Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2018) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

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

Greenhouse Gas Emissions Associated with Road Transport Projects: Current Status, Benchmarking, and Assessment Tools

Francisco D.B. Albuquerque[a], Munjed A. Maraqa[a], Rezaul Chowdhury[b], Timur Mauga[a], and Mohammed Alzard[a]

[a]*United Arab Emirates University, Al Ain, 15551, UAE*
[b]*University of Southern Queensland, Toowoomba, Australia*

Abstract

Global warming and climate change have been two much-debated topics in recent times due to their malevolent consequences not only to ecosystems, but also to the human race. They are indeed negative by-products of greenhouse gas (GHG) emissions. The transportation sector is a major contributor of GHG emissions, accounting for approximately 20 percent of all carbon dioxide (CO_2) emissions globally, and road transportation accounts for the large majority of those emissions. This paper reviews literature related to GHG emissions produced by construction, operation, and maintenance phases of road projects. It compares country-specific GHG emission levels and provides input on assessment tools that can be used to estimate road project-specific GHG emissions. Lastly, the paper draws conclusions in regards to the magnitude of GHG emissions produced by road transportation, as well as to the status of assessment tools readily available in the market. The authors find that GHG emissions continue to be a concern, especially in the Gulf Cooperation Countries (GCC), and recognize the need for reliable modeling tools capable of estimating project-specific GHG emissions. As a result, a model framework is proposed as the first step towards a comprehensive modeling tool capable of estimating GHG emissions produced during the entire life-cycle of a road project. The authors disclose that such tool is currently under development.

Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY.

Keywords: Type your keywords here, separated by semicolons ;

2352-1465 © 2018 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY

1. Introduction

Global warming and climate change have been two much-debated topics in recent times due to their malevolent consequences not only to ecosystems, but also to the human race. Their negative impacts may include increases in temperature, rising sea levels, changes in precipitation patterns, droughts, floods, heat waves, and hurricanes (Dai, 2011; Emanuel, 2011). Moreover, they have been found to affect certain economic sectors such as agriculture and tourism (Sanghi and Mendelsohn, 2008; Giles and Perry, 1998; Eide and Heen, 2002; Ng and Zhao, 2011). Global warming and climate change are indeed negative by-products of greenhouse gas (GHG) 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, transportation, and agriculture (IPCC, 2014). The six GHGs identified by the Kyoto Protocol are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC), perfluorinated compounds (PFC), and sulfur hexafluoride (SF_6) (United Nations, 1998).

Agricultural activities have been the major source of CH_4 and N_2O, industrial processes and refrigeration have been the major source of HFC, PFC, and SF_6, whereas the combustion of fossil fuel has been the major source of CO_2 emissions (IPCC, 2014). CO_2, however, has been found to be the most predominant gas emitted, often accounting for over 60 percent of the total direct GHG emissions (Sperling and Cannon, 2010), which often leads quantification of GHG emissions to be in terms of CO_2-equivalent (Galli et al., 2011). Carbon footprint is a commonly used term to describe the total amount of GHGs or CO_2-equivalent emitted by a product or service over its entire life cycle, and it can be estimated at the national, sector, household, or individual levels. Despite their malevolent consequences, global CO_2 emissions have grown steadily. Between 2004 and 2025, global CO_2 emissions are expected to grow to 39 billion tons from 26 billion tons, resulting in a 2 percent annualized increase (ADB, 2010a). Not surprisingly, climate change modeling has suggested an increase in averaged surface temperatures of more than 1 degree Celsius over the period from 1990 to 2100.

Indeed, global emissions from fossil fuels have increased by 90 percent since 1900 (Galli et al., 2011). The transportation sector has been found to be one of the major carbon footprint producers over the last century. Currently, almost 15 percent of energy-related CO_2-equivalent emissions come from the transportation sector. Almost all of the world's transportation energy comes from the 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 transportation. 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 transport. 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, 2010a; 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 required (TAGG, 2013), as shown in Figure 1.

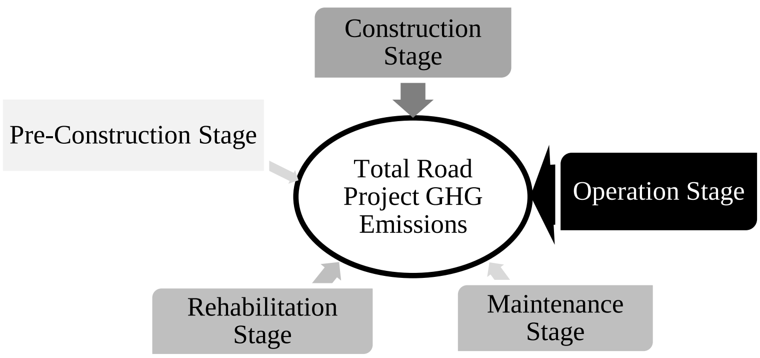

Figure 1. Road Project Stages Contributing to Full Life-Cycle GHG Emissions

The objective of the present paper is fourfold: 1) to examine the contribution of different road project stages (i.e., construction, operation, as well as maintenance and rehabilitation) to GHG emissions, 2) to conduct a country-specific comparison of emission levels, 3) to identify any analytical assessment tools capable of estimating GHG emissions resulting from the entire life-cycle of a road project, and 4) present a framework under which a software tool can be developed and used to estimate road-project-related GHG emissions.

2. Methods

A comprehensive review of research studies was conducted. These research studies had to be written in the English language and published in peer-reviewed journals. Nearly 75 percent of the studies included in this manuscript were published in the past decade, while the remaining 25 percent of the citations refer to studies published as early as the 1990s. By including not only relatively recent publications, but also those published several years, even decades, ago, one may have a grasp on the historical evolution of the topics being investigated in the present work. In addition, data gathered by governmental agencies and findings from work done by private and non-profit organizations were also studied.

The rationale behind preparing this work is that even though the Gulf Cooperation Countries (GCC) possess large fossil fuel reserves and currently produce a significant amount of GHG emissions, their pursuit of sustainable initiatives in regards to their infrastructure plans may be on the rise (Nagraj, 2013; EAD, 2012). As a result, questions may arise while pursuing some of these initiatives, such as:

(1) Does road transportation significantly contribute to the GCC's total GHG emissions?
(2) Which project phase (i.e., construction, maintenance, or operation) should be emphasized on in order to significantly reduce emissions from road projects?
(3) How do the GCC countries compare in terms of GHG emission levels to both other developing countries and to those considered to be more developed?
(4) Are there assessment tools currently available capable of determining the amount of GHG emissions produced by road projects throughout their entire life-cycle?
(5) If not, what should such tool be capable of?

The present work intends to shed light on these questions.

3. Carbon footprint produced by road transportation

The transportation sector is one of the major contributors of GHG emissions worldwide. Almost 15 percent of the global GHG and over 20 percent 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, 2010a). However, sources of GHG emissions in the road sector also include construction materials, machinery use, removal of vegetation, as well as transportation of labor, equipment, and materials as shown in Table 1 (ADB, 2010a).

Table 1. Sources of GHG Emissions During the Life Cycle of a Road Project (ADB, 2010a)

<table>
<tr><th rowspan="2">Sources of Carbon Dioxide</th><th colspan="3">Road Project Stage</th></tr>
<tr><th>Construction</th><th>Maintenance</th><th>Operation</th></tr>
<tr><td>Materials</td><td colspan="2">-------- Embodied Carbon ---------</td><td rowspan="3">NA</td></tr>
<tr><td>Machinery Use</td><td colspan="2" rowspan="2">----- Direct GHG Emissions ------</td></tr>
<tr><td>Transportation</td></tr>
<tr><td>Vegetation Removal</td><td colspan="3">----------------- Sequestration Potential Lost -----------------</td></tr>
<tr><td>Road Use</td><td colspan="2">NA</td><td>Direct GHG Emissions</td></tr>
</table>

In recent years, over 50 percent of global primary oil consumption has been used to meet over 90 percent of the total transport energy demand, with bio-fuels supplying only 2 percent, electricity 1 percent, and natural gas and other fuels 3 percent. More specifically, about 72 percent of the total direct and indirect GHG 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 items such as cement, steel, aggregate, and bitumen, as well as hours of machinery use, fuel consumption, and vegetation removal (ADB, 2010a; Barandica et al., 2013; EAPA and, Eurobitume, 2004).

3.1 Road construction and maintenance

As shown in Table 1, sources of carbon emission during road construction and maintenance include construction materials, fuel consumed by construction machinery as well as by material and labour transport, and removal of vegetation (Egis, 2010). However, even though there are several tasks included in road construction/maintenance contributing to GHG emissions such as site clearing, sub-grade preparation, production and transport of construction materials, and construction machinery use, previous studies have estimated that road construction/maintenance account for only a small proportion of the total GHG emissions produced throughout a road project's life cycle (Park et al., 2003; BIS, 2010).

Research has found that construction contributes to less than 2 to 5 percent of the total life-cycle emission of a road project (Park et al., 2003). An analysis of a four-lane, 1-km long highway in the Republic of Korea found that total non-operating emissions were mostly associated with four phases: the manufacturing of construction materials, construction, maintenance/repair, and demolition/recycling. It was estimated that 57 percent of the total non-operating emissions were produced in the manufacturing stage 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 percent of total non-operating emissions. Construction accounted for 2 percent and demolition only 1 percent (BIS, 2010). Other research found that earthwork activity contributed to the majority of the emissions produced during the road construction stage, accounting for 60 to 85 percent of the total emissions. In this case, earthwork included the extraction, the supply and internal transport of earth, and the disruption of environmental systems. Off-road machinery use, however, accounted for most of total emissions, followed by construction material-related emissions and environmental systems disruption. 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 percent of the total emissions produced during construction of expressway facilities. To a lesser extent, pavement, culverts, and earthwork also presented contributions to GHG emissions. Pavement was the main contributor of GHG emissions during the construction of lower-class road facilities (Angelopoulou et al., 2009). Fabrication and extraction of construction materials have been found to be the main GHG contributors. Aggregate and base materials, cement, bitumen, and steel reinforcement have been found to be the construction materials used in largest quantities (Egis, 2010).

Other key issues that have been raised as contributing factors to GHG emissions during road construction/maintenance are: the use of older machinery, under-designed drainage systems resulting in high maintenance requirements, pavement life-shortening due to overloading, deficiency of suitable materials, inappropriate compacting 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 percent of the total GHG emissions produced during the construction of expressway facilities (Angelopoulou et al., 2009).

The selection of pavement type has been proven to also be an important consideration. Concrete pavement has been found to produce significantly higher amounts of GHG emissions as compared to asphalt pavement, 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 asphalt mixture course construction, the use of efficient equipment for laying, mixing, and transporting have been recommended to decrease the GHG emissions (Ma et al., 2016).

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 the 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 percent of all transportation-related CO_2 emissions in the United States are produced by cars and trucks (ITF, 2010). Moreover, a significant increase in the vehicle fleet size, 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 emission levels back in 2000 (ADB, 2010b). In China, CO_2 emissions from fuel combustion experienced 172 percent growth between 1990 and 2007. Passenger road transport accounts for approximately 30 percent of China's total road sector CO_2 emissions, while heavy trucks account for approximately 40 percent (Marland et al., 2008). Undeniably, CO_2 emissions produced by fuel combustion have experienced an exponential-like growth globally as shown in Table 2 (ITF, 2010). For instance, in the Emirate of Abu Dhabi, part of the United Arab Emirates (UAE), four types of fuel are generally consumed in the transport sector. These types are namely gasoline, diesel, natural gas, and jet kerosene. These fuel types produce a total GHG emissions amount of over 18 Gg CO_2-equivalent annually. The amount of different GHG emissions produced by the transport sector in the Emirate of Abu Dhabi is shown in Table 3 (EAD, 2012). As can be seen, roads contribute to about 63 percent of the direct GHG emissions in the transport sector, of which more than 98 percent is attributed to CO_2 emissions produced by fuel combustion.

Table 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	1630	5	692
1970	4075	14	1152
1980	5297	26	1263
1990	6096	50	1314
1998	6608	79	1487

Table 3. GHG Emissions from the Transport Sector in the Emirate of Abu Dhabi (EAD, 2012)

	Roads		**Aviation**		**Total Transport Sector**
Emissions	Gg CO_2 eq.	**%**	Gg CO_2 eq.	**%**	Gg CO_2 eq.
Total GHG	11,735.60	63.27	6,774.00	36.52	18,547.28
CO_2	11,549.38	63.04	6,735.37	36.76	18,321.59
CH_4	15.24	91.75	1.36	8.19	16.61
N_2O	170.98	81.77	37.27	17.82	209.09

But it is not just fuel combustion that plays a role in the production of GHG emissions. As indicated in Table 1, carbon sequestration potential lost due to vegetation removal is also a major contributing factor to GHG emissions during not only the road construction and maintenance stages, but especially 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 atmosphere during the road project's entire life cycle (i.e., construction, operation, and maintenance) had vegetation not been destroyed. This occurs since vegetation often needs to be cut off and removed to give way to the infrastructure pertaining to a road project (Lal, 2008; Le Quéré et al., 2012).

4. Country-specific emission levels

China, The United States, India, The Russian Federation, Japan, Germany, The United Kingdom, and France have been found to be major emitters, in terms of CO2 emissions, since the 1970's. 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 4 shows a comparison among seven countries/states in regards to their emission levels in terms of CO_2-equivalent. The United States and The United Kingdom may represent developed countries with more mature economies and, therefore, slower annualized economic growth. On the other hand, China, Russia, 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 4 shows the amount of emissions roads account for in relation to the whole transport sector. For instance, in the Emirate of Abu Dhabi, emissions produced by road transportation accounted for 63 percent of the emissions produced by the transport sector as a whole. Table 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 of 10^3 km of road) are 0.029 and 0.061 Mt CO_2-equivalent, which are considerably lower than those from the Emirate of Abu Dhabi (i.e., 0.179 and 0.571 Mt CO_2-equivalent, respectively). Normalizing emissions is important in order to draw meaningful conclusions about emission levels from different countries/states. For example, the total emissions produced by the road sector in the Emirate of Abu Dhabi is only approximately 12 Mt CO_2-equivalent. 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 production rate.

The two right-most columns of Table 4 show the ratios in terms of Mt CO_2-equivalent produced per area of land and kilometer of road, respectively, between the Emirate of Abu Dhabi and other countries listed. For instance, the ratio of 9.36 indicates that the emission levels in the Emirate of Abu Dhabi, in terms of Mt CO_2-equivalent per kilometer 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_2-equivalent), the 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 differences in road transportation emission levels between China and the Emirate of Abu Dhabi probably stem from the fact that even though they both are usually categorized as "emerging" economies, they may present 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 travelled per capita is higher in the Emirate due to its higher income per capita and cheaper fuel, but also its proportion of heavier vehicles such as sport utility vehicles (SUVs) is higher than that in China.

Table 4. Comparison of Annual Emission Rates among Countries (ITF, 2010)

Country/ State	Roads Only (Mt CO2-eq.)	% Road Emissions	Area (10^3 km^2)	Network Length (10^3 Km)	Emission Rate (Mt CO2-eq./10^3 km^2)	Emission Rate (Mt CO2-eq./10^3 km-road)	Ratio (Area)	Ratio (Km-road)
Abu Dhabi	12	63	67	21	0.179	0.571	1	
Saudi Arabia	88	84	2,149	221	0.041	0.398	4.36	1.43
India	110	83	3,287	4,699	0.033	0.023	5.42	24.8
Russia	120	35	17,098	1,283	0.007	0.093	25.57	6.13
China	280	58	9,596	4,577	0.029	0.061	6.17	9.36
United Kingdom	119	69	243	394	0.489	0.302	0.36	1.89
United States	1528	78	9,833	6,586	0.155	0.232	1.15	2.46

5. Carbon footprint assessment tools

A number of carbon-footprint-related assessment tools have been developed over the years. 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 Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) evaluates the sustainability of road projects and pinpoints ways to improve them based on a set of pre-established criteria defined by specialists (US FHWA, 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 the environmental impact of transporting freight by various transport modes. The tool allows the user to input parameters such as transport mode (e.g., road, rail, water, or air), vehicle type, and emission factors (IFEU Heidelberg et al., n.d.). The Motor Vehicle Emission Simulator (MOVES) estimates emissions from cars and trucks under different user-defined vehicle operating characteristics and road types (US EPA, 2016). The Motor Vehicle Emission Inventory (MVEI) model was developed by the California Air Resources Board and is used to evaluate pollutants released by the road transportation network at several regional levels. While other GHGs (CH_4, N_2O) still need to be included in this model, MVEI can be a practical model for evaluating different scenarios and performing sensitivity analysis (El-Fadel and Bou-Zeid, 1999).

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 4 have been determined 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 (EPA, 2003). The greenhouse gases, regulated emissions, and energy-use in the 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 the 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 Harmonised Assessment and Normalisation of Greenhouse-Gas Emissions (CHANGER) was released in 2009, and it enables an estimation of the carbon footprint of road construction activities. CHANGER estimates GHG emissions produced by each road construction activity and material taken into consideration. CHANGER considers three GHGs (i.e., CO_2, CH_4, and N_2O) and converts them all into a CO_2-equivalent. 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). CO_2NSTRUCT was developed in Spain and makes use of a relatively large dataset of construction materials and machinery, energy sources, electricity mixes, and transport vehicles. However, just like CHANGER, CO_2NSTRUCT 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 from road projects and assessing alternative construction practices to limit GHG emissions (World Bank, 2010).

Carbon Gauge is a tool to estimate GHG emissions from 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 during major road activities related to construction, operation, and maintenance. It is a Microsoft Excel macro-enabled spreadsheet. While it provides a comprehensive list of default values for emission factors, it neither quantifies emissions from traffic operations nor accounts for sequestration, irrigation requirements, or activities such as sewage, water, and telecommunication work.

6. Conclusions

This paper concludes that GHG emissions produced by road transportation represent a good-sized slice of the global-GHG-output pie, and they continue to steadily grow despite the latest development in greener practices, technologies, and policies (Sperling and Cannon, 2010; ADB, 2010a).

It can also be concluded that, as GHG emission output is normalized by km of road, the GCC region may present a high road transport GHG emission rate as evidenced by data in Table 4. In fact, the Emirate of Abu Dhabi and the Kingdom of Saudi Arabia presented the highest emission rates, in terms of Mt CO_2-equivalent per kilometer of road, even as they are compared to countries such China and the United States which have historically been large GHG producers. Possessing some of the world's largest oil and gas reserves, the GCC region may be presently enjoying high energy consumption rates which, in turn, translate inTO high GHG emission production levels. This enormous amount of CO_2-equivalent produced by the GCC countries' road transportation may reflect the GCC region's steady economic growth which has resulted in high vehicle ownership and ridership levels (Shahbandari, 2015; Sambidge, 2010). Other factors such as harsh summer climate conditions and inexpensive fuel prices may also make other transport modes less attractive in the GCC region, exacerbating its private vehicle travel.

Another finding worth noting is that while road projects have been found to produce GHG emissions at different stages (Egis, 2010; ADB, 2010), road operation is by far the single, largest GHG producer throughout a road project's life-cycle (Egis, 2010). Therefore, it is important to consider a full-cycle approach. Nevertheless, road construction and rehabilitation may still offer ways to minimize the 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, 2015), suggesting that CO_2 emissions may be reduced by as much as one-third in the construction stage and by more than four-fifths during the maintenance phase by adopting measures such as low-energy asphalt and LED lighting.

Finally, a number of assessment tools capable of estimating the carbon footprint from road- and transportation-related projects have been developed over the past several years (Ekström et al., 2004; EPA, 2003; Wang et al., 2007; ISSRC, 2008; Fernández-Sánchez et al., 2015; World Bank, 2010). 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 (Paul, 2008; HDM Global, 2016; US FHWA, 2016; El-Fadel and Bou-Zeid, 1999). Others are focused on assessing emissions produced by either private vehicles, public transit, or freight transportation (WRI, 2001; IFEU Heidelberg, et al., n.d.; US EPA, 2016; Smit et al., 2007; Ntziachristos et al., 2009; EPA, 2003; Wang et al., 2007; ISSRC, 2008). Further, others may only estimate emissions based on a single project stage (e.g., construction phase) (Huang et al., 2013; World Bank, 2010). Some of these tools may also have adopted emission factors based on localized conditions and, as a result, they may not be adequate for use elsewhere (Fernández-Sánchez et al., 2015), limiting their geographical usefulness.

7. Recommendations

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. A number of software tools have been developed to date. However, these software tools not only do not cover all phases of a road project (i.e., construction, operation, maintenance, and rehabilitation), but they also may be based on local emission factors which may limit their geographical application. Lastly, future software-based analysis tools should ideally make use of inventory data instead of data from bill-of-quantities. Making use of inventory data should more reliably reflect the actual resources consumed.

Therefore, given the stunning as well as increasing amount of GHG emissions continually being produced by road projects and, especially, the lack of assessment tools capable of analyzing GHG emission from road projects based on a full life-cycle approach, the authors identify the need for the prompt development of an analytical tool capable of: (1) quantifying CO_2-equivalent produced by road projects throughout complete life-cycles including pre-construction, construction, operation, and maintenance/rehabilitation stages; and (2) allowing users to assess the impact of mitigation measures. The authors acknowledge that the development of such a tool is ongoing. The framework on which this tool is being based is shown in Figure 2. This framework proposes a model capable of addressing emissions produced throughout the entire life-cycle of a road project (i.e., pre-construction, construction, operation, maintenance, and rehabilitation phases). The model should, therefore, contain an extensive list of materials and activities often consumed by road-related projects. The model should allow users to modify default values, including emissions factors. Once resources are quantified, they should be linked with their associated emission factors, resulting in the total quantified GHG emissions produced by the full life-cycle of a road project.

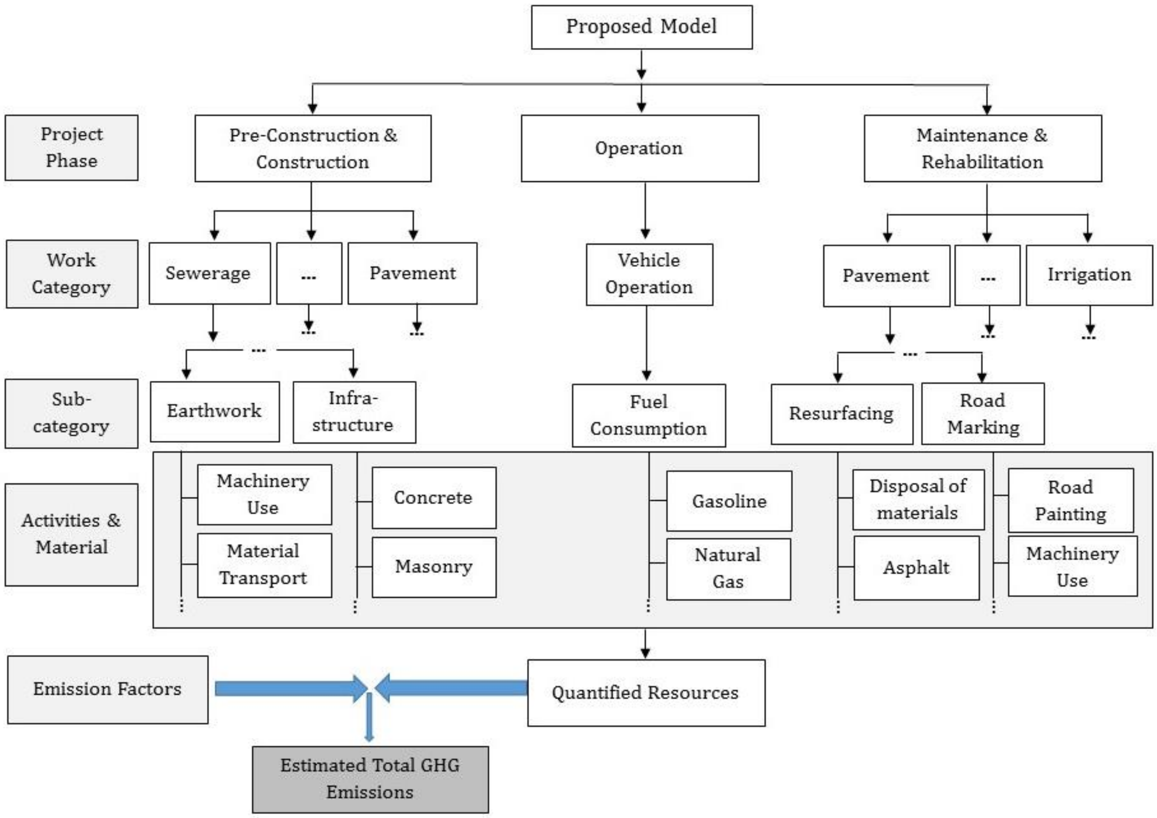

Figure 2. Framework for the Proposed Road-Project-GHG-Estimation Model

8. Limitations

The road network length data used in this paper does not reflect built infrastructure in terms of lane-kilometers. This is worth noting since roads in different countries may have different number of lanes. For example, significant portion of rural roads in the Emirate of Abu Dhabi are 3-, 4-, and even 5-lane roads in each direction, whereas there should be 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 yields a higher absolute amount of emissions, but they also carry faster traveling vehicles which translates into higher emission rates in terms of CO_2-equivalent per vehicle-km travelled. Even though data in terms of lane-kilometers would be ideal, such data has not been made available.

9. Acknowledgement

The authors would like to thank The Abu Dhabi City Municipality for funding this research effort under grant number 21R021.

10. References

1- ADB, Asian Development Bank, 2010a. Methodology for Estimating Carbon Footprint of Road Projects – Case Study: India.

2- ADB, Asian Development Bank, 2010b. Reducing Carbons Emissions from Transport Projects.

3- Angelopoulou, G.I., Koroneos, C.J., Loizidou, M., 2009. Environmental impacts from the construction and maintenance of a motorway in Greece, 1st International Exergy, Life Cycle Assessment, and Sustainability Workshop & Symposium (ELCAS). URL http://www.lcube.eu.com/ELCAS%20Greece%202009/C23%20Angelopoulou%20et%20al%20Greece0609.pdf (accessed 8.30.17).
4- Barandica, J.M., Fernández-Sánchez, G., Berzosa, Á., Delgado, J.A., Acosta, F.J., 2013. Applying life cycle thinking to reduce greenhouse gas emissions from road projects. Journal of Cleaner Production, 57, 79–91. doi:10.1016/j.jclepro.2013.05.036
5- Berkowicz, R., Winther, M., Ketzel, M., 2006. Traffic pollution modelling and emission data. Environ. Model. Softw., Urban Air Quality Modelling 21, 454–460. doi:10.1016/j.envsoft.2004.06.013
6- BIS, 2010. Department for Business Innovation & Skills. Estimating the Amount of CO2 Emissions that the Construction Industry can Influence: Supporting material for the Low Carbon Construction IGT Report [WWW Document]. URL https://www.gov.uk/government/publications/low-carbon-construction-igt-report-co2-emissions-influenced-by-the-construction-industry (accessed 8.30.17).
7- Boriboonsomsin, K., Barth, M.J., Vu, A., 2011. Evaluation of driving behavior and attitude toward eco-driving: Southern California limited case study. Presented at the Transportation Research Board 90th Annual Meeting, Transportation Research Board.
8- Burón, J.M., López, J.M., Aparicio, F., Martín, M.Á., García, A., 2004. Estimation of road transportation emissions in Spain from 1988 to 1999 using COPERT III program. Atmos. Environ. 38, 715–724. doi:10.1016/j.atmosenv.2003.10.020
9- Casper, J.K., 2010. Fossil Fuels and Pollution: The Future of Air Quality. Infobase Publishing. doi:10.1002/wcc.81
10- Dai, A., 2011. Drought under global warming: a review. Wiley Interdiscip. Rev. Clim. Change 2, 45–65. doi:10.1002/wcc.81
11- Dilger, A., Riley, C., Young, S., Bengtsson, J., and Kneppers, B., 2013. Greenhouse Gas Assessment Workbook for road projects, Transport Authorities Greenhouse Group Australia and New Zealand.
12- EAD, 2012. The Environment Agency - Abu Dhabi. Greenhouse Gas Inventory for Abu Dhabi Emirate – Inventory Results Executive Summary [WWW Document]. URL https://www.ead.ae/Documents/PDF-Files/AD-Greenhouse-gas-inventory-Eng.pdf (accessed 8.30.17).
13- EAPA and Eurobitume, 2004. European Asphalt Pavement Association. Environmental Impacts and Fuel Efficiency of Road Pavements [WWW Document]. URL http://www.eapa.org/usr_img/position_paper/fuel_efficiency_report.pdf (accessed 8.30.17).
14- Egis, 2010. Introduction to Greenhouse Gas Emissions in Road Construction and Rehabilitation [WWW Document]. URL http://siteresources.worldbank.org/INTEAPASTAE/Resources/GHG-ExecSummary.pdf (accessed 8.30.17).
15- Eide, A., Heen, K., 2002. Economic impacts of global warming. Fish. Res. 56, 261–274. doi:10.1016/S0165-7836(01)00324-1
16- Ekström, M., Sjödin, Å., Andreasson, K., 2004. Evaluation of the COPERT III emission model with on-road optical remote sensing measurements. Atmos. Environ., Contains Special Issue section on Measuring the composition of Particulate Matter in the EU 38, 6631–6641. doi:10.1016/j.atmosenv.2004.07.019
17- El-Fadel, M., Bou-Zeid, E., 1999. Transportation GHG emissions in developing countries. Transp. Res. Part Transp. Environ. 4, 251–264. doi:10.1016/S1361-9209(99)00008-5
18- Emanuel, K., 2011. Global warming effects on U.S. hurricane damage. Weather Clim. Soc. 3, 261–268. doi:10.1175/WCAS-D-11-00007.1
19- EPA, 2003.U.S Environmental Protection Agency Users Guide to MOBILE6.1 and MOBILE6.2: Mobile Source Emission Factor Model (Technical Report No. 420R03010).
20- Fernández-Sánchez, G., Berzosa, Á., Barandica, J.M., Cornejo, E., Serrano, J.M., 2015. Opportunities for GHG emissions reduction in road projects: a comparative evaluation of emissions scenarios using CO2NSTRUCT. J. Clean. Prod. 104, 156–167. doi:10.1016/j.jclepro.2015.05.032
21- Galli, A., Wiedmann, T.O., Ercin, Ertug, Knoblauch, D., Ewing, B.R., Giljum, S., Water Engineering and Management, 2011. Integrating Ecological, Carbon and Water Footprint: Defining the Footprint Family and its application in tracking human pressure on the planet. One Planet Economy Network.

22- Giles, A.R., Perry, A.H., 1998. The use of a temporal analogue to investigate the possible impact of projected global warming on the UK tourist industry. Tour. Manag. 19, 75–80. doi:10.1016/S0261-5177(97)00093-9

23- HDM Global, 2016. HDM-4 Applications [WWW Document]. URL http://www.hdmglobal.com/hdm-4-version-2/about-hdm-4/hdm-4-applications/ (accessed 9.11.17).

24- Huang, Y., Hakim, B., Zammataro, S., 2013. Measuring the carbon footprint of road construction using CHANGER. International Journal of Pavement Engineering, 14, 590–600. doi:10.1080/10298436.2012.693180

25- IFEU Heidelberg, INFRAS Berne, IVE mbH/RMCon, n.d. Ecological Transport Information Tool for Worldwide Transports- Methodology and Data Update [WWW Document]. URL http://www.ecotransit.org/download/EcoTransIT_World_Methodology_Report_2014-12-04.pdf (accessed 9.3.17).

26- IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

27- ISSRC, 2008. International Sustainable Systems Research Center. IVE Model Users Manual - UsersManual.pdf (Technical report). 605 South Palm Street, Suite C, La Habra, CA 90631.

28- ITF, 2010. International Transport Forum. Reducing Transport Greenhouse Gas Emissions: Trends and Data 2010 (Research).

29- Keijzer, E.E., Leegwater, G.A., de Vos-Effting, S.E., and de Wit, M.S., 2015. Carbon footprint comparison of innovative techniques in the construction and maintenance of road infrastructure in the Netherlands. J. Environmental Science & Policy 54, 218–225.

30- Lal, R., 2008. Carbon sequestration. Philos. Trans. R. Soc. B Biol. Sci., 363, 815–830. doi:10.1098/rstb.2007.2185

31- Le Quéré, C., Andres, R.J., Boden, T., Conway, T., Houghton, R.A., House, J.I., Marland, G., Peters, G.P., van der Werf, G., Ahlström, A., Andrew, R.M., Bopp, L., Canadell, J.G., Ciais, P., Doney, S.C., Enright, C., Friedlingstein, P., Huntingford, C., Jain, A.K., Jourdain, C., Kato, E., Keeling, R.F., Klein Goldewijk, K., Levis, S., Levy, P., Lomas, M., Poulter, B., Raupach, M.R., Schwinger, J., Sitch, S., Stocker, B.D., Viovy, N., Zaehle, S., Zeng, N., 2012. The global carbon budget 1959–2011. Earth System Science Data Discussions, doi:10.5194/essdd-5-1107-2012.

32- Liu, Z., 2015. China's Carbon Emissions Report 2015.

33- Ma, F., Sha, A., Lin, R., Huang, Y., Wang, C., 2016. Greenhouse gas emissions from asphalt pavement construction: A case study in China. Int. J. Environ. Res. Public Health, 13, 351. doi:10.3390/ijerph13030351

34- Marland, G., T.A. Boden, R.J. Andres, 2008. Global, Regional, and National Fossil-Fuel CO2 Emissions [WWW Document]. URL http://cdiac.ornl.gov/trends/emis/overview.html (accessed 9.11.17).

35- Nagraj, A., 2013. Top 10 Countries With The World's Biggest Oil Reserves. Gulf Business.

36- Ng, P., Zhao, X., 2011. No matter how it is measured, income declines with global warming. Ecol. Econ. 70, 963–970. doi:10.1016/j.ecolecon.2010.12.012

37- Ntziachristos, L., Gkatzoflias, D., Kouridis, C., Samaras, Z., 2009. COPERT: A European Road Transport Emission Inventory Model, in: Information Technologies in Environmental Engineering, Environmental Science and Engineering. Springer, Berlin, Heidelberg, pp. 491–504. doi:10.1007/978-3-540-88351-7_37

38- Park, K., Hwang, Y., Seo, S., Seo, H., 2003. Quantitative assessment of environmental impacts on life cycle of highways. Journal of Construction Engineering and Management, 129, 25–31. doi:10.1061/(ASCE)0733-9364(2003)129:1(25)

39- Paul, A., 2008. Environmental Accounting for People and Places - Stockholm Environment Institute [WWW Document]. URL https://www.sei-international.org/mediamanager/documents/Publications/Climate/reap.pdf (accessed 9.3.17).

40- Sambidge, A., 2010. Toyota, BMW top UAE, Saudi car brands survey. ArabianBusiness.

41- Sanghi, A., Mendelsohn, R., 2008. The impacts of global warming on farmers in Brazil and India. Glob. Environ. Change, 18, 655–665. doi:10.1016/j.gloenvcha.2008.06.008

42- Shahbandari, S., 2015. For every two Dubai residents, there is one car. GulfNews.

43- Smit, R., Smokers, R., Rabé, E., 2007. A new modelling approach for road traffic emissions: VERSIT+. Transp. Res. Part Transp. Environ. 12, 414–422. doi:10.1016/j.trd.2007.05.001

44- Sperling, D., Cannon, J.S., 2010. Driving Climate Change: Cutting Carbon from Transportation. Academic Press.

45- TAGG, 2013. Transport Authorities Greenhouse Group Australia and New Zealand. Greenhouse Gas Assessment Workbook for Road Projects - greenhouse-gas-assessment-workbook-road-projects.pdf [WWW Document]. URL http://www.rms.nsw.gov.au/documents/about/environment/greenhouse-gas-assessment-workbook-road-projects.pdf (accessed 8.30.17).

46- United Nations, 1998. Kyoto Protocol to The United Nations Framework Convention on Climate Change [WWW Document]. URL https://unfccc.int/resource/docs/convkp/kpeng.pdf (accessed 8.30.17).

47- US EPA, 2016. U.S Environmental Protection Agency. MOVES2014a: Latest Version of Motor Vehicle Emission Simulator (MOVES) [WWW Document]. US EPA. URL https://www.epa.gov/moves/moves2014a-latest-version-motor-vehicle-emission-simulator-moves (accessed 8.1.17).

48- US FHWA, 2016. U.S Federal Highway Administration. INVEST (Infrastructure Voluntary Evaluation Sustainability Tool) [WWW Document]. URL https://www.sustainablehighways.org/ (accessed 9.3.17).

49- Wang, M., Wu, Y., Elgowainy, A., 2007. Operating Manual for GREET: Version 1.7 (Research report No. ANL/ESD/05-3).

50- World Bank, 2010. ROADEO Toolkit User Manual - Greenhouse Gas Emissions Mitigation in Road Construction and Rehabilitation – A Toolkit for Developing Countries.

51- WRI, 2001. World Resources Institute. The Greenhouse Gas Protocol: a corporate accounting and reporting standard