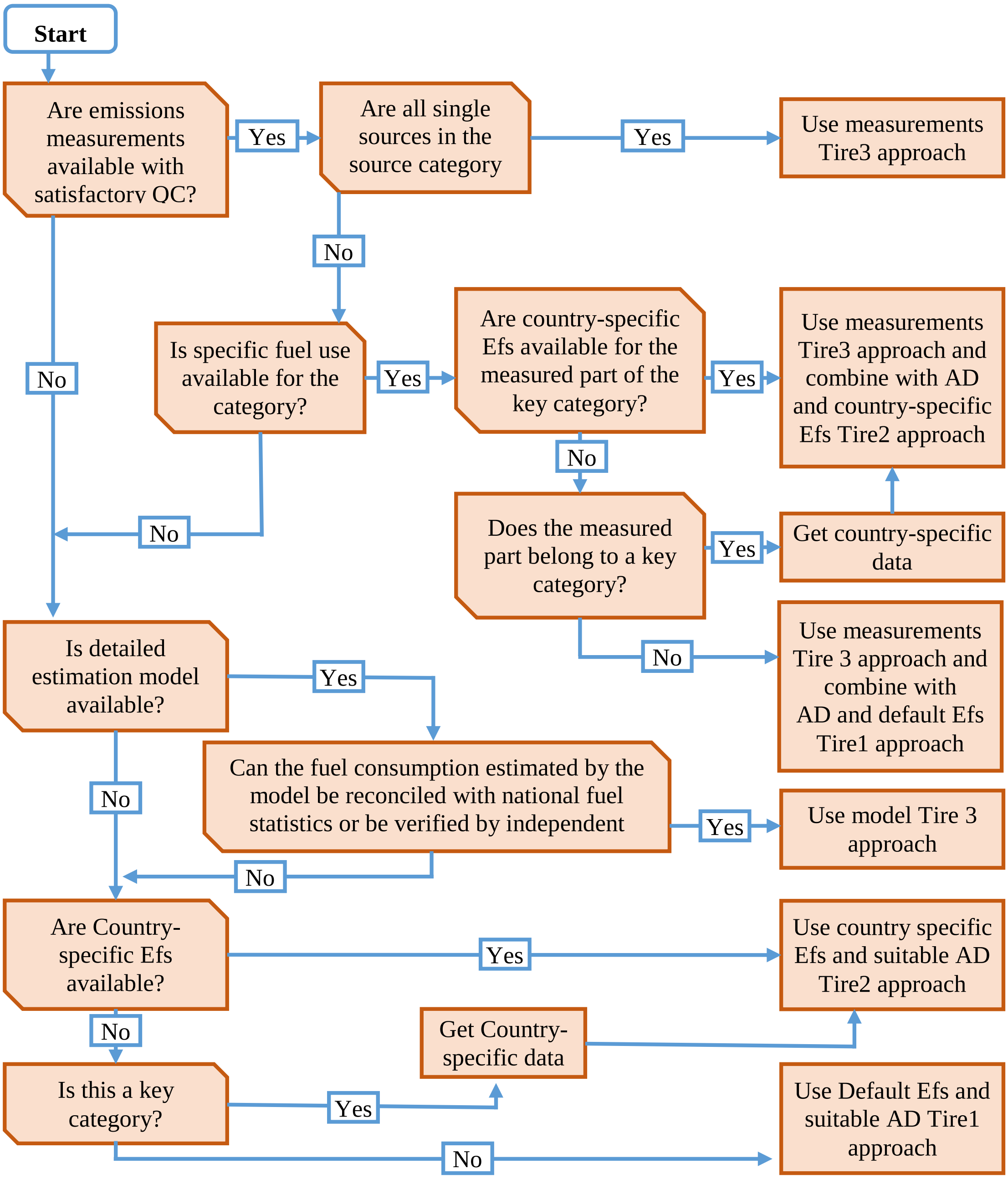


Figure 3.5: IPCC decision tree

3.3.1 Pre-Construction

The pre-construction phase is the initiation stage of the project. Though it does not include many activities, but it still involves activities that emit GHGs. In the design stage, several meetings take place, some of which could involve traveling long distances. Ground investigating, site clearing and demolition, and establishing site offices and laboratories are also activities contributing to the pre-construction phase GHG emissions share. These activities involve the use of various materials, the use of construction equipment, transportation (material, equipment, personnel, labor, and waste), and the use of electricity. RoadCO_2 quantifies these resources, finds the appropriate emission factors associated with the different activities, and estimates the GHG emissions. Table 3.2 shows the RoadCO_2 model required data to be able to carry on the calculations of GHG emissions for the pre-construction phase.

Table 3.2: $RoadCO_2$ input and output parameters of the pre-construction, construction, maintenance, and rehabilitation phases

	Input*	Input unit	$RoadCO_2$ role	Output
Material	Type used	Type	Calculate GHG emissions caused by the used material and its transportation	GHG emission (kg CO_2eq)
	Quantity	kg		
	Transportation	km		
Equipment	Type	Type	Calculate GHG emissions caused by equipment and its transportation	
	Quantity	Number		
	Duration	Hours		
	Fuel used	Type used		
Labor trans.	Type	Type	Calculate GHG emissions caused by labor transportation	
	Distance	km		
Detouring	Vehicle class	Class	Find the appropriate electricity consumption rate	
	Vehicle model	Model		
	Road speed	City, Highway, Combination		
	Traffic volumes	Vehicles counts	Find the vehicle kilometre travelled	
	Fuel Used	Type	Find the emission factor	
	Bulb type	Type	Find bulb's wattage	
	Quantity of bulbs	Number	Find total electricity consumed	
	Operation duration	Hours		

*Some inputs are provided by $RoadCO_2$ in the form of a drop list

3.3.2 Construction Phase

The construction phase can be defined as the time between obtaining development approvals and funding (pre-construction) and handing over the asset to the relevant authority at the end of the defect liability period (Dilger et al., 2013). The basic building blocks in the $RoadCO_2$ model are the materials, equipment, fuels, transportation (fright and personnel) used in the construction. These are considered the top GHG contributors in this phase. Table 3.2 shows the RoadCO$_2$ model required data to be able to carry on the calculations of GHG emissions for the construction phase.

For quantification of materials used in the different phases of road projects, unit adjustment is necessary before entering the data in the model. Input data for the RoadCO$_2$ model can be obtained from the BOQs. The unit provided for materials in the BOQs could take different forms ranging from cubic meter, square meter, linear meter, or number of quantities. The IPCC emission factors for materials are expressed in terms of mass. Thus, materials data given in cubic meter should be converted to mass by multiplying it with the density of that material. In case the materials data is given in square meter, linear meter or number of quantities, their volume should be calculated from the drawings of that particular BOQs project and then should be multiplied by the corresponding density to obtain the mass of the material. Once the mass of the material used is known, it will be multiplied by the emission factor of that materials and the emissions will be calculated as shown in Eq. 3.2. Density values for different materials are given in Appendix C.

$$Emissions\ (kg\ CO_2\ eq\ ) = \left[Quantity\ (m^3) \times Density\ \left(\frac{kg}{m^3}\right)\right] \times EF_i\ \left(\frac{kg\ CO_2\ eq}{kg\ material_i}\right) \tag{3.2}$$

To account for GHG emissions of the construction materials, RoadCO$_2$ requires knowledge of the type of equipment used, duration of operation, and type of fuel used for operation (see Table 3.2). Based on the type of equipment used, and appropriate fuel consumption rate (FCR) (see Appendix D) is selected. Emissions from equipment usage are calculated based on Eq. 3.3.

$$Emissions\ (kg\ CO_2\ eq\ ) = \left[FCR\ \left(\frac{L\ fuel}{Eq.\ hr}\right) \times Quantity \times Duration\ (hr)\right] \times EF\ \left(\frac{kg\ CO_2\ eq}{L\ fuel}\right) \quad (3.3)$$

To determine emissions from transportation of material and equipment to the site, Eq. 3.4 is used. Estimation of emissions from transporting material or equipment requires knowledge of transportation mode, mass of equipment/material transported, and travel distance. Note that equipment masses are available in RoadCO$_2$ database (see Appendix D), while construction materials masses are determined by the user.

$$Emissions\ (kg\ CO_2\ eq\ ) = [Mass\ (kg) \times Distance\ (km)] \times EF\ \left(\frac{kg\ CO_2\ eq}{kg\ material.km}\right) \quad (3.4)$$

In case of unavailability of project data, certain assumptions must be made. This applies for material transport to the site, which include, but not limited to, trucks that transport concrete, trailers for the transport of bricks, and pick up for the transport of pipes. On the other hand, data for heavy machinery that are operated during the construction of roads are mostly available with the contractor working on the project or can be obtained by consultation with the expert engineer working in the field of interest. In case such data are not available, they can be assumed based on the length of the road. These assumptions are related to excavation and backfilling equipment, rollers and graders.

3.3.3 Operation Phase

Vehicle movement, traffic signals, road lighting, irrigation, stormwater pumping, and sequestration are considered road operations that contribute to the road's GHG emissions. While they vary in their contribution of GHG emissions/sink, it is agreed that these activities are the main contributors to GHG emissions compared to activities in other road phases. This is due to the fact that the contributors in this phase are emitting huge amounts of GHG over the whole life cycle of the project which can span from a few years to decades (ADB, 2010). RoadCO_2 takes into consideration all of the activities in the operation phase. However, different variables are needed for these activities to be fully assessed for their GHG emissions as detailed below.

3.3.3.1 Vehicle Movement

To account for the emissions caused by vehicle movement, four variables are needed for the calculation. These variables are fuel consumption rate (FCR), traffic volume, vehicle kilometer travelled, and fuel type used (Eq. 3.5). The first three variables will allow the model to quantify the amount of fuel consumed by different types of vehicles traveling on a particular road (or activity data), while the last variable will determine the choice of emission factor. Though manufacturing of these vehicles contributes to GHG emissions, RoadCO_2 does not take these emissions into account. The reason for that is to avoid double counting as these vehicles use the whole network and not only the road of interest.

$$Emissions\left(\frac{kg\ CO_2\ eq}{yr}\right) = \left[FCR\ \left(\frac{L\ fuel}{km.\ veh}\right) \times Traffic\ volume\ x\ Distance\ (km) \times Quantity\ (\frac{veh}{yr})\right] \times EF\ \left(\frac{kg\ CO_2\ eq}{L\ fuel}\right) \tag{3.5}$$

FCR is an essential parameter for the calculation of GHG emissions. Thus, the choice of the appropriate rate is important. Selection of the FCR value depends on three factors, which are: vehicle class, vehicle model, and posted speed. The RoadCO_2 model database includes three vehicle categories and models ranging from 1995 to 2017 (see Appendix D). These categories are passenger cars, light trucks, and heavy trucks. Each category includes a different number of vehicle classes. The passenger cars category contains two seaters, mini-compact, sub-compact, compact, mid-size, full-size, small station wagon, and mid-sized station wagon. Light trucks contain small pickup truck, standard pickup truck, sport utility vehicles, minivan, cargo van, and passenger van. The heavy trucks category is a class by itself. The last factor in determining the FCR is the road posted speed. Three speed ranges are provided based on data from Natural Resources Canada (2016). These ranges are city (60-80 km/h), highway (100-120 km/h), and combination (vehicles are moving at city speed 55% of the distance and 45% at highway speed) (Natural Resources Canada, 2016). It is important to mention that these fuel consumption ratings are derived from emissions generated during five laboratory driving cycles. Each cycle test resembles different driving conditions that are most likely faced by the drivers. These conditions are stop and go driving in an urban setting, cold temperature driving, air conditioner use, and driving at a high speed with more rapid acceleration and braking. FCR is expressed in units of L/km/veh.

Traffic volume is the second variable that the RoadCO_2 model requires to carry on the GHG emission calculations. Traffic volume is usually obtained directly from the road using different counting methods or through a traffic study. The RoadCO_2 model deals with annual traffic volumes. It should be noted that the model does not carry on traffic simulation to determine traffic volume, but relies on the users' input of traffic volume.

The third variable that is needed to determine the amount of fuel consumed by the different classes of travelling vehicles on the road is the vehicle kilometer travelled. RoadCO_2 takes the data initially provided by the user about the road distance and combines it with the previous variables. This allows RoadCO$_2$ to quantify the amount of fuel consumed by the entire fleet within a specified duration. The quantity of fuel consumed is expressed in Liters.

Fuel type is the fourth and last variable used to calculate emissions due to vehicles movement by RoadCO$_2$. The model contains 3 types of fuel that are most commonly used in Abu Dhabi City. These are gasoline, natural gas, and diesel (EAD, 2016). Each fuel type is associated with an emission factor in the RoadCO$_2$ database. These emission factors are expressed in units of kg CO$_2$eq/L. Table 3.3 summarizes the RoadCO$_2$ required data to be able to carry on the calculations of GHG emissions due to vehicle movement during the operation phase.

Table 3.3: RoadCO$_2$ input and output parameters of vehicle movement during the operation phase

Input*	**Input unit**	**RoadCO$_2$ role**	**Output**
Vehicle class	Class	Find the appropriate fuel consumption rate	GHG emissions (kg CO$_2$eq)
Vehicle model	Model		
Road speed	City, Highway, Combination		
Traffic volumes	Vehicles counts	Find the vehicle kilometre travelled	
Fuel Used	Type	Find the emission factor	

*Some inputs are provided by RoadCO$_2$ in the form of a drop list

RoadCO$_2$ accounts for electrical vehicles. Though the variables are different, emission estimation methodology for both fuel and electricity powered vehicles is the same. For electrical vehicles, the RoadCO$_2$ model first quantifies the amount of electricity used and then multiplies it by the electricity emission factor. Similar to fuel quantification, the RoadCO$_2$ model uses vehicle class, model, road posted speed, and traffic volume to determine the electricity consumption rate. This rate is then multiplied by the traffic volume and the vehicle kilometer travelled to quantify the amount of electricity consumed. This quantification is expressed in units of kWh. This amount is then multiplied by the electricity emission factor (expressed in unit kg CO_2eq/kWh) to get the amount of GHGs emitted from electrical vehicles. Table 3.4 summarizes RoadCO$_2$ data requirement to be able to carry on the calculations of GHGs emitted from electrical vehicles during the operation phase.

Table 3.4: RoadCO$_2$ input and output parameters for electrical vehicles movement during the operation phase

Input*	**Input unit**	**RoadCO$_2$ role**	**Output**
Vehicle class	Class	Find the appropriate electricity consumption rate	GHG emissions (kg CO_2eq)
Vehicle model	Model		
Road speed	City, Highway, Combination		
Traffic volume	Vehicle counts	Find the vehicle kilometre travelled	
Fuel used	Type	Find the emission factor	

*Some inputs are provided by RoadCO$_2$ in the form of a drop list

3.3.3.2 Traffic Signals

Traffic signals are a vital component in road operation, yet they cause GHG emissions. The RoadCO$_2$ model considers the role of these signs in the calculations of the total carbon emissions during the operation phase. The main source of GHG emissions for traffic signals is its electricity consumption. Electricity consumption differ with traffic signals. The RoadCO$_2$ model takes the difference in electricity consumption into consideration and gives the user the option to input several types of traffic signals, their quantities, and the period they are expected to operate. The RoadCO$_2$ model recognizes the type, the quantity, and the operation duration and multiply it with the emission factor associated with electricity consumption to determine emission from traffic signals as demonstrated in Eq. 3.6.

$$Emissions\left(\frac{kg\ CO_2\ eq}{yr}\right) = \left[Wattage\ (Watt) \times Quantity \times Duration\left(\frac{hr}{d}\right) \times \frac{365.25\ (\frac{d}{yr})}{1000\ (\frac{Watt}{kW})}\right] \times EF\ \left(\frac{kg\ CO_2\ eq}{kWh}\right) \tag{3.6}$$

Table 3.5 shows the RoadCO$_2$ required data to be able to carry on the calculations of GHG emissions for traffic signals during the operation phase.

Table 3.5: RoadCO$_2$ input and output parameters for traffic signals during the operation phase

Input*	**Input unit**	**RoadCO$_2$ role**	**Output**
Traffic sign type	Type	Find the annual electricity consumption rate	GHG emission (kg CO$_2$eq)
Quantity of traffic signals	Number		
Operation duration	Hours		

*Some inputs are provided by RoadCO$_2$ in the form of a drop list

3.3.3.3 Road Lighting

In the Emirate of Abu Dhabi road lighting is generally divided into three classes; traffic routes where the needs of the driver are dominant, subsidiary roads where lighting is primarily intended for pedestrians and cyclists, and urban centers, where lighting is designed for public safety and security, while also providing an attractive night-time environment (DMAT, 2016e). The RoadCO$_2$ model calculates the GHG emissions for the first class. Similar to traffic signals, the primary source of emissions of road lights is in its electricity consumption. Electricity consumption rates differ among different types of lights. The RoadCO$_2$ model requires the type of bulbs used on the road to determine the electricity consumption per hour. It also requires the expected operating hours to calculate the total amount of electricity consumed (as shown in Eq. 3.6). Table 3.6 shows the RoadCO_2 model required data to be able to carry on the calculations of GHG emissions due to street lighting.

Table 3.6: RoadCO_2 input and output parameters of road lighting during the operation phase

Input*	**Input unit**	**RoadCO_2 role**	**Output**
Bulb type	Type	Find bulb's wattage	GHG emission (kg CO_2eq)
Quantity of bulbs	Number	Find total electricity consumed	
Operation duration	Hours		

*Some inputs are provided by RoadCO_2 in the form of a drop list

3.3.3.4 Irrigation

To calculate the GHG emissions caused by irrigating the plants along the side of the road, the RoadCO_2 model quantifies the amount of GHG emitted due to use of water and the part emitted due to water transmission. Different types of plants are usually used along the side of the roads. These plants have different irrigation requirements (ADUPC, 2017). The RoadCO_2 model calculates the GHG emissions due to water usage in three steps (see Eq. 3.7). First, it identifies the irrigation rate per day (L/d) based on the user's input of plant type, plant age, and plant irrigation intensity. These irrigation rates are listed in Appendix E. Second, it quantifies the amount of water used to irrigate by multiplying the irrigation rate per plant found in the first step by the irrigation duration and the number of plants of the type used. The third step is to select the emission factor. Based on the selection of the type of water used, the RoadCO_2 model selects the appropriate emission factor (kg CO_2eq/L) from its database and utilizes it in the calculation.

$$Emissions\left(\frac{kg\ CO_2\ eq}{yr}\right) = \left[Irrigation\ rate\left(\frac{L}{d.tree}\right) \times Quantity \times Duration\left(\frac{d}{yr}\right)\right] \times EF\left(\frac{kg\ CO_2\ eq}{L}\right) \quad (3.7)$$

The RoadCO$_2$ model also calculates the GHG emissions due to water transmission. Based on the type of pump used, and the operation hours of that pump, the RoadCO$_2$ model quantifies the amount of electricity used and then multiplies it by emission factor associated with electricity consumption to get the GHG emissions. The final RoadCO$_2$ model output for the irrigation part will be the summation of emissions due to water usage and its transmission. Table 3.7 shows the RoadCO$_2$ required data to be able to carry on the calculations of GHG emissions for road irrigation.

Table 3.7: RoadCO$_2$ input and output parameters for road irrigation during the operation phase

	Input*	**Input unit**	**RoadCO$_2$ role**	**Output**
Water	Plant type	Type	Find the amount of water consumed for irrigation	GHG emissions (kg CO$_2$eq)
	Plant age	Years		
	Irrigation intensity	High, Medium, Low		
	Plant quantity	Number		
	Irrigation period	Hours		
	Water type used	Type	Select the emission factor	
Water transmission	Pump type	Type	Find electricity consumption	
	Operation duration	Hours		

*Some inputs are provided by RoadCO$_2$ in the form of a drop list

3.3.3.5 Stormwater Pumping

The RoadCO$_2$ model calculates the GHG emissions caused by stormwater pumping. The primary source of emissions of the pumping system is the electricity consumed by the pumps. Electricity consumption rates differ among different types of pumps. To estimate emissions due to stormwater pumping, RoadCO$_2$ requires knowledge of the number of pumps used in the system, their power (in hp or kW), and the expected annual operating hours of the pumps (Eq. 3.8). Table 3.8 shows the RoadCO$_2$ model required data to be able to carry on the calculations of GHG emissions due to stormwater pumping system.

$$Emissions\left(\frac{kg\ CO_2\ eq}{yr}\right) = \left[Power\ \left(\frac{hp}{pump}\right) \times Quantity \times Duration\left(\frac{hr}{yr}\right) \times \left(\frac{0.746\ kW}{hp}\right)\right] \times EF\ \left(\frac{kg\ CO_2\ eq}{kWh}\right) \quad (3.8a)$$

$$Emissions\left(\frac{kg\ CO_2\ eq}{yr}\right) = \left[Power\ \left(\frac{kW}{pump}\right) \times Quantity \times Duration\left(\frac{hr}{yr}\right)\right] \times EF\ \left(\frac{kg\ CO_2\ eq}{kWh}\right) \quad (3.8b)$$

Table 3.8: RoadCO$_2$ input and output parameters of stormwater pumping system during the operation phase

Input*	**Input unit**	**RoadCO$_2$ role**	**Output**
Number of pumps	Number	Find total electricity consumed	GHG emission (kg CO$_2$eq)
Pump power	Horse power or kilo Watt		
Operation duration	Hours		

*Some inputs are provided by RoadCO$_2$ in the form of a drop list

3.3.3.6 Sequestration

The RoadCO$_2$ model calculates carbon sequestration by individual trees, such as trees typically planted along the road. To do so, RoadCO$_2$ requires input data related to plant type, plant age, and plant growth rate. These inputs are utilized to determine the sequestration rate for each plant. In addition, the quantity of plants is needed to calculate the annual carbon sequestration (Eq. 3.9).

$$Sequestration \left(\frac{kg\ CO_2\ eq}{yr}\right) = [Quantity\ (tree)] \times ASR \left(\frac{kg\ CO_2\ eq}{tree.yr}\right) \tag{3.9}$$

Table 3.9 shows the RoadCO$_2$ required data to be able to carry on the calculations of GHG sink (or removal) for the sequestration part during the operation phase. The model database contains a list of sequestration rates as listed in Appendix F.

Table 3.9: RoadCO$_2$ input and output parameters of the sequestration part during the operation phase

Input*	**Input unit**	**RoadCO$_2$ role**	**Output**
Plant type	Type	Find sequestration rate	GHG sink (kg CO$_2$eq)
Plant age	Years		
Growth rate	Slow, Moderate, Fast		
Plant quantity	Number	Find annual carbon sink	

*Some inputs are provided by RoadCO$_2$ in the form of a drop list

3.3.4 Maintenance Phase

The maintenance phase is the third phase in the road project life cycle. Usually it happens after a certain period after the operation phase. Maintenance works includes minor works related to the eight main categories mentioned in the construction phase. It may also include detouring works. Routine maintenance is an on-going activity, and thus this phase is made up of the materials and fuels consumed. Similar to the construction phase, maintenance works emit GHGs because of the use and transportation of materials, the use and transportation of machinery, and the use of energy either to power the machinery or to generate electricity. Usually vehicle movement, traffic signals, road lights, irrigation, and sequestration carry on as usual during maintenance unless otherwise disturbed. For example, vehicle speed may drop due to maintenance works. Thus, the user will choose the new speed to allow the

$RoadCO_2$ model to take this change into consideration in the calculation of emitted GHGs. Road cleaning is also a source of GHG emissions. Equipment used to clean the road contribute to the GHG emissions by burning fuel. Also treating the collected waste contribute to the maintenance phase GHG emissions. Table 3.2 shows the $RoadCO_2$ required data to be able to carry on the calculations of GHG emissions for the maintenance phase.

3.3.5 Rehabilitation Phase

The rehabilitation phase is made up of major maintenance events that happen in longer periods of time (longer than the maintenance works). It is somehow similar to the construction phase in terms of GHG emissions sources, but there could be some differences in the activities involved. It is also similar to the maintenance phase, yet in the rehabilitation phase one or more components of the operation phase will be heavily disturbed. The $RoadCO_2$ model covers the GHG emissions during the rehabilitation phase and accounts for them in a similar manner as it does for the construction phase. Materials used, their transportation, equipment used, their transportation, fuel burned in labor transportation and the GHG emissions due to detours (if exists). Table 3.2 shows the $RoadCO_2$ required data to be able to carry on the calculations of GHG emissions for the rehabilitation phase.

3.4 Model Structure

The $RoadCO_2$ web application is developed using ASP.net with Model-View-Controller (MVC) architecture, html, javascript, jquery, angularjs, css etc., in an Integrated Development Environment (IDE), specifically the Microsoft Visual Studio®.NET. The model application uses a Microsoft SQL Server database for storing data. It is currently compatible and tested with Google Chrome. The MVC design pattern is very useful for architecting interactive software systems. As shown in Figure 3.6, MVC architectural pattern separates an application into three main components: the model, the view, and the controller.

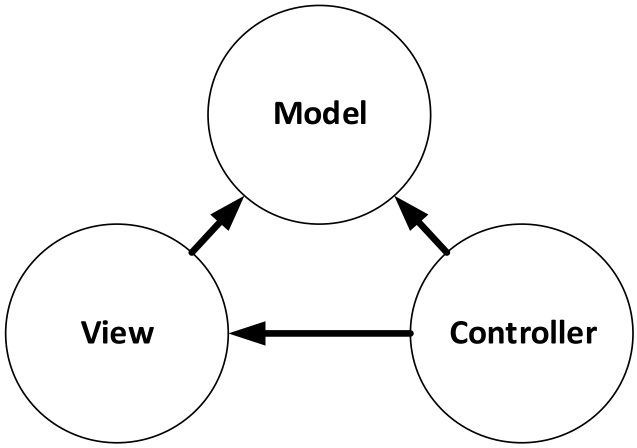


Figure 3.6: MVC architecture

The Model component corresponds to all the data-related logic that the user works with. This can represent either the data that is being transferred between the View and Controller components or any other business logic-related data. It helps in retrieving the information from the database, manipulate it and update it back to the database or use it to render data. The View component is used for all the User Interface (UI) logic of the application such as text boxes, dropdowns, etc. that the final user interacts with. Controllers act as an interface between Model and View components to process all the business logic and incoming requests, manipulate data using the Model component and interact with the Views to render the final output.

As discussed previously, the model application is envisioned to calculate the GHG emissions over the lifecycle of roadway projects. The GHG estimates differ with the varying characteristics of road projects such as project environment, availability of construction materials, quantity of items required etc. So, the model demands input information of the particular project to be evaluated and also, the flexibility to add or change details in relation to the activities of the project. The application consists of input interface, data processing interface and output interface. The input interface facilitates the user to enter information into the application. Then the information is processed and GHG emissions are calculated with the use of data processing interface and finally the output interface is used to display the total GHG emissions with respect to phases. It will also facilitate the user to view or download the complete report consisting of all the items related to the calculation of emission in specific formats.

To account for this, the model structure primarily comprises of two modules such as the 'User Module' and 'Admin Module' (User and Admin manuals are provided as separate documents along with RoadCO_2 model). The 'User Module' interface allows the front end user to input the essential project attributes and besides, generate the output reports of the GHG emissions for specific user related projects. On the other hand, the 'Admin Module' helps to modify the model parameters such as material, equipment, transportation etc., and their respective CO_2 emission factors considered in the estimation process. The following section describes the user actions involved in the 'User Module' and 'Admin Module' of the developed model application.

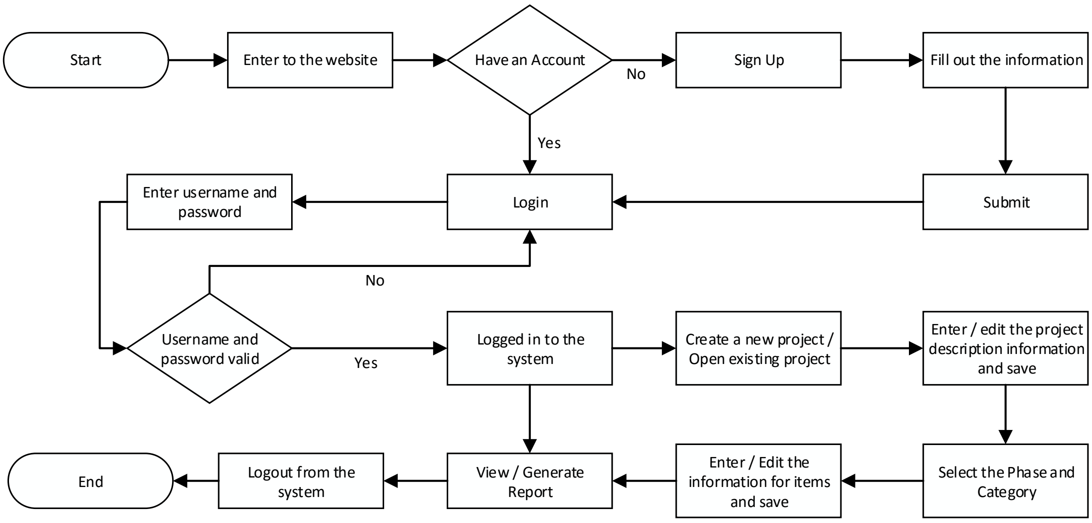


Figure 3.7: RoadCO$_2$ user map

As shown in Figure 3.7, the framework entails the exercises involved for the 'User Module' which includes the account setup, user inputs and output reports. To commence with, the user needs to register to perform operations in the web based model application. After registration the user have access to the user dashboard as shown in Figure 3.8, where the user can create new projects, open existing projects and view or download reports for the existing projects.

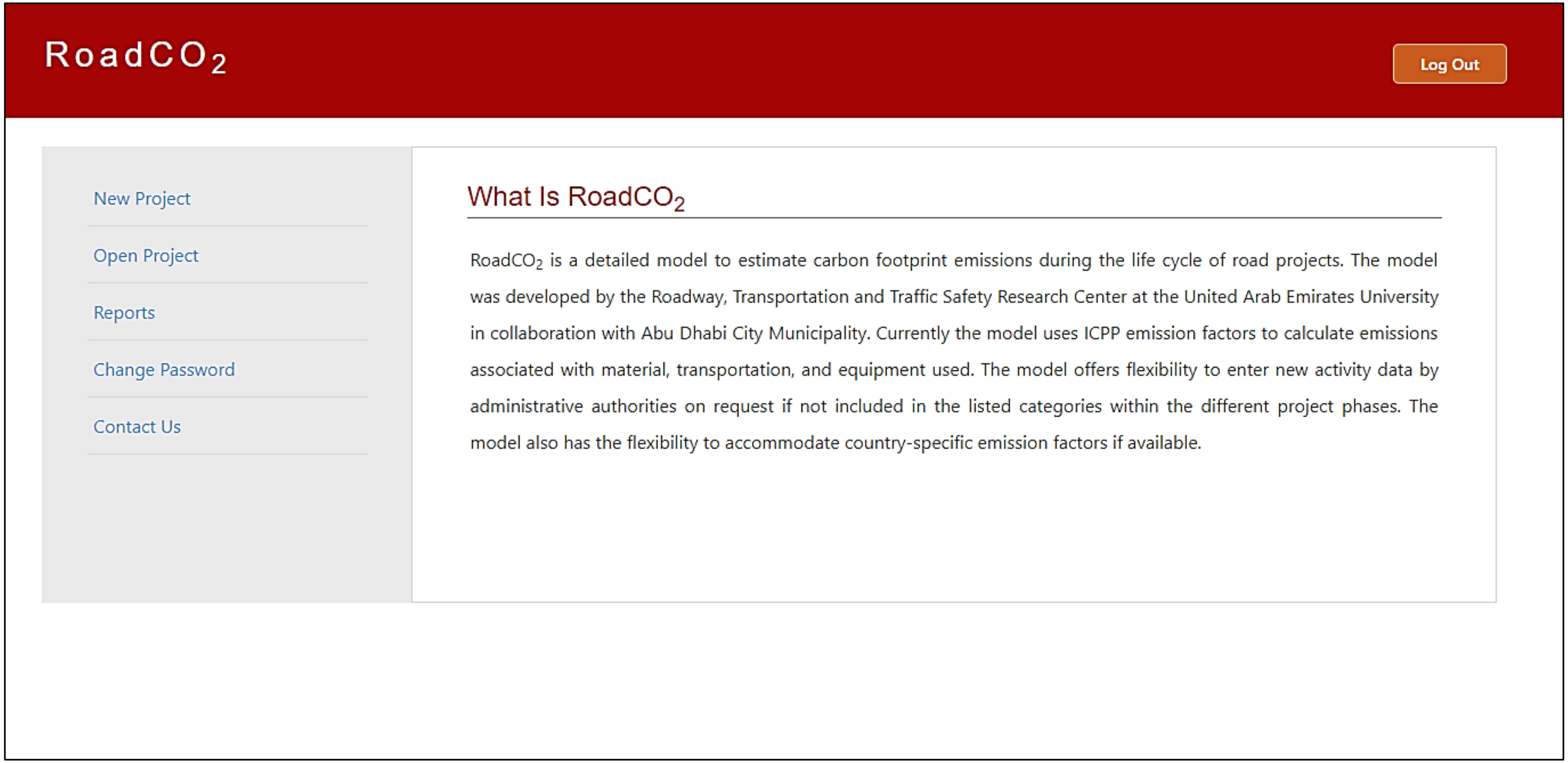


Figure 3.8: RoadCO_2 user-dashboard

While creating a new project the user needs to define the particulars confined to a specific project such as:

- Project number
- Project title
- Project location (urban or rural area)
- Nature of project
- Value of project ($)
- Duration of project (years)
- Road length (km)
- Total width (m)
- Number of lanes
- Pavement width (m)
- Number of interchanges
- Number of bridges
- Number of tunnels
- Length of tunnels (m)
- Road design life time (years)

Once the project descriptions are defined the user can input activity data such as material type, material quantity for items related to specific phases and categories of the project life cycle as shown in Figure 3.9.

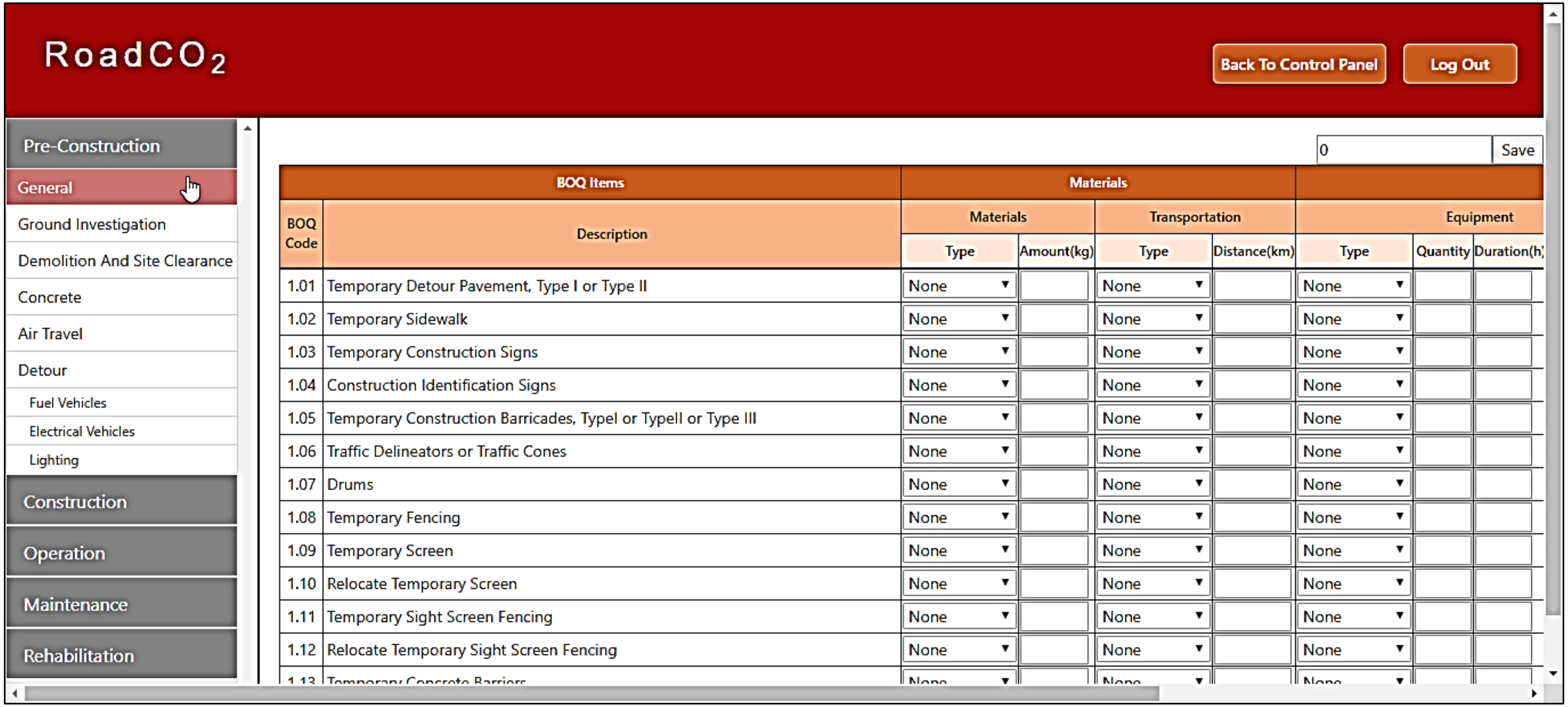


Figure 3.9: RoadCO_2 main page

The registered user can access any existing project particulars they developed before. The interface also allows the user to modify information confined to a particular project available in the project archives. Based on the user defined inputs, the RoadCO_2 model estimates the GHG emission values for the specific project. The GHG output estimates are generated in the form of interactive graphs (pie diagram) with phase specific percent outputs as shown in Figure 3.10 and document reports as shown in Figure 3.11. The user can download the output reports in specific formats.

On the other hand, the ‘Admin Module’ is recognized to edit/modify the model parameters, supposedly to change over period of research findings in relation to model parameter calibration, additional factors to be included, difference in range estimates of CO_2 emission, etc. The ‘Admin Module’ is restricted for public user and is accessible by authorized authorities/agencies involved in the model development.

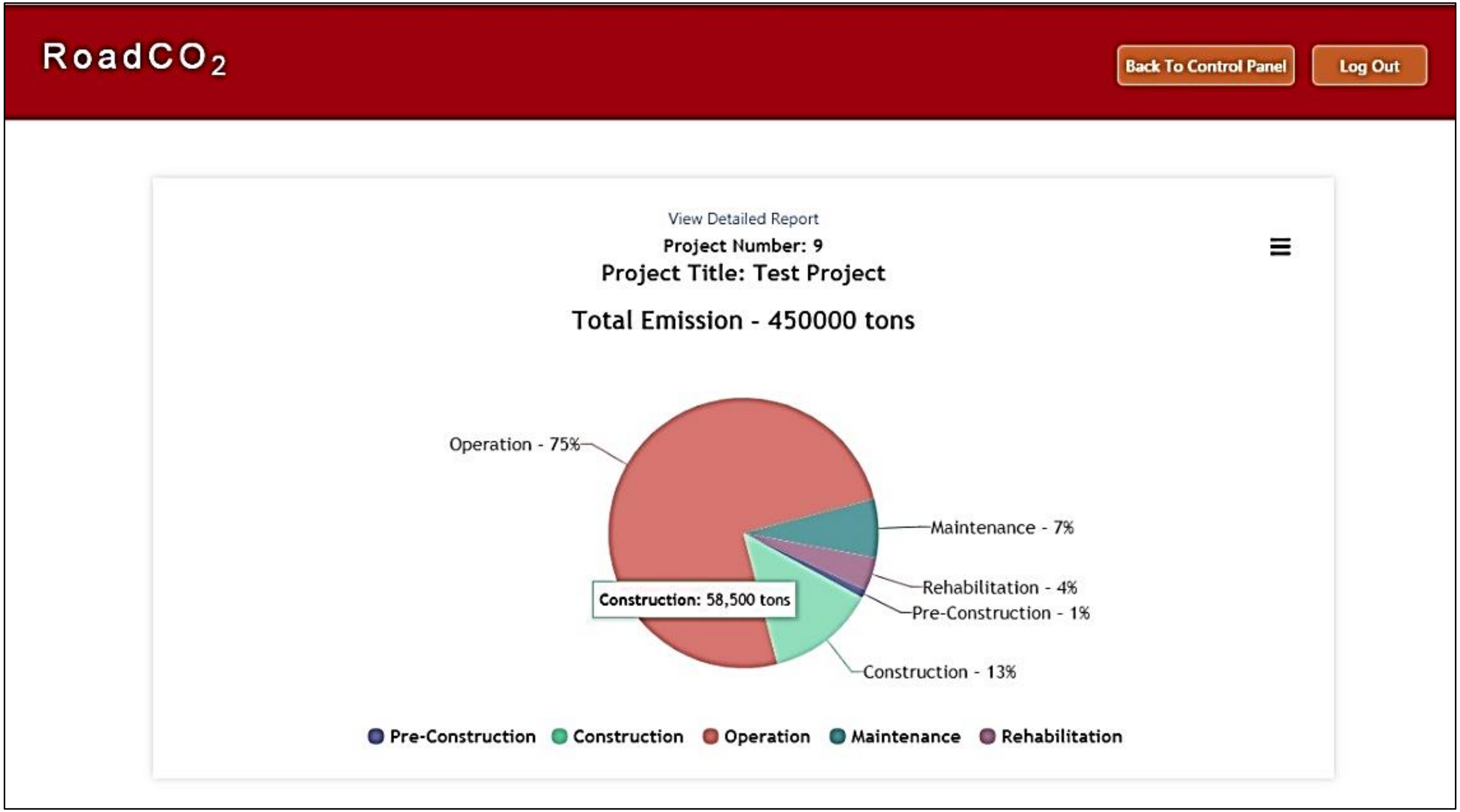
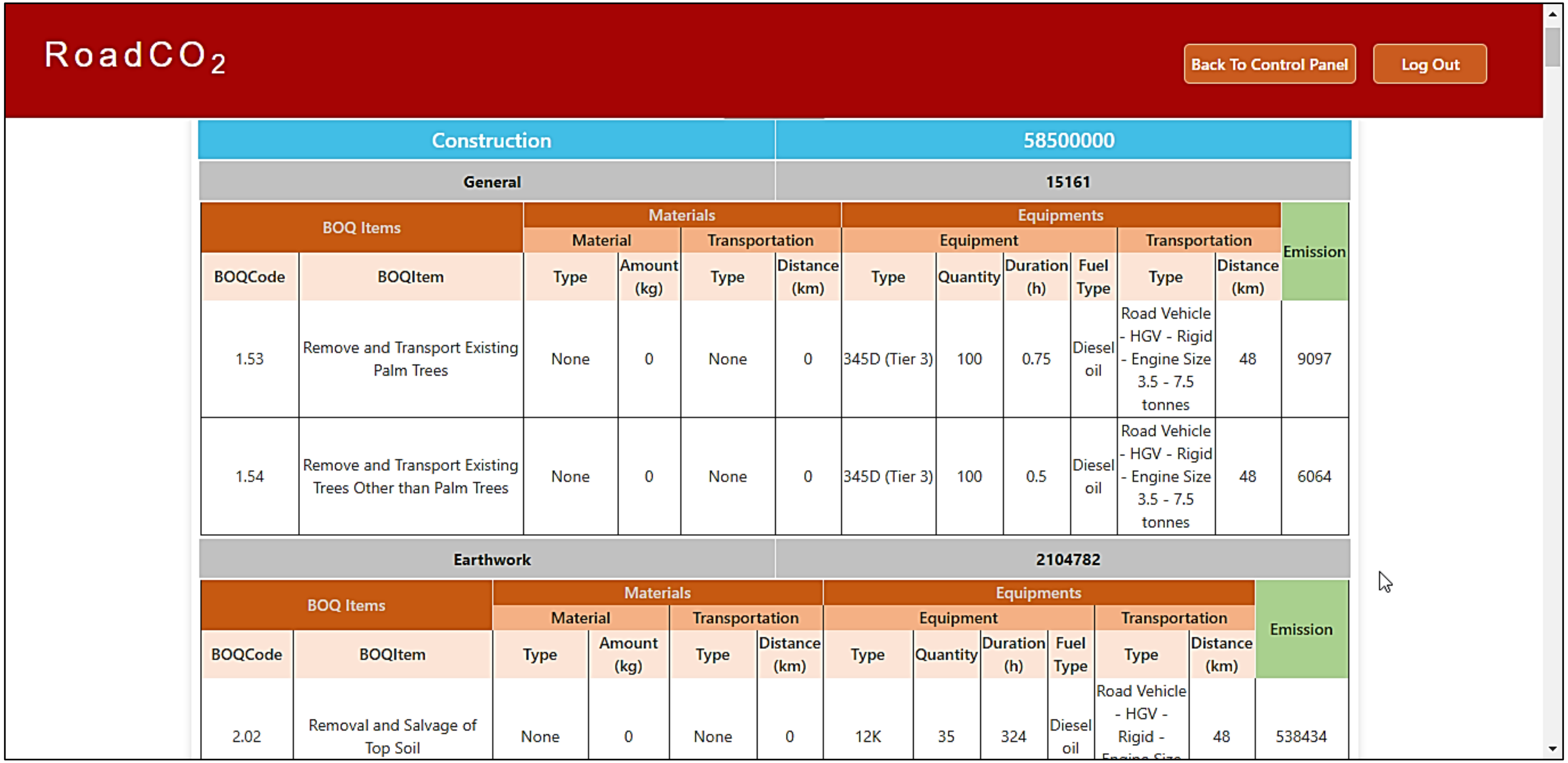


Figure 3.10: RoadCO_2 output 1



RoadCO2 | Back To Control Panel | Log Out

Construction	58500000
General	15161

BOQ Items		Materials				Equipments						Emission
		Material		Transportation		Equipment				Transportation		
BOQCode	BOQItem	Type	Amount (kg)	Type	Distance (km)	Type	Quantity	Duration (h)	Fuel Type	Type	Distance (km)	
1.53	Remove and Transport Existing Palm Trees	None	0	None	0	345D (Tier 3)	100	0.75	Diesel oil	Road Vehicle - HGV - Rigid - Engine Size 3.5 - 7.5 tonnes	48	9097
1.54	Remove and Transport Existing Trees Other than Palm Trees	None	0	None	0	345D (Tier 3)	100	0.5	Diesel oil	Road Vehicle - HGV - Rigid - Engine Size 3.5 - 7.5 tonnes	48	6064

Earthwork	2104782

BOQ Items		Materials				Equipments						Emission
		Material		Transportation		Equipment				Transportation		
BOQCode	BOQItem	Type	Amount (kg)	Type	Distance (km)	Type	Quantity	Duration (h)	Fuel Type	Type	Distance (km)	
2.02	Removal and Salvage of Top Soil	None	0	None	0	12K	35	324	Diesel oil	Road Vehicle - HGV - Rigid -	48	538434

Figure 3.11: RaodCO$_2$ output 2

3.5 Model Limitations

RoadCO$_2$ can be used to carry on carbon footprint calculations in its current state, but the model still has some limitations. Currently, the model uses IPCC default emissions factor which is the best practice since UAE lacks country-specific factors, but IPCC factors do not necessary reflect GHG emissions behavior in the UAE. For that, the model needs to be revised to include country-specific factors to obtain results that better reflect the situation in UAE.

A second limitation of the ROADCO$_2$ is related to the operation phase calculations in particular. The model does not take into consideration the effect of traffic variations in terms of speed variability. This can lead to uncertainty in the results. Speed changes have an effect on the fuel consumption rate. Thus, GHG emissions will differ depending on the speed of the vehicle.

A third limitation of RoadCO$_2$ is that it cannot exactly be used at the early stages of road projects. Usually at the early stages (planning), a great deal of the information that RoadCO$_2$ requires to carry on the calculations are not available. Thus, studying and comparing alternatives cannot be easily done with the model.

Finally, the RoadCO$_2$ model uses emission factors that are already measured in units of CO$_2$eq. This means that the model does not have the ability to report emissions of individual GHGs.

Chapter 4: Emissions of Selected Road Projects in Abu Dhabi City

4.1 Introduction

Road transport has grown continuously over the last decades and further increase in the demand for transport is projected (Smit et al., 2007). Nonetheless, the transportation sector is one of the major contributors to global climate change through emissions of CO_2 and other GHGs. Being part of the transportation sector, road transportation is responsible for more than 70% of these emissions globally (World Bank, 2010).

Abu Dhabi Emirate is the largest Emirate in the UAE, occupying about 87% of the whole country. The total paved road network in the UAE is about 4080 km, ranking it the 156th in the world (CIA, 2016). The total length of external roads in Abu Dhabi Emirate is about 2705 km (SCAD, 2016). The transportation sector in the emirate contributed about 18.547 $MtCO_2eq$ in 2010. CO_2 dominated these emissions at 98.78%, while the remaining 1.22% consisted of other GHGs (EAD, 2012). Roads accounted for about 63% of the total direct GHG emissions in the transport sector; this is mainly due to the extensive and well-developed road network in the emirate.

This chapter includes a description of the three selected road project cases in Abu Dhabi City. It also includes details of the collected data needed to carry on the estimation of emissions of these cases by $RoadCO_2$. Results of emitted CO_2 from the construction and operation phase of the selected cases are then presented.

4.2 Description of Studied Cases

Three road projects were selected in the city of Abu Dhabi as case studies based on their functional class and posted speed. RoadCO_2 was used to estimate the emissions during the construction and operation phase for these case studies. The three cases that were studied are:

- Case study 1: Construction of internal roads and services network in Al Rahba City
- Case study 2: Upgrading of Al Salam Street (official name is Sheikh Zayed Bin Sultan Street), including the construction of a new tunnel on the street
- Case study 3: Widening of the Eastern Abu Dhabi Corniche Road

A detailed description of the studied cases is presented in the following subsections.

4.2.1 Case 1: Construction of Internal Roads and Services Network in Al Rahba City

The project includes construction of internal roads and services in Al Rahba area in the city of Abu Dhabi along the Abu Dhabi-Dubai highway. The internal roads are classified as urban local roads with posted speed of 40 km/h (design speed of 60 km/hr). The size of the project is 30-km of single carriageway (i.e. two-lane roadway), 7.30 m wide, with 0.35 m wide outer shoulders and 2.0 m wide footpaths (sidewalks). The project duration was 20 months (June 2014 – February 2016). Figure 4.1 shows the location of the project and Figure 4.2 shows a photo of part of the city after project completion.

Figure 4.1: Location of the project (case study 1) in Al Rahba City (Google Earth)

Figure 4.2: Photo of Al Rahba area

Activities other than construction carriageways included in the project are construction of parking areas, footpaths (non-sidewalks), protection and relocation of existing services, ducts for future utility crossing, street lighting, stormwater drainage works and ancillary works. Data on the pavement structure of the carriageway constructed is shown in Table 4.1.

Table 4.1: Pavement design of Al Rahba road

Component	**Pavement Type 1 (Carriageway)**	**Pavement Type 2 (Driveway)**
Bituminous Wearing Course	50 mm	60 mm
Bituminous Base Course	60 mm	-
Aggregate Base Course Type C	150 mm	150 mm

A schematic representation of the pavement structure in Table 4.1 is presented in Figure 4.3. This figure is an extract from Section 8 of Volume 1 of the report "Preliminary design of internal roads and services in Al Rahba City".

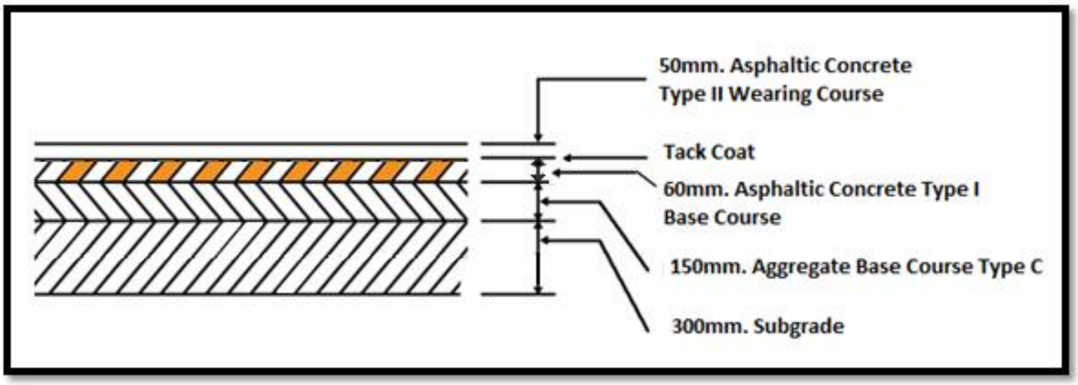


Figure 4.3: Schematic representation of a typical pavement thickness

New construction of major features of utility works along with the construction of the 30-km long carriageway was considered. The features include:

- Water ducts for future crossings under paved areas

- Electrical ducts for future crossings under paved areas
- Telephone ducts for Etisalat for future crossings under paved areas
- Ducts for agriculture division of ADM for future crossing under paved areas
- Stormwater and sewerage drainage

Installation of street lighting was undertaken with 400-Watt metal halide (MH) lantern mounted on 10-m high street lighting poles along the single carriageways. The carriageway was constructed in two stages. The first stage included the following:

- Earthworks
- Construction of bituminous base course
- Construction of curb stone only along the portion of the roads that will not be affected by future building construction
- Construction of sidewalks only along permanent parts of road network
- Construction of ducts for all departments, including ducts for street lighting
- Construction of sewerage network
- Construction of stormwater drainage network
- Construction of street lighting along the road network
- Construction of road furniture

The second stage consisted of the followings:

- Completion of earthwork
- Completion of roadways with bituminous wearing course along the internal roads
- Construction of parking areas and entrances to plots
- Completion of curb stones (curbs)

- Construction of sidewalks
- Construction of ducts for utilities
- Completion of street lighting
- Completion of road furniture
- Completion of stormwater drainage network

4.2.2 Case 2: Upgrading of Al Salam Street

Upgrading of Al Salam Street involved construction of a tunnel (known as the Sheikh Zayed tunnel) from the Dalma Street to the Corniche and Mina Port. Surface roads were also widened and several interchanges were constructed. The tunnel is 3.6 km long with 4 lanes in each direction. The posted speed ranges from 60 to 80 km/hr. The project duration was 27 months (April 2007 – July 2009). Figure 4.4 shows a photo of the Sheikh Zayed tunnel.

The objective of the project was to upgrade some sections of Al Salam Street, providing free flow traffic and facilitating connections to adjoining roads and sectors. The project involved four sections running from Al Salam Bridge to Al Mina Street and also consisted of five tunnels, a bridge, bypasses, surface and service roads. Major construction activities of the project are divided into three sections as detailed below.

Section 1: Mina Road – Al Salam Street Tunnel (IP-41 to IP-36)

The tunnel consists of both covered and uncovered sections. The closed sections consist of a cast-in-place concrete box, with a precast, pre-tensioned I-grid roof deck. The open sections and access ramps consist of cast-in-place concrete bases to counter uplift pressure. Figure 4.4 shows the location of the tunnel.

Figure 4.4: Location of the Sheikh Zayed tunnel constructed on Al Salam Street (Google Earth)

Section 2: Eastern Abu Dhabi Corniche Road (IP-111 and IP-111A)

On the Eastern Abu Dhabi Corniche Road, two interchanges were constructed at IP-111 (intersection with Street 31) and IP-111A (intersection near Khalifa Park) as shown in Figure 4.5. The tunnels (underpasses) at the IP-111 and IP-111A consist of cast-in-place closed box type with voided deck slabs. The uncovered portions of the underpass are cast-in-place concrete base slabs with retaining walls.

Figure 4.5: Section of Eastern Abu Dhabi Corniche Road (IP 111 to IP 111A) (Google Earth)

Section 3: Al Salam Street (IP-44 and Sea Palace intersection)

Al Salam Street tunnel (underpass) at IP-44, shown in Figure 4.6, consists of cast-in-place concrete closed box type with voided deck slab. The uncovered portion of the underpass consists of cast-in-place concrete base slab and retaining walls. Tension piles were used along the tunnel.

Figure 4.6: Section of the IP44 and Sea Palace Intersection (Google Earth)

Hazza Bin Zayed Street bridge structure over Al Salam Street is a post-tensioned, cast-in-place concrete box girder. The substructure consists of cast-in-place, reinforced concrete piers, abutments, and short wing walls. The foundation for these substructures included 1200 mm diameter cast-in-place concrete piles, while the retaining walls consisted of mechanically-stabilized earth (MSE) walls. Similar construction is found at the Ramp ES bridge structure over Al Salam Street and Hazza Bin Zayed Street.

Al Salam Street tunnel at the Sea Palace consists of cast-in-place concrete closed box type with solid deck slab. The uncovered portion of the underpass is cast-in-place concrete base slab and retaining walls. Tension piles are used along the tunnel.

The project consisted of four construction contracts for grade-separated interchanges, tunnels, road widening and other improvements.

4.2.3 Case 3: Widening of the Eastern Abu Dhabi Corniche Road

The scope of this project covers widening of the existing Eastern Abu Dhabi Corniche Road from IP69 (Station 15+750) to IP98 (Station 15+200) by adding a fourth traffic lane of 3.65 meters and a shoulder of 3 meters in each direction. Necessary work for widening was a temporary detour of traffic and use of existing lanes without severe congestion. Temporary construction signs and temporary sight screen fencing were also placed during construction period. The project duration was 27 months (October 2009). Figure 4.7 shows a top view of the Eastern Abu Dhabi Corniche project.

Construction included addition of an extra lane and shoulder while moving the sub-surface utilities to the new location. Earthwork consisted of clearing, grubbing, removing and disposal of debris, vegetation, buildings, fences, structures, walls, old pavement and abandoned pipelines. Also, construction involved placing and compacting of borrow materials, unclassified excavation, structure excavation and backfilling.

Figure 4.7: Section of the Eastern Abu Dhabi Corniche Road at IP 69 to IP 98 (Google Earth)

4.3 Data Collection

The RoadCO_2 model was used to estimate the GHG emissions associated with the construction and operation phase of the three case studies. To run the model, data in different forms are needed for each phase (as explained in Chapter 3). Some assumptions were made to fill in the gaps in the data provided by ADM. These assumptions were made based on engineering judgment or based on findings from the literature. Table 4.2 shows the availability of the data for the different phases for the three studied cases.

Table 4.2: Data availability for the three studied cases

Phase	**Case**		
	1. Al Rahba City	**2. Salam St.**	**3. Corniche Rd**
Pre-Construction	X	X	X
Construction	√	√	√
Operation	√	√	√
Maintenance	X	X	X
Rehabilitation	X	X	X

Table 4.3 shows a list of the documents that were reviewed from which some of the needed data were extracted to complete the exercise of estimating CO_2 emissions for the selected cases. These documents were obtained from or through ADM.

Table 4.3: List of documents from which some input data to RoadCO_2 were obtained

No.	Document
1	Contractual documents for internal roads and services in Al Rahba city case study and its drawings and design data
2	Contractual documents for upgrading of Al Slam street case study and its drawings and design data
3	Contractual documents for widening the Eastern Abu Dhabi Corniche Road case study and its drawings and design data
4	ADM Technical Specifications and Design Manuals
5	ADM Volume IV - Standard Drawings
6	Public Realm Design Manual (version 2)
7	As built drawings for Al Salam Street
8	BOQ VAL 10: Main irrigation line from Mafraq WWTP to Al Faya
9	Information on the distribution of desalinated water and TSE for landscaping
10	Information on the type of concrete mix at Al Salam Street
11	Information about stormwater pumping at Al Salam Street
12	Traffic counts at Al Rahba city internal roads
13	Daily traffic volume and speed by class (weight) at Al Salam Street
14	Hourly traffic data by class (weight) at Al Salam Street
15	Traffic counts for the Eastern Abu Dhabi Corniche Road

4.3.1 Construction Phase

For the construction phase, data for the three case studies were obtained from ADM. Quantities of construction materials and types of construction equipment that were used were all obtained from the BOQ documents supplied by ADM. According to ADM conventional standard BOQ template, the whole construction process can by categorized into 26 items depending on the nature of the work. GHG emissions from the construction phase can be categorized in eight main categories. These categories contain the 26 categories described in ADM’s standard BOQ template. The eight main categories are sewerage works, road works, lighting & electrical, landscaping & street furnishing, irrigation network, storm water network, telecommunication network, and water network. Table 4.4 shows the relationship between RoadCO$_2$ model's categories and ADM BOQ items. It should be indicated that the BOQs received from ADM for the three cases followed the old forms which differ from the conventional BOQ forms in their sequence and naming, but not their content.

Quantities of materials used during construction are expressed in different units in the BOQ documents. These units are square meter, linear meter or number of quantities. For now, RoadCO$_2$ model can only deal with materials in mass units (kg), and because of that, data related to material quantities must be converted into mass units. To perform this conversion, volumes of these materials were multiplied by their densities, and to do so, the standard drawings provided by ADM were used (document # 5 of Table 4.3). The drawings were particularly helpful in showing the dimensions of the components these construction materials were used for. For materials that were expressed in square meters, the thickness was found to determine the volume. For materials expressed in liner meters, the cross-sectional area was extracted from the drawings to get the volume. Appendix C contains the densities that were used to covert volume to mass for the different used materials.

Table 4.4: Relationship between $RoadCO_2$ model's categories and ADM BOQ items

#	BOQ Item / Category	1	2	3	4	5	6	7	8
		Sewerage	Road works	Lighting & electrical	Landscaping & furnishing	Irrigation network	Stormwater network	Telecom. network	Water network
1	General		√						
2	Earthworks		√						
3	Pavement		√						
4	Concrete works		√						
5	Reinforcing steel		√						
6	Masonry		√						
7	Incidental construction	√	√	√	√	√	√	√	√
8	Traffic markings and signs		√						
9	Traffic signal system			√					
10	Illumination			√					
11	Stormwater drainage						√		
12	Utilities	√		√	√	√	√	√	√
13	Drilled piles		√						
14	Driven piles		√						
15	Ground anchors		√						
16	Earth retaining system		√						
17	Concrete structures		√						
18	Steel structures		√						
19	Painting	√	√	√	√	√	√	√	√
20	Bridge deck joint systems		√						
21	Railings		√						
22	Water proofing		√						
23	Miscellaneous items for structures		√						
24	Precast concrete culverts		√						
25	Road tunnels		√						
26	Bridge and tunnel load testing		√						

Construction equipment data were also provided in the documents obtained from ADM. These documents show the type of equipment used, their quantity, and the usage duration. To carry on the estimation using RoadCO_2, the operational period of each type of equipment in hours is needed. In addition to that, the type of fuel used by each type of equipment is needed. RoadCO_2 uses these inputs to calculate the amount of fuel consumed by each type of construction equipment. RoadCO_2 considers the amount of fuel burned by the construction equipment as the primary source of GHG emissions. It does not take into account the amount of GHG emissions emitted during the manufacturing of these equipment (as described in Chapter 3). Construction equipment were assumed to work eight hours per day, 6 days a week. Moreover, diesel was assumed to be the type of fuel used to operate these equipment.

Transportation of both construction material and equipment were also considered. Collected information about the studied cases does not indicate the transportation mode used to transfer the material and equipment to the site or the number of trips that were made. Also lacking is the place where the material and equipment were transported from. These data are key inputs in RoadCO_2 to calculate the GHG emissions due to transportation. To carry on the estimation process, the mode of transportation, the distance, and the number of trips were assumed. Dumpers, trailers, pickups, six wheelers, and trucks were used to transport the materials to the site. Since there were no available data on their specifications, the mode of transportation was assumed to be rigid heavy goods vehicles (HGV) road transportation with unknown engine size. This assumption was also used for the trailers that were used to transport the construction equipment to the site. Both construction material and equipment were assumed to be transported from Mussafah Industrial Area. The distance depends on the location of the road project selected. In addition to the assumptions made regarding the mode of transportation used and the distance, the number of trips was also assumed. This assumption was made based on the capacity of the mode used and the amount of both construction materials and equipment that needs to be transported. Table 4.5 shows the distances used to estimate emission due to transportation of material and equipment to the three sites of the investigated case studies.

Table 4.5: Transportation distances considered for the three case studies (km)

	Case 1: Al Rahba City	**Case 2: Al Salam St.**	**Case 3: Corniche Rd.**
Material	96	55	70
Aggregate	501	598	598
Equipment	96	55	70

*Distances shown in the table represent a round trip from Mussafah Industrial Area to the project's site.

4.3.1.1 Construction Phase Data for Case 1

The BOQ (document #1 of Table 4.3) for the construction of the internal roads and services network in Al Rahba city (Case study 1) included complete activities carried out on the site. It was prepared before implementation of the project and hence actual activities and quantities might have deviated from those listed in the BOQs. The tender BOQs were used since actual data were not available. The quantity of materials used is presented in Table 4.6. Concrete mixes used in this case are composed of 100% Portland cement (PC). Equipment that were used on site for carrying out the construction activities are listed in Table 4.7. RoadCO_2 model depends on the fuel consumption rate for the different types of construction equipment. It uses the entered data to quantify the total amount of fuel used by all equipment and then estimates the total GHG emissions based on the selected fuel type. Transporting the construction materials and equipment were assumed to take place from Mussafah Industrial Area

(48 km from the site), except for the aggregate which is transported from Fujairah with a distance of 501 km from Al Rahba city (see Table 4.5).

Table 4.6: Materials used for Al Rahba City (Case Study 1)

Materials/Activities	**Quantity**	**Unit**
Section-1: Earthwork		
Concrete - K140	428.4	m^3
Borrowing material	100,350	m^3
Backfill	16,500	m^3
Excavation	166,650	m^3
Section-2: Sub-base and base courses		
Aggregate base	36,200	m^3
Section-3: Asphalt works		
Asphalt	2,858	m^3
Remove and transport covers	75	No.
Demolishing - Jackhammer	100	m^3
Cold planning	150	m^3
Section-4: Concrete works		
Steel	91	ton
Concrete - K140	1,606	ton
Concrete - K250	1,080	ton
Pedestrian pavers	440	m^3
Section-5 Stormwater Drainage		
Aggregate	21978	m^3
Concrete - K250	69	m^3
Concrete - K455	5342	m^3
PVC	125	ton
GRP	195	ton
Geotextile Fabrics	5.5	ton
Section-7 Telephone Works		
Concrete - K250	20	m^3
Section-8 Sewerage Works		
Concrete - K140	468	m^3
Concrete - K250	230	m^3
Steel	91	ton
GRP	2.1	ton
PVC	57	ton

Table 4.7: Equipment used for constructing Al Rahba roads (Case Study 1)

Equipment type	**Quantity**	**Operating hours**
Excavator	129	720
Bobcat	168	720
Compactor	148	720
Cutter	55	680
Loader	172	760
Grader	35	680
Tipper	62	720
Water trailer	18	640
Rollers	10	400
JCB	13	520
Rock breaker	10	400
Dozer	18	640
Grader checker	18	640
Air compressor	10	400
Double drum roller	9	360
Baby roller	10	400
Pneumatic tyre roller (PTR)	13	400
Steel vibrating roller (SVR)	9	360
Milling machine	10	400
Paver	10	400

4.3.1.2 Construction Phase Data for Case 2

Al Salam road project involved construction of a tunnel of 3.6 km length with 4 lanes in each direction (document #2 of Table 4.3). BOQ items obtained from ADM were for the construction of section 2 of Al Salam Street. The materials used to the site are presented in Table 4.8. Concrete mixes used in this case for non-structural purposes are composed of 65% Portland cement (PC) and 35% fly Ash, while concrete mixes used for structural purposes are composed of 30% PC and 70% ground granulated blast-furnace slag (GGBFS). Construction equipment used in this project are listed in

Table 4.9. Transportation distance of the construction materials and equipment is referred to in Table 4.5.

Table 4.8: Materials used for Al Salam Street (Case Study 2)

Material/Activities	**Quantity**	**Unit**
Section-1: General		
Irrigation water on site	100,000	Imperial gallon
Section-2: Earthwork		
Concrete - K140 (65% PC, 35% Fly ash)	800	m^3
Borrowing material	60,500	m^3
Backfill	122,200	m^3
Geotextile fabric	28.8	ton
Stone rip-rap	1,500	m^3
Excavation	657,200	m^3
Section-3: Sub-base and Base Courses		
Aggregate base	39,150	m^3
Sand asphalt	266.4	m^3
Section-4: Asphalt works		
Asphalt	120	m^3
Remove/transport covers & frames	30	No.
Demolishing	10	m^3
Cold planning	1,700	m^3
Section-5: Concrete Works		
Steel	13,580	ton
Concrete - K140 (65% PC, 35% fly ash)	10,063	m^3
Concrete - K250 (65% PC, 35% fly ash)	1,400	m^3
Concrete - K415 (30% PC, 70% GGBFS)	143,901	m^3
Pedestrian pavers	960	m^3
Transport of concrete pavers	400	m^2
Quarry tiles	65	m^3
Asphalt	354	ton
Section-6: Storm Water Drainage System		
PVC	32,240	kg
GRP	1,446,510	kg
Concrete - K455 (30% PC, 70% GGBFS)	212	m^3
Concrete - K550 (30% PC, 70% GGBFS)	92.46	m^3
Steel	8.6	ton
Excavation & backfill	70,900	m^3

Table 4.8: Materials used for Al Salam Street (Case Study 2) (Continued)

Material/Activities	**Quantity**	**Unit**
Section-7: Water Works		
Concrete - K250 (65% PC, 35% fly ash)	290	m^3
GRP	45,840	kg
Removal of concrete slabs	100	m^2
Section-7B: Development of Water Works		
Concrete - K140 (65% PC, 35% fly ash)	21	m^3
HDPE	42,7460	kg
Steel	1,158	m^3
Aluminium	2,945	kg
Section-8: Site Laboratory		
Establishing & removal of site lab	2	Item
Section-9: Concrete Pile Foundation		
Concrete - K415 (30% PC, 70% GGBFS)	5,225	m^3
Section-10: Metal Works		
Extruded aluminum	60,400	kg
Cast aluminum	9,400	kg
Section-11: Irrigation Works		
Concrete - K250 (65% PC, 35% fly ash)	200	m^3
PVC	208,978	kg
GRP	16,460	kg
Section-11B: Irrigation Pipelines		
Concrete	0.47	m^3
HDPE	3,6008	kg
Steel	103	kg
uPVC	28,936	kg
Section-12: A Lighting and Electrical Distribution Works		
Concrete - K140 (65% PC, 35% fly ash)	2,555	m^3
PVC	162,693	kg
Tiles	333	m^3
Section-12B: Relocation of existing 132 kV Cables		
Concrete - K140 (65% PC, 35% fly ash)	75	m^3
Copper	181,013	kg
PVC	2,720	kg
Section-12C: Relocation of existing 33 kV XLPE Cable Circuits at IP41		
Copper	452,458	kg
PVC	906	kg
Section 13: Traffic Control System		
Concrete - K140 (65% PC, 35% fly ash)	100	m^3

Table 4.8: Materials used for Al Salam Street (Case Study 2) (Continued)

Material/Activities	**Quantity**	**Unit**
PVC	12,352	kg

Table 4.8: Materials used for Al Salam Street (Case Study 2) (Continued)

Material/Activities	**Quantity**	**Unit**
Section-14: Telephone		
Concrete - K140 (65% PC, 35% fly ash)	240	m^3
Concrete - K250 (65% PC, 35% fly ash)	150	m^3
PVC	26,531	kg
Section-14B: Telephone Relocation Works		
Concrete - K140 (65% PC, 35% fly ash)	1,415	m^3
uPVC	38,166	kg
Section-15: Sewerage Works		
Concrete - K250 (65% PC, 35% fly ash)	390	m^3
GRP	43,000	kg
Section-15B: Sewerage Relocation Works		
Concrete - K140 (65% PC, 35% fly ash)	30	m^3
GRP	832,396	kg
uPVC	306	kg
Section-16: Street Furniture		
Concrete - K140 (65% PC, 35% fly ash)	2	m^3
Section-17: Mechanical Works		
Galvanized iron pipe	41	ton
Concrete - K250 (65% PC, 35% fly ash)	200	m^3

Table 4.9: Equipment used for constructing Al Salam Street (Case Study 2)

Equipment	Quantity	Operating hours
Crane	73	13,260
Excavator	97	17,940
Loader	65	15,600
Grader	41	17,940
Bob cat	30	19,500
Soil compactor	66	17,160
Truck	367	17,940
JCB	84	18,720
Mounty crane	8	6,240
Finisher	36	9,360
Milling machine	7	5,460
Asphalt compactor	27	7,020
Spray	18	7,020
Water tanker	64	3,120
Tire compactor	36	9,360
Saw cutter	9	7,020

4.3.1.3 Construction Phase Data for Case 3

This case study involved addition of an extra lane and a shoulder on both sides of the already existing roadways. The length of widening was 2.87 km. The width of the new lane was 3.65 m and the width of the new shoulder was 3 m (document #3 of Table 4.3). Materials used during construction are given in Table 4.10. Concrete mixes used in this case are composed of PC only. Construction equipment used in this project are listed in Table 4.11. Transportation distance of the construction materials and equipment is listed in Table 4.5.

Table 4.10: Materials used for Corniche Road (Case Study 3)

Material / Activities	**Quantity**	**Unit**
Section-1: General		
Irrigation Water on Site	100,000	Imperial gallon
Section-2: Earthwork		
Concrete - K140	1	m^3
Geotextile fabric	9,365	kg
Borrowing material	32,900	m^3
Backfill material	9,100	m^3
Excavation	32,648	m^3
Section-3: Sub-base and Base Courses		
Aggregate base	5,825	m^3
Section-4: Asphalt works		
Asphalt	42	ton
Geo grid	200	kg
Demolishing	3,500	m^3
Section-5: Concrete Works		
Steel	5	ton
Concrete - K140	2,063	m^3
Interlocking pedestrian pavers	1,350	m^3
Section-6: Storm Water Drainage System		
Concrete - K550	33	m^3
PVC	45,136	kg
GRP	37,290	kg
Excavation	5,985	m^3
Section-7: A- Water Works		
Concrete - K250	20	m^3
GRP	10,440	kg
Demolishing	10	m^3
Section-8: Irrigation Works		
HDPE	268,785	kg
PVC	3,753	kg
Demolishing	194	m^3
Section-9: A Lighting and Electrical Distribution Works		
Concrete - K140	282	m^3
Concrete - K250	9	m^3
PVC	8,025	kg
Cable covering tile	5	m^3

Table 4.10: Materials used for Corniche Road (Case Study 3) (Continued)

Material/Activities	**Quantity**	**Unit**
Section-10: Traffic Control System		
Concrete	71	m^3
PVC	10,736	kg
Section-11: Telephone Works		
Concrete - K140	45	m^3
Concrete - K250	6.88	m^3
PVC	3,286	kg
Section-12: Civil Works		
Concrete - K140	30	m^3
Asphalt	138	m^3
Road base	105	m^3

Table 4.11: Equipment used for constructing Corniche Road (Case Study 3)

Equipment type	**Quantity**	**Operating hours**
Hydraulic excavator	4	142.5
Truck	13	134
Pick up	7	1840
Air compressor	4	20
Tractor	1	20
Cutter	2	20
Concrete paving spread	2	20
Tractor	2	20
Excavator	3	20
Dozer	3	60
Crawler loader	5	100
Grader	2	20
Landfill compactor	3	40
Drum roller	1	20
Vibratory roller	3	20
Drum truck	5	20
Water tanker	3	20
Dewatering	3	60

4.3.2 Operation Phase

Road operation is the next step in the life span of the road. The operation phase extends over the road service lifetime, which is usually between 30-50 years. Vehicle movement, traffic signals, road lighting, irrigation, stormwater pumping, and sequestration are activities that contribute to the road GHG emissions during the operation phase. While they vary in their contribution of GHG emissions/sink, it is agreed that these activities are the main contributors to the road's operation phase GHG emissions. RoadCO_2 was used to estimate the GHG emissions/sink of these activities. However, some assumptions, discussed below, were made to carry on the estimation. These assumptions were made because of lack of data.

4.3.2.1 Vehicle Movement

As discussed in Chapter 3, an important component in the GHG estimation of vehicle movement is traffic volume. Actual traffic counts were obtained from ADM for all the cases. These traffic counts varied in form, so some adjustment were made. In addition to the traffic data, RoadCO_2 requires the class of the vehicles, their model, their speed, the travelled distance (road length), and the type of fuel used by these vehicles. Assumptions regarding the vehicles' class, model, speed, and fuel used were made. Traffic counts provided by ADM classify vehicles based on their length, while RoadCO_2 provides different classes that are based on the type of the vehicle. The first assumption was regarding the vehicles' class. Table 4.12 shows how ADM's classifications were converted into RoadCO_2 model classification and it also shows how the results are being reported.

Table 4.12: Classifications assumptions

RoadCO2 classification	**ADM classification**	**Reported results**
Two-seater	Class 1 (> 3.5m)	Passenger car (PC)
Mini-compact		
Sub-compact		
Compact		
Mid-sized		
Full-sized		
Station wagon, small		
Station wagon, mid-sized		
Pickup truck, small	Class 2&3 (3.5-8m)	Light trucks (LT)
Pickup truck, standard		
Sport utility vehicle		
Minivan		
Van, cargo		
Van, passenger		
Heavy trucks	Class 4, 5, & 6 (< 8m)	Heavy trucks (HT)

In case of Al Rahba City case, traffic counts were measured at 13 different locations covering the whole network (Appendix H). Measurements were conducted for different days during late 2017 and early 2018 (document #12 of Table 4.3). Obtained traffic counts for the limited measurement days were extrapolated to come up with average annual traffic counts for each vehicle class as shown in Table 4.13.

Table 4.13: Vehicle counts for Al Rahba City case study

Vehicle class	**Annual average traffic counts (veh/yr)**	
Passenger car	3,193,090	11,902,715
Light trucks	6,714,804	
Heavy trucks	1,994,821	

In Al Salam Street, ADM provided traffic counts for a two-year period (July 2014 – July 2016) in one direction (document #13 and 14 of Table 4.3). The annual traffic counts were calculated as the average over the two years. The average was then multiplied by two to get the average annual traffic counts for Al Salam Street case.

Table 4.14 shows the annual vehicle counts for each class considered in RoadCO$_2$ for the case of Al Salam Street.

Table 4.14: Vehicle counts for Al Salam Street case study

Vehicle class	**Annual average traffic counts (veh/yr)**	
Passenger car	27,550,010	73,052,286
Light trucks	37,669,054	
Heavy trucks	7,833,222	

For the Corniche Road, ADM provided a one-hour traffic counts at 7am on 27/04/2015 for the two directions (document #15 of Table 4.3). To carry on the calculations using this limited data set, the annual traffic counts for the Corniche Road is assumed to be proportional to that of Al Salam Street since the latter is an extension of the former. Thus, the annual traffic counts on the Corniche Road was estimated as the annual traffic counts on Al Salam Street multiplied by the traffic count for the Corniche Road at 7 am on 27/4/2015 and divided by the traffic count for Al Salam Street at 7 am on the same day. Table 4.15 shows the average annual traffic counts considered in RoadCO$_2$ for the case of the Corniche Road.

Table 4.15: Vehicle counts for the Corniche Road case study

Vehicle class	**Annual average traffic counts (veh/yr)**	
Passenger car	30,372,274	80,535,871
Light trucks	41,527,928	
Heavy trucks	8,635,669	

The second assumption was regarding the vehicles speed using the road. It was assumed that the vehicles using Al Salam Street were moving at a speed that ranges between 60 and 120 km/h. For Al Rahba City case, it was assumed that the vehicles using the road network were at a speed that ranges between 60 to 80 km/h. For the

Corniche Road case, it was assumed that the vehicles were moving at a speed that ranges between 60 to 120 km/h. The last assumption was related to the type of fuel used by these vehicles. This assumption applies for all case studies. For passenger cars (or class 1), it was assumed that the whole passenger cars fleet uses gasoline as a fuel. For light trucks (or classes 2 & 3), it was assumed that 60% of the light trucks fleet uses gasoline while the remaining 40% uses diesel. As for heavy trucks, diesel was assumed to be the used fuel.

The last piece of information needed to carry on the estimation is the distance travelled by the vehicles. Distance for the three cases was measured using Google Earth. For Al Rahba City case, the whole city was divided into 3 zones. These segments correspond to the locations where traffic counters were placed. The distance from the center of each zone to the nearest exit were 0.93, 2.57, and 2.64 km (see Figure 4.8). For Al Salam Street case, the travelled distance was assumed to be equal to the length of the newly constructed segment. This assumption is valid since the traffic characteristics of the segment for which traffic data are available is similar to that of the constructed segment. The distance for Al Salam Street segment was therefore considered to be 3.6 km. As for the Corniche Road, the distance was 2.87 km (i.e., identical to the length of the constructed segment).

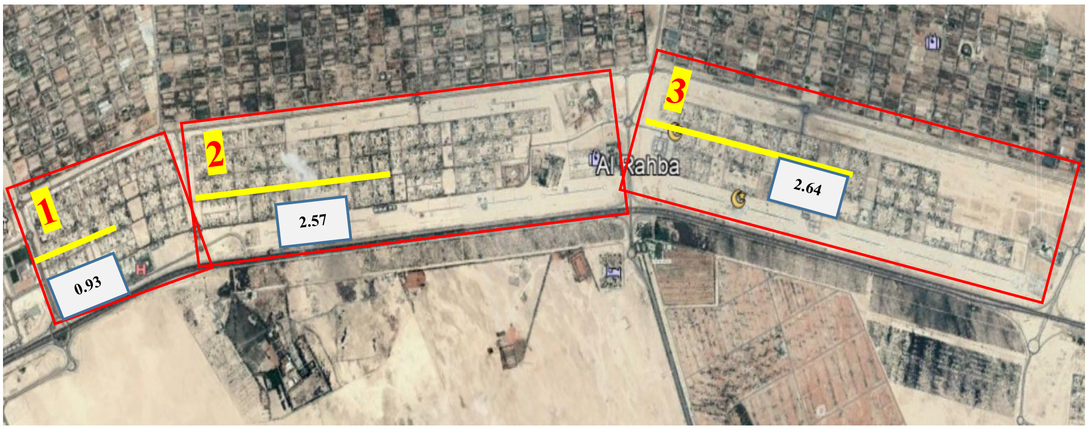


Figure 4.8: Travelled distance (in km) of each zone in Al Rahba City (Google Earth)

Collected data and made assumptions were incorporated into RoadCO$_2$ to obtain the GHG estimation due to traffic operation. Table 4.16 summaries the input parameter values used in RoadCO$_2$ for the three studied cases.

Table 4.16: RoadCO$_2$ model input data for vehicle movement

Case	Vehicle class	Annual traffic volume	Distance travelled (km)	Fuel used
1. Al Rahba City	Passenger car	3,193,090	0.93, 2.57, 2.64	Gasoline
	Light trucks	6,714,804		Gasoline and diesel
	Heavy trucks	1,994,821		Diesel
2. Al Salam Street	Passenger car	27,550,010	3.6	Gasoline
	Light trucks	37,669,054		Gasoline and diesel
	Heavy trucks	7,833,222		Diesel
3. Corniche Road	Passenger car	30,372,274	2.87	Gasoline
	Light trucks	41,527,928		Gasoline and diesel
	Heavy trucks	8,635,669		Diesel

4.3.2.2 Traffic Signals

Data on traffic signals were not available for the three studied cases.

4.3.2.3 Street Lights

To estimate emissions from usage of street lights, RoadCO_2 needs the quantity of lamps used, their wattage, and their type. It also requires the operation period of the lamps. Data on the quantity and the wattage of the lamps are available in the BOQ documents provided by ADM for the case of Al Salam Street and the Corniche Road. For Al Rahba city case study, data on the quantity of electrical poles and bulbs were collected through a limited field survey to the site. For this case, it was found that there are about 1,271 poles with one 400-watt bulb each.

Based on consultation with ADM, street lamps operate on the average 11 hr/day, with a total operation of 4018 hr/yr. It was further assumed that any broken light is replaced with the same type and wattage. RoadCO_2 provided the emissions caused by operating these lights for a full year. Table 4.17 summarizes the quantities of lamps used in each case, and their wattage.

Table 4.17: RoadCO_2 model input data for the street lights

Case	**Lamp type**	**Quantity**	**Wattage**
1. Al Rahba City	HPS lantern	1,271	400
2. Al Salam Street	Lanterns	60	1,000
	Lanterns	10	400
	HPS lantern	368	1,000
	HPS lantern	1,080	400
	HPS lantern	60	150
3. Corniche Road	Lanterns	200	1,000
	Lanterns	30	400

4.3.2.4 Irrigation

To estimate emissions from usage of water for landscaping, RoadCO_2 needs the amount of water used. To figure out this quantity, one needs to know the irrigation rates for the used plants on the road. Irrigation rates are selected in $RoadCO_2$ based on the user input of plant type and irrigation requirements. $RoadCO_2$ then uses the user's inputs of duration and type of water used to estimate the quantity of water and the GHG emissions associated with water usage. Data on water transmission was not available, so this item was not accounted for in the estimation of GHG emissions.

Data on the type of plant used on the road, their quantities, and irrigation requirements were not fully available, thus some assumptions were made to carry on the estimation by $RoadCO_2$. Using the BOQ documents provided by ADM, the type and the quantity of plants existing on the road was determined for both Al Salam Street and the Corniche Road. It was assumed that all the removed or relocated plants form the site (as mentioned in BOQ documents) were re-planted on the road. For Al Rahba City case, the number of plants were obtained through a limited survey of the site. The second assumption was that these plants have a medium irrigation requirement. ADM requires that 75% of the irrigation water should be treated sewerage effluent (TSE), while the remaining 25% to be desalinated water (document #9 of Table 4.3). Table 4.18 summarizes these data.

Table 4.18: $RoadCO_2$ model input data for irrigation

Case	**Plant type**	**Plant quantity**	**Irrigation requirement**	**Duration (day/year)**
1. Al Rahba City*	Palm trees	-	Medium	365.25
	Other trees	1,538		
2. Al Salam Street	Palm trees	400		
	Other trees	200		
3. Corniche Road	Palm trees	320		
	Other trees	90		

* Based on data collected during a limited survey of the site

4.3.2.5 Stormwater Pumping

To estimate emissions from the stormwater pumping system, RoadCO_2 needs the amount of electricity consumed. To figure out this quantity, one needs to know how many pumps exist in the system, the power of the pumps (either in horse power of kW), and the operation duration for each pump. These inputs allow RoadCO_2 to quantify the amount of electricity that is consumed and then find the GHG emissions associated with the operation of the system. Al Salam Street has two pumping stations, these are stormwater pumping stations in UB15 and UB23 (document #11 of Table 4.3). Data regarding these two pumping stations were provided by ADM and are shown in Table 4.19. An assumption was made that each pump operates 6 hours per raining day. Based on the data provided by ADM, there were five raining days in 2017. Thus, stormwater pumps on Al Salam Street operate 30 hours per year. No data were available for stormwater pumping in Al Rahba City or for the Corniche Road case study.

Table 4.19: RoadCO_2 model input data for stormwater pumps

Case	**Location**	**Number of pumps**	**Pump power (kW)**	**Operation duration (h/yr)**
Al Salam Street	UB15	2	16	30
	UB24	2	35	30

4.3.2.6 Sequestration

To estimate the effect of sequestration due to road plantation, data related to plant type, age, and growth rate are needed. As mentioned before, data on these plants are not fully available, so it was assumed that all removed or relocated plants form the site (as mentioned in the BOQ documents) were re-planted on the road for both Al Salam Street case and the Corniche Road case, while plants number in Al Rahba City case were counted in a limited site survey. All the plants were assumed to be hardwood, with a moderate growth rate. These plants were assumed to be 10 years old. Table 4.20 summarizes the data used in RoadCO_2 to get the annual rate of sequestration.

Table 4.20: RoadCO_2 model input data for sequestration

Case	**Plant type**	**Plant age (yr)**	**Growth rate**	**Quantity**
1. Al Rahba City	Hardwood	10	Moderate	1,538
2. Al Salam Street				600
3. Corniche Road				410

4.4 Results of GHG Emissions of the Studied Cases

4.4.1 Construction Phase GHG Emissions

The total emissions from construction of the studied three cases are: 42,703 ton CO_2eq for Al Rahba case, 291,581 ton CO_2eq for Al Salam Street case, and 16,472 ton CO_2eq for the Corniche Road case. The distribution of these emissions as per the conventional BOQ items that were collected from ADM are listed in Table 4.21. The relative distribution of emissions among the 8 different construction categories is shown in Figures 4.9, 4.10, and 4.11 for Al Rahba, Al Salam and the Corniche case studies, respectively. The absolute contribution of the different construction-related categories to GHG emissions of the three cases studies is shown in Figure 4.12.

Table 4.21: Contribution of BOQ items to emissions for the studied cases

BOQ items	**Emissions (ton CO_2eq)**		
	Case 1	**Case 2**	**Case 3**
General	15	60	48
Earthworks	18,713	31,624	4,629
Pavement	2,058	27,799	4,807
Concrete works	-	6,320	197
Reinforcing steel	256	37,926	26
Masonry	-	-	-
Incidental construction	4,932	110,535	3,923
Traffic markings and signs	-	-	-
Traffic signal system	-	-	153
Illumination	-	4,805	467
Storm water drainage	11,480	50,965	1,284
Utilities	5,248	19,003	939
Drilled piles	-	2,533	-
Driven piles	-	-	-
Ground anchors	-	-	-
Earth retaining system	-	-	-
Concrete structures	-	-	-
Steel structures	-	-	-
Painting	-	-	-
Bridge deck joint systems	-	10	-
Railings	-	-	-
Water proofing	-	-	-
Miscellaneous items for structures	-	-	-
Precast concrete culverts	-	-	-
Road tunnels	-	-	-
Bridge and tunnel load testing	-	-	-
Total	42,703	291,581	16,472

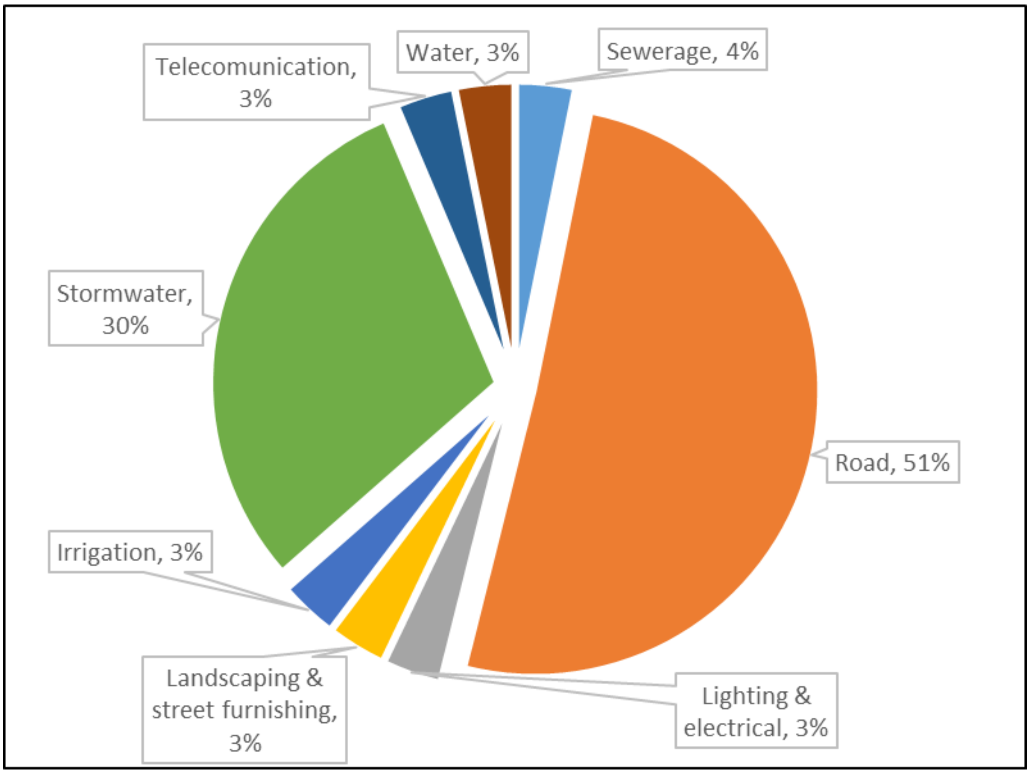


Figure 4.9: Distribution of emissions among the 8 different construction categories for Al Rahba Road case study

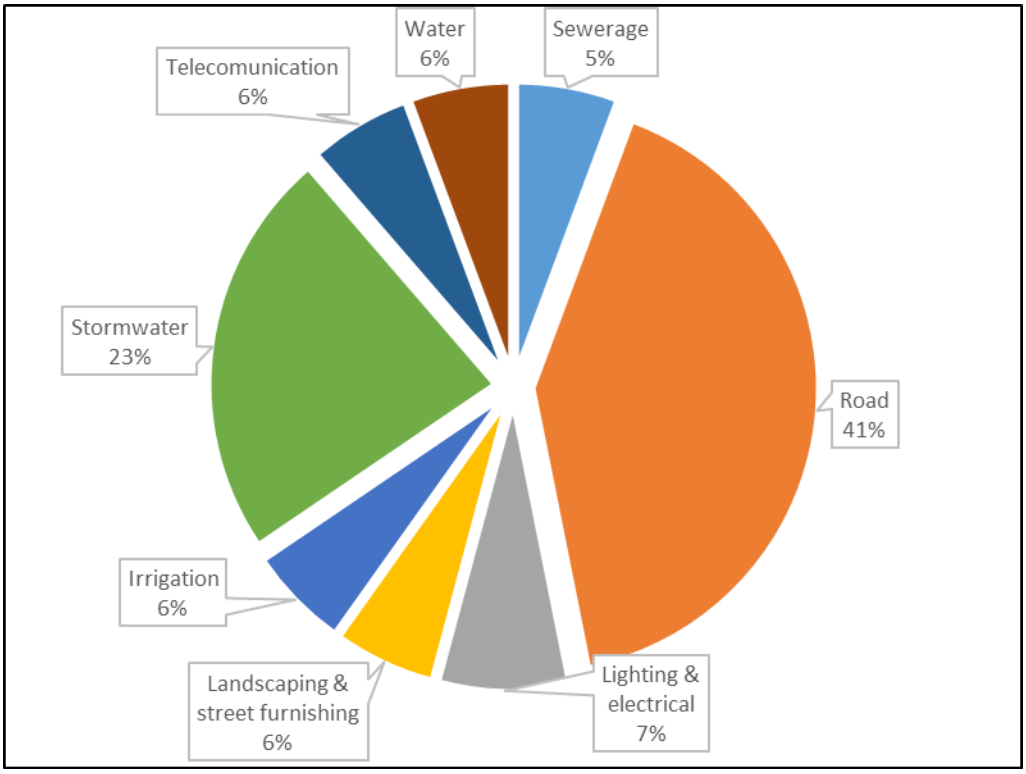


Figure 4.10: Distribution of emissions among the 8 different construction categories for Al Salam Street case study

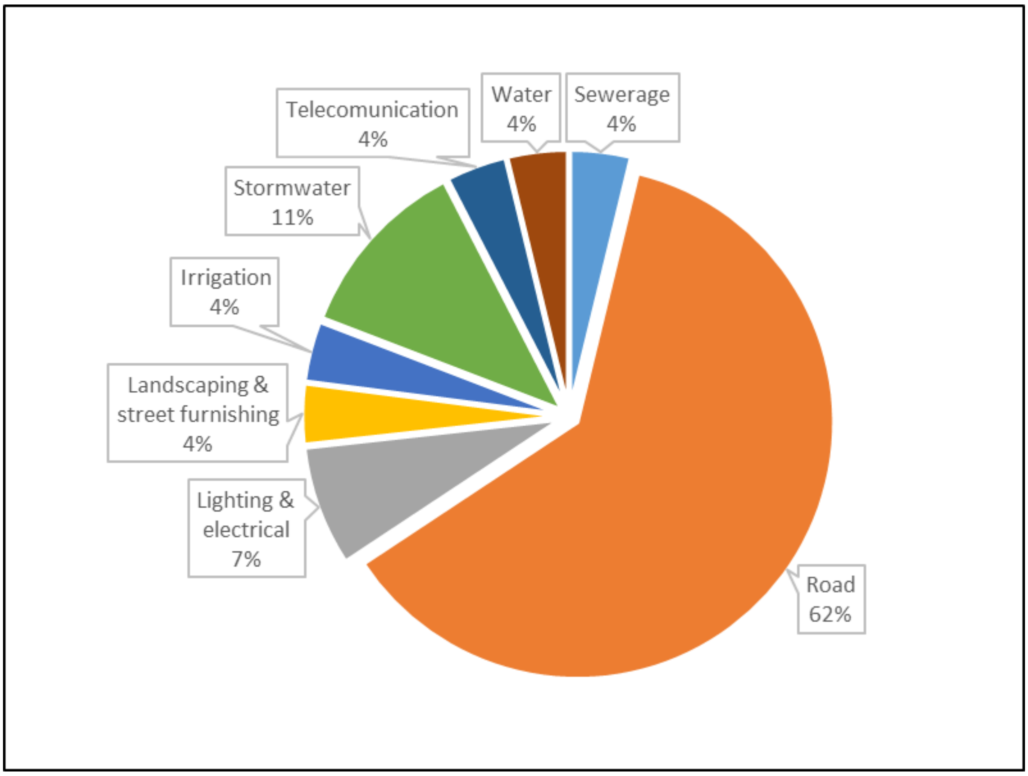


Figure 4.11: Distribution of emissions among the 8 different construction categories for the Corniche Road case study

As shown in Figures 4.9-4.11, road works contributed the most (41%-62%) to GHG emissions during the construction phase followed by stormwater works (11%-30%). The other remaining 6 categories contributed almost equal proportion to the total GHG emissions, but vary from one project to another. The relative contribution of material and equipment (including accompanied transportation) to GHG emissions of the three case studies is listed in Table 4.22. The relatively high contribution of the drainage system to GHG emissions for the case of Al Rahab, as compared to the other cases, is because of the establishment of a new infrastructure for a newly planned residential city. The relatively higher contribution of equipment used in the construction of the road network at Al Rahba is because of the extensive use of compactors, loaders and excavators. Compactors were used in the compaction of sub-base and base grade as well as asphalt pavement for the 30-km road network at the site.

Table 4.22: Relative contribution of material and equipment to GHG emissions of the three case studies

Case	**Material (%)**	**Equipment (%)**
Case 1: Al Rahba roads	30.1	69.9
Case 2: Al Salam Street	84.9	15.1
Case 3: Corniche Road	79.4	20.6

Upgrading of Al Salam Street includes the construction of a tunnel of length 3.6 km with 4 lanes on each side. The tunnel is a concrete structure with three interchanges. Thus, a relatively high proportion of material would be expected because of the used quantities of concrete and steel in addition to the use of asphalt. Despite the relatively low contribution of the equipment (15.1%) for this case, it has a large quantity of emitted GHGs that reached 44,000 ton CO_2eq. This is mainly attributed to the use of trucks that were used to transport concrete and other materials to the site.

For the Corniche Road case study, material contributed 80% of the total GHG emissions during the construction phase. This is due to the high contribution of road works (62%) in addition to the high use of concrete for relocating the existed sub-surface network of utilities.

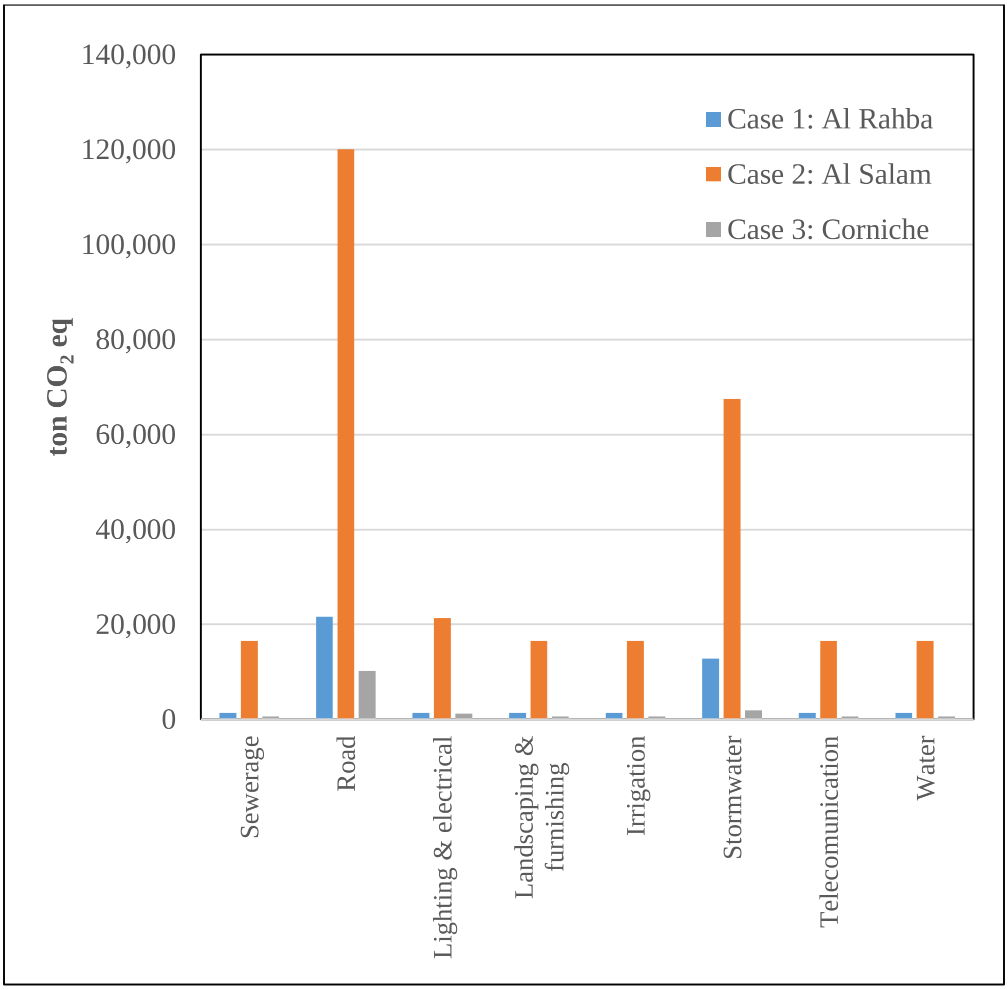


Figure 4.12: Comparison of emissions of different categorized activities during the construction phase of the studied cases

4.4.2 Operation Phase GHG Emissions

Table 4.23 summarizes the results of annual CO_2 emissions during the operation phase for the three studied cases. Activities studied include emissions due to vehicle movement, those due to lighting, those due to irrigation of street trees, and those due to stormwater pumping. In addition, the effect of sequestration as a carbon sink is included. For the three cases, the main contributor to emissions during operation is vehicle movement, followed to a lesser extent by street lighting. As for the contribution of irrigation, it was found to be of very low impact for the three cases, which does not exceed 200 ton CO_2eq/yr. Meanwhile, the positive effect of sequestration was not found to be that significant for these cases, with the highest sink found in Al Rahba city case of about 50 ton CO_2eq per year.

Table 4.23: Emissions from different activities during the operation phase

Category	**Item**	**Emissions (ton CO_2eq/yr)**		
		Case 1	**Case 2**	**Case 3**
Vehicle movement	Passenger cars	2,109	24,331	21,195
	Light trucks	6,357	50,150	44,099
	Heavy trucks	4,879	28,129	24,722
	All vehicles	13,345	102,610	90,016
Street lights		2,045	5,318	852
Irrigation	Palm	-	39	32
	Trees	152	20	9
	All trees	152	59	41
Stormwater pumping		-	2.6	-
Sequestration		-48.4	-19	-13
All operation categories		**15,494**	**107,971**	**90,896**

4.4.3 Overall GHG Emissions

To assess the overall GHG emissions associated with the three cases, emissions from the construction phase were divided by the service lifetime of the project, which is assumed here to be 40 years as demonstrated in Table 4.24. Figure 4.13 shows the percentage contribution of both the construction and operation phase. The figure demonstrates that the operation phase is the main contributor to GHG emissions for the three cases. The operation phase contribution ranges between 94 to 98%, while the construction phase contribution ranges between 2 to 6%. The differences between the three cases in construction emissions goes back to the difference in the nature of work that was involved in each case. In case of Al Salam Street, for example, construction involved a tunnel that required a huge amount of materials and transportation of these materials.

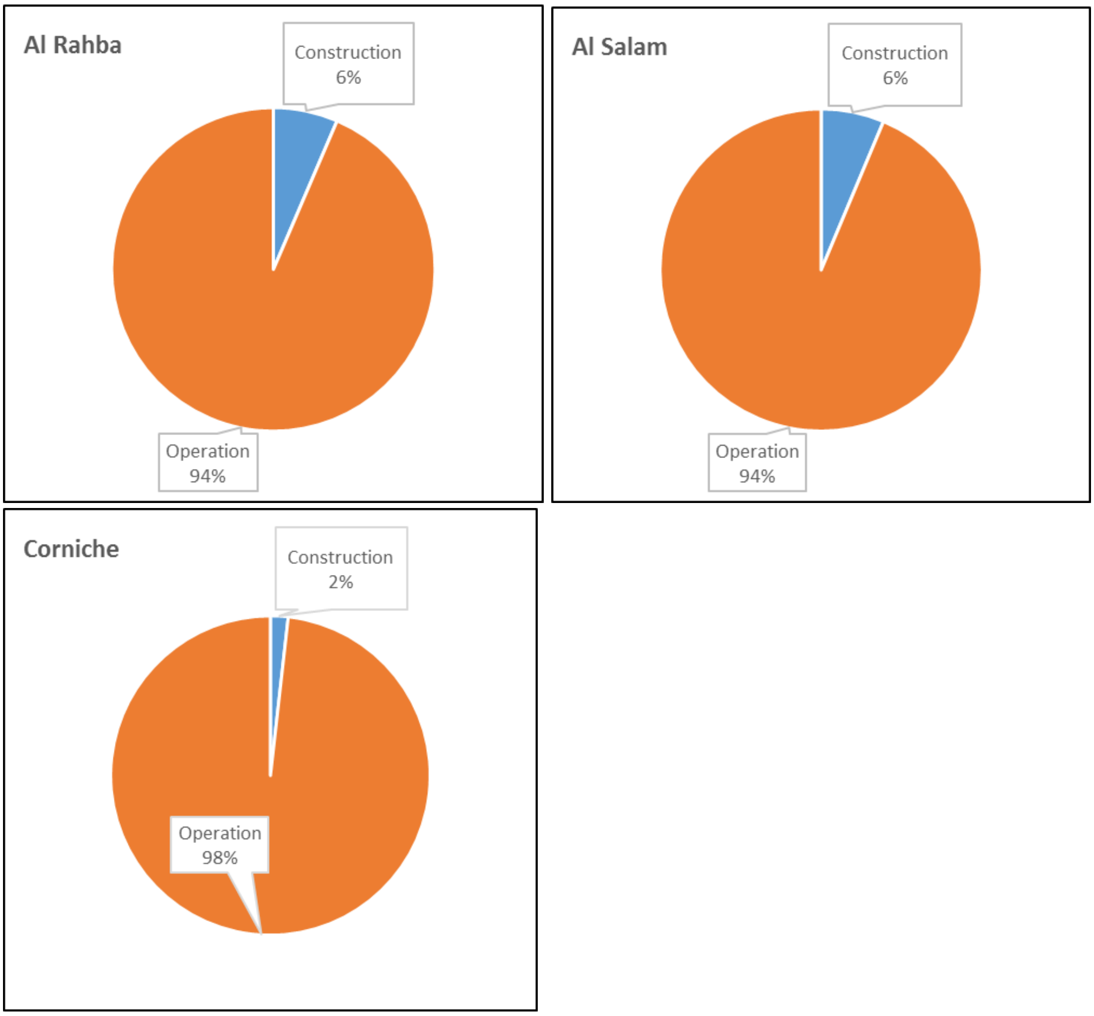


Figure 4.13: Relative contribution of the construction and operation phases to GHG emissions for the three studied cases

Table 4.24 shows the values of emissions from the three studied road projects bench-marked to a unit paved length and a unit paved area. Each year, Al Salam road contributes about 115,000 ton CO_2eq, emissions from Al Rahba roads contribute about 17,000 ton CO_2eq, and emissions from the Corniche Road contributes about 23,000 ton CO_2eq. When scaled by a unit paved area, the emissions become 76, 1,096, and 1,104 kg CO_2/m^2/yr for Al Rahba roads, Al Salam Street, and the Corniche Road case study, respectively.

Since the roads in Al Rahba City (Case study 1) are internal conventional roads, the normalized emissions from their construction are low relative to the normalized emissions from the other two case studies. Their pavement design, load bearing capacity and posted speed limit are less as compared to the other two studied cases.

The Corniche project (Case study 3) is similar to a previous case study conducted by Huang et al. (2013) in the emirate of Abu Dhabi, which involved addition of lanes on an existing road. Haung et al. (2013) used CHANGER software to carry on the estimation of emissions during the construction phase. They expressed emissions in terms of ton CO_2eq/lane/km. Using the same expression units used by Haung et al. (2013), the normalized emission from the Corniche project (Case study 3) for the construction phase is 2,870 ton CO_2eq/lane/km (number is not listed in Table 4.24), while the value obtained by Huang et al. (2013) road case study is 2,140 ton CO_2eq/lane/km. The two values are comparable, but the value obtained in this study is slightly higher probably due to consideration of additional categories, other than those related to road works and stormwater network, that contribute to emissions during the construction phase. It should be stressed that the final results cannot be properly understood without considering the scope established by researchers.

Table 4.24: Emissions from the three studied road projects bench-marked to different units

Parameter	Case 1: Al Rahba roads	Case 2: Al Salam St.	Case 3: Corniche Rd.
Length (km)	30	3.6	2.87
Lanes	2	8	2
Total paved width (m)	7.3	29.2	7.3
Construction (ton CO_2eq/yr)	1,068	7,290	412
Operation (ton CO_2eq/yr)	15,494	107,971	22,724*
Operation excluding vehicles (ton CO_2eq/yr)	2,149	5,361	220*
Total (ton CO_2eq/yr)	16,561	115,260	23,136*
Total (kg CO_2eq/m/yr)	552	32,017	6,887*
Total (kg CO_2eq/m^2/yr)	76	1,096	1,104*
Total excluding vehicles (ton CO_2eq/yr)	3,217	12,651	632*
Total excluding vehicles (kg CO_2eq/m/yr)	107	3,514	220*
Total excluding vehicles (kg CO_2eq/m^2/yr)	15	120	30*
Roadworks plus operation excluding vehicle movement (kg CO_2eq/m/yr)	74	1518	89

* Includes the share of operation phase emissions for two constructed lanes only.

Several studies were conducted in the European Union to assess carbon footprint emissions from road projects. Estimation usually excludes the effect of vehicle movement and activities other than road works, but takes into consideration the effect of lighting and sequestration. If one is to consider the effect of road works and activities contributing to emissions during the operation phase excluding those associated with vehicle movement, the emissions associated with the three case studies conducted in this study would be 74 kg CO_2eq/m/yr for the case of Al Rahba, 1,518 kg CO_2/m/yr for the case of Al Salam Street, and 89 kg CO_2/m/yr for the case of the Corniche Road. According to Keijzer et al. (2015), GHG emissions of asphalt roads (with consideration of road works and excluding emissions from vehicle in the operation phase) are between 14 kg CO_2/m/yr for roads within the secondary road network and 64 kg CO_2eq/m/yr for roads within the main road network. Hill et al.

(2012) reported almost a similar range of 24 to 55 kg CO_2eq/m/yr for traffic route and motorway, respectively. The values obtained in this study are much higher than those reported by Hill et al. (2012) and Keijzer et al. (2015) for some European countries.

For the case of Al Rahba internal roads the values are about 4 times higher (based on a European range of emission values of 14-24 kg CO_2/m/yr). Roadworks in Al Rahba contributed 2 kg CO_2/m/yr while the operation phase excluding vehicle movement contributed 72 kg CO_2/m/yr. Thus, higher values for the case of Al Rahba is mainly due to emissions during the operation phase in which the main contributor to this is street lighting.

Both Al Salam Street and the Corniche Road are considered main roads. Thus, comparison should be made with the upper range values (55-64 kg CO_2eq/m/yr) reported by Hill et al. (2012) and Keijzer et al. (2015). For the case of Al Salam Street, the values are about 25 times higher. For this case, roadworks contributed 28 kg CO_2/m/yr while road operation excluding vehicles movement contributed 1489 kg CO_2/m/yr. Emissions from roadworks is mainly due to usage and transportation of concrete and steel needed to construct the tunnel and other concrete structures on this road in addition to those originating from earthwork. Given that the road length is short, the impact of constructing the tunnels and other concrete structures amplifies the normalized emission rates for construction as compared to those of Al Rahba case. However, the tremendous normalized emissions for this case is due to street lighting which is mainly attributed to the continuous lighting of the tunnel.

For the case of the Corniche Road, normalized emission values are 50% higher than the upper range values reported by Hill et al. (2012) and Keijzer et al. (2015). For this case, roadworks contributed 12 kg CO_2/m/yr while road operation excluding vehicles contributed 77 kg CO_2/m/yr. Emissions of roadworks is mainly due to asphalt and concrete usage. The added wide shoulders on both sides of the road resulted in higher values as it is not considered as part of the paved width in the normalization of the emission values. In addition, usage of Portland cement also increased emissions during construction as compared to those resulting from the use of blast furnace cement in concrete mix. But once again, the high normalized emissions estimated for this case, aside from those of road traffic, are mainly due to street lighting.

There are other possible reasons that could have led to higher normalized emission values for the studied case as compared to values reported by Hill et al. (2012) and Keijzer et al. (2015). First, irrigation rates in the UAE is much higher than that in Europe, leading to higher consumption of water for landscaping. Second, the role of sequestration is probably less in the UAE given the extent of greenery on roads in the country. Third, the possibility of overdesign of road elements in the UAE will result in higher emission values.

4.5 Potential Mitigation Measures Based of the Results

Based on the findings presented in the previous section, a number of mitigation measures can be applied to reduce GHG emissions from road projects. Although this is beyond the scope of the study, results are amenable to some discussion in this regard. Mitigation measures to reduce GHG emissions from road projects could be related to activities carried out during all phases of a road life cycle, starting as early as the design stage. Emissions could be reduced by either reducing the quantity associated with an activity, substituting an activity with another that has a lower emission factor, or by changing the two parameters at the same time, if possible. As reviewed in Chapter 2, possible mitigation measures fall under different categories, ranging from improvement in road construction practices, traffic demand management, alteration of traffic characteristics, alteration of speed limit, and reduction in electricity and water consumption during the operation phase in addition to those related to rehabilitation and maintenance.

A possible mitigation measure that falls under traffic demand management is reducing traffic volume. Reduction of traffic volume should have a significant impact on emission reduction, given the significant contribution of traffic volume to produced emissions. This could be achieved in different ways including, use of other transportation modes (buses, metro and carpooling), increase fuel taxes or apply road tolls to reduce the number of travel trips, or by constructing new pedestrian and bicycle facilities. Emissions, on the other hand, could be reduced by alteration of traffic characteristics which could be achieved by increasing the use of higher efficiency vehicles or by increasing the use of liquefied natural gas (LNG) and electrical vehicles. Such options can be promoted by using incentive programs or by applying taxation on low efficiency vehicles.

Although the contribution of the construction phase to total emissions is not as significant as of the operation phase, looking at options to reduce emissions during construction could offer other environmental benefits, save resources and reduce land-use. Several mitigation measures could be explored with the intention of improving road construction practices and consequently reducing associated GHG emissions. These include increasing the use of recycled materials or increasing the use of regional materials. An increase in the use of recycled materials could be achieved by recycling construction waste into road projects or by using reclaimed asphalt. On the other hand, increasing the use of regional materials is expected to reduce transportation impacts.

Emissions could also be reduced by using innovative materials or innovative techniques. An example of an innovative technique is to reduce construction duration by using thinner pavement layers with improved materials such as the use of asphalt with a high stiffness modulus in the base layer to reduce layer thickness (Keijzer et al, 2015). This, in fact, will have double effect as it reduces the compaction effort and thus the compaction time and it further reduces the quantity of material used. Another example is demonstrated in the work of Blankendaal et al. (2014) who evaluated several measures to reduce the environmental impact of concrete and asphalt. These authors quantified the effect of low-energy production techniques and the application of secondary materials. The evaluated concrete-mixes point out that the highest potential for improvement can be realized through application of alternative cement types, with a maximum reduction of 39% in environmental impact. The authors further found that the most substantial impact reduction in asphalt was achieved through application of warm-mix asphalt instead of hot-mix asphalt, which yielded a reduction of about 33%. This is consistent with the findings of Jacob et al. (2010), who found a 30% reduction in CO_2 by adopting the warm mix asphalt technique.

Replacement of PC by GGBFS or fly ash will have a significant reduction in emissions due to use of concrete in road projects. Tait and Cheung (2016) found that the use of fly ash considerably reduces CO_2 emissions when compared to PC, but the inclusion of GGBFS environmentally optimizes the mix design even further without loss of performance. Actually, the use of GGBFS and fly ash was adopted in Al Salam case study, but PC was used in concrete mix in Al Rahba and the Corniche case studies.

Reducing electricity and water consumption during the operation phase will lead to a reduction in the GHG emissions. To reduce electricity consumption during the operation phase, one can use solar or light emitting diode (LED) that replace conventional lamps. In fact, ADM Lighting Manual calls for use of LED for street lighting. This should appositive impact on reducing GHG emissions from lighting.

Water consumption reduction can be achieved by promoting the use of local plants that require less water, reducing plantation area, or by using soil amendment to increase soil water capacity.

Chapter 5: Conclusion and Recommendations

5.1 Conclusion

Road transportation is a major contributor to GHG emissions, and its contribution continues to steadily grow despite the latest development in greener practices, technologies, and policies. The reviewed literature showed that a number of measures have been implemented as a means to mitigate the amount of GHG emissions produced by road transportation, such as the increased use of public transit and active transport, which have consistently shown to reduce emission levels per capita. Despite that, countries located in the Gulf Cooperation Council (GCC) region have shown particularly high road transport GHG emission output; especially, as GHG emission output is normalized by the length of the road.

A number of assessment tools capable of estimating carbon footprint from road- and transportation-related projects have been developed over the past several years. However, some of these tools are meant to be used on a macro-level by helping decision makers assess the carbon footprint of transport policies. Other tools focused on assessing emissions produced by either private vehicles, public transit, or freight transportation. Others may only estimate emissions based on a single project stage (e.g., construction phase). Some of these tools may also have adopted emission factors based on localized conditions and, as a result, are limited in their geographical usefulness.

A web-based model (referred to as RoadCO_2) was developed to estimate the carbon footprint of road projects during the road life cycle (i.e., pre-construction, construction, operation, maintenance, and rehabilitation). RoadCO_2 is a model with a database that covers almost all activities that emit GHGs including those originating from direct or indirect (embodied) sources. Although the model mainly uses the IPCC emission factors, it is designed in such a way that it can be updated with local emission factors once available.

The RoadCO_2 model was used to estimate GHGs emissions from three road projects located in Abu Dhabi city. These case studies are: (1) Al Rahba City internal roads and services, (2) upgrading of Al Salam Street to an expressway, and (3) widening of the Eastern Corniche Road. Results of CO_2 emissions of the studied cases demonstrate that the operation phase is the main contributor to GHG emissions as opposed to emission from the construction phase, with a share of more than 94% of the total due to emissions from vehicles and use of lighting.

Emissions from the construction of the investigated case studies were found to be about 43, 292, and 16 thousand ton CO_2eq, respectively. Road works contributed the most to GHG emissions during the construction phase followed by stormwater works. Other categories considered in the construction phase contributed almost equal proportion to the total GHG emissions, but vary from one project to another.

The relative contribution of material and equipment (including accompanied transportation) to GHG emissions of the three case studies varies. For the case of Al Rahba about 30% of emissions was due to material use and transportation while 70% was due to equipment use and transportation. For the case of Al Salam Street and the Corniche Road, a higher relative contribution of material to GHG emissions was found (about 80%) as compared to emissions due to the use and transportation of equipment. This is because of the high use of concrete and steel in constructing the tunnel for Al Salam Street case and due to the high contribution of road works (62%) and the high use of concrete for relocating the existed sub-surface network of utilities for the Corniche Road case.

In the operation phase, Al Salam Street project produced about 108 thousand ton CO_2eq/year, whereas the Corniche Road produced approximately 91 thousand ton CO_2eq/year. Operation of the road network within Al Rahba City produced approximately 15 thousand ton CO_2eq/year. The significant difference in emissions between Al Rahba case study and the other two studies is in line with the major dissimilarities between their corresponding transportation facilities. Emissions from light trucks dominate in Al Rahba City internal roads, whereas light and heavy trucks dominate in the case of Al Salam Street and the Corniche Road.

Street lighting was also found to be a major contributor to GHG emissions during the operation phase of the three studied cases, with the highest found for the case of Al Salam Street due to the 24-lighting of the tunnel. As for irrigation of planted trees on road, it was found to have a very low impact on GHG emissions. The same applies for sequestration.

5.2 Recommendation

Currently, RoadCO_2 relies on different parameters obtained from different sources. Emission factors used in RoadCO_2 are mainly from the IPCC. It is, therefore, recommended to initiate a project to develop emission factors that are specific to the UAE. In fact, it is a key recommendation of the Abu Dhabi GHG emissions inventory (EAD, 2012) to develop local emission factors in the country. The use of country-specific emission factors will lead to more accurate estimates of GHG emissions from road and other infrastructure projects. In addition to the development of emission factors, it is important to also develop a fuel consumption rate database for various types of vehicles.

Accurate determination of GHG emissions from road projects requires also accurate activity data. In the case studies presented in Chapter 4, most of the activity data were obtained from quantified items in the BOQs. These data are considered estimates and may not necessarily be similar to actual quantities used during road project phases. It is, therefore, recommended that actual activity data be collected to estimate GHG emissions more accurately. Comparison could then be made between emissions estimated based on BOQ items and those estimated based on actual quantity values.

RoadCO_2 is solely developed to estimate GHG emissions from road projects. Aside from the environmental issue, several other factors influence the design of road projects. These factors include cost, safety, and social aspects. All factors should be considered to achieve an optimal design of a project. Thus, it is recommended that a decision matrix be developed to assist in achieving an optimal road design.

For design and scoping purposes, detailed data are usually not available. RoadCO_2 could still be utilized to carry on estimation of GHG emissions at this stage, but entered activity data will be mainly subject to designers' interpretation and speculations. To assist in obtaining reasonable estimates, it is recommended that the model be expanded to include another module which includes default values collected from reviewing several previous projects or based on default design values. In this case, only significant activities could be included as the purpose at this stage is to compare between alternatives or to have rough estimates.

In this study, RoadCO$_2$ was validated by comparing the results obtained for the three cases by the results reported in literature. However, further validation is required to evaluate the overall accuracy of the model. Validation process could include a comparison between RoadCO$_2$ results along with the results of other well-established models. Since the scope of RoadCO$_2$ covers more than what other models do, different models can be used to validate emissions from certain activities. For instance, the calculations of the construction phase in the RoadCO$_2$ can be compared to models that are well known for that such as CHANGER, CO2NSTRUCT, and Carbon Tool. As for the operation phase, one can use MOVES, COPERT 4, SIDRA, and MVEI to validate the results of vehicle movement estimated by RoadCO$_2$.

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Appendix A: Abu Dhabi Sustainable Road Initiatives

A.1 Abu Dhabi Sustainable Road Rating System (ADSRRS)

ADSRRS scaled credit points and their respective requirements (information is extracted from CH2MHILL (2015))

Sub-category	Subcategory title	Credits	Requirements
Project Planning			
PP-01	Integrated Road Development Strategy	15	Demonstrate that an Integrated Development Process has been adopted and for the project
PP-02	Lifecycle Cost Analysis	6	Implement a Lifecycle Cost Analysis
PP-03	Lifecycle Assessment	3	Conduct a Lifecycle Inventory
		3	Conduct a Lifecycle Assessment
PP-04	Natural Systems Design & Management Strategy	6	Demonstrate the preparation of the Natural Systems Design and Management Strategy on the project
PP-05	Plan 2030	10	Demonstrate that the proposed road and infrastructure project supports the vision of the Emirate of Abu Dhabi
PP-06	Urban Systems Assessment	3	Undertake a detailed urban system assessment report
PP-07	Community Water Strategy	8	Develop and integrate a comprehensive water strategy
PP-08	Environmental Review Process	5	Document a comprehensive environmental review of the roadway project
		5	Adhere to the final environmental decisions during design
		5	During construction, do not alter design elements that achieve the final environmental design decisions
PP-09	Neighborhood Connectivity	3	Demonstrate minimum average Connectivity Index 1.5 and achievement of Adjacency Standards
		1	Demonstrate that at least 75% of the intersections meet the Average standard

Sub-category	Subcategory title	Credits	Requirements
PP-09	Neighborhood Connectivity	1	Demonstrate that revitalization of neighborhood has increased connectivity by 50%
PP-10	Guest Worker Accommodation	8	Develop and implement a Construction Guest Worker Accommodation Plan
PP-11	Open Space Network	2	Demonstrate provision of an open space and management strategy
		2	Demonstrate an accessible interconnected system of open space
		2	Demonstrate the multiple use of open spaces
PP-12	Optimize Use of ROW	3	Demonstrate that at least 75% of the site area has been previously developed
Project design – Public good, Materials, Energy, Ecology			
PG-01	Sustainability Educational Outreach	8	Perform 4 of the Credit Requirements
PG-02	Context Sensitive Solutions	8	Demonstrate the use of context sensitive solutions in the project development process
PG-03	Cultural and Historic Preservation	2	Minimize impacts to historical, archeological or cultural qualities
		3	Avoid impacts; to historical, archeological or cultural qualities
PG-04	Safety Awareness	8	Perform and document a safety performance examination
		3	Demonstrate building awareness among the public
PG-05	Pedestrian Facilities	8	Design and construct new pedestrian facilities throughout the project footprint that include both safe and comfortable features and convenient and connected features
PG-06	Bicycle Facilities	8	Design and construct new bicycle facilities throughout the project footprint that include both safe and comfortable features and convenient and connected features
PG-07	Transit&High Occupancy Vehicle (HOV) Access	8	Implement physical or constructed changes to the roadway structure, dimensions or form that provide dedicated transit access within the right-of-way

Sub-category	Subcategory title	Credits	Requirements
PG-08	Traffic Emissions Reduction	6	Utilize congestion pricing on the project and quantify the greenhouse gas emissions reduction as compared to the non-priced project
MT-01	Recycled Materials	1	Incorporate minimum 25% recycled material in non-structural concrete within the project site
		1	Incorporate minimum 25% recycled material in road base/sub-base within the project road pavement section
		1	Incorporate minimum 25% recycled material in fill sections within the project site
		1	Incorporate minimum 25% recycled material in asphalt pavement layers within the project road pavement section
		2	Incorporate minimum 50% recycled material in non-structural concrete within the project site or in road base/sub-base within the project road pavement section
		2	Incorporate minimum 50% recycled material in fill sections within the project site or in asphalt pavement layers within the project road pavement section
MT-02	Regional Materials	2	Demonstrate the use of regional materials
MT-03	Long Life Pavement	8	Design at least 75% of the total new or reconstructed pavement surface area for regularly trafficked lanes of pavement to meet long life pavement design criteria
MT-04	Introduction of Innovative Materials	8	Prepare a formal document to demonstrate the development and benefits of the proposed innovative design materials
EN-01	Smart Infrastructure Systems	11	Demonstrate installation and operation of at least 1 application in 6 separate categories
EN-02	Energy Efficiency Lighting	8	100% higher efficacy than current DMA Specification version stated minimum

Sub-category	Subcategory title	Credits	Requirements
EN-03	Urban Heat Reduction	4	Demonstrate the pavement surface has a minimum albedo of 0.3 for a minimum of 50% of the total project pavement surfacing by area
		4	Demonstrate that at least 70% of the hardscape has a minimum SRI of 35
EC-01	Sustainability in Stormwater Management	4	Minimize peak stormwater discharge and protect the stormwater drainage system
EC-02	Sustainability in Plantings & Irrigation	15	Develop a sustainability in plantings & irrigation plan
EC-03	Ecological Connectivity	1	Demonstrate completing a site specific wildlife assessment for the roadway project
		3	Replace in kind, retrofit, or upgrade any and all existing ecological connectivity features or construct new ecological connectivity features consistent with the site specific wildlife assessment
EC-04	Ecological Enhancement	1	Demonstrate the replacement/installation of dedicated wildlife crossing structures and protective fencing
		2	Demonstrate 70% plants specified for planting meet the requirements listed and non-potable water is used for all irrigation
EC-05	Light Pollution Mitigation	4	Demonstrate that the lighting requirements are met
Construction			
CN-01	Construction Environmental Management Plan (EMP)	3	Prepare a Construction Environmental Management Plan (CEMP) in accordance with Environment Agency Abu Dhabi’s (EAD) Construction EMP Technical Guidance Document
CN-02	Construction Quality Control Plan	8	Prepare a formal construction Quality Control Plan
CN-03	Construction Environmental Management System (EMS)	3	Demonstrate having a documented EMS that meets the stated requirements

Sub-category	Subcategory title	Credits	Requirements
CN-03	Construction Environmental Management System (EMS)	3	Demonstrate having a documented EMS that meets the stated requirements
CN-04	Construction Environment, Health & Safety Training	4	Conduct and document construction EHS training plan
CN-05	Construction Air Pollution Reduction	3	Demonstrate the use emission reduction exhaust retrofits and add on fuel efficiency technologies to meet the credit requirements
CN-06	Construction Site Recycling Plan	1	Demonstrate the establishment, implementation, and maintenance a formal Site Recycling Plan
		3	Demonstrate achieving a minimum final recycle/salvage rate of 70% of construction and demolition waste (by weight or volume)
CN-07	Construction Contractor Warranty	3	Utilize a 3-year defects warranty for the constructed portions of the pavement structure and surfacing as well as underlying layers
Operations & maintenance			
OM-01	Facilities Maintenance Plan	6	Have a facilities management system in place that includes quantifiable performance metrics and goal setting
OM-02	Pavement Management System (PMS)	5	Have a PMS in place that includes quantifiable performance metrics and goal setting
OM-03	Maintenance Management System (MMS)	5	Have a MMS to assess maintenance needs, performance, sources of budget, priorities, methods of repair and QA/QC Procedures
OM-04	Bridge Management Systems (BMS)	5	Have a BMS in place that includes quantifiable performance metrics and goal setting
Innovative practices			
IP-01	Innovative Practices	4	Innovative solution report
		4	Implement the innovative solution, update the innovative solution report and produce guideline documentation

A.2 Estidama

Estidama scaled points for credits and their requirements (Information is extracted from ADUPC (2010))

Sub-category	Subcategory title	Credits	Requirements
`Precious Water			
PW-1.1	Community Water Use Reduction: Landscape (Plant Selection)	1	All public park landscaping in aggregate does not require more than 8 $l/m^2/day$
		Or 2	All public park landscaping in aggregate does not require more than 6 $l/m^2/day$
		Or 3	All public park landscaping in aggregate does not require more than 4 $l/m^2/day$
		1	All streetscape landscaping in aggregate does not require more than 5 $l/m^2/day$
		Or 2	All streetscape landscaping in aggregate does not require more than 3 $l/m^2/day$
		1	All remaining landscaping in aggregate does not require more than 2 $l/m^2/day$
		Or 2	All remaining landscaping in aggregate does not require more than 0 $l/m^2/day$
PW-1.1	Community Water Use Reduction: Landscape Irrigation System (Irrigation)	7	Demonstrate that the average irrigation requirement of all landscape areas is minimized
		2	Demonstrate that a Water Efficient Irrigation System has been incorporated into all public realm landscaping
		2	Demonstrate that an Irrigation Operation and Maintenance Plan has been developed
		2-3	Demonstrate that a proportion of the community irrigation demand can be served using the exterior water allowance
PW-1.1	Community Water Use Reduction: Landscape (Recycled Water)	2	A minimum of 75% of the community's irrigation demand can be served using the exterior water allowance
		Or 3	Demonstrate that 100% of the community's irrigation demand can be served using the exterior water allowance

Sub-category	Subcategory title	Credits	Requirements
PW-1.2	Heat Rejection	2	Demonstrate that 25% of the community's DC plant water make-up requirements can be served using the exterior water allowance
		Or 3	Demonstrate that 50% of the community's DC plant water make-up requirements can be served using the exterior water allowance
		Or 4	Demonstrate that 75% of the community's DC plant water make-up requirements can be served using the exterior water allowance
		Or 5	Demonstrate that 100% of the community's DC plant water make-up requirements can be served using the exterior water allowance
		2	No water-cooled district cooling is present
PW-1.3	Water Features	2	Demonstrate that the water make-up requirements for all exterior water features in the public realm can be served using the Exterior Water Allowance
		1	Demonstrate that all external swimming pools are supplied with permanently installed retractable pool blankets
		Or 4	Demonstrate that there are no exterior water features or swimming pools within the public realm
PW-2	Stormwater Management	2	Demonstrate that the post-development peak runoff rate and quantity from the 2-year 24-hour design storm does not exceed the pre-development peak runoff rate and quantity through structural methods, or a combination of both structural and non-structural methods
		Or 4	Demonstrate that the post-development peak runoff rate and quantity from the 2-year 24-hour design storm does not exceed the predevelopment peak runoff rate and quantity through the use of non-structural methods only
		1	Stormwater management system is designed to meet Quality Control criteria as per Credit Requirements
		1	An OMP has been developed

Sub-category	Subcategory title	Credits	Requirements
PW-3	Water Efficient Buildings & Plots	1	Demonstrate that the average water reduction target, W_{bldg}, achieves 16% improvement over the baseline building performance
		Or 2	Demonstrate that the average water reduction target, W_{bldg}, achieves 22% improvement over the baseline building performance
		Or 3	Demonstrate that the average water reduction target, W_{bldg}, achieves 28%improvement over the baseline building performance
		Or 4	Demonstrate that the average water reduction target, W_{bldg}, achieves 34% improvement over the baseline building performance
		Or 5	Demonstrate that the average water reduction target, W_{bldg}, achieves 40% improvement over the baseline building performance
		2	Demonstrate that the building plot average landscape irrigation demand, IBL < 4 liters/m^2/day
		Or 3	Demonstrate that the building plot average landscape irrigation demand, IBL < 2 liters/m^2/day
Resourceful Energy			
RE-1	Community Strategies for Passive Cooling	2	Demonstrate that two of the conceptual analysis strategies have been incorporated into the community design
		Or 3	Demonstrate that three of the conceptual analysis strategies have been incorporated into the community design
		3	Demonstrate that advanced solar and wind analysis techniques have been used to optimize pedestrian comfort and verify the performance of the selected strategies
RE-2	Urban Heat Reduction	1	Demonstrate that 70% of all community hardscape areas have utilized strategies to reduce the buildup of heat
		Or 2	Demonstrate that 90% of all community hardscape areas have utilized strategies to reduce the buildup of heat

Sub-category	Subcategory title	Credits	Requirements
RE-3.1	Efficient Infrastructure: Lighting	4	Demonstrate that the power density of all Roadway, Pathway and Amenity lighting shall not exceed 80% of the figure specified for exterior areas and 50% of the figure specified for landscape features in the IECC 2009
		2	Demonstrate that suitable controls have been installed to limit the use of lighting during unnecessary periods
RE-3.2	Efficient Infrastructure: District Cooling	2	Demonstrate the community includes a District Cooling (DC) network that achieves a Coefficient of Performance (COP) weighted average >4.5
		Or 4	Demonstrate the community includes a District Cooling (DC) network that achieves a Coefficient of Performance (COP) weighted average > 5.5
		1	Demonstrate that the peak DC system cooling demand has been reduced by 25% through the use of thermal energy storage
		1	Demonstrate that all refrigerants used in the DC system have a Global Warming Potential (GWP) of 10 or less.
RE-3.3	Efficient Infrastructure: Smart Grid Technology	2	Demonstrate that smart meters are proposed and that two smart grid strategies have been adopted in 50% of the building Gross Floor Area (GFA)
		4	Demonstrate that smart meters are proposed and that two smart grid strategies have been adopted in 75% of the building GFA
RE4.1	Renewable Energy: Onsite	1	Demonstrate that 1% of the community's energy consumption is to be supplied by on-site renewable energy
		Or 2	Demonstrate that 3% of the community's energy consumption is to be supplied by on-site renewable energy
		Or 3	Demonstrate that 5% of the community's energy consumption is to be supplied by on-site renewable energy
		Or 4	Demonstrate that 7% of the community's energy consumption is to be supplied by on-site renewable energy

Sub-category	Subcategory title	Credits	Requirements
RE4.1	Renewable Energy: Onsite	Or 5	Demonstrate that 10% of the community's energy consumption is to be supplied by on-site renewable energy
		Or 6	Demonstrate that 15% of the community's energy consumption is to be supplied by on-site renewable energy
		Or 7	Demonstrate that 20% of the community's energy consumption is to be supplied by on-site renewable energy
		Or 8	Demonstrate that 25% of the community's energy consumption is to be supplied by on-site renewable energy
RE-4.2	Renewable Energy: Offsite	3	Demonstrate that the total energy consumption of all community infrastructure will be provided by offsite renewable generation and contracts are signed for 5 years
RE-5	Energy Efficient Buildings	1	Demonstrate that the weighted average performance target (by GFA), C_{bldg}, achieve 15% improvement compared to the baseline building energy consumption
		Or 2	Demonstrate that the weighted average performance target (by GFA), C_{bldg}, achieve 20% improvement compared to the baseline building energy consumption
		Or 3	Demonstrate that the weighted average performance target (by GFA), C_{bldg}, achieve 25% improvement compared to the baseline building energy consumption
		Or 4	Demonstrate that the weighted average performance target (by GFA), C_{bldg}, achieve 30% improvement compared to the baseline building energy consumption
		1	Demonstrate that the weighted average performance target (by GFA), V_{bldg}, achieve 10% improvement compared to the baseline building
		Or 2	Demonstrate that the weighted average performance target (by GFA), V_{bldg}, achieve 20% improvement compared to the baseline building

Sub-category	Subcategory title	Credits	Requirements
RE-5	Energy Efficient Buildings	Or 3	Demonstrate that the weighted average performance target (by GFA), V_{bldg}, achieve 30% improvement compared to the baseline building
Stewarding Materials			
SM-1	Modular Pavement and Hardscape Cover	1	Demonstrate at least 70% (by surface area) of hardscape public realm and right-of–way, excluding transit and motor vehicle travelled way, are specified with modular materials with minimum SRI of 29
SM-2	Regional Materials	1	Cost of regional materials specified equal to 10% of Total Material Cost
		2	Cost of regional materials specified equal to 20% of Total Material Cost
SM-3	Recycled Materials	1	At least 15% of all aggregates specified are recycled
		Or 2	At least 30% of all aggregates specified are recycled
SM-3	Recycled Materials	1	Specified concrete mix and reduction in cement use will achieve an embodied GHG of concrete as per Table SM3.1, rows B1, C1 and D1 (ADUPC, 2010)
		Or 2	Specified concrete mix and reduction in cement use will achieve an embodied GHG of concrete as per Table SM3.1, rows B1, C1 and D1 (ADUPC, 2010)
		1	Cost of specified recycled materials equal to at least 10% of Total Material Cost
SM-4	Reused or Certified Timber	1	Demonstrate that 50% (by cost) of the timber specified for the project comply with the Credit Requirements
		Or 2	Demonstrate that 70% (by cost) of the timber specified for the project comply with the Credit Requirements
		Or 3	Demonstrate that 90% (by cost) of the timber specified for the project comply with the Credit Requirements
SM-5	Improved Construction Waste Management	1	Demonstrate that Construction & Demolition Waste Management Plan aims for a minimum of 60% demolition and construction waste (by weight or volume) to be recycled / salvaged

Sub-category	Subcategory title	Credits	Requirements
SM-5	Improved Construction Waste Management	Or 2	Demonstrate that CDWMP aims for a minimum of 70% demolition and construction waste (by weight or volume) to be recycled / salvaged
SM-6	Improved Operational Waste Management (OWM)	1	Develop an OWM Plan for a minimum targeted diversion rate of 50% (by weight or volume)
		Or 2	An OWM Plan is developed for a minimum targeted diversion rate of 60% (by weight or volume)
SM-7	Organic Waste Management	1	Landscaping waste or food waste collection and/or treatment is proposed onsite
		Or 2	Food and landscaping waste collection and/or treatment are proposed onsite
SM-8	Hazardous Waste Management	1	Allocate a location on the development for the safe collection of potentially hazardous consumer waste
Innovating practice			
IP-1	Innovative Cultural & Regional Practices	1	Develop a design strategy for incorporating solutions that showcase cultural and regional practices
IP-2	Innovating Practice	2	Develop an innovative solution report

Appendix B: Emission Factors

B.1 Materials

Material*	EF (kg CO_2eq/kg)	Material	EF (kg CO_2eq/kg)
Aggregate	0.0052	Shingle	0.3
Aluminium		Slag (GGBS)	0.083
Cast Products (Virgin)	13.1	Silver	6.31
Cast Products (Recycled)	1.45	Straw	0.01
Exturded (Virgin)	12.5	Terrazzo Tiles	0.118
Exturded (Recycled)	2.12	Vanadium	228
Rolled (Virgin)	12.8	Vermiculite - Expanded	0.52
Rolled (Recycled)	1.79	Vermiculite - Natural	0.032
Asphalt		Quartz powder	0.023
Asphalt, 4% (bitumen) binder content (by mass)	0.066	Wood stain/Varnish	5.35
Asphalt, 5% binder content	0.071	Yttrium	84
Asphalt, 6% binder content	0.076	Zirconium	97.2
Asphalt, 7% binder content	0.081	Paint	
Asphalt, 8% binder content	0.086	General	2.91
Bitumen	0.49	Waterborne Paint	2.54
Bricks	0.24	Solventborne Paint	3.76
Cement	0.74	Paper	
Ceramics		Paperboard (general for construction use)	1.29
Fittings	1.14	Fine Paper	1.49
Sanitary Products	1.61	Wallpaper	1.93
Tiles and Cladding Panels	0.78	Plaster	
Clay		General (Gypsum)	0.13
General- Baked Products	0.24	Plasterboard	0.39
Tile	0.48	Plastics	
Vitrified clay pipe DN 100 & DN 150	0.46	General	3.31
Vitrified clay pipe DN 200 & DN 300	0.5	ABS	3.76
Vitrified clay pipe DN 500	0.55	General Polyethylene	2.54
Concrete		HDPE Resin	1.93
Class K140 (100% PC)	0.4362	HDPE Pipe	2.52
Class K140 (65% PC-35% fly ash)	0.2966	LDPE Resin	2.08
Class K140 (30% PC-70% GGBFS)	0.1658	LDPE Film	2.6

Material*	**EF (kg CO_2eq/kg)**	**Material**	**EF (kg CO_2eq/kg)**
Class K250	0.4484	Nylon (Polyamide) 6 Polymer	9.14
Class K250 (65% PC-35% fly ash)	0.3049	Nylon (polyamide) 6,6 Polymer	7.92
Class K250 (30% PC-70% GGBFS)	0.1704	Polycarbonate	7.62
Class K 550	0.5547	Polypropylene, Oriented Film	3.43
Class K550 (65% PC-35% fly ash)	0.3772	Polypropylene, Injection Moulding	4.49
Class K550 (30% PC-70% GGBFS)	0.2108	Expanded Polystyrene	3.29
General	0.107	General Purpose Polystyrene	3.43
16/20 Mpa (100% PC)	0.1	High Impact Polystyrene	3.42
16/20 Mpa (65% PC-35% fly ash)	0.068	Thermoformed Expanded Polystyrene	4.39
16/20 MPa (30% PC, 70% GGBFS)	0.038	Polyurethane Flexible Foam	4.84
20/25 MPa (100% PC)	0.107	Polyurethane Rigid Foam	4.26
20/25 MPa (65% PC-35% fly ash)	0.0728	PVC General	3.1
20/25 MPa (30% PC-70% GGBFS)	0.0407	PVC Pipe	3.23
25/30 MPa (100% PC)	0.113	Calendered Sheet PVC	3.19
25/30 MPa (65% PC-35% fly ash)	0.0768	PVC Injection Moulding	3.3
25/30 MPa (30% PC, 70% GGBFS)	0.0429	UPVC Film	3.16
28/35 MPa (100% PC)	0.12	Rubber	2.85
28/35 MPa (65% PC-35% fly ash)	0.0816	Sand	0.0051
28/35 MPa (30% PC, 70% GGBFS)	0.0456	Soil	
32/40 MPa (100% PC)	0.132	General (Rammed Soil)	0.024
32/40 MPa (65% PC-35% fly ash)	0.0898	Cement stabilised soil @ 5%	0.061
32/40 MPa (30% PC-70% GGBFS)	0.0502	Cement stabilised soil @ 8%	0.084
40/50 MPa (100% PC)	0.151	GGBS stabilised soil	0.047
40/50 MPa (65% PC-35% fly ash)	0.1027	Fly ash stabilised soil	0.041

Material*	EF (kg CO_2eq/kg)	Material	EF (kg CO_2eq/kg)
40/50 MPa (30% PC-70% GGBFS)	0.0574	Sealants and adhesives	
Copper		Epoxide Resin	5.7
EU Tube & Sheet (Virgin)	3.81	Melamine Resin	4.19
EU Tube & Sheet (Recycled)	0.84	Phenol Formaldehyde	2.98
Glass		Urea Formaldehyde	2.76
Primary Glass	0.91	Steel	
Secondary Glass	0.59	Pipe (Virgin)	2.87
Fibreglass (Glasswool)	1.54	Plate (Virgin)	3.27
Toughened	1.35	Section (Virgin)	3.03
Insulation		Section (Recycled)	0.47
General Insulation	1.86	Wire - Virgin	3.02
Cork	0.19	Stainless	6.15
Fibreglass (Glasswool)	1.35	Stones	
Flax (Insulation)	1.7	Granite	0.7
Mineral wool	1.28	Limestone	0.09
Paper wool	0.63	Marble	0.13
Rockwool	1.12	Marble tile	0.21
Woodwool (Board)	0.98	Sandstone	0.06
Iron	2.03	Shale	0.002
Lime	0.78		
Miscellaneous			
Calcium Silicate Sheet	0.13		
Chromium	5.39		
Cotton, Padding	1.28		
Cotton, Fabric	6.78		
Flax	1.7		
Fly Ash	0.008		
Grit	0.007		
Ground Limestone	0.032		
GRP - Fibreglass	8.1		
Lithium	5.3		
Mandolite	1.4		
Mineral Fibre Tile(Roofing)	2.7		
Manganese	3.5		
Mercury	4.94		
Molybedenum	30.3		
Nickel	12.4		
Perlite - Expanded	0.52		
Perlite - Natural	0.03		

*(IPCC, 2006; WRI, 2011)

B.2 Fuel

Fuel Type*	**EF (kg CO_2eq/L)**
Gasoline	2.384
Diesel oil	2.669
Natural Gas	1.436

*(IPCC, 2006)

B.2 Transportation

Personnel transportation*	**EF (kg CO_2eq/P km)**
Land Transportation	
Train - Light Rail	0.0768
Train - Tram	0.0768
Train - Average (Light Rail and Tram)	0.0768
Train - National Rail	0.0534
Train - Subway	0.07414
Taxi	0.1523
Bus - Local Bus	0.15726
Bus - Coach	0.03
Bus - Type Unknown	0.13394
Air Transport	
Domestic	0.17147
Short Haul - Seating Unknown	0.097
Short Haul - Economy Class	0.09245
Short Haul - First/Business Class	0.13867
Long Haul - Seating Unknown	0.11319
Long Haul - Economy Class	0.08263
Long Haul - Economy+ Class	0.13221
Long Haul - Business Class	0.23963
Long Haul - First Class	0.33052

*(WRI, 2014)

Freight transportation*	EF (kg CO_2eq/kg km)
Air transport	
Air - Domestic	0.00196073
Air - Short Haul	0.00147389
Air - Long Haul	0.00061324
Land transport	
Rail	0.0000285
Road Vehicle - HGV - Rigid - Engine Size 3.5 - 7.5 tonnes	0.00065946
Road Vehicle - HGV - Rigid - Engine Size 7.5 - 17 tonnes	0.00041243
Road Vehicle - HGV - Rigid - Engine Size >17 tonnes	0.00020027
Road Vehicle - HGV - Rigid - Engine Size Unknown	0.00025115
Road Vehicle - HGV - Articulated - Engine Size 3.5 - 33 tonnes	0.00015262
Road Vehicle - HGV - Articulated - Engine Size >33 tonnes	0.00008678
Road Vehicle - HGV - Articulated - Engine Size Unknown	0.00008869
Road Vehicle - HGV - Type Unknown	0.00012427
Road Vehicle - Light Goods Vehicle - Petrol - Engine Size < 1.305 tonnes	0.001173514
Road Vehicle - Light Goods Vehicle - Petrol - Engine Size 1.305 - 1.74 tonnes	0.000820633
Road Vehicle - Light Goods Vehicle - Petrol - Engine Size 1.74 - 3.5 tonnes	0.000496007
Road Vehicle - Light Goods Vehicle - Diesel - Engine Size < 1.305 tonnes	0.00094952
Road Vehicle - Light Goods Vehicle - Diesel - Engine Size 1.305 - 1.74 tonnes	0.00087386
Road Vehicle - Light Goods Vehicle - Diesel - Engine Size 1.74 - 3.5 tonnes	0.00052197
Road Vehicle - Light Goods Vehicle - LPG or CNG - Engine Size ≤3.5 tonnes	0.00061742
Road Vehicle - Light Goods Vehicle - Fuel and Engine Size Unknown	0.00058651
Water transport	
Watercraft - Large RoPax Ferry	0.0000495
Watercraft - Shipping - Small Tanker (844 tonnes deadweight)	0.0000333
Watercraft - Shipping - Large Tanker (18371 tonnes deadweight)	0.0000091
Watercraft - Shipping - Very Large Tanker (100000 tonnes deadweight)	0.0000059
Watercraft - Shipping - Small Bulk Carrier (1720 tonnes deadweight)	0.0000292
Watercraft - Shipping - Large Bulk Carrier (14201 tonnes deadweight)	0.0000079
Watercraft - Shipping - Very Large Bulk Carrier (70000 tonnes deadweight)	0.0000041
Watercraft - Shipping - Small Container Vessel (2500 tonnes deadweight)	0.00002
Watercraft - Shipping - Large Container Vessel (20000 tonnes deadweight)	0.0000125

*(WRI, 2014)

B.3 Waste Treatment

Waste treatment method*	EF (kg CO_2eq/tonne)
Landfill	300
Recycled	10
Composting	30

*(WRI, 2013)

B.4 Electricity

Energy type*	EF (kg CO_2eq/kWh)
Electricity	1.0389

*(Brander et al., 2011)

B.5 Water

Water type	EF (kg CO_2eq/L)
Desalinated water*	0.02158
Treated sewerage effluent (TSE)**	0.0001475

*Kennedy et al. (2012). ** IPCC (2006)

Appendix C: Density of Materials Used

Material	Density (kg/m^3)	Reference
Aggregate - Quarried	2,240	Hammond and Jones (2011)
Aluminium	2,700	Hammond and Jones (2011)
Asphalt	1,300	Lide (2003)
Asphaltic Concrete	2,483	Lide (2003)
Bitumen (Asphalt Binder)	1,000	Hammond and Jones (2011)
Bricks	1,800	Lide (2003)
Cement Mortar	2,000	Lide (2003)
Cement - Portland	1,860	Hammond and Jones (2011)
Cement General – 25% fly ash	1,860	Hammond and Jones (2011)
Cement General – 50% fly ash	1,860	Hammond and Jones (2011)
Cement General – 25% blast furnace slag	1,860	Hammond and Jones (2011)
Cement General – 50% blast furnace slag	1,860	Hammond and Jones (2011)
Clay	2,200	Lide (2003)
Concrete	2,300	Hammond and Jones (2011)
Copper	8,960	Lide (2003)
Glass	2,600	Lide (2003)
GRP	1,950	Hammond and Jones (2011)
HDPE	955	Lide (2003)
Plastic - General	960	Hammond and Jones (2011)
PVC	1,405	Lide (2003)
Soil - common	1,460	Hammond and Jones (2011)
Steel – general, section, sheet, wire, stainless	7,800	Lide (2003)
Steel – bar and rod	7,900	Hammond and Jones (2011)
Timber - Softwood (e.g. pine)	450	Lide (2003)
Timber- Hardwood	800	Hammond and Jones (2011)
Timber - Plywood	700	Hammond and Jones (2011)

Appendix D: Fuel Consumption Rates

D.1 Construction Equipment

Data about construction equipment fuel consumption rates were obtained from Caterpillar Performance Handbook (CAT, 2017) as listed below.

Equipment	Fuel Consumption (L/hr)	Mass (kg)
Air Compressor, 175 CFM	5.7	950
Telescopic Man Lift, 40ft.	3.9	9934
Concrete Paving Spread	32.3	9500
Cat 563 Padfoot Roller	14.2	11580
Ramex Roller	1.7	1410
Hand Tamp	1.6	150
Clip Machine	16.2	500
Dump Truck, 6x4, 12 CY	20.2	21000
35 Ton Art Dump	23.7	35000
Truck, Flat Bed 14'	10.0	13995
Fuel Truck, 2000 Gal	6.8	15000
Lube Truck	6.8	10000
Mechanics Truck, 1 Ton	6.8	1000
Pickup 4 x 4	6.8	3196
Water Truck, 4000 Gal	14.2	16000
Water Truck, 8000 Gal Off Rd	37.8	30000
Track-Type Tractors		
D3K	7.9	7795
D4K	8.6	8147
D5K	9	9408
D5N	16	9408
D6G	22	15034
D6K	21.5	13311
D6N	21.4	16757
D6R Series 3 (138 kW/185 hp)	25.7	19066
D6R Series 3 (149 kW/200 hp)	29.1	19914
D6T (138 kW/185 hp)	28.8	21600
D6T (149 kW/200 hp)	29.5	20580
D7E	27.2	26055
D7G	29	28525
D7R Series 2	31.4	25455
D8R	41.5	37920
D8T Tier 3	43.5	39751
D9T Tier 3	56.4	47872

Equipment	Fuel Consumption (L/hr)	Mass (kg)
D10T	79.5	70171
D11R	113	104236
D11T	109.8	112718
Skid steer loaders, multi terrain loaders and compact track loaders		
216B2	7.4	2588
226B2	10.94	2588
232B2	10.94	2818
236B2	10.37	2818
242B2	10.94	3166
246C	10.37	3367
247B2	10.94	3367
256C	11.36	3500
257B2	10.94	3600
262C	11.36	3634
272C	12.59	3977
277C	11.36	4000
279C	11.36	4000
287C	11.36	4280
289C	11.36	4300
297C	12.59	4390
299C	12.59	5000
Load haul dump units (underground)		
R1300G	18.9	27750
R1600G	28.3	40000
R1700G	34	52500
R2900G	45.4	67409
R2900G XTRA	47	75575
Excavators		
301.5	2.9	1720
301.6C	1.8	1720
301.8C	1.8	1785
302.5C	2.4	2850
303 CR/SR	4.7	3555
304 CR	5.6	4920
305 CR/SR	6.6	5320
307D	4.9	7075
308D CR	4.9	7850
311D RR (Tier 3)	9.5	12710
312D (Tier 3)	11.5	13150
314D CR (Tier 3)	11.5	14200
315D (Tier 3)	14.5	17280
319D (Tier 3)	15.5	19500
320D (STD Tier 3)	18	20300

Equipment	Fuel Consumption (L/hr)	Mass (kg)
320D (HHP Tier 3)	18.5	21500
321D CR (STD Tier 3)	18	24180
321D CR (HHP Tier 3)	18.5	24180
323D (Tier 3)	18.5	23190
324D (STD Tier 3)	21	24240
324D (HHP Tier 3)	24	24790
324D (STD Tier 2)	20	26060
324D (HHP Tier 2)	23	25370
328D CR (Tier 3)	26	34700
329D (STD Tier 3)	24	26900
329D (HHP Tier 3)	26	29240
329D (STD Tier 2)	23	29560
329D (HHP Tier 2)	24.5	28540
336D (Tier 3)	34.5	33750
336D (Tier 2)	32.5	36151
345D (Tier 3)	45.6	45375
345D (Tier 2)	43.3	46970
365C (Tier 3)	49.2	70348
365C (Tier 2)	46.7	70348
374D (Tier 3)	56.4	71132
374D (Tier 2)	53.6	71132
385C (Tier 3)	61	84128
385C (Tier 2)	58	86549
M313D	16	16200
M315D	18	18300
M316D	17	19800
M318D	18	20100
M322D	23	22500
M325C MH	23.8	22500
M325C L MH	27	22500
W330B MH	33	22500
W345B MH	42	22500
Front shovels		
5090	68	87500
5130B (Tier1)	120.2	182000
5230B (Tier1)	323.5	328100
PIPELAYERS		
PL61	15.1	17000
572R Series 2	15.7	31845
583T	21.8	45359
587R	20.8	53442
587T	28.3	53070

Equipment	Fuel Consumption (L/hr)	Mass (kg)
Wheel tractor-scrapers		
613G Tier 3	25	33995
621G Tier 3	48.8	33995
623G Tier 3	52.6	37510
627G Tier 3	79.5	37922
631G Tier 3	63	47628
637G Tier 3	95.9	51963
657G Tier 3	130.9	68384
Backhoe loaders		
416D (NA)	10.2	6750
416D (T)	11.4	6750
416E	11.4	6750
420E (T)	11	6895
422E (T)	10.2	7599
424D (NA)	10.2	7867
428E (T)	11.4	8135
430E (T)	12.8	7125
432E (T)	11.9	8448
434E (T)	11.9	8979
438D	13.1	8880
442E (T)	13.1	8782
444E (T)	13.1	9759
446D (T)	15.1	10355
450E	17	10950
Off highway trucks		
770	40.8	34642
772	47.1	35864
773E	54.9	45480
773F	56.6	45069
775F	57.4	45620
777D	75	72575
777F	74.2	72739
785C	107.5	96353
785D	108.5	96353
789C	141.2	132845
793D	181.6	383739
793F	193.3	383739
797F	293.7	623583
Articulated trucks		
725	20.8	46775
730 Ejector	24.5	54100
730	23	51305
735	32.4	64200

Equipment	Fuel Consumption (L/hr)	Mass (kg)
740	32.6	74400
740 Ejector	34.2	74000
Telehandlers		
TH210	10.1	5000
TH215	10.1	5500
TH220B (59-74 kW/80-99 hp)	14	6700
TH220B (92 kW/123 hp)	16	6700
TH330B (59-74 kW/80-99 hp)	14	7200
TH330B (92 kW/123 hp)	16	7200
TH340B	14	7700
TH350B	14	8480
TH355B	14	9225
TH360B	14	9970
TH460B	14	10500
TH560B (59-74 kW/80-99 hp)	15	12000
TH560B (92 kW/123 hp)	17	12000
TH580B	10.7	13670
Wheel dozers/soil compactors/landfill compactors		
814F	30	21713
815F	42	21713
816F	42	20755
824H	45.8	28724
825H	67.3	32734
826H	43.8	
834H	52.2	47106
836H	51.7	
844	62	70815
854G	76	98100
Paving Products - Compactors		
CP-323C	15	4620
CS-323C	15	4173
CS-423E	17	6745
CS-431C	13	6509
CP-442	11.9	7295
CS-443	11.9	6900
CS-531D	14	9650
CP-533E	13	11320
CS-533E	13	10485
CP-563E	17	11361
CS-563E	17	11414
CP-573E	18	11414
CS-573E	18	11414
CS-583E	19	11414

Equipment	Fuel Consumption (L/hr)	Mass (kg)
CP-663E	19	11414
CS-663E	19	11414
CS-683E	21	11414
CB-214D	3.5	2430
CB-224D	4	2610
CB-225D	3.5	2390
CB-334E	7	3940
CB-335E	6.5	3670
CB-434C	17	6485
CB-434D	11.4	6485
CB-534D	11.4	10390
CB-544	9.4	10700
CB-562D	11.4	10700
CB-564D	10.45	12600
CB-640	9.4	12600
CB-634C	19	12600
PS-150C	13	12600
PS-200B	13	13010
PF-300C	17	21000
PS-300C	17	14000
PS-360C	12.4	8500
Compaction equipment — utility compactors		
CB14	2	1620
CB22	5.5	2421
CB24, CB24 XT	5.5	2620
CC24	5	2320
CB32	5.5	3150
CB34, CB34 XW	4.5	4120
CC34	4.5	3590
Asphalt pavers		
AP-650B (97 kW/130 hp)	28.4	13917
AP-800D (97 kW/130 hp)	28.4	12115
AP-500E (106 kW/142 hp)	19	12590
AP-555E (106 kW/142 hp)	19	16145
AP-600D (129 kW/174 hp)	24.7	14197
AP-655D (129 kW/174 hp)	24.7	15320
AP-1050B (129 kW/174 hp)	30	16015
AP-1000D (167 kW/224 hp)	28.4	15490
AP-1055D (167 kW/224 hp)	28.4	16556
BG-600D (129 kW/174 hp)	24.7	14197
BG-655D (129 kW/174 hp)	24.7	15320
BG-245C (129 kW/174 hp)	30	16015
BG-260D (167 kW/224 hp)	28.4	14514

Equipment	**Fuel Consumption (L/hr)**	**Mass (kg)**
BG-2455D (167 kW/224 hp)	28.4	17601
COLD PLANERS		
PM-201	83.4	35110
PM-465	57	14333
PM-565B	68	38595
Road reclaimers/soil stabilizers		
RM-250C	41.6	16780
RM-300	41.6	24454
RM-350B	83.4	24040
RM-500	68.1	28145
TRACK LOADERS		
933C	13	7030
939C	15	9480
953D	24.4	15517
963D	29.2	20220
973D	44.3	28058
Wheel loaders and integrated tool carriers		
904H	8.2	4368
906H	7.6	5630
907H	7.6	5810
908H	8.6	6465
914G, IT14G	10.5	7950
924H, 924Hz	8.1	11635
928H, 928Hz	8.5	12618
930H	8.5	13174
938H, IT38H	10.4	14919
950H	14.7	16880
962H, IT62H	15.1	17941
966H	16.9	19730
972H	21	24490
980H	26	20000
988H	52.6	35800
990H	75	20000
992K	98.4	97294
993K	113.6	133637
994F	160	195434
Concrete Mixer	32.2	29500
Dewatering Systems (Deep-Well System)		
Electrical 30KVA	6	53
Electrical 40KVA	8	53
Electrical 65KVA	13	53
Electrical 80KVA	16	53
Electrical 100KVA	20	53

Equipment	Fuel Consumption (L/hr)	Mass (kg)
Electrical 150KVA	30	53
Electrical 160KVA	32	53
Electrical 200KVA	40	53
Dewatering Systems (Well-Point System)		
Diesel Motor System, 4", GP100	2.29	905
Diesel Motor System, 6", GP150	3.1545	1133
Diesel Motor System, 8", GP200	7.26	1570
Saw Cutter	2.6	
Motor grader		
120K	14.8	13032
120M	16.8	14466
12K	17.85	14334
12M	18.05	14999
140K	20.3	14768
140M	18.85	16197
160K	23	15795
160M	20.45	16506
14M	25.75	21226
16M	33.5	26959
24M	58.65	62457

D.2 Road Vehicles

Data about vehicle fuel consumption rates were obtained from Natural Resources Canada (2016) as listed below. These rates are expressed in unit (L/km)

Model Year 1995				Model Year 1996			
Class	**Fuel Consumption**			**Class**	**Fuel Consumption**		
	City	Highway	Comb		City	Highway	Comb
Cars				**Cars**			
Two Seater	0.16	0.1087	0.1343	Two Seater	0.133	0.0955	0.116
Minicompact	0.1438	0.1004	0.1244	Minicompact	0.1359	0.0955	0.1177
Subcompact	0.1223	0.088	0.1069	Subcompact	0.1194	0.0861	0.1044
Compact	0.1279	0.0908	0.1112	Compact	0.1219	0.0867	0.1061
Mid-size	0.1483	0.1022	0.1274	Mid-size	0.146	0.1	0.1254
Full-size	0.1573	0.1047	0.1336	Full-size	0.1526	0.1005	0.1293
St. Wagon, Small	0.1198	0.0877	0.1053	St. Wagon, Small	0.1165	0.085	0.1025
St. Wagon, Mid-Sized	0.1357	0.0953	0.1175	St. Wagon, Mid-Sized	0.1348	0.0949	0.1169
Light Trucks				**Light Trucks**			
Pickup truck, Small	0.1477	0.1086	0.1301	Pickup truck, Small	0.1338	0.1004	0.1186
Pickup truck, Std	0.1804	0.1365	0.1607	Pickup truck, Std	0.1781	0.1327	0.1577
Sport utility vehicle	0.1631	0.1285	0.1474	Sport utility vehicle	0.1615	0.1255	0.1452
Minivan	0.1476	0.112	0.1316	Minivan	0.1506	0.1105	0.1326
Van, Cargo	0.188	0.148	0.17	Van, Cargo	0.184	0.1422	0.1652
Van, Passenger	0.1918	0.1496	0.1729	Van, Passenger	0.1921	0.1436	0.1702
Heavy Trucks	0.375			**Heavy Trucks**	0.375		

Model Year 1997				Model Year 1998			
Class	Fuel Consumption			Class	Fuel Consumption		
	City	Highway	Comb		City	Highway	Comb
Cars				**Cars**			
Two Seater	0.1425	0.101	0.1238	Two Seater	0.1664	0.1112	0.1416
Minicompact	0.1391	0.0979	0.1207	Minicompact	0.1324	0.0928	0.1146
Subcompact	0.1237	0.0879	0.1076	Subcompact	0.1254	0.0877	0.1085
Compact	0.125	0.0878	0.1083	Compact	0.1244	0.0872	0.1077
Mid-size	0.1416	0.0968	0.1214	Mid-size	0.1367	0.0941	0.1176
Full-size	0.1519	0.1009	0.1288	Full-size	0.1511	0.1003	0.1283
St. Wagon, Small	0.1148	0.0815	0.0999	St. Wagon, Small	0.1102	0.0795	0.0965
St. Wagon, Mid-Sized	0.1338	0.0938	0.1159	St. Wagon, Mid-Sized	0.1315	0.0924	0.1138
Light Trucks				**Light Trucks**			
Pickup truck, Small	0.137	0.1007	0.1204	Pickup truck, Small	0.1441	0.1064	0.1271
Pickup truck, Std	0.1742	0.1287	0.1536	Pickup truck, Std	0.1776	0.1314	0.1568
Sport utility vehicle	0.157	0.1222	0.1414	Sport utility vehicle	0.1614	0.1239	0.1446
Minivan	0.1514	0.1102	0.1331	Minivan	0.1491	0.1072	0.1303
Van, Cargo	0.1771	0.1338	0.1575	Van, Cargo	0.1833	0.1345	0.1615
Van, Passenger	0.1896	0.141	0.1677	Van, Passenger	0.1869	0.1385	0.1653
Heavy Trucks	0.375			**Heavy Trucks**	0.375		

Model Year 1999				Model Year 2000			
Class	Fuel Consumption			Class	Fuel Consumption		
	City	Highway	Comb		City	Highway	Comb
Cars				**Cars**			
Two Seater	0.1678	0.1129	0.1431	Two Seater	0.1685	0.1141	0.1441
Minicompact	0.132	0.0927	0.1143	Minicompact	0.1489	0.1019	0.1279
Subcompact	0.1231	0.0874	0.1071	Subcompact	0.1295	0.0909	0.1122
Compact	0.1231	0.0866	0.1068	Compact	0.1224	0.0871	0.1066
Mid-size	0.1384	0.0952	0.1189	Mid-size	0.1381	0.0959	0.1191
Full-size	0.1516	0.101	0.1288	Full-size	0.1455	0.0969	0.1237
St Wagon, Small	0.1157	0.0934	0.1165	St Wagon, Small	0.1205	0.0855	0.105
St Wagon, Mid-Sized	0.1353	0.0825	0.1009	St Wagon, Mid-Sized	0.1325	0.0937	0.115
Light Trucks				**Light Trucks**			
Pickup truck, Small	0.1423	0.1028	0.1246	Pickup truck, Small	0.1423	0.1028	0.1247
Pickup truck, Std	0.1745	0.1319	0.1553	Pickup truck, Std	0.1737	0.1318	0.1549
Sport utility vehicle	0.1617	0.1249	0.1451	Sport utility vehicle	0.1619	0.1263	0.1459
Minivan	0.1536	0.1073	0.1327	Minivan	0.1567	0.1105	0.1358
Van, Cargo	0.1869	0.1401	0.1658	Van, Cargo	0.1833	0.1371	0.1624
Van, Passenger	0.1886	0.1411	0.1673	Van, Passenger	0.1909	0.1448	0.1702
Heavy Trucks	0.375			**Heavy Trucks**	0.375		

Model Year 2001				Model Year 2002			
Class	**Fuel Consumption**			**Class**	**Fuel Consumption**		
	City	Highway	Comb		City	Highway	Comb
Cars				**Cars**			
Two Seater	0.1457	0.0996	0.1249	Two Seater	0.1569	0.1072	0.1345
Minicompact	0.1511	0.1031	0.1295	Minicompact	0.1498	0.1029	0.1287
Subcompact	0.1236	0.0885	0.1078	Subcompact	0.1352	0.0945	0.1168
Compact	0.121	0.0862	0.1053	Compact	0.1211	0.0866	0.1055
Mid-size	0.1387	0.0955	0.1192	Mid-size	0.1391	0.0964	0.1198
Full-size	0.1477	0.0981	0.1252	Full-size	0.1419	0.0978	0.122
St Wagon, Small	0.1193	0.0853	0.1042	St Wagon, Small	0.1284	0.0918	0.121
St Wagon, Mid-Sized	0.1307	0.0927	0.1135	St Wagon, Mid-Sized	0.1296	0.0916	0.1125
Light Trucks				**Light Trucks**			
Pickup truck, Small	0.1608	0.1168	0.1408	Pickup truck, Small	0.1617	0.1177	0.1417
Pickup truck, Std	0.1745	0.1326	0.1556	Pickup truck, Std	0.181	0.1398	0.1624
Sport utility vehicle	0.1601	0.1242	0.144	Sport utility vehicle	0.1673	0.1281	0.1498
Minivan	0.1491	0.1068	13.02	Minivan	0.1513	0.1093	0.1325
Van, Cargo	0.1873	0.1409	0.1665	Van, Cargo	0.1852	0.1413	0.1655
Van, Passenger	0.1896	0.1419	0.1683	Van, Passenger	0.1911	0.1449	0.1702
Heavy Trucks	0.375			**Heavy Trucks**	0.375		

Model Year 2003				Model Year 2004			
Class	**Fuel Consumption**			**Class**	**Fuel Consumption**		
	City	Highway	Comb		City	Highway	Comb
Cars				**Cars**			
Two Seater	0.1639	0.1099	0.1396	Two Seater	0.1655	0.1116	0.1412
Minicompact	0.1392	0.097	0.1203	Minicompact	0.1311	0.0922	0.1135
Subcompact	0.1412	0.0987	0.1221	Subcompact	0.1343	0.0942	0.1163
Compact	0.1196	0.0862	0.1046	Compact	0.1216	0.0872	0.1061
Mid-size	0.1385	0.0961	0.1194	Mid-size	0.1381	0.0951	0.1187
Full-size	0.1479	0.0992	0.1259	Full-size	0.1572	0.1052	0.1338
St Wagon, Small	0.1197	0.0889	0.106	St Wagon, Small	0.122	0.0889	0.1072
St Wagon, Mid-Sized	0.1245	0.0905	0.1093	St Wagon, Mid-Sized	0.133	0.0938	0.1153
Light Trucks				**Light Trucks**			
Pickup truck, Small	0.1523	0.1058	0.131	Pickup truck, Small	0.18	0.141	0.162
Pickup truck, Std	0.1741	0.1339	0.156	Pickup truck, Std	0.1786	0.1361	0.1595
Sport utility vehicle	0.1659	0.1261	0.148	Sport utility vehicle	0.1702	0.1296	0.1518
Minivan	0.1535	0.11	0.131	Minivan	0.146	0.1028	0.1266
Van, Cargo	0.1943	0.1469	0.156	Van, Cargo	0.193	0.1456	0.1717
Van, Passenger	0.1915	0.147	0.148	Van, Passenger	0.1857	0.1441	0.1669
Heavy Trucks	0.375			**Heavy Trucks**	0.375		

Model Year 2005				Model Year 2006			
Class	**Fuel Consumption**			**Class**	**Fuel Consumption**		
	City	Highway	Comb		City	Highway	Comb
Cars				**Cars**			
Two Seater	0.1588	0.1082	0.136	Two Seater	0.1553	0.1057	0.1329
Minicompact	0.1477	0.1009	0.1266	Minicompact	0.135	0.0935	0.1162
Subcompact	0.1305	0.0919	0.1132	Subcompact	0.1313	0.915	0.1134
Compact	0.1226	0.0875	0.1068	Compact	0.1246	0.88	0.1081
Mid-size	0.1387	0.0947	0.1189	Mid-size	0.1389	0.095	0.119
Full-size	0.1604	0.1083	0.137	Full-size	0.1578	0.1063	0.1347
St Wagon, Small	0.1233	0.0891	0.1079	St Wagon, Small	0.1194	0.0869	0.1049
St Wagon, Mid-Sized	0.1344	0.094	0.1162	St Wagon, Mid-Sized	0.1348	0.0959	0.1172
Light Trucks				**Light Trucks**			
Pickup truck, Small	-	-	-	Pickup truck, Small	-	-	-
Pickup truck, Std	0.1746	0.1312	0.155	Pickup truck, Std	0.17	0.1271	0.1507
Sport utility vehicle	0.1647	0.1244	0.1465	Sport utility vehicle	0.1595	0.1189	0.1413
Minivan	0.1525	0.1079	0.1325	Minivan	0.1521	0.1074	0.1319
Van, Cargo	0.1772	0.1351	0.1583	Van, Cargo	0.1794	0.1377	0.1605
Van, Passenger	0.1822	0.1395	0.163	Van, Passenger	0.1829	0.1421	0.1644
Heavy Trucks	0.375			**Heavy Trucks**	0.375		

Model Year 2007				Model Year 2008			
Class	**Fuel Consumption**			**Class**	**Fuel Consumption**		
	City	Highway	Comb		City	Highway	Comb
Cars				**Cars**			
Two Seater	0.1596	0.1076	0.1362	Two Seater	0.1584	0.1081	0.1358
Minicompact	0.1419	0.0981	0.1220	Minicompact	0.1403	0.0971	0.1207
Subcompact	0.1332	0.0916	0.1144	Subcompact	0.1317	0.0905	0.1132
Compact	0.1281	0.0897	0.1109	Compact	0.1293	0.0901	0.1117
Mid-size	0.1364	0.0942	0.1174	Mid-size	0.1375	0.0947	0.1183
Full-size	0.1579	0.1067	0.1349	Full-size	0.1590	0.1079	0.1360
St Wagon, Small	0.1208	0.0865	0.1054	St Wagon, Small	0.1218	0.0861	0.1058
St Wagon, Mid-Sized	0.1323	0.0931	0.1147	St Wagon, Mid-Sized	0.1319	0.0926	0.1142
Light Trucks				**Light Trucks**			
Pickup truck, Small	-	-	-	Pickup truck, Small	0.1488	0.1119	0.1322
Pickup truck, Std	0.1717	0.1285	0.1523	Pickup truck, Std	0.1825	0.1355	0.1614
Sport utility vehicle	0.1536	0.1133	0.1355	Sport utility vehicle	0.1522	0.1121	0.1342
Minivan	0.1576	0.1103	0.1363	Minivan	0.1512	0.1058	0.1306
Van, Cargo	0.1959	0.1499	0.1753	Van, Cargo	0.1958	0.1539	0.1770
Van, Passenger	0.2073	0.1612	0.1867	Van, Passenger	0.2050	0.1607	0.1850
Heavy Trucks	0.375			**Heavy Trucks**	0.375		

Model Year 2009				Model Year 2010			
Class	Fuel Consumption			Class	Fuel Consumption		
	City	Highway	Comb		City	Highway	Comb
Cars				**Cars**			
Two Seater	0.1678	0.1135	0.1434	Two Seater	0.1641	0.1101	0.1398
Minicompact	0.1258	0.0887	0.1089	Minicompact	0.1300	0.0913	0.1125
Subcompact	0.1319	0.0908	0.1134	Subcompact	0.1291	0.0896	0.1113
Compact	0.1286	0.0895	0.1110	Compact	0.1216	0.0862	0.1056
Mid-size	0.1381	0.0952	0.1188	Mid-size	0.1337	0.0924	0.1151
Full-size	0.1586	0.1065	0.1351	Full-size	0.1602	0.1079	0.1366
St Wagon, Small	0.1154	0.0841	0.1013	St Wagon, Small	0.1098	0.0824	0.0974
St Wagon, Mid-Sized	0.1328	0.0922	0.1145	St Wagon, Mid-Sized	0.1316	0.0910	0.1133
Light Trucks				**Light Trucks**			
Pickup truck, Small	0.1443	0.1099	0.1288	Pickup truck, Small	0.1450	0.1090	0.1288
Pickup truck, Std	0.1814	0.1333	0.1597	Pickup truck, Std	0.1879	0.1371	0.1650
Sport utility vehicle	0.1520	0.1111	0.1336	Sport utility vehicle	0.1447	0.1071	0.1278
Minivan	0.1455	0.1013	0.1256	Minivan	0.1447	0.1022	0.1256
Van, Cargo	0.1942	0.1518	0.1754	Van, Cargo	0.2057	0.1570	0.1838
Van, Passenger	0.2025	0.1578	0.1825	Van, Passenger	0.2153	0.1648	0.1925
Heavy Trucks	0.375			**Heavy Trucks**	0.375		

Model Year 2011				Model Year 2012			
Class	Fuel Consumption			Class	Fuel Consumption		
	City	Highway	Comb		City	Highway	Comb
Cars				**Cars**			
Two Seater	0.1530	0.1047	0.1312	Two Seater	0.1427	0.0983	0.1226
Minicompact	0.1304	0.0915	0.1129	Minicompact	0.1283	0.0905	0.1113
Subcompact	0.1265	0.0880	0.1091	Subcompact	0.1270	0.0878	0.1093
Compact	0.1168	0.0826	0.1014	Compact	0.1136	0.0810	0.0990
Mid-size	0.1242	0.0869	0.1074	Mid-size	0.1213	0.0846	0.1047
Full-size	0.1569	0.1047	0.1334	Full-size	0.1519	0.1009	0.1290
St Wagon, Small	0.1110	0.0830	0.0984	St Wagon, Small	-	-	-
St Wagon, Mid-Sized	0.1323	0.0943	0.1153	St Wagon, Mid-Sized	0.1088	0.0817	0.0966
Light Trucks				**Light Trucks**			
Pickup truck, Small	0.1448	0.1087	0.1285	Pickup truck, Small	0.1436	0.1073	0.1272
Pickup truck, Std	0.1862	0.1353	0.1634	Pickup truck, Std	0.1845	0.1338	0.1618
Sport utility vehicle	0.1448	0.1062	0.1274	Sport utility vehicle	0.1453	0.1061	0.1277
Minivan	0.1492	0.1041	0.1290	Minivan	0.1398	0.0986	0.1212
Van, Cargo	0.2076	0.1598	0.1860	Van, Cargo	0.2093	0.1603	0.1871
Van, Passenger	0.2376	0.1723	0.2081	Van, Passenger	0.2388	0.1717	0.2086
Heavy Trucks	0.375			**Heavy Trucks**	0.375		

Model Year 2013				Model Year 2014			
Class	**Fuel Consumption**			**Class**	**Fuel Consumption**		
	City	Highway	Comb		City	Highway	Comb
Cars				**Cars**			
Two Seater	0.1307	0.0914	0.1131	Two Seater	0.1336	0.0924	0.1151
Minicompact	0.1145	0.0825	0.1002	Minicompact	0.1170	0.0844	0.1024
Subcompact	0.1284	0.0889	0.1106	Subcompact	0.1274	0.0882	0.1098
Compact	0.1132	0.0801	0.0984	Compact	0.1092	0.0779	0.0951
Mid-size	0.1148	0.0801	0.0992	Mid-size	0.1154	0.0798	0.0994
Full-size	0.1478	0.0974	0.1252	Full-size	0.1437	0.0944	0.1216
St Wagon, Small	0.1072	0.0810	0.0954	St Wagon, Small	0.1075	0.0799	0.0951
St Wagon, Mid-Sized	0.1113	0.0837	0.0993	St Wagon, Mid-Sized	0.1162	0.0855	0.1025
Light Trucks				**Light Trucks**			
Pickup truck, Small	0.1768	0.1288	0.1553	Pickup truck, Small	0.1375	0.1063	0.1236
Pickup truck, Std	0.1154	0.0890	0.1034	Pickup truck, Std	0.1701	0.1244	0.1496
Sport utility vehicle	0.1454	0.1059	0.1276	Sport utility vehicle	0.1436	0.1046	0.1261
Minivan	0.1413	0.0990	0.1222	Minivan	0.1431	0.1006	0.1239
Van, Cargo	0.2091	0.1602	0.1870	Van, Cargo	0.2088	0.1606	0.1872
Van, Passenger	0.2386	0.1714	0.2084	Van, Passenger	0.2323	0.1676	0.2033
Heavy Trucks	0.375			**Heavy Trucks**	0.375		

Model Year 2015				Model Year 2016			
Class	**Fuel Consumption**			**Class**	**Fuel Consumption**		
	City	Highway	Comb		City	Highway	Comb
Cars				**Cars**			
Two Seater	0.1347	0.0914	0.1153	Two Seater	0.1362	0.0934	0.1170
Minicompact	0.1172	0.0849	0.1027	Minicompact	0.1165	0.0842	0.1020
Subcompact	0.1191	0.0821	0.1024	Subcompact	0.1203	0.0823	0.1032
Compact	0.1090	0.0771	0.0946	Compact	0.1078	0.0766	0.0937
Mid-size	0.1131	0.0774	0.0970	Mid-size	0.1116	0.0774	0.0961
Full-size	0.1445	0.0944	0.1220	Full-size	0.1423	0.0936	0.1205
St Wagon, Small	0.0966	0.0729	0.0861	St Wagon, Small	0.0971	0.0731	0.0863
St Wagon, Mid-Sized	0.1094	0.0816	0.0971	St Wagon, Mid-Sized	0.1081	0.0823	0.0967
Light Trucks				**Light Trucks**			
Pickup truck, Small	0.1328	0.1017	0.1189	Pickup truck, Small	0.1284	0.0977	0.1144
Pickup truck, Std	0.1630	0.1176	0.1426	Pickup truck, Std	0.1617	0.1173	0.1417
Sport utility vehicle	0.138	0.1006	0.1212	Sport utility vehicle	0.1345	0.0989	0.1185
Minivan	0.1416	0.1001	0.1228	Minivan	0.1405	0.0998	0.1221
Van, Cargo	0.2088	0.1606	0.1872	Van, Cargo	0.2088	0.1606	0.1872
Van, Passenger	0.2308	0.1584	0.1982	Van, Passenger	0.2086	0.1519	0.1829
Heavy Trucks	0.375			**Heavy Trucks**	0.375		

Model Year 2017				Battery Electrical 2012-2017			
Class	**Fuel Consumption**			**Class**	**Fuel Consumption**		
	City	Highway	Comb		City (kWh)	Highway (kWh)	Comb (kWh)
Cars				**Cars**			
Two Seater	0.1411	0.0969	0.1212	Two Seater	0.1720	0.2250	0.1960
Minicompact	0.1095	0.0815	0.0969	Minicompact	-	-	-
Subcompact	0.1235	0.0856	0.1064	Subcompact	0.1625	0.2018	0.1798
Compact	0.1079	0.0773	0.0941	Compact	0.1874	0.2124	0.1992
Mid-size	0.1107	0.0784	0.0962	Mid-size	0.1744	0.2140	0.1923
Full-size	0.1368	0.0921	0.1167	Full-size	0.2222	0.2124	0.2179
St Wagon, Small	0.0914	0.0722	0.0826	St Wagon, Small	0.1720	0.2185	0.1933
St Wagon, Mid-Sized	0.0989	0.0754	0.0884	St Wagon, Mid-Sized	0.0000	0.0000	0.0000
Light Trucks				**Light Trucks**			
Pickup truck, Small	0.1301	0.1004	0.1167	Pickup truck, Small	-	-	-
Pickup truck, Std	0.1610	0.1181	0.1418	Pickup truck, Std	-	-	-
Sport utility vehicle	0.1352	0.1003	0.1194	Sport utility vehicle	0.2375	0.2261	0.2322
Minivan	0.1323	0.0940	0.1152	Minivan	-	-	-
Van, Cargo	0.2088	0.1606	0.1872	Van, Cargo	-	-	-
Van, Passenger	0.2059	0.1481	0.1797	Van, Passenger	-	-	-
Heavy Trucks	0.375			**Heavy Trucks**	0		

Appendix E: Irrigation Rates

Data about the irrigation rates were obtained from Abu Dhabi Public Realm Design Manual (ADUPC, 2017).

Plant	Irrigation Category	Average Irrigation Rate (L/day)
Palms	High	108.1
	Medium	49.1
	Low	0
Trees	High	63.1
	Medium	49.1
	Low	21.8
Shurbs	High	12.3
	Medium	7.8
	Low	3.5
Ground cover	High	7.3
	Medium	6.3
	Low	5
Succulents and perennials	High	12.3
	Medium	7.8
	Low	3.4
Climbers	High	12.3
	Medium	7.8
	Low	0

Appendix F: Sequestration Rates

Data about the annual sequestration rates were obtained from the US Environmental Protection Agency (EPA, 1998) as listed below.

Annual Sequestration Rate (kg CO_2/tree/year)							
Type		Hardwood			Conifer		
Growth Rate		Slow	Moderate	Fast	Slow	Moderate	Fast
Age (year)	0	0.59	0.86	1.23	0.32	0.45	0.64
	1	0.73	1.23	1.82	0.41	0.68	1.00
	2	0.91	1.59	2.45	0.50	0.91	1.41
	3	1.09	1.95	3.13	0.64	1.14	1.86
	4	1.27	2.36	3.86	0.73	1.41	2.36
	5	1.45	2.77	4.59	0.86	1.68	2.91
	6	1.68	3.22	5.36	1.00	2.00	3.45
	7	1.86	3.68	6.17	1.14	2.32	4.04
	8	2.09	4.13	7.04	1.27	2.63	4.63
	9	2.27	4.63	7.90	1.41	3.00	5.31
	10	2.50	5.08	8.76	1.59	3.36	5.99
	11	2.72	5.58	9.67	1.73	3.72	6.67
	12	2.95	6.13	10.58	1.91	4.13	7.40
	13	3.18	6.63	11.53	2.09	4.49	8.13
	14	3.41	7.17	12.49	2.22	4.90	8.90
	15	3.68	7.67	13.48	2.41	5.36	9.72
	16	3.90	8.22	14.48	2.59	5.77	10.53
	17	4.13	8.81	15.48	2.77	6.22	11.35
	18	4.40	9.35	16.48	3.00	6.67	12.21
	19	4.63	9.94	17.52	3.18	7.13	13.08
	20	4.90	10.53	18.61	3.36	7.58	13.98
	21	5.18	11.08	19.66	3.59	8.08	14.89
	22	5.45	11.71	20.75	3.77	8.58	15.84
	23	5.68	12.30	21.84	4.00	9.08	16.80
	24	5.95	12.89	22.97	4.18	9.58	17.75
	25	6.22	13.53	24.11	4.40	10.08	18.75
	26	6.49	14.16	25.24	4.63	10.62	19.75
	27	6.81	14.76	26.38	4.86	11.17	20.75
	28	7.08	15.39	13.94	5.08	11.71	21.79
	29	7.35	16.03	28.74	5.31	12.26	22.84
	30	7.63	16.71	29.92	5.54	12.80	23.93
	31	7.95	17.34	31.10	5.77	13.39	25.02

Annual Sequestration Rate (kg CO_2/tree/year)							
Type		Hardwood			Conifer		
Growth Rate		Slow	Moderate	Fast	Slow	Moderate	Fast
Age (year)	32	8.22	18.02	32.32	6.04	13.94	26.11
	33	8.49	18.66	33.51	6.27	14.53	27.19
	34	8.81	19.34	34.73	6.49	15.12	28.33
	35	9.08	20.02	36.00	6.76	15.75	29.46
	36	9.40	20.70	37.23	7.04	16.34	30.65
	37	9.72	21.38	38.50	7.26	16.93	31.83
	38	9.99	22.06	39.77	7.54	17.57	33.01
	39	10.31	22.79	41.04	7.81	18.21	34.19
	40	10.62	23.47	42.31	8.04	18.84	35.41
	41	10.94	24.20	43.63	8.31	19.48	36.64
	42	11.26	24.88	44.95	8.58	20.11	37.86
	43	11.53	25.61	46.26	8.85	20.79	39.13
	44	11.85	26.33	47.58	9.13	21.43	40.41
	45	12.17	27.06	48.90	9.40	22.11	41.68
	46	12.53	27.78	50.26	9.67	22.79	42.99
	47	12.85	28.51	51.57	9.99	23.47	44.27
	48	13.17	29.28	52.94	10.26	24.15	45.58
	49	13.48	30.01	54.30	10.53	24.88	46.94
	50	13.80	30.78	55.71	10.85	25.56	48.26
	51	14.12	31.51	57.07	11.12	26.29	49.62
	52	14.48	32.28	58.48	11.44	26.97	50.98
	53	14.80	33.05	59.84	11.71	27.69	52.39
	54	15.16	33.82	61.24	12.03	28.42	53.75
	55	15.48	34.59	62.65	12.35	29.15	55.16
	56	15.80	35.37	64.10	12.62	29.92	56.57
	57	16.16	36.14	65.51	12.94	30.65	58.02
	58	16.48	36.91	66.97	13.26	31.42	59.43
	59	16.84	37.68	68.37	13.57	32.14	60.88

Appendix G: Al Rahba City Counts Locations