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Estimation of Greenhouse Gas Emissions Produced by Road Projects in Abu Dhabi, United Arab Emirates

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Abstract: Assessing the current levels of greenhouse gas (GHG) emissions from road transportation projects allows for benchmarking and is essential for potential emissions reduction. The objective of this study was to estimate the GHG emissions associated with the construction and operation of three road cases—two primary roads and one secondary road network—in Abu Dhabi, United Arab Emirates. The GHG emissions produced by the study cases were estimated using the RoadCO$_2$ estimation tool. Results showed that the total emissions (in kg CO$_2$e/m^2/y) range from 76 for the secondary road case to 1100 for the primary road cases. The operation phase is responsible for 94–98% of these emissions; the construction phase is responsible for the rest. Road works contributed the most to GHG emissions during the construction phase. The contribution of the remaining categories of the construction phase fluctuates within a certain case and among the considered cases. The equipment used in the construction phase for the three cases contributed 15–70% of the total phase emissions, while the remaining emissions were due to construction materials. In the operation phase, emissions were mainly generated by vehicle movement. Street lighting also contributed to emissions during the operation phase. On the other hand, the irrigation of planted trees along the road had a very low impact on GHG emissions, and carbon sequestration by these trees had a negligible effect in terms of acting as a carbon sink. The results obtained from this study were compared with other cases reported in the literature.

Keywords: greenhouse gases; road lifecycle; RoadCO$_2$; road construction; road operation

1. Introduction

Global greenhouse gas (GHG) emissions are generated by different regional dynamics over time. GHGs, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and natrium trifluoride (NF_3), are established contributors to climate change [1]. According to the International Energy Agency (IEA), transport accounted for approximately 8 Gt CO_2 in 2016 (the equivalent of one-quarter of the total global GHG emissions), which marks a 71% increase from 1990 [2]. The transport sector was responsible for the second-largest amount of GHG emissions in 2016, following the electricity and heat generation sector [2]. For the same period, 74% of transport sector emissions were attributed to road transport [3]. Road transport will continue to grow, with a projected global increase of 60% in the total length of roads by 2050 over that in 2010 [4].

Road projects release GHGs throughout their entire lifecycle. These emissions first occur during the construction phase (emissions in materials production, manufacturing, and construction), then in the operation phase, and finally, albeit to a lesser extent, in the maintenance and rehabilitation phase (rebuilding or demolition). Due to their long service lifetimes, roads determine to a large extent how the carbon emissions of a society change over time [5]. A thorough review of the GHG emissions associated with road transport was recently provided by Albuquerque et al. [6].

According to the IEA, the United Arab Emirates (UAE) produced approximately 20 million tons of GHG emissions per capita [7]. Abu Dhabi is the largest emirate in the UAE, occupying about 87% of the whole country. The total length of primary roads in this emirate is about 2705 km [8]. Based on the state of the environment report published by the Environment Agency of Abu Dhabi in 2017, the transportation sector in the emirate contributed about 19.32 $MtCO_2e$ [9]. Road vehicles accounted for about 97% of the total direct GHG emissions of the transport sector [9].

As a result of international efforts, several methodologies have been suggested to estimate GHG emissions. Meanwhile, a number of tools have been developed for estimating the GHG emissions produced by road projects. These tools vary in the extent of coverage of the different road project phases as well as the activities involved within each phase [10]. For example, the Calculator for Harmonized Assessment and Normalization of Greenhouse Gas Emissions (CHANGER) [11] and the Carbon Emissions Calculation Tool [12]) focus mainly on activities related to the pre-construction, construction, maintenance, and rehabilitation phases. Other tools such as the Motor Vehicle Emission Simulator (MOVES) [13], the Computer Programme to Calculate Emissions from Road Transport (COPERT 4) [14], and the Motor Vehicle Emissions Inventory (MVEI) [15] focus only on activities within the operation phase. Some other tools such as CO2NSTRUCT [16], Carbon Gauge [17], Carbon Footprint Estimation Tool (CFET) [18], and Life Cycle Considerations in EIA of Road Infrastructure (LICCER) [19] cover selected activities within all road project phases. Alzard et al. [10] have recently developed a tool (called $RoadCO_2$) to estimate GHG emissions that considers all phases associated with the lifecycle of a road project and accounts for all activities encountered within a certain phase.

In today's era of rapid development, the scientific community is more concerned about the environment and is actively focusing on sustainable development. Thus, the prevailing interest in sustainable development could be used to shape environmental policy [20], with the higher involvement of scientists and practitioners. For road projects, efforts have recently been directed towards possible innovative techniques that could be utilized to reduce the carbon footprint throughout the project lifecycle [21]. However, an essential step for making effective propositions for emissions reduction is to establish detailed baseline conditions that serve as a reference for future improvements.

Previously published cases that reported estimates of GHG emissions from road projects were limited in their scope and level of detail. Moreover, limited work has been done to estimate the carbon footprint of road projects in the UAE. Thus, the main objective of this study was to estimate the GHG emissions of road projects in Abu Dhabi and highlight the activities that contribute the most to their carbon footprint. This enables the establishment of baseline conditions that can be applied for benchmarking with road projects elsewhere. The outcome of the study could be utilized as the basis for future carbon reduction plans for the road sector across the country.

2. Methodology

2.1. Case Studies

Three road projects were selected as case studies in Abu Dhabi, UAE. The locations of the three roads are shown in Figure 1. Several internal documents related to the construction and operation phases of these cases were obtained from the Abu Dhabi City Municipality (ADM), as listed in Table 1. These documents are referred to in the text by the identification number listed in the table. The selection of these cases was based on road type, nature of activities involved, and availability of data. Two of the investigated cases are considered primary roads, while the third is a secondary road. Figure 2 schematically shows the typical thicknesses of layers of the two types of roads in Abu Dhabi. In terms of the nature of activities, one case involves the construction of a residential road network (Case 1); another involves upgrading a road and includes the construction of a new tunnel (Case 2); and a third case involves the widening of a road (Case 3). Table 2 lists some characteristics of the case studies. More details about these cases are provided below.

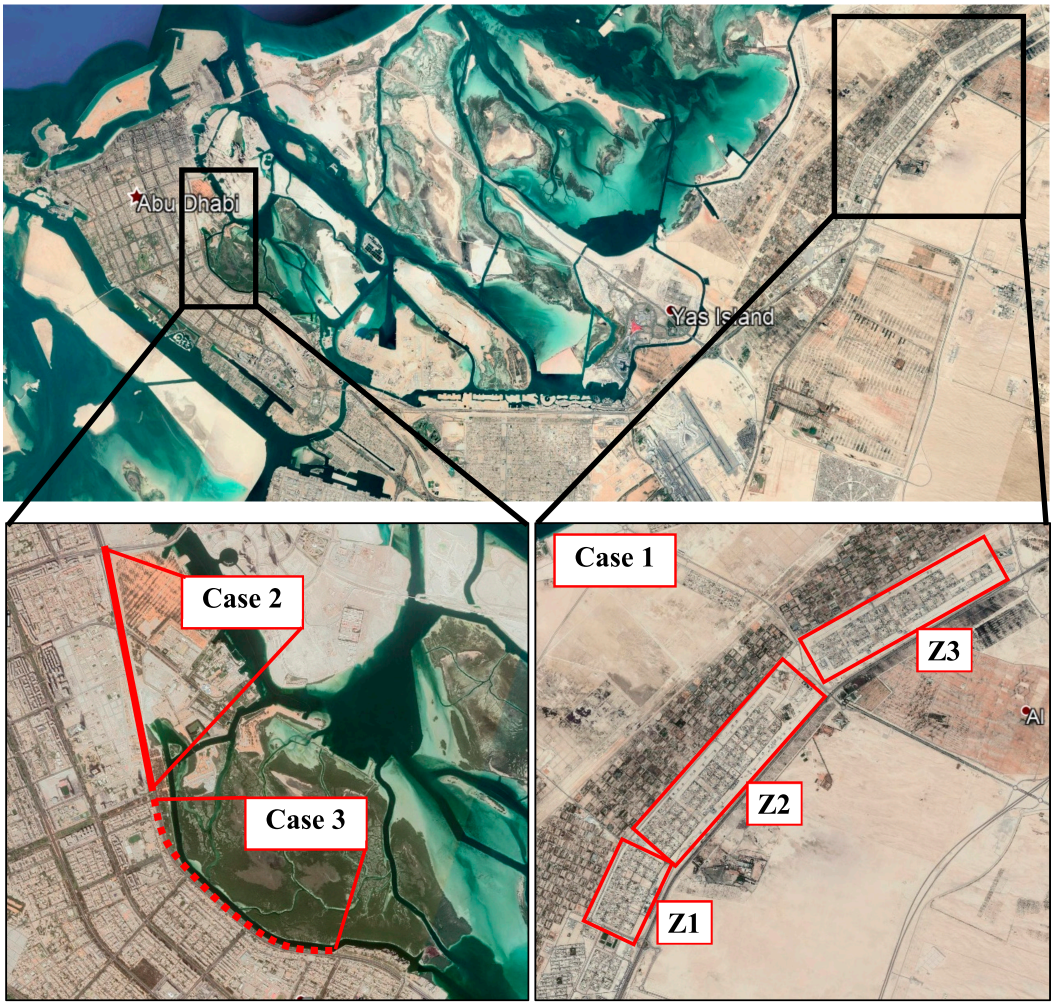

Figure 1. Location of the roads in the three case studies in the City of Abu Dhabi (magnified parts of the map are of different scales) [22].

Table 1. List of internal documents obtained from ADM.

Document	Description
ADM-1	Contractual documents for secondary roads and services in Al Rahba city with drawings and design data, 2014.
ADM-2	Contractual documents for upgrading of Al Salam Street with drawings and design data, 2007.
ADM-3	Contractual documents for widening of the Eastern Abu Dhabi Corniche Road with drawings and design data, 2009.
ADM-4	Technical Specifications and Design Manual, Version 2.0, 2014.
ADM-5	Standard Drawings, Abu Dhabi City Municipality, 2014.
ADM-6	Traffic counts at Al Rahba City secondary roads, 2017.
ADM-7	Traffic counts at Al Salam Street, 2015.
ADM-8	Traffic counts at the Corniche Road, 2016.
ADM-9	Public Realm Design Manual, Version 2, 2017.
ADM-10	Distribution of desalinated water and TSE for landscaping, 2017.
ADM-11	Stormwater pumping at Al Salam Street, 2017.

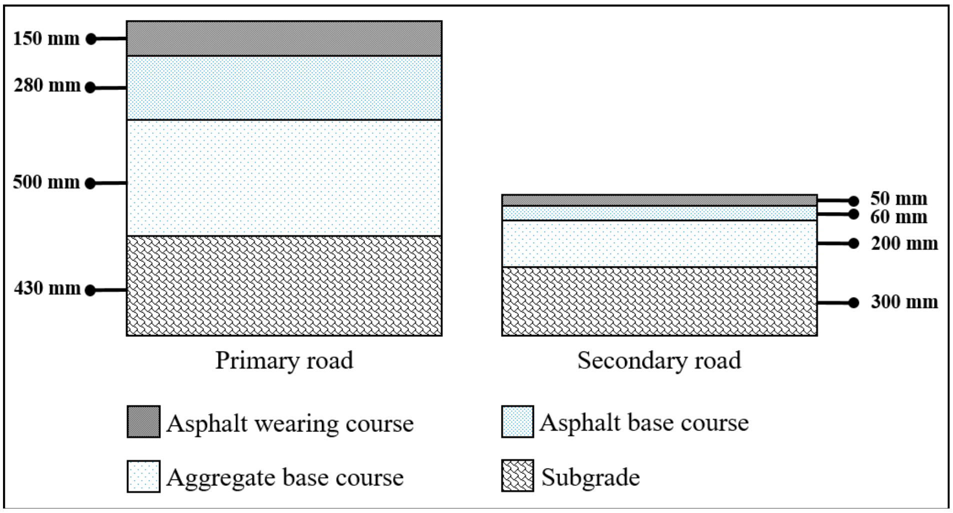

Figure 2. Typical layer thicknesses of a primary and a secondary road in Abu Dhabi (Source: ADM-1 and ADM-2 of Table 1).

Table 2. Characteristics of the case studies.

Parameter	Case 1	Case 2	Case 3
Road type	Secondary	Primary	Primary
Length (km)	30	3.6	2.87
Posted speed limit (km/h)	60	120	120
Number of constructed lanes	2	8	2
Lane width (m)	3.65	3.65	3.65
Total paved width excluding shoulders (m)	7.3	29.2	7.3

Case 1 involves the construction of an urban local secondary road network and services in the Al Rahba area along the Abu Dhabi-Dubai highway. These secondary roads are single carriageways (i.e., two-lane roadways) with a 30 km length and a width of 7.30 m, with 0.35-m wide outer shoulders and 2.0-m wide footpaths (sidewalks). The project duration of Case 1 was 20 months (initiated in June 2014). The new construction of major features of utility works was considered along with the construction of the carriageway for their future crossing under paved areas. These features included water ducts, electrical ducts, telephone ducts, ducts for agriculture, as well as stormwater and sewerage drainage (Table 1, ADM-1).

Case 2 involves the upgrading of Al Salam Street, along with the construction of a tunnel (known as the Sheikh Zayed tunnel). Surface roads were also widened. The length of the road segment is 3.6 km with four lanes in each direction and includes a 0.6-km long tunnel (Table 1, ADM-2). The project lasted 27 months (initiated in April 2007). The objective of the project was to upgrade Al Salam Street, providing a free flow of traffic and facilitating connections to adjoining roads and sectors.

Case 3 covers the widening of the existing Eastern Abu Dhabi Corniche Road. The project's duration was 27 months (initiated in October 2009). Construction included the addition of a fourth traffic lane of 3.65 m width and a shoulder of 3 m in each direction, while moving the sub-surface utilities to a new location. Earthwork consisted of clearing, grubbing, removing and disposing of debris, vegetation, buildings, fences, structures, walls, old pavement, and abandoned pipelines. Moreover, the construction involved placing and compacting of borrow materials, unclassified excavation, structure excavation, and backfilling (Table 1, ADM-3).

2.2. Estimation of GHG Emissions

GHG emissions of the three road projects were calculated for the construction and operation phase of each case. Emissions were estimated using the RoadCO_2 estimation tool [10]. RoadCO_2 is a web-based tool developed to estimate GHG emissions during the entire lifecycle of a road project. The tool is equipped with a database that covers almost all GHG-emitting, road-related activities, including those originating from both direct and indirect sources. RoadCO$_2$ utilizes the methodology proposed by the Intergovernmental Panel on Climate Change (IPCC) [23] for GHG emissions estimation. The general equation for estimating GHG emissions (E) for a particular activity is given by:

$$\mathrm{E} = \mathrm{AD} \times \mathrm{EF}, \tag{1}$$

where AD is the activity data and EF is the emission factor.

GHG emissions (kg CO$_2$e) associated with the use of material ($E_{material}$), equipment ($E_{equipment}$), and their transportation ($E_{transportation}$) during the construction phase were estimated using Equations (2)–(4), respectively [10]:

$$\mathrm{E_{material}} = \left[\mathrm{Quantity}\left(\mathrm{m^3}\right) \times \mathrm{Density}\left(\frac{\mathrm{kg\ material}}{\mathrm{m^3}}\right)\right] \times \mathrm{EF}\left(\frac{\mathrm{kg\ CO_2e}}{\mathrm{kg\ material}}\right) \tag{2}$$

$$\mathrm{E_{equipment}} = \left[\mathrm{FCR}\left(\frac{\mathrm{L\ fuel}}{\mathrm{Eq.h}}\right) \times \mathrm{Quantity\ (Eq)} \times \mathrm{Duration\ (h)}\right] \times \mathrm{EF}\left(\frac{\mathrm{kg\ CO_2e}}{\mathrm{L\ fuel}}\right) \tag{3}$$

$$\mathrm{E_{transportation}} = \left[\mathrm{Mass\ (kg\ transported)} \times \mathrm{Distance\ (km)}\right] \times \mathrm{EF}\left(\frac{\mathrm{kg\ CO_2e}}{\mathrm{kg\ transported.km}}\right), \tag{4}$$

where FCR is the fuel consumption rate.

For the operation phase, annual emissions (kg CO$_2$e/y) due to traffic movement ($E_{traffic}$), road lighting ($E_{lighting}$), road plant irrigation ($E_{irrigation}$), stormwater pumping ($E_{stormwater\ pumping}$), and carbon sink due to sequestration were estimated using Equations (5)–(9), respectively [10]:

$$\mathrm{E_{traffic}} = \left[\mathrm{FCR}\left(\frac{\mathrm{L\ fuel}}{\mathrm{km.veh}}\right) \times \mathrm{Traffic\ volume}\left(\frac{\mathrm{veh}}{\mathrm{y}}\right) \times \mathrm{Distance\ (km)}\right] \times \mathrm{EF}\left(\frac{\mathrm{kg\ CO_2e}}{\mathrm{L\ fuel}}\right) \tag{5}$$

$$\mathrm{E_{lighting}} = \left[\mathrm{Wattage}\left(\frac{\mathrm{kW}}{\mathrm{lamp}}\right) \times \mathrm{Quantity\ (lamp)} \times \mathrm{Duration}\left(\frac{\mathrm{h}}{\mathrm{y}}\right)\right] \times \mathrm{EF}\left(\frac{\mathrm{kg\ CO_2e}}{\mathrm{kWh}}\right) \tag{6}$$

$$\mathrm{E_{irrigation}} = \left[\mathrm{Irrigation\ rate}\left(\frac{\mathrm{L}}{\mathrm{day.tree}}\right) \times \mathrm{Quantity\ (tree)} \times \mathrm{Duration}\left(\frac{\mathrm{d}}{\mathrm{y}}\right)\right] \times \mathrm{EF}\left(\frac{\mathrm{kg\ CO_2e}}{\mathrm{L}}\right) \tag{7}$$

$$\mathrm{E_{stormwater\ pumping}} = \left[\mathrm{Power}\left(\frac{\mathrm{kW}}{\mathrm{pump}}\right) \times \mathrm{Quantity\ (pump)} \times \mathrm{Duration}\left(\frac{\mathrm{h}}{\mathrm{y}}\right)\right] \times \mathrm{EF}\left(\frac{\mathrm{kg\ CO_2e}}{\mathrm{kWh}}\right) \tag{8}$$

$$\mathrm{Sequestration} = \left[\mathrm{Quantity\ (tree)}\right] \times \mathrm{Annual\ sequestration\ rate}\left(\frac{\mathrm{kg\ CO_2e}}{\mathrm{tree.y}}\right). \tag{9}$$

2.3. Data Collection

Most of the activity data of the considered cases were extracted from the tender bill of quantities (BOQ) documents (Table 1); however, other activities encountered during road construction and operation have been included. RoadCO$_2$ was used to estimate the GHG emissions associated with the construction and operation phases of the three case studies. To use the tool, data in different forms were required for each phase. Unavailable data were either collected through site visits or estimated based on engineering judgment or findings from the literature.

2.3.1. Construction Phase

The quantities of construction materials and the type of construction equipment used were obtained from the relevant tender BOQ (Table 1, ADM-4). The ADM BOQ template consists of 26 items that cover all activities related to road construction. These items were grouped into eight categories for the estimation of GHG emissions from the construction phase. The categories include road works, sewerage works, lighting and electrical, landscaping and street furnishing, irrigation network, stormwater network, telecommunication network, and water network.

The quantities of materials in the BOQ documents are expressed in different units. Because RoadCO_2 requires the quantity of material to be expressed in units of mass, standard drawings of road elements (Table 1, ADM-5), along with the density of the material, were utilized to convert these quantities into mass in cases where they were initially expressed in units of volume, area, or length.

Data related to the construction equipment specify the type of equipment used, their quantity, and usage duration. The construction equipment was assumed to operate eight hours per day, six days a week. Moreover, diesel was assumed to be the type of fuel used to operate this equipment. RoadCO_2 uses the above input data to calculate the amount of fuel consumed by the equipment, which is considered the primary source of GHG emissions.

Transportation of both construction materials and the equipment were also considered. Both construction materials and equipment were transported from the Mussafah Industrial Area (about 24–48 km from the location of the case studies), whereas the aggregates were transported from the emirate of Fujairah (~250–300 km from the location of the studied cases). Collected information about the case studies does not, however, indicate the transportation mode used nor the number of trips that were made. Thus, the mode of transportation and the number of trips were assumed. Dumpers, trailers, pickups, six-wheelers, and trucks were used to transport the materials to the site. Because there were no available data on their specifications, the mode of transportation was assumed to be rigid heavy-goods vehicles of unknown engine size. This assumption was also used for the trailers that were used to transport the construction equipment to the site. In addition, the number of trips was also assumed based on the capacity of the transportation mode used and the amount of both construction materials and equipment that had to be transported.

The quantity of materials used in the three case studies is presented in Table 3, and the equipment used on site for the construction activities is listed in Table 4. Concrete mixes used in Case 1 and 3 were composed of Portland cement (PC). The concrete mixes used for non-structural purposes in Case 2 were composed of 65% PC and 35% fly ash (FA), and those used for structural purposes were composed of 30% PC and 70% ground granulated blast-furnace slag (GGBFS).

Table 3. Materials used for the three study cases and their corresponding EF values [1].

Material	Unit	Case 1	Case 2	Case 3	EF [2] (kg CO_2e/kg)
Concrete: Class K140	m^3	2502	0	2421	0.4362
Concrete: Class K140 (65% PC and 35% FA)	m^3	0	15,301	0	0.2966 [3]
Concrete: Class K250	m^3	1399	0	36	0.4484
Concrete: Class K250 (65% PC and 35% FA)	m^3	0	2630	0	0.3049 [3]
Concrete: Class K415 [d] (30% PC and 70% GGBFS)	m^3	0	149,126	0	0.132 [3]
Concrete: Class K455 [d]	m^3	5342	0	0	0.151
Concrete: Class K455 (30% PC and 70% GGBFS)	m^3	0	212	0	0.0574 [3]
Concrete: Class K550 [4]	m^3	0	0	33	0.5547
Concrete: Class K550 (30% PC and 70% GGBFS)	m^3	0	92	0	0.2108 [3]
Aggregates	m^3	153,490	293,710	49,280	0.0052
Asphalt	m^3	2858	2440	180	0.071
Steel	ton	182	14,850	5	2.87
Water	gallon	NA	400,000	100,000	0.003
Pipes: Polyvinyl chloride	ton	182	514	71	3.23
Pipes: Glass fiber reinforced plastics	ton	197	2384	48	8.1
Pipes: High-density polyethylene	ton	NA	463	269	2.52
Pipes: Galvanized iron	ton	NA	41	NA	2.03
Concrete tiles	m^3	NA	1898	5	0.4362
Aluminum	ton	NA	73	NA	12.5
Copper	ton	NA	633	NA	3.81

[1] NA means not available. [2] Adopted from IPCC [23]. [3] Based on the findings of Tait and Cheung [24]. [4] Weighted average of the emission factors of the individual components comprising the mix.

Table 4. Equipment used for constructing the road cases [1].

Equipment Type	Case 1		Case 2		Case 3	
	Quantity	Operating Hours	Quantity	Operating Hours	Quantity	Operating Hours
Excavator	129	720	97	17,940	3	20
Skid steer loaders	168	720	30	19,500	0	0
Soil compactor	148	720	66	17,160	3	40
Cutter	55	680	9	7020	2	20
Loader	172	760	65	15,600	5	100
Grader	35	680	41	17,940	2	20
Tipper	62	720	367	17,940	18	134
Water tanker	18	640	64	3120	3	20
Rollers	10	400	0	0	0	0
Backhoe loader	13	520	84	18,720	0	0
Rock breaker	10	400	0	0	0	0
Dozer	18	640	0	0	3	60
Grader checker	18	640	36	9630	2	20
Air compressor	10	400	0	0	4	20
Double drum roller	9	360	27	7020	1	20
Baby roller	10	400	0	0	0	0
Pneumatic tire roller	13	400	36	9360	0	0
Steel vibrating roller	9	360	0	0	3	20
Milling machine	10	400	0	0	0	0
Paver	10	400	0	0	2	20
Crane	0	0	73	13,260	0	0
Mounty crane	0	0	8	6240	0	0
Spray	0	0	18	7020	0	0
Pickup	0	0	0	0	7	1840
Tractor	0	0	0	0	3	20
Hydraulic excavator	0	0	0	0	4	143
Dewatering system	0	0	0	0	3	60
Dozer	0	0	0	0	3	60

[1] Quantities of material for Cases 1, 2, and 3 were extracted from ADM-1, ADM-2, and ADM-3 (Table 1), respectively.

2.3.2. Operation Phase

Road operation is the next stage in the lifecycle of the road. The operation phase extends over the road's service lifetime, which is usually between 30 and 50 years. Vehicle movement, street lighting, irrigation, stormwater pumping, and sequestration are activities that contribute to road GHG emissions during this phase. Input data for some activities of this phase for the three case studies are listed in Table 5. It should be noted that the collected activity data pertinent to road operation for Case 3 were for the entire road segment. Thus, the data for this case were divided by four to determine the share of the newly constructed lanes.

Table 5. Input data for some activities of the operation phase.

Activity	Item	Case 1	Case 2	Case 3 [1]
Vehicle movement	Passenger cars	3,193,090	27,550,010	7,593,069
	Light trucks	6,714,804	37,669,054	10,381,982
	Heavy trucks	1,994,821	7,833,222	2,158,917
Street lighting	Lantern lamps (400 W)	0	10	8
	Lantern lamps (1000 W)	0	60	50
	HPS lantern lamps (150 W)	0	60	0
	HPS lantern lamps (400 W)	1271	1080	0
	HPS lantern lamps (1000 W)	0	368	0
Irrigation/sequestration	Palm trees	0	400	80
	Other trees	1538	200	23

[1] Includes the share for two constructed lanes only.

Vehicle Movement

Traffic volume is an important component in the GHG estimation of vehicle movement. Actual traffic counts were obtained from ADM for all the cases. For Case 1 (Al Rahba area), traffic counts were measured at 13 different locations covering the entire network. Measurements were conducted between late 2017 and early 2018 (Table 1, ADM-6), and the results were extrapolated to obtain an average annual traffic count for each vehicle class. As for Case 2 (Al Salam Street) and Case 3 (the Corniche Road), annual traffic counts were extracted from ADM-7 and ADM-8 (Table 1), respectively. Table 5 shows the average annual traffic counts considered for the three case studies.

Traffic counts provided by ADM classify vehicles as passenger cars (<3.5 m length), light trucks (3.5–8 m length), and heavy trucks (>8 m length). However, RoadCO_2 requires a more detailed classification of passenger vehicles and light trucks that is based on the type of the vehicle. Based on information obtained through consultations with Abu Dhabi's Department of Transport (DOT), the passenger car traffic count consists of almost equal proportions of two-seaters, mini-compacts, subcompacts, compacts, mid-sized and full-sized passenger cars, small and mid-sized station wagons. The traffic count of light trucks consists of almost equal proportions of small pickup trucks, standard pickup trucks, sport utility vehicles, minivans, cargo vans, and passenger vans.

In addition to traffic data and vehicle classification, RoadCO_2 requires information about vehicle speed, traveled distance (road length), and type of fuel used by these vehicles. RoadCO_2 classifies speed ranges into three categories (city, highway, or combination of both), following the classification set by the Natural Resources Canada [25]. Accordingly, the "combination" category was assumed in Case 2 and 3, while the "city" category was assumed in Case 1.

Most vehicles in Abu Dhabi use gasoline and diesel. Based on consultation with the DOT, all passenger cars and 60% of light trucks use gasoline. The remaining 40% of light trucks and all heavy trucks use diesel. The emission factors of gasoline (2.384 kg CO_2e/L) and diesel (2.669 kg CO_2e/L) were obtained from the IPCC [23].

The traveled distance for the three cases was measured using Google Earth. For Case 1 (Al Rahba area), the area was divided into three zones (Z1, Z2, and Z3, shown in Figure 1). The distance from the center of each zone to the nearest exit was assumed to be the traveled distance for that zone. These distances are 0.93 km for Z1, 2.57 km for Z2, and 2.64 km for Z3. For Case 2 and Case 3, the traveled distance was assumed to be equal to the length of the constructed segment (Table 2).

Street Lighting

To estimate emissions from street lights, the number of lamps used, as well as their wattage, type, and the operation period are needed. The data depicting the quantity and the wattage of the lamps are available from the BOQ documents provided by ADM for Case 2 and 3 (Table 1, ADM-2 and ADM-3). For Case 1, the number of electrical poles and lamps were collected from the site.

Street lamps in Abu Dhabi operate on the average 11 h/day. An exception are lights in tunnels, which operate for 24 h. Table 5 lists the number of lamps in each of the cases based on their wattage. The electricity emission factor was 1.0389 kg CO_2e/kWh [26].

Irrigation

To estimate emissions from the usage of water for landscaping, the quantity of water used for irrigation needs to be determined. This was done based on the irrigation rates for the vegetation along the road, which depend on the plant type and irrigation requirements.

The BOQ documents for Case 2 and 3 provided data on the type and quantity of the existing plants. It was assumed that all removed or relocated plants form the sites (as mentioned in BOQ documents) were re-planted along the road. For Case 1, the number of plants were obtained by a survey of the site. Abu Dhabi's Public Realm Design Manual categorizes plants as palm trees and "other" trees. The manual also sets recommendations for plant water requirements, which allows for the calculation of the daily irrigation rate. Plants along Abu Dhabi roads are assumed to have a medium irrigation requirement, and they are irrigated daily (Table 1, ADM-9). ADM requires that 75% of the water used for the irrigation of road plants is treated sewage effluent (TSE), while the remaining portion is desalinated water (Table 1, ADM-10). The EF for TSE was 0.0001475 kg CO_2e/L [23], while that for desalinated water was 0.02158 kg CO_2e/L [27]. Table 5 lists the type and number of trees in the studied cases.

Stormwater Pumping

Emissions due to stormwater pumping are attributed to electricity consumption. The annual amount of electricity consumed in stormwater pumping depends on the number of active pumps, their power, and annual operation duration. No data were available for stormwater pumping for Case 1 and 3. In Case 2, there are two pumping stations, with pumping powers of 16 kW and 35 kW (Table 1, ADM-11). Based on the data provided by ADM, each pump operated for 6 h per rainy day in 2017, with a total of five rainy days in that year.

Sequestration

To quantify the amount of carbon sequestered by road vegetation, data specifying the plant type, age, and growth rate are needed [28]. To this end, all the plants were assumed to be hardwood, 10 years old, with a moderate growth rate.

3. Results

3.1. Construction Phase GHG Emissions

The total emissions from the construction phase of Cases 1, 2, and 3 are 42.7, 291.6, and 16.5 thousand-tons CO_2e, respectively. The relative distribution of emissions among the eight different construction categories is listed in Table 6.

Table 6. Percent contribution to total phase GHG emissions of different construction categories.

Category	Case 1	Case 2	Case 3
Road works	36	21	54
Stormwater works	28	16	9
Sewerage works	13	9	0
Water network	9	8	10
Telecommunication network	4	8	5
Irrigation network	5	13	9
Lighting and electrical works	2.5	13	8
Landscaping and street lighting works	2.5	12	5

The results presented in Table 6 show that road works contributed the most (21–54%) to GHG emissions during the construction phase. The contribution of stormwater works ranges from 9% in Case 3 to 28% in Case 1. The high contribution of the stormwater system to GHG emissions in Case 1 (Al Rahba area), as compared with the other cases, is due to the establishment of a new infrastructure for a newly planned residential area. The contribution of the remaining categories varies within a certain case and among the considered cases.

The relative contributions of materials and equipment (including the transportation of both) to GHG emissions at the construction phase are listed in Table 7. The relatively higher contribution of equipment used in the construction of the street network in Case 1 is because of the extensive use of compactors, loaders, and excavators. Compactors were used in the compaction of sub-base and base grade materials, as well as the asphalt pavement for the 30-km road network at the site.

Table 7. Percent contribution of materials and equipment to the emissions of the construction phase.

Phase	Case 1	Case 2	Case 3
Materials	30	85	79
Equipment	70	15	21

The upgrading of Al Salam Street (Case 2) includes the construction of a 0.6-km long tunnel with four lanes on each side. The tunnel is a concrete structure with three interchanges. Thus, a relatively high quantity of material would be expected because of the required quantities of concrete and steel in addition to the use of asphalt. Despite the relatively low contribution of the equipment (15%) for this case, the emitted GHGs reached a high value of 44 thousand-tons CO_2e.

In Case 3 (the Corniche Road), the material contributed 79% of the total GHG emissions during the construction phase. This is due to the high contribution of road works (54%), in addition to the abundant use of concrete for relocating the existing sub-surface utility network.

Emissions produced by the materials in the three cases were mainly attributed to the use of concrete, steel, and pipes. For Case 1, 55% of the emissions from materials was due to the use of concrete, followed by 21% due to the use of pipes. As for Case 2, steel accounted for almost half of the emissions from materials, followed by the use of pipes (26%), then concrete (17%). For Case 3, concrete accounted for 65% of the emissions followed by the use of pipes (34%).

Variations in the relative contribution of each equipment type was also noticed among the three cases. For Case 1, excavators, loaders, and soil compactors contributed 21%, 19%, and 18% of the equipment emissions, respectively. For Case 2, tippers, excavators, and backhoe loaders contributed the most at 47%, 14%, and 7%, respectively. As for Case 3, pickup trucks contributed 48%, followed by tippers (27%), and then excavators (6%).

3.2. Operation Phase GHG Emissions

The annual contribution to GHG emissions by the operation phase for the three cases is summarized in Table 8. For all cases, the main emissions contributor during the operation phase is vehicle movement, with emissions from light and heavy trucks dominating in all three cases. The contribution of traffic movement to phase emissions in the secondary road case is 86%, while the contribution increases to 95% or more in the primary road cases. The second emissions contributor, although to a much lesser extent, is street lighting. Irrigation was found to have a very low impact contributing with less than 200 tons CO_2e/y. Meanwhile, sequestration did not have a significant effect for these cases.

Table 8. Emissions based on constructed lanes (ton CO_2e/y) from different activities during the operation phase [1].

Activity	Item	Case 1	Case 2	Case 3
Vehicle movement	Passenger cars	2109	24,331	5299
	Light trucks	6357	50,150	11,025
	Heavy trucks	4879	28,129	6181
	All vehicles	13,345	102,610	22,504
Street lights		2045	5318	213
Irrigation	Palm trees	0	39	8
	Other trees	152	20	2
	All trees	152	59	10
Stormwater pumping		NA	2.6	NA
Sequestration		48.4	19	3
All operation phase activities [2]		15,494	107,971	22,724

[1] NA means not available. [2] Sequestration is considered as a sink term when added to the total.

3.3. 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 to be 40 years. Table 9 shows the annual contribution of both the construction and the operation phases for the case studies normalized to the paved area (m^2).

Table 9. Comparison of emissions/sinks (kg $CO_2e/m^2/y$) produced during different activities of the construction and operation phase. The percent values are of the total emissions per case.

Activity	Case 1		Case 2		Case 3	
	Value	Percent	Value	Percent	Value	Percent
Construction phase	4.9	6.5	69.3	6.3	19.7	1.8
Road works	1.76	2.32	14.56	1.33	10.62	0.96
Stormwater works	1.37	1.81	11.10	1.01	1.77	0.16
Sewerage works	0.63	0.84	6.24	0.57	0.00	0.00
Water network	0.44	0.58	5.55	0.51	1.97	0.18
Telecommunication network	0.20	0.26	5.55	0.51	0.98	0.09
Irrigation network	0.24	0.32	9.02	0.82	1.77	0.16
Lighting & electrical works	0.12	0.16	9.02	0.82	1.57	0.14
Landscaping & street lighting works	0.12	0.16	8.32	0.76	0.98	0.09
Operation phase	70.8	93.6	1027.1	93.7	1084.6	98.2
Vehicle movement	60.94	80.58	976.12	89.02	1074.13	97.27
Street lighting	9.34	12.35	50.59	4.61	10.17	0.92
Irrigation	0.69	0.92	0.56	0.05	0.48	0.04
Stormwater pumping	0.00	0.00	0.02	0.002	0.00	0.00
Sequestration [1]	0.22	0.29	0.18	0.02	0.14	0.01
Total	75.63	100	1096.5	100	1104.3	100

[1] Sequestration is considered as a sink term when added to the total.

The annual amount of GHG emissions differs among the three cases. Case 1 contributes approximately 76 kg $CO_2e/m^2/y$; Case 2, approximately 1096 kg $CO_2e/m^2/y$; and Case 3, approximately 1104 kg $CO_2e/m^2/y$. Because the streets in Case 1 (Al Rahba area) are secondary roads, the normalized emissions from their construction are lower than those from the other two case studies. Their pavement design, load bearing capacity, and posted speed limit are likewise lower compared with the other two cases. Also, the table shows that the operation phase contributes about 94–98% of the emitted gases in the three cases, while the construction phase contribution ranges between about 2% and 6%. The differences between the three cases in construction emissions are attributed to differences in the nature of work that was involved in each case. Overall, the activity that contributes the most to emissions in the three cases is vehicle movement (81–97%). This is followed by street lighting (1–12%) and road works (about 1–2%).

4. Discussion

Several studies were conducted to assess carbon footprint emissions produced by road projects. Estimation usually does not cover the full lifecycle of road projects. For example, some estimations exclude the effect of vehicle movement and activities other than road works, some might take into consideration the effect of lighting and sequestration, and some might focus on vehicle movement (Albuquerque et al., 2019) [6]. For the purpose of comparing the results obtained in this study with those reported in the literature, the values of emissions were normalized to other units of measurement as shown in Table 10. The table shows that Case 1 contributes annually approximately 17 thousand-tons CO_2e; Case 2, approximately 115 thousand-tons CO_2e; and Case 3, approximately 23 thousand-tons CO_2e.

Table 10. Emissions from the three studied cases expressed in different units of measurement.

Parameter	Case 1	Case 2	Case 3
Construction (ton CO_2e)	42,700	291,600	16,500
Construction (ton CO_2e/lane/km)	712	10,125	2875
Construction (ton CO_2e/y)	1068	7290	412
Operation (ton CO_2e/y)	15,494	107,971	22,724
Total (ton CO_2e/y)	16,561	115,260	23,136
Total (kg CO_2e/m/y)	552	32,017	8061
Operation excluding vehicles (ton CO_2e/y)	2149	5361	220
Total excluding vehicles (ton CO_2e/y)	3217	12,651	632
Total excluding vehicles (kg CO_2e/m/y)	107	3514	220
Total excluding vehicles (kg CO_2e/m^2/y)	15	120	30
Road works plus operation excluding vehicles (kg CO_2e/m/y)	85	1914	155

Case 3 (the Corniche Road) is similar to a previous case study conducted by Huang et al. [29] in the emirate of Abu Dhabi, which involved the addition of lanes to an existing road. Haung et al. [29] used CHANGER software to calculate the emissions during the construction phase. They expressed emissions in terms of ton CO_2e/lane/km. Using the same units, the normalized emissions for the construction phase of Case 3 is 2875 ton CO_2e/lane/km (Table 10), while the value reported by Huang et al. [29] is 2140 ton CO_2e/lane/km. Whereas the two values are comparable, the value obtained in this study is slightly higher probably due to consideration of categories other than those related to road works and the stormwater network, which likewise contribute to emissions during the construction phase. It should be stressed that comparison of results among different studies cannot be properly established without considering the scope adopted by researchers.

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 (in kg CO_2e/m/y) associated with Cases 1, 2 and 3 would be 84, 1914, and 154, respectively (Table 10). According to Keijzer et al. [21], GHG emissions of asphalt roads (with consideration of road works and excluding emissions from vehicles in the operation phase) are between 14 kg CO_2e/m/y for roads within the secondary road network and 64 kg CO_2e/m/y for roads within the main (primary) road network. Hill et al. [30] reported similar values of 24 kg CO_2e/m/y and 55 kg CO_2e/m/y for a traffic route and motorway, respectively. The values obtained in this study are much higher than those reported by Keijzer et al. [21] and Hill et al. [30] for some European countries (Figure 3). For Case 1 (Al Rahba area), the values are approximately four times higher (based on the range of emission values of 14–24 kg CO_2e/m/y in Europe). Road works in Case 1 contributed 13 kg CO_2e/m/y, while the operation phase, excluding vehicle movement, contributed 72 kg CO_2e/m/y. Thus, the higher values for Case 1 are mainly due to emissions during the operation phase, where the main contributor is street lighting, with the exclusion of vehicle movement.

Cases 2 and 3 (Al Salam Street and the Corniche Road) are considered primary roads. Thus, comparisons are made with the upper range of values (55–64 kg CO_2e/m/y) reported by Keijzer et al. [21] and Hill et al. [30]. For Case 2, the values are approximately 32 times higher than those reported. In this case, road works contributed 425 kg CO_2e/m/y, while road operation excluding vehicle movement contributed 1489 kg CO_2e/m/y. Emissions from road works are from the use and transportation of concrete and steel needed to construct the tunnel and other concrete structures on this road, in addition to the emissions originating from earthwork. Given that the road is short, the impact of the construction of a tunnel and other concrete structures amplifies the normalized emission rates in the construction phase as compared with Case 1. However, the tremendous normalized emissions for this case are mainly due to street lighting, which is attributed to the continuous lighting of the tunnel.

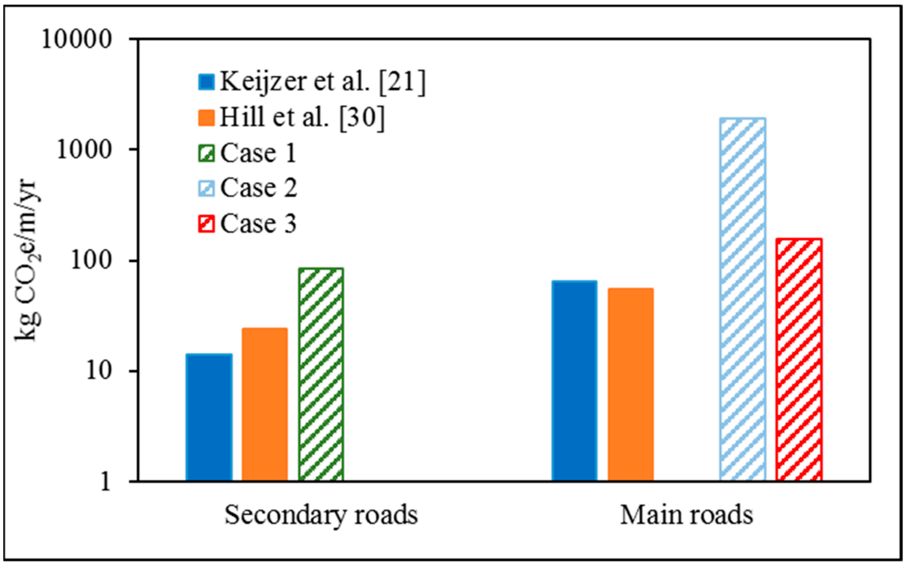

Figure 3. Comparison between emissions obtained in this study and those reported in the literature.

In Case 3, the normalized emission values are three times higher than the upper range of values reported by Keijzer et al. [21] and Hill et al. [30]. In this case, road works contributed 78 kg CO_2e/m/y and road operation excluding vehicle movement contributed a similar value of 77 kg CO_2e/m/y. Emissions of road works stem from asphalt and concrete usage. The wide shoulders added on both sides of the road resulted in higher emission values, as they were not considered as part of the paved width in the normalization. In addition, the usage of PC also increased emissions during construction, as compared with those resulting from the use of GGBFS in the concrete mix. The high normalized emissions during the operation phase estimated for this case, aside from those of road traffic, are once more due to street lighting.

There are other putative reasons that could have led to higher normalized emission values for the cases of this study as compared with values reported by Hill et al. [30] and Keijzer et al. [21]. First, the emission factor for electricity consumption used in this study is approximately 40% higher than the one used by Keijzer et al. [21]. Second, possible larger road features in Abu Dhabi could result in higher emission values. For example, the required depth of the asphalt and aggregate layers above the subgrade in the design of primary roads in the UK is 630 mm, whereas the depth of the asphalt and aggregate layers above the subgrade of primary roads in Abu Dhabi is 930 mm (Figure 2). Third, the irrigation rates in the UAE are much higher than those in Europe, leading to higher consumption of water for landscaping. Fourth, the role of sequestration is probably smaller in the UAE, given the amount of vegetation along roads in the country.

The elevated values of the carbon footprint associated with the case studies imply the need for adoption and implementation of carbon reduction strategies during the road lifecycle. While the major portion of emissions in road projects are associated with vehicle movement during the operation phase, adoption of carbon reduction strategies during the construction phase or for other activities in the operation phase could be beneficial not only in reducing emissions, but also in saving resources and possibly in recycling waste material. We are currently working on a study to explore different scenarios for reducing carbon emissions of road projects in the Abu Dhabi emirate, with consideration of the three presented cases as the baseline for comparison. This work is currently in preparation.

5. Conclusions

GHG emissions from three road projects located in Abu Dhabi were estimated. The case studies comprise two primary roads and one secondary road network. The total emissions range from 76 kg CO_2e/m^2/y for the secondary road case to 1100 kg CO_2e/m^2/y for the primary road cases. For the three cases, the main contributor of emissions (81–97%) during the operation phase is traffic movement, followed by street lighting (1–12%). Regarding the construction phase, road works generally contributed the most to GHG emissions. The relative contribution of material and equipment to GHG emissions varies among the three case studies. For the primary road cases, a higher relative contribution of material to GHG emissions (approximately 80%) was found compared with emissions from the use of equipment.

In the operation phase, traffic movement in the two primary road cases produced 90% or more of the phase emissions, whereas, traffic operating in the case of the secondary road network produced 81% of the phase emissions. The difference in GHG emissions between the two types of roads is due to differences in traffic volume. Nonetheless, emissions from light and heavy trucks dominated all three cases. Street lighting was also found to be a major contributor to GHG emissions for the three cases. Irrigation of vegetation along the road was found to have a very low impact on GHG emissions. Similarly, carbon sequestration was found to have a minor impact on reducing carbon emissions for the investigated cases.

Normalized GHG emissions rates for roads in Abu Dhabi, after excluding the effect of vehicle movement, are higher than those reported for some European countries. While the main reason for this is street lighting, additional factors include the use of wide shoulders, the use of PC in concrete, higher irrigation rates for landscaping, a lower role of sequestration, a higher emission factor for electricity consumption, and possible larger road features in Abu Dhabi.

The results obtained in this study indicate the need for development of plans and strategies to reduce GHG emissions from road projects in Abu Dhabi. Effective management of GHG emissions, while ensuring sustainable development, is a challenge. Nonetheless, these efforts need to be integrated with active participation and strong commitments from all stakeholders to ensure the development and successful implementation of appropriate GHG emissions reduction strategies for road projects.

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