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A METHODOLOGICAL FRAMEWORK FOR THE COMPARATIVE ANALYSIS OF THE ENVIRONMENTAL PERFORMANCE OF ROADWAY AND RAILWAY TRANSPORT

ABSTRACT

Low-carbon transport is a priority in addressing climate change. Transport is still almost totally dependent on fossil fuels (96%) and accounts for almost 60% of global oil use. Sustainable transport systems, both passenger and freight, should be economically and technically feasible, but also low-carbon and environmentally friendly. The calculation of greenhouse gas emissions in transport projects is becoming a primary target of transport companies as a part of an endeavor for low-carbon strategies to reduce the energy demand and environmental impact. This paper investigates the CO_2 impact of construction and operation of the main highway and railway line infrastructure in Greece, which connects Athens and Thessaloniki, the capital and the second biggest cities in Greece respectively and provides a comparative analysis in roadway and railway transport.

KEY WORDS

CO_2 emissions; transport system operation; road infrastructure; road transport; rail infrastructure;

1. INTRODUCTION

Climate change is fast becoming an issue of global interest. Under a business-as-usual scenario, greenhouse gas (GHG) emissions could rise by 25–92% from 2000 to 2030, resulting in a global mean surface temperature increase of 1.4–5.8 ºC from 1990 to 2100 [1]. Scientific evidence confirms that the primary cause of climate change is the release of GHG emissions produced by human activities. Today, all sectors should evaluate the environmental repercussions of their activities and develop necessary actions to decrease the negative impacts. Transport is a major contributor to these emissions; while transport activity is a key component of economic development and human welfare, it is responsible for 27.6% of global energy use and for 22.7% of global CO_2 emissions from fuel combustion. It is still almost totally dependent on fossil fuels (96%) and accounts for almost 60% of global oil use. 73.8% of this global energy amount is consumed by road transport, while only 2.2% is consumed by rail transport [2]. Since 1970, CO_2 emissions from transport have more than doubled globally, increasing at a rate faster than any other economic sector. From 1990 to 2013, CO_2 emissions decreased by about 24% in all main sectors of the European Union (EU) economy, except transport, where these emissions increased by 19.4% over this period. While road is responsible for 72.6% of the total energy-related EU CO_2 emissions, rail is responsible for only 3.3% of EU CO_2 emissions [3]. The transport sector is now under pressure to review current practices and materials and to examine the carbon emissions reduction potential.

Carbon footprint is a measure of the total amount of CO_2 of an activity or product (considering all relevant sources, sinks, and storage) that allows the sources of the impacts to be understood, investigated, and managed. Life cycle assessment or analysis (LCA) has been accepted as a robust method for measuring carbon footprint. The life cycle of transport infrastructure comprises four stages: the construction materials production, the construction process, the maintenance and dismantling process, and the recycling process. In this paper, the estimation of CO_2 emissions is conducted over the construction and operation of the main highway and railway line infrastructure in Greece, which connects Athens (the capital of Greece) and Thessaloniki (the second biggest city in Greece), and a comparative analysis between the two modes of transport is presented.

2. THE ROLE OF LCA IN TRANSPORT ANALYSIS

LCA is one of the techniques developed in order to understand and address the possible impacts associated with products, both manufactured and consumed. LCA addresses the environmental aspects and assesses comprehensively the potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave) [4]. Stripple [5] and Kloepffer [6] describe the structure of LCA as goal definition and scoping, inventory analysis, impact assessment, and interpretation.

Recently, due to the increased awareness about the importance of environmental protection, specifically due to concerns over climate change, a variety of stakeholders have called for ways to measure CO_2 emissions associated with consumer products (goods and services). The use of LCA in transport studies is a method to inform decision makers and help them develop strategies to meet environmental and sustainability goals. Many transport authorities are seeking to develop and implement carbon management systems, which can be applied to specific aspects of their activities. This provides a comprehensive system for recording and measurement of the carbon footprint across different activities. Quantifying the carbon footprint of a transport system activity allows the sources of the impacts to be understood, investigated, and managed. From a broad view of analysis, both direct (vehicle propulsion) and indirect processes and emissions (infrastructure life cycle, vehicle life cycle, and fuel life cycle) are taken into consideration. The contribution of direct emissions from the use of road transport to global warming is already well known and may decrease more as a result of advances in technology, fuel, and vehicle manufacturing. In the future, it is likely that indirect CO_2 emissions associated with the construction of road infrastructure will become increasingly significant.

Part of the existing literature focuses on various environmental impacts deriving from different transport modes. Chester and Horvath [7] present results of a comprehensive life-cycle energy, greenhouse gas emissions, and selected criteria air pollutant emissions inventory for automobiles, buses, trains, and airplanes in the US, including vehicles, infrastructure, fuel production, and supply chains. Chester et al. [8] developed a comparative life-cycle energy and emissions inventory for three metropolitan regions in the United States of America (San Francisco, Chicago, and New York City). The inventory used both vehicle operation (direct fuel or electricity consumption) and non-operation components (e.g. vehicle manufacturing, roadway maintenance, infrastructure operation, and material production, among others). The contribution of indirect environmental impacts was significant for all modes, up to 20 times that of vehicle operation. Chester and Horvath [9] apply LCA to transport modes in the California corridor, comparing existing modes with the high-speed rail system to evaluate direct and indirect energy and emissions impacts in the decision for a high-speed rail system construction. Kimball et al. [10] present an integrated transportation and land-use life cycle assessment framework to quantify the long-term impacts from residential infill using light rail system. The environmental effects from construction, vehicle manufacturing, and energy feedstock prove to be significant. Manzo and Salling [11] suggest the integration of the LCA approach into standard transport cost-benefit analysis, in order to indicate the importance of the indirect environmental impacts in assessing transport sustainability. Their analysis shows that if indirect environmental impacts represent a relevant share of the estimated costs of the project, they can modify the weight of the different components of the overall project cost and affect the final project evaluation. Dimoula et al. [12] presented a holistic approach for the estimation of GHG emissions caused by the construction and operation of the main road and rail infrastructure to better understand the significance of these emissions and the potential influence on designing optimal routes towards lower long-term transport GHG emissions.

3. METHODOLOGY OF THE ANALYSIS

The comparative analysis of the roadway and railway infrastructure environmental performance was based on the following steps:

- defining the purpose of the analysis
- system boundaries
- environmental parameters
- functional units
- gathering data
- calculating emissions

The purpose of the analysis is to evaluate and compare life cycle stage CO_2 emissions for two different modes of transport, highway and railway, in Greece. Specifically, the two infrastructures are: motorway A1 and the railway line connecting Athens and Thessaloniki. Motorway A1 is the second longest motorway and the principal north-south road connection in Greece. It is a closed dual motorway with a central reserve totaling 495 km in length. It has two traffic lanes plus an emergency lane per direction for 343 km (total paved width of 20.4 m) and three traffic lanes plus an emergency lane per direction for 152 km (total paved width of 27.5 m). A small part of the total length, of about 25 km, is under construction in order to be upgraded in motorway standards; this part includes the longest road tunnel in the Balkans with an approximate length of 6 km.

The railway line from Athens to Thessaloniki is 509 km in length and consists of three sections with different types of infrastructure:

- Double-track normal gauge line without electrification. This type of infrastructure amounts to 156 km and is designed for speeds over 200 km h^{-1}.
- Single-track normal gauge line without electrification. This type of infrastructure amounts to 121 km and is designed for speeds up to 140 km h^{-1}.
- Double-track normal gauge line with electrification. This type of infrastructure amounts to 232 km and is designed for speeds over 200 km/h.

Passenger operations use diesel locomotives (ADtranz, IC-5, Railbus, MAN-2000) for the non-electrified parts of the network, and Siemens-120 and Desiro locomotives for the electrified parts of the network. Freight operations use only diesel locomotives (MLW 450, MLW 500).

System boundaries

The main objective, when defining system boundaries in an LCA study, is to include in the system the activities relevant to the purpose of the study. Generally, there are several stages in the life of transport infrastructure: manufacture of construction materials, infrastructure construction, infrastructure operation, infrastructure end of life. Each stage in turn involves inputs, processes, and outputs that generate emissions and energy. In this analysis, the manufacture of construction materials and construction of infrastructure of each transport mode has been examined. Moreover, the stage of the operation of vehicles of each transport mode has been examined and compared.

Environmental parameters

The analysis tackles the CO_2 emissions which have a direct effect on global warming. Each stage of the study has been examined according to the inputs, processes, and outputs that generate carbon emissions.

Functional units

In order to compare the environmental performance of roadway and railway transport system correctly, there is a need for all impacts to be related and expressed quantitatively in the same functional unit. In the construction stage, the functional unit in terms of length is used (t CO_2 per km of lane for roadway, and km of track line for railway). In the operation stage, the same functional unit is used, which is g CO_2 per passenger-km (pkm) or ton-km (tkm).

Gathering emission data

Because the analysis is based on two different transport modes' existing main infrastructure that is constructed and in operation, the data on the activities and emission factors come from different sources. The estimation of CO_2 emissions due to the infrastructure construction was based on several scientific studies found in the literature using the LCA methodology to assess roadway and railway infrastructure, while the estimation of CO_2 emissions due to infrastructure operation was based on specific models using real data from relevant administrative authorities. All relevant references are presented in the analysis subsequently.

4. CARBON FOOTPRINT OF HIGHWAY INFRASTRUCTURE

Road infrastructure is an important factor, not only due to environmental impacts and resource use, but also due to its effect on vehicle fuel consumption because of road alignment and rolling resistance. The complete life cycle of a road construction project includes the extraction of raw materials, their processing, and transport of the final materials to the work site, the construction process, the road operation and maintenance, and the road disposal or reuse after the end of its life. CO_2 emissions attributed to road infrastructure, as described above, range from 10% [13] to 35% [14] of the total road lifecycle emissions, considering also vehicle and fuel life cycle. The first LCA study of an entire road construction project was conducted by Stripple [15] in Finland; emissions from the life cycle of all phases were estimated, starting from the extraction of raw materials to the final repair and maintenance stage for a 1-km stretch of hypothetical road. The service life of the road is considered as 40 years. The total energy consumption during the construction, operation, and maintenance of 1 km of a road stretch during the 40-year period is found to be 23 TJ for asphalt roads and 27 TJ for concrete roads. This difference is due to the cement production, which has a high-energy demand. This study formulates a very comprehensive inventory analysis for each stage of road construction. The composition of the model structure for road construction, operation, and maintenance is based on the sub-components constituting this model.

The growing interest in CO_2 emissions for the complete life cycle analysis of road infrastructure is reflected in the large number of studies published. Birgisdóttir [16] and Birgisdóttir and Pihl [17] studied a typical Danish highway of 11 km in length, consisting of four lanes and two emergency lanes with a life-cycle of 100 years. This study uses five alternative road construction material options that were evaluated for their environmental effects. The above comparison shows that the thin asphalt construction method produces the lowest CO_{2-e} emissions. The total contribution to climate change for this 11-km highway using traditional asphalt materials is 2,670 t CO_{2-e} km^{-1}. Approximately, 60% of the total impact is related to the highway maintenance and operation phase, and 40% is related to the construction phase.

Angelopoulou et al. [18] studied the environmental impacts of the motorway construction and maintenance in Greece (Attiki Odos motorway). The total length studied is 100 km consisting of 3 lanes per direction; its lifespan depends on both the traffic load serviced and the maintenance methodology used. In this case, the first maintenance would take place after 7 or 8 years of use and the second after 15 years of use. The road construction includes a variety of relevant engineering works required, and the resulting emissions were produced due to the consumption of electricity and fossil fuels. Thus, during the construction of 1 km of asphalt highway the produced emissions are estimated at 19,482 t CO_2, while after the first maintenance additional 1,525 t CO_2 are produced, and finally after the second maintenance additional 7,910 t CO_2 are released.

Milachowski et al. [19] studied a 1-km highway segment with 2 lanes per direction, a typical section of 31 m in Germany, having a lifespan of 30 years. The study examined various scenarios for different materials for the two cases of pavement, using both asphalt and concrete, under the scope of optimizing the environmental impact. For the various alternatives examined, it is shown that the construction of 1 km of highway with an asphalt surface is responsible for almost 40% less CO_2 emissions compared to that constructed with a concrete surface.

Muench [20] provides a literature review of 14 roadway construction LCA documents and reveals some common observations about the ecological impacts of roadway construction. Some key features are: a) total CO_2 emissions during roadway construction vary between 200 and 600 t per lane mile total over the analysis period, depending on the pavement section, maintenance activities, and LCA scope; b) materials production accounts for 60–90% of CO_2 emissions; c) maintenance emits about one-fifth of the CO_2 of initial construction. In the report of Carlson [21], 10 scientific studies using the LCA methodology of roads and pavements in Europe are described. The results of these studies are not directly comparable since their characteristics vary, namely having differences in life cycle stages, analysis periods, and road construction design. Barandica et al. [22] present the results of many studies on LCA based on the carbon footprint of road infrastructure. The CO_2 emissions related to road infrastructure based on the analysis of three reports, namely by Hill et al. [23], Claro [14], and Baron et al. [24], and the average emission factors based on several sources [23] are shown in *Table 1*.

The results of the mentioned studies are very heterogeneous due to the differences in analysis periods, system boundaries, regional differences, difference in input data (such as pavement materials, civil engineering structures – bridges, tunnels, viaducts, culverts – use of alternative materials or energy, maintenance activities). According to the Claro study, the major contributor to the estimated emissions is the construction stage, due to the emissions generated for the land preparation (45.7% of the total).

Table 1 – GHG emissions related to road infrastructure

Source	Stages of total infrastructure	Percentage [%]	GHG emissions [t CO_{2-e} km^{-1} y^{-1}]
Hill et al. [23] (width 13 m)	Construction (production, transport, and application of pavement materials)	50	9–27
	Maintenance (surface of pavement)	10	1–5
	Operation (road lighting, traffic lights, cleaning)	40	6–18
	Total	100	16–50
Claro [14] (width 10 m)	Construction	80	120
	Maintenance	7	10
	Operation	13	20
	Total	100	150
Average emission factors based on literature sources (width 12 m)	Construction		14.7
	Maintenance		3.3
	Operation		12.4
	Total	100	30.4
Baron et al. [24]	Total	100	73

5. CARBON FOOTPRINT OF RAILWAY INFRASTRUCTURE

Rail infrastructure is typically made up of several elements, including stations, ballast, track, overhead line equipment (OLE), signaling and telecommunications, road crossings, culverts, tunnels, and bridges. Generally, close attention should be paid in the various infrastructure components, as the construction phase is not dominated the same. For example, the energy demand of the construction phase for the rail tracks is 15 times higher compared to the use phase, while for railway stations the energy consumed during the use phase is twice as high as the construction phase [25]. In addition, the construction of rail infrastructure has different requirements in urban and rural environments due to the topography and many environmental constraints that have effects on cost and released emissions. Jonsson [26] conducts a thorough decomposition of the energy used for construction of rail infrastructure. The infrastructure phase (rail track, stations, and related structures) is about 28% of total LCA of rail (fuel, in-use, rolling stock); 48% of the total embedded GHG emissions from the infrastructure phase is for construction, 34% for maintenance, and 18% for operation. The estimated emissions for the railway life cycle of the Claro study show that the construction stage accounts for most emissions (75% of the total), followed by operation (23%) and maintenance (2%). While Spielmann and Scholz [13] estimate that the majority of embedded emissions (70%) derive from the operation phase of the infrastructure LCA, and the construction, maintenance, and disposal of infrastructure are responsible for 20%, and the remaining 10% is attributed to vehicle manufacture, maintenance, and disposal. Network Rail [27] compared the environmental impact of conventional and high-speed rail. It is estimated that up to a 40% reduction in CO_2 impact could be achieved if the rail network was to move from conventional track design to a double-headed embedded rail design. The type of track laid has a significant impact on the total emissions, i.e., about 30–40 t CO_2 CO_2 per rail track-km. The use of concrete and steel is attributed to 75% of total emissions. *Table 2* provides average GHG emissions for different components and materials for rail infrastructure construction [23].

The International Union of Railways provides a carbon analysis of four new high-speed rail lines [24]; two of them are situated in France and the other two in Asia (China and Taiwan). The emissions from the construction of the high-speed rail lines considered are within the range between 58 and 176 t $CO_{2\text{-e}}$ km-line^{-1} y^{-1}, depending on the parameters of constructed tunnels and viaducts or the use of quicklime or cement for soil stabilization. Claro [14] has estimated that the emissions due to the construction of railway are about 87 t $CO_{2\text{-e}}$ km-line-1 y-$^{-1}$. Tuchschmid et al. [28] researched the carbon footprint of railway infrastructure construction, defining a methodology and calculating the carbon footprint for several countries. According to his study, the most important factor, besides electricity mix and load factor, is the share of bridges and tunnels.

Table 2 – Rail infrastructure GHG emissions for different components and materials

Components of infrastructure	Material	GHG emissions [t CO_2 track-km^{-1} y^{-1}]
Rail	Steel	29.1
Ballast	Gravel	4.3
	Concrete	5.8
Ballastless track	Concrete	13.2
	Steel	6.8
Stations	Concrete	1.1×10^{-3}
	Bricks	2.5×10^{-3}
Overhead line equipment	Steel	52
	Aluminum	25.8
	Copper	7.8

6. CARBON FOOTPRINT OF HIGHWAY OPERATION

Åkerman [29] estimates the future energy use and emissions from the use of vehicles in a study regarding passenger and freight transport in Sweden; emissions are therefore assessed for passenger cars at 63 g $CO_{2\text{-e}}$ pkm^{-1} in 2025, while for trucks at 52 g $CO_{2\text{-e}}$ pkm^{-1} in 2030. The Department of Energy and Climate Change of the United Kingdom [30, 31] presented an annual study on the estimation of GHG emissions by recording or by calculation using activity data (such as the amount of fuel used) and by applying the relevant conversion factors (e.g. emission factors). Emission factors for road vehicles were developed according to the data on the New European Driving Cycle (NEDC) provided by the car industry to the British Ministry of Transport. For passenger cars, DEFRA includes the average CO_2 emission factors and total vehicle registrations for the years 1997–2012 per engine capacity category and per vehicle category. For road freight transport, and specifically for light trucks (LGVs) up to 3.5 t of gross weight, the average CO_2 emissions per vehicle-kilometer were calculated according to the relevant sources of the National Atmospheric Emissions Inventory (NAEI) for the year 2011 depending on the fuel. In the case of heavy trucks (HGVs), GHG conversion rates are associated with the test data from the European ARTEMIS project, which shows that fuel efficiency and therefore CO_2 emissions vary depending on vehicle load.

6.1 Estimation of CO_2 emissions of passenger cars

To calculate the CO_2 emissions resulting from passenger cars using the examined Athens-Thessaloniki motorway, it was required to find the annual vehicle volumes in the above route and to acquire and process the relevant vehicle data from the official authorities. The following steps are required for the estimation of CO_2 emissions from passenger cars:

1) Data was collected from the competent agencies of the Ministry of Infrastructure for the annual passage of passenger cars (PC), including two-axle vehicles with height up to 2.20 m, per toll node (front) on the Athens-Thessaloniki route for the years 2008–2014.
2) Statistical data was collected from the Association of Automobile Representatives in Greece on the specific CO_2 emissions (g km^{-1}) and fuel consumption (l 100 km^{-1}) of PCs with respect to the NEDC; as the percentage of diesel-powered vehicles is very low in Greece [32], only vehicles using gasoline were taken into account.
3) PCs are classified according to their engine displacement into 3 categories:
   Category I: Gasoline PCs with an engine of ≤ 1.4 l (1,400 cm^3)
   Category II: Gasoline PCs with an engine between 1.4 l (1,400 cm^3) and 2.0 l (2,000 cm^3)
   Category III: Gasoline PCs with an engine of ≥2.0 l (2,000 cm^3)
4) The available data is processed for the calculation of the annual CO_2 emissions for two-axle PCs for the years 2008–2014. More specifically, based on the Association of Automobile Representatives data of 2014 for all brands of gasoline PCs and per engine displacement, for each category the following are calculated:

- The average CO_2 emissions (g km^{-1}) on NEDC, the fuel consumption (FC) (l 100 km^{-1}) on NEDC and the FC (l 100 km^{-1}) on the extra-urban part of NEDC (EUDC) for each car model separately, because of the plurality of values depending on their technical characteristics
- The average CO_2 emissions (g km^{-1}) on NEDC, the FC (l 100 km^{-1}) on NEDC and the FC (l 100 km^{-1}) on EUDC for all gasoline vehicles belonging to a category
- The CO_2 emission factor (g l^{-1}) on NEDC obtained by dividing the average CO_2 emissions (g km^{-1}) by FC (l 100 km^{-1})
- The CO_2 emissions (g km^{-1}) on EUDC is obtained by multiplying the CO_2 emission factor (g l^{-1}) by the average FC (l 100 km^{-1})

The annual traffic volume of PCs for both directions of the Athens-Thessaloniki route is shown in *Table 4*, according to the data recorded by the Ministry of Infrastructure.

According to statistics from the annual brochure of the Association of Automobile Representatives on the developments on new PCs per year, it is shown that vehicles with smaller engine displacement have had a greater demand on the market, especially after the beginning of the economic crisis in Greece. The average values of *Table 5* are used as the standard category share in the present study.

The annual CO_2 emissions (g) per displacement class (I, II, III) for the Athens-Thessaloniki route length, in both directions, is calculated using following formula (own elaboration):

Table 3 – CO_2 emissions (g km^{-1}), FC (l 100 km^{-1}), and CO_2 emission factor (g l^{-1}) for (gasoline) engine PCs based on data from the Association of Automobile Representatives in Greece

Vehicle category	EUDC average FC [l 100 km^{-1}]	CO_2 conversion factor [g l^{-1}]	EUDC CO_2 emissions [g km^{-1}]
I	4.38	2,392.43	104.76
II	5.15	2,426.70	124.98
III	7.77	2,444.22	189.91

Table 4 – Annual traffic volume of PCs (height up to 2.20 m, both directions)

Year	2008	2009	2010	2011	2012	2013	2014
Annual traffic [veh]	58,075,632	62,448,592	53,197,514	47,795,998	39,956,457	37,190,400	33,537,979

Table 5 – Market share of new passenger cars 2008–2011

Engine	2008	2009	2010	2011	Average
<1.4 l	73.55%	68.24%	54.24%	57.46%	63.37%
1.4 l ≤ 2.0 l	25.45%	29.78%	40.21%	37.34%	33.20%
>2.0 l	1.00%	1.98%	5.55%	5.19%	3.43%

Table 6 – Annual traffic volume of heavy-duty vehicles (height above 2.20 m, both directions)

Year	2008	2009	2010	2011	2012	2013	2014
Annual traffic of three-axle vehicles	4,231,476	4,362,178	4,342,582	4,004,487	3,478,691	3,287,980	3,079,306
Annual traffic of four-axle vehicles	5,176,218	4,903,556	4,651,388	5,349,226	4,340,801	4,050,141	3,864,049

$$\begin{aligned} &Annual\ CO_2\ emissions\,(g) = \\ &= \sum_{i=1}^{3} Fuel\ consumption\left(\frac{l}{100km}\right) \cdot \\ &\cdot Motorway\ length\,(km) \cdot Emission\ factor\left(\frac{g}{l}\right) \cdot \\ &\cdot Number\ of\ PCs \end{aligned} \tag{1}$$

where i=1-3 are the three engine categories.

In order to produce comparable results, the annual total CO_2 emissions for PCs should be determined in grams (g) per passenger (p) per kilometer (km). It is assumed that the average vehicle occupancy for the Athens-Thessaloniki-Athens route is 1.76 p veh^{-1} (according to the Greek National Origin-Destination Study of 2002–2003 which is considered as constant for all years from 2008 to 2014). The annual number of passengers is calculated from the total number of PCs in the Athens-Thessaloniki motorway for both directions (as calculated for each year from 2008 to 2014) and the average occupancy vehicle estimate. The passenger-kilometers for each year in each direction result from the calculation of passengers per year and the total travel distance traveled by two-axle vehicles. The total annual CO_2 emissions of PCs in g pkm^{-1} per direction derive from the total annual CO_2 emissions (t) and the annual passenger-kilometers. These calculations result in an average amount of carbon emissions from road operation of about 78 g CO_2 pkm^{-1}.

6.2 Estimation of CO_2 emissions of freight operation

The annual CO_2 emissions deriving from the commercial traffic of heavy-duty vehicles having 3 axles and a height of over 2.20 m and those having 4 or more axles and a height of more than 2.20 m, for the Athens-Thessaloniki motorway, are calculated using the same methodology and assumptions used for the estimation of CO_2 emissions from passenger cars, in the years 2008–2014. The annual traffic volume of heavy-duty vehicles for each category, in both directions of the Athens-Thessaloniki route is shown in *Table 6*.

Similar to the calculations made for vehicle-kilometers for PCs per year, for the years 2008 to 2014, the vehicle-kilometers for heavy-duty vehicles in each category on the Athens-Thessaloniki motorway are calculated per direction per year using the same assumptions. Calculations of CO_2 emissions from heavy-duty vehicles were estimated based on fuel consumption depending on their size. In a study conducted in Great Britain to reduce GHG from road transport, data was presented for the years 2000, 2005, and 2009 on the average fuel consumption for trucks, in miles per gallon, with respect to the size of each vehicle [33]. It is assumed that heavy-duty vehicles of the 3-axle category on the Athens-Thessaloniki route and in the opposite direction belong to the 12 t category with a fuel consumption rate of 26.9 l 100 km^{-1}, while heavy-duty vehicles of the multi-axle category belong to the 18 t category with a fuel consumption of 32.1 l 100 km^{-1}. It is also assumed that the CO_2 conversion factor for diesel vehicles is equal to 3.06 kg l^{-1}. From the above analysis, the average amount of carbon emissions from the road axis operation is about 137.2 g CO_2 tkm^{-1} for three-axle and 109.1 for four-axle heavy-duty vehicles.

7. CARBON FOOTPRINT OF RAILWAY OPERATION

Several studies focusing on the carbon footprint of rail operation have been conducted in recent years. Most notable amongst them are the ones conducted by the International Energy Agency and the International Union of Railways [34] and Network Rail [27]. Some of the results of these studies are presented in *Table 7*, which shows the GHG emissions of rail infrastructure based on the rail performance in pkm.

Table 7 – Rail transport infrastructure life cycle emissions

Literature source	g CO_{2-e} pkm^{-1}
UIC: HS-Lines in France	5.7
UIC: Train in Asia	39.2–42.9
Network Rail (high speed rail)	18.5
Network Rail (conventional rail)	22.7
Claro	22.02

High speed rail (HSR) trains with a maximum service speed that exceeds 250 km h^{-1} produces significantly lower GHG emissions than conventional rail system.

7.1 Estimation of CO_2 emissions of passenger railway

For the calculation of CO_2 emissions from passenger rail operation, relevant data were collected from official sources in Greece. These data include the number, type, and energy consumption levels of all trains passing through each of the railway sections annually, as well as the number of passengers transported annually. The following assumptions are made in order to estimate the carbon emissions from passenger rail operation:

- The average fuel consumption for diesel locomotives (k) is taken as 3.3 l km^{-1}, while the average energy consumption of the electric locomotives (K) is taken as 4.104 kWh.
- The CO_2 emissions coefficient (σ) is taken as 3,060 g l^{-1} for diesel locomotives, while the CO_2 emissions coefficient (Σ) for electric ones is taken as 1,100 g kWh^{-1}.
- To calculate the CO_2 emissions of passenger railway transport, the following methodology is used:

1) The annual train-km figures for each railway section are calculated separately by multiplying the number of passing trains from each section by the length of the appropriate section.
2) The annual sum of train-km for the entire line is divided by the length of the entire line (509 km) in order to produce a theoretical annual number of passing trains for the entire Athens-Thessaloniki route in each direction.
3) The annual CO_2 emissions for each direction and for each type of train are calculated using the following formula (own elaboration):

$$\begin{aligned} &Annual\ CO_2\ emissions\,(g) = Number\ of\ \ passing\ trains\ \cdot \\ &\cdot Length\ of\ \ entire\ line\,(km) \cdot Consumption\ rate\,(l\ km^{-1}\ or\ kWh) \cdot \\ &\cdot CO_2\ emissions\ coefficient\ (g\ l^{-1}\ or\ g\ kWh^{-1}) \end{aligned} \quad (2)$$

4) The total annual number of passengers for each direction is multiplied by the entire length of the line to calculate the annual pkm for each direction.
5) The annual CO_2 emissions for each direction are divided by the appropriate number of pkm.

The results of this methodology are given in *Table 8*. From the above analysis, the average of carbon emissions from passenger railway amounts to about 66.5 g CO_2 pkm^{-1}.

7.2 Estimation of CO_2 emissions of freight railway

A similar approach is taken in order to calculate railway freight transport. However, some of the assumptions differ, namely:

- The average consumption (k) of locomotives is taken as 4.0 l km^{-1}. This is the consumption for a fully loaded train.
- All trains are considered to be fully loaded with 1,200 t.

In order to calculate the CO_2 emissions of freight railway transport, the following methodology is used:

Steps 1 to 3 are the same as with passenger railway transport.

4) The annual tkm for each direction are calculated by multiplying the theoretical number of trains by the total distance (509 km) and then again by the maximum load (1,200 t).
5) The total emissions in g CO_2 tkm^{-1} are calculated by dividing the values from step 3 by the tkm calculated in step 4.

The results of this methodology are given in *Table 9*. From the above analysis, the average value of the carbon emissions from freight railway amounts to about 10.2 g CO_2 tkm^{-1}.

It is important to note that, especially in the case of passenger railway operation, there is a significant drop in CO_2 emissions in 2009. This may be attributed to the fact that 2009 was the year when electric locomotives started operation in parts of the Athens-Thessaloniki line. Since electrification was never introduced for freight operation, the total emission levels appear to be constant.

Table 8 – CO2 emissions from railway passenger operations

Year	Direction	Number of passengers per year	Annual CO_2 emissions [g] 10^{-6}	Passenger-km	Total emissions [g CO_2 pkm^{-1}]
2008	Athens	708,192	34,687.12	361,135.428	96.05
	Thessaloniki	708,201	34,124.1	361,140.252	94.49
2009	Athens	812,485	25,321.9	414,318.601	61.12
	Thessaloniki	798,941	24,947.29	407,411.974	61.23
2010	Athens	801,460	23,673.41	408,696.512	57.92
	Thessaloniki	773,341	23,554.02	394,357.51	59.73
2011	Athens	648,539	19,889.8	330,715.978	60.14
	Thessaloniki	629,625	19,781.30	321,070.72	61.61
2012	Athens	607,483	19,889.8	309,779.881	64.21
	Thessaloniki	621,381	19,781.30	316,867.03	62.43
2013	Athens	612,598	18,490.78	312,388.224	59.19
	Thessaloniki	616,996	18,512.39	314,630.94	58.84
2014	Athens	570,649	19,889.8	290,996.751	68.35
	Thessaloniki	571,080	19,256.24	291,216.535	66.12

Table 9 – CO2 emissions from railway freight operations

Year	Direction	Theoretical number of trains	Train-km	Annual CO_2 emissions [g] 10^{-6}	Total emissions [g CO_2 tkm^{-1}]
2008	Athens	1603	980,837.604	10,004.54	10.2
	Thessaloniki	1337	818,130.192	8,344.93	10.2
2009	Athens	757	463,057.404	4,723.19	10.2
	Thessaloniki	753	460,751.64	4,699.67	10.2
2010	Athens	457	279,896.364	2,854.94	10.2
	Thessaloniki	455	278,148.247	2,837.11	10.2
2011	Athens	260	159,282.512	1,624.68	10.2
	Thessaloniki	247	151,019.656	1,540.40	10.2
2012	Athens	260	159,282.512	1,624.68	10.2
	Thessaloniki	247	151,019.656	1,540.40	10.2
2013	Athens	182	111,405.832	1,136.34	10.2
	Thessaloniki	171	104,599.289	1,066.91	10.2
2014	Athens	547	334,759.552	3,414.55	10.2
	Thessaloniki	532	325,549.577	3,320.61	10.2

8. DISCUSSION

A study was carried out to assess and compare the relative environmental performance of the two main transport modes, highway and railway systems, in Greece. Life-cycle assessment which is used in this study led to comparable results for the examined modes. The amount of GHG emissions from the construction of infrastructure and total transport operation, passengers and freight, were examined. *Table 10* shows the obtained results. Comparing the results, the proportion of emissions attributed to highway construction seems smaller than that of the railway infrastructure. On the other hand, railway system operation is more environmentally friendly than highway operation. Transport infrastructure, both highway and railway systems, involves the construction, operation, and maintenance of infrastructure. It is obvious that such a system is very complex and its analysis requires both a structured methodology and analytical tools. The potential environmental impact can be reduced by optimizing the production of the construction materials. The evaluation of a service period determines the influence of the maintenance role in the total environmental impact.

There is a number of relevant studies suggesting methods to assess the negative impacts and proposing various methodologies for the evaluation of each system separately and locally. Available literature on life-cycle assessment approach for highway and railway system infrastructure is briefly examined. The characteristics of transport infrastructure as geotechnical conditions, materials used and construction engineering methods make it difficult to perform a representative life cycle inventory. The construction of different engineering works, such as bridges or tunnels, requires more input materials (concrete, steel), increasing significantly the amount of GHG emissions. Reducing the amount of steel needed or reducing the emissions of CO_2 per t of steel, using renewable energy in the processes, would minimize the total environmental impact. The objective of LCA provides a basis for assessing potential improvements in the environmental performance of the system. The latter can be of particular importance to engineers and environmental managers, because it can suggest ways to modify or design a system in order to decrease its overall environmental impacts. Using the appropriate materials and construction techniques can have a positive impact in the overall environmental impact of each mode, while technologically advanced and more environmentally friendly vehicles, combined with improved operational models, can decrease the carbon footprint produced throughout the life cycle of each transport system.

Table 10 – Results obtained from the study

	Infrastructure [t $CO_{2\text{-}e}$ km^{-1} y^{-1}]	Operation	
		Passenger [g CO_2 pkm^{-1}]	Freight [g CO_2 tkm^{-1}]
Highway	30*	78	137.2 (3-axle) | 109.1 (4-axle)
Railway	60*	66.5	10.2

**average from literature*

9. CONCLUSIONS

The challenges of addressing climate change are increasingly seen as major transport policy issues. Low-carbon transport including more fuel-efficient vehicles and less carbon-intensive fuels must be a priority. However, carbon footprint analysis in transport projects is becoming a primary target of transport companies as a part of an endeavor for low-carbon strategies to reduce the energy demand and environmental impact. This analysis would provide tools for sustainable development of transport modes as well as for deciding on alternative models of construction and strategic decisions concerning the development of transport modes. In this paper, an approach to transport-related environmental problems is presented based on an analysis of the entire transport system in a holistic approach, including a life cycle assessment, an approach concerning not only transport operations but also transport infrastructure. There is a range of studies that explore specific aspects in detail for both road and rail infrastructure. Considering the available information for different modes while taking into account the CO_2 emissions from infrastructure development and operation may foster selection of optimal environmental and sustainable methods. Such considerations have an important effect on relevant future research and development projects at local, regional, and national levels.

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ΜΕΘΟΔΟΛΟΓΙΚΗ ΠΡΟΣΕΓΓΙΣΗ ΓΙΑ ΤΗΝ ΣΥΓΚΡΙΤΙΚΗ ΑΝΑΛΥΣΗ ΤΗΣ ΠΕΡΙΒΑΛΛΟΝΤΙΚΗΣ ΑΠΟΔΟΣΗΣ ΤΩΝ ΟΔΙΚΩΝ ΚΑΙ ΤΩΝ ΣΙΔΗΡΟΔΡΟΜΙΚΩΝ ΜΕΤΑΦΟΡΩΝ

ΠΕΡΙΛΗΨΗ

Οι μεταφορές χαμηλών εκπομπών άνθρακα αποτελούν προτεραιότητα στην αντιμετώπιση της κλιματικής αλλαγής. Οι μεταφορές εξακολουθούν να εξαρτώνται σχεδόν εξ ολοκλήρου από τα ορυκτά καύσιμα (96%) και αντιπροσωπεύουν σχεδόν το 60% της παγκόσμιας χρήσης πετρελαίου. Τα βιώσιμα συστήματα μεταφορών, τόσο επιβατικών όσο και εμπορευματικών μεταφορών, πρέπει να είναι οικονομικά και τεχνικά εφικτά, αλλά και χαμηλής περιεκτικότητας σε άνθρακα και φιλικά προς το περιβάλλον. Ο υπολογισμός των εκπομπών αερίων του θερμοκηπίου στα έργα μεταφορών καθίσταται πρωταρχικός στόχος των εταιρειών μεταφορών ως μέρος μιας προσπάθειας για στρατηγικές χαμηλών εκπομπών διοξειδίου του άνθρακα για τη μείωση της ζήτησης ενέργειας και των περιβαλλοντικών επιπτώσεων. Η παρούσα εργασία διερευνά τις επιπτώσεις της κατασκευής και λειτουργίας της κύριας υποδομής των αυτοκινητοδρόμων και των σιδηροδρομικών γραμμών στην Ελλάδα, η οποία συνδέει την Αθήνα και τη Θεσσαλονίκη, την πρωτεύουσα και τη δεύτερη μεγαλύτερη πόλη στην Ελλάδα αντίστοιχα, και παρέχει συγκριτική ανάλυση στις οδικές και σιδηροδρομικές μεταφορές.

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ

Εκπομπές CO_2; λειτουργία συστήματος μεταφορών; οδική υποδομή; οδικές μεταφορές; σιδηροδρομική υποδομή;

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