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A Holistic Approach for Estimating Carbon Emissions of Road and Rail Transport Systems

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ABSTRACT

Environmental issues have become of crucial importance in the transport sector. Transport is the second biggest greenhouse gas emitting sector after energy and is responsible for 25% of the EU's total emissions. The challenges posed by climate change have added to the urgency for developing low-carbon transportation. In this paper, estimation of greenhouse gas emissions was conducted over the construction and the operation of the main road and rail axes infrastructure in Greece. The objective of this analysis is to better understand the significance of these emissions and their possible influence on designing optimal routes in order to achieve long-term greenhouse gas reductions from transport. The present study shows that the environmental impact due to the highway construction is smaller than that of the railway construction. However, the railway system operation is more environmentally friendly than the highway operation.

Keywords: Transport system; CO_2 emissions; Road infrastructure; Rail system.

INTRODUCTION

Transport is the second biggest greenhouse gas (GHG) emitting sector after energy and is responsible for 25% of the European Union's (EU) total emissions. While greenhouse gas emissions from other sectors have decreased by 24% between 1990 and 2009, emissions from transport were reported increasing by 29% in the same period. Despite improved vehicle efficiency, this increase occurred because of the boost of passenger and freight transport (EU Transport GHG, 2012). The European Commission has the commitment to face the consequences of climate change. The EU has the overall goal of achieving a 60 % reduction in transport GHG emissions from 1990 levels by 2050, with an intermediate goal of reducing by 20% transport GHG emissions from 2008 levels by 2030, an + 8% compared to 1990 levels (EEA, 2014).

Several studies have been carried out in order to assess the entire life cycle impact of transportation systems, specifically of the role of GHG emissions resulting from infrastructure construction and transport operation, vehicle manufacturing and end of life of vehicles. Transport sector emissions have been dominated by direct emissions from the operational use of vehicles. However, a holistic approach is needed to investigate the impact of each of the above phases of the transport system in the overall amount of GHG emissions (Asian Development Bank, 2010; EU Transport GHG, 2012).

In this paper, the estimation of GHG emissions was conducted over the construction and the operation of the main road and rail axis infrastructure in Greece. The objective of this analysis is to better understand the significance of these emissions and their possible influence on designing optimal routes in order to achieve long-term GHG reductions from transport. The estimation of GHG emissions for the construction of highway and rail infrastructure was based on data from former studies, while the estimation of GHG emissions due to transport the operation was based on specific models using traffic data obtained from the relevant administrative authorities.

DATA AND METHODOLOGY USED

The estimation of GHG emissions was conducted for the construction and the use of a part of Motorway A2 (Egnatia Odos) and the rail system axis connecting Thessaloniki (Greece's second largest city), and Alexandroupolis, a town in the northeastern part of the country. Egnatia Odos is the modern reincarnation of the Roman Via Egnatia; it was

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designed to the specifications of the Trans-European road network and it is of crucial importance for Greece. The new highway, with the total length of 670 km, begins at the Greek-Turkish border on the Evros river and ends at the western Greek port of Igoumenitsa, which is connected to the ports of Brindisi, Bari, Ancona and Venice by ferry ships. It is a closed dual motorway with a central reserve, two traffic lanes plus an emergency lane per direction, for a total paved width of 24.5 meters over its greatest part, except for the road's mountainous sections. The length of the examined part of Egnatia Odos, connecting Thessaloniki - Alexandroupolis, is 301 km.

The infrastructure of the rail line Thessaloniki - Alexandroupolis is composed of a single standard gauge (1,435 mm) track, 442 km long, of which 116 km are constructed with modern superstructure materials (UIC 54 rails and B70 concrete monoblock sleepers) and the remaining 326 km with old infrastructure (twin-block concrete, wooden and steel sleepers, and UIC 54-UIC 50 rails).

Life Cycle Analysis (LCA), was adopted as thr computational method, a valuation tool that analyses and quantifies the environmental impacts (emissions and material consumption) associated with a particular service or product over its entire life cycle or over a specific analysis period. Thus, this analysis includes all processes connected to a specific product, from raw material extraction until waste treatment after the product is no longer usable. This process is also called the "cradle-to-grave" model. Fig. 1 shows the main phases of a LCA. This methodology aims to determine the environmental relevance, the reduction potentials, or the optimum variant of a product, project or service regarding specific environmental impacts. Furthermore, it can be used to raise the environmental awareness of stakeholders concerned with the product, project or service (Gschösser, 2011).

LCA OF ROAD INFRASTRUCTURE CONSTRUCTION

The complete life cycle of a road project construction includes the extraction of raw materials, the processing and the transport of materials in the work site, the construction process, the operation and maintenance of road and the disposal or reuse of the road after the end of its lifespan. In the last decade, many studies on LCA on road construction have been conducted worldwide (Muench, 2010). Generally, CO_{2e} emissions associated with the construction of road infrastructure have been estimated at 9–27 tCO_{2e} km^{-1} y^{-1} (EU Transport GHG, 2012).Transport Scotland's systemized approach to gathering data on emission-releasing activities and the subsequent estimation of operational and project carbon dioxide (Carbon management system (CMS)) (Fox *et al.*, 2011).

The first study of on LCA of an entire road construction project was conducted by Stirpple (2003) in Finland. It estimates the emissions from the life cycle of all phases, 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 was taken as 40 years. The total energy consumption during construction, operation and maintenance of 1 km of the stretch of road during the 40 years period is found to be 23TJ for asphalt roads and 27TJ for concrete roads. This difference is due to the consumption of coal for the manufacturing of cement. This study formulated a very comprehensive inventory analysis of each stage of road construction. The composition of the model structure for construction, operation and maintenance of a road is based on the sub- components that constitute the model. Taking into account the parameters and analysis of each sub-stage, the total tCO_{2e} per lane km^{-1} of the construction of road surface was estimated. Tables 1 and 2 show some of the results of the studies on LCA based on the carbon footprints. Specifically, Table 1 shows the emissions of tCO_{2e} km^{-1} of three studies of road construction, including all life cycle stages of an entire road construction. As the different studies took into consideration a different lifespan, each result is concerted to annual emissions tCO_{2e} km^{-1} $year^{-1}$ to facilitate the comparison. It must be noticed that the results of each of the previous studies are very heterogeneous, since their scope, their data sources, their system boundaries and their assumptions are different. Some of these studies are focused on precise phases, such as the preservation or the construction of surfaces. Other studies have a quite different scope, such as the impact of the extension of land use changes, the use of recycled waste as raw materials and the impact of maintenance activities on the environment. Also, the methodology is different; for example, Barandica *et al.* (2013) in their study took into consideration the construction of tunnels and viaducts, but this is not taken into account in other studies. Thus, the estimated amount of CO_2 of each project is different.

However, the previous studies lead to some notable common remarks:

- Total CO_2 emissions during the road construction phase depends on the type of pavement section, maintenance activities and boundaries system of LCA,
- Material production contributes to 60%–90% of total CO_2 emissions,
- Construction activities at the worksite contribute to 5–7% of total CO_2 emissions,
- Transportation of materials, associated with construction of the road, corresponds to about 10% of total CO_2 emissions,
- Maintenance activities, for preventive and corrective actions related to road surfaces, produce about 1–5 tCO_{2e} km^{-1} y^{-1}, over the entire life of the road.
- The operation stage, namely the lighting of the road, the use of traffic lights and the road surface de-icing, produces about 6–18 tCO_{2e} km^{-1} y^{-1}.

LCA OF RAIL INFRASTRUCTURE CONSTRUCTION

The rail infrastructure is made up of a number of elements (track with ballast) including stations, tunnels, bridges, signaling and telecommunications. A study by Stripple and Erlandsson (2004) estimates the total energy consumption for 1 km of railroad during 60 years (including its construction,

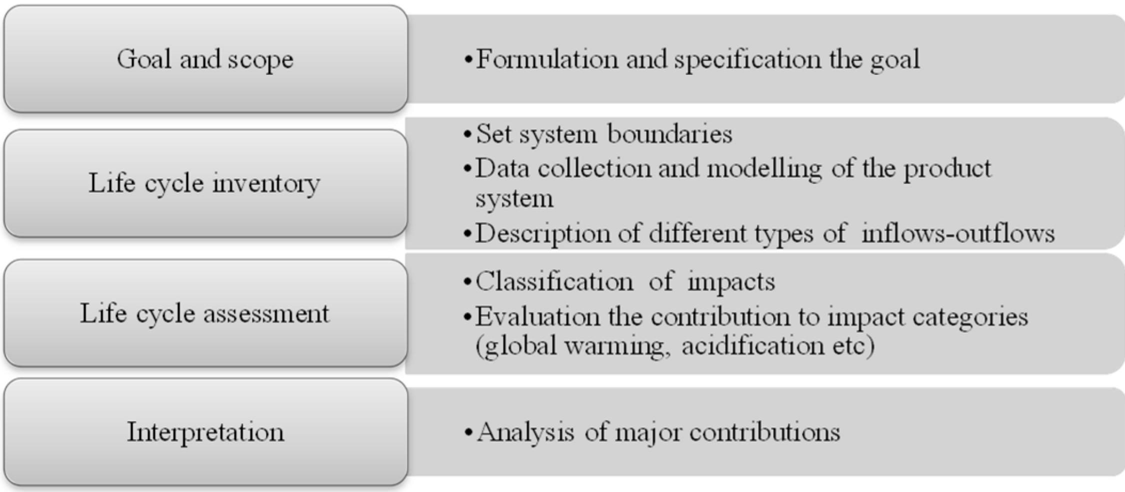

Fig. 1. Main phases of a LCA.

Table 1. Infrastructure life-cycle emissions (tCO_{2e} km^{-1} y^{-1}) of the road construction.

Author	Country/Year	Lifespan (y)	tCO_{2e} km^{-1} y^{-1}
1. Park	Korea/2003	20	447
2. Carlo	Spain/2010	50	160
3. Loijos	USA (Massachusettes)/2011	40	10–162

Table 2. tCO_{2e} km^{-1} of road construction of some studies.

Author	Country/Year	Lifespan (y)	tCO_{2e} km^{-1} y^{-1}
1. Mroueh	Filand/2000	50	6–12
2. Stripple	Sweden/2001	40	50–62.5
3. Athena Institute	Canada/2006	50	1–25.3
4. Birgisdottir	Denmark/2006	100	26.7
5. SUSCON	Greece/2006	50	18.8
6. Milachowski *et al.*	Germany/2011	30	56.5
7. Barandica *et al.*	Spain/2012	50	177–1006
8. Huang	UK India/2012	25	35.9–385

operation and maintenance phases) to 4.3×10^7 MJ. Von Rozycki *et al.* (2003) investigated the environmental effects caused by the German high-speed passenger train system (ICE). This study showed that the rail infrastructure contributes to less than 15% of the total CO_2 emissions, while the operation phase is the main responsible contributor (about the 64% of the energy of the life cycle). The amount of CO_2 emissions per pkm are calculated as being 69 $grCO_2$ pkm^{-1}. Similarly, Spielman and Scholz (2005) found that the operation phase corresponds to about 70% of the cycle CO_2 emissions. The construction and the maintenance correspond to about 20% of CO_2 emissions and the remaining 10% is attributed to vehicle manufacturing.

On the contrary, in Scandinavian countries, the construction and maintenance of infrastructure is the dominant contributor. The study of Stripple and *et al.* (2010) showed that the infrastructure construction phase stands for the main part of the greenhouse gas emissions (CO_2), about the 93.3%, while the train traffic contribution is only 6.7%. Emissions from the operation are very small due to the use of green electric power (hydropower about 99% and biomass fuel about 1%) in the electricity grid. The high infrastructure load per passenger, namely few travel passengers, is also a significant parameter. The extraction and processing of raw materials, steel and cement, used for the construction of the infrastructure stands for the 75% of the total CO_2 emissions. Moreover, there is a significant share of the contribution to global warming (about 18%) coming from deforestation, namely forest areas that are cut down and transformed to railway land. Similarly, Claro (2010) estimated the emissions for the railway life cycle. This work showed that the construction stage accounts for the 60% of the total emissions, the operation for 23%, the manufacture of materials for 15% and the end of life for 2%. The total amount emissions of the above analysis were estimated to about 87 tCO_{2e} per km^{-1} y^{-1}.

Schlaupitz (2008) used lifecycle analysis to estimate energy use and emissions of CO_2 of road, railroad and air transportation in Norway. The calculation period used was 100 years and different elements of railway infrastructure having different life lengths were taken into account. The dual-track railway analyzed in the study consisted of the following elements: tunnel (37%), bridge (5%), crossing bridge (0.5%), plain railway (without tunnels and bridges) (53.5%). The total amount of estimated CO_2 was 362.5 tCO_{2e} y^{-1}. It is clear that tunnels and bridges contribute significantly to the total emissions.

The type of track laid has a significant impact on the total emissions, about 30–40 tCO_{2e} $rail^{-1}$ track km^{-1}. About 75% of the total emissions come from the use of concrete and steel.

International Union of Railways (UIC) has published the "Carbon Footprint of High Speed Rail: Final Report" (2011) presenting the results of a carbon footprint analysis of four high speed rail lines, two in the Mediterranean and two in Taiwan and China. Earthwork, transport of construction materials, engineering structures, like bridges and tunnels, rolling stock manufacture, electrical and signaling equipment have been taken into account in the construction analysis. The total emissions from the construction of the high-speed rail are in the range of 58–156 tCO_2 km^{-1} of line $year^{-1}$. The difference is depending on the space or relief constraints.

According to the analysis of data from former studies from literature review, the environment impact of highway construction is smaller than the construction of railway. In Fig. 2 the comparison of CO_2e from road and rail construction is presented.

LCA OF ROAD OPERATION

The following describes the methodology for estimating CO_{2e} emissions from the use of passenger and freight road transport on Egnatia Motorway, in the Thessaloniki - Alexandroupolis route of a total length of 301 km.

The annual traffic volume on the reference axis is calculated according to the data of "Egnatia Odos" Observatory records. Based on these data, the average daily number of vehicles, for the years 2004–2011, in both directions and the corresponding percentage of heavy vehicles is presented in Table 3.

For passenger road transport the private passenger vehicles are taken into account, whereas buses are exempt. Data from previous studies are used and assumptions for the variation rates of vehicle trips are made in order to simulate the Greek reality.

Only petrol cars are taken into account since sales of petrol cars are at the top of consumers' preferences, opposite to diesel, occupying 52% of the Greek market share. Car engine categories considered include: a. Category I (engines up to 1.4 lt), b. Category II (engines up to 2.0 lt) and c. Category III (engines of more than 2.0 lt). It is considered that the distribution of current petrol vehicles is 65% of Category I, 33% of Category II and Category III of 2% (Papagiannaki *et al.*, 2009).

The CO_2 emissions per vehicle category, for the interurban cycle, are estimated based on data from Greek vehicle manufacturing companies. Specifically, in order to estimate the fuel consumption (lt/100 km) per vehicle category for the corresponding driving cycle, various models with different characteristics are taken into account. The range of CO_2 emissions in gr km^{-1} (minimum-maximum values) is recorded per vehicle for various vehicles of the same type, according to the data provided by the manufacturing companies (Table 4).

The total passenger-kilometer estimates for the years 2004–2011 based on the data of Egnatia Odos Observatory records, using the factor of 1.67 passengers per vehicle are presented in Table 5. The amount of CO_2 emissions presented in Table 5 is calculated on an annual basis.

In freight road transport, three-axle and multi-axle trucks that serve the main part of freight transport in interurban transportation are taken into consideration. The appropriate three-axle and multi-axle fuel consumption data are taken from the study of McKinnon (2009). Regarding the allocation of vehicles on the reference axis, the average fuel consumption value was 24.8 lt 100 km^{-1} for all three-axis vehicles and 31.39 lt 100 km^{-1} for multi-axis vehicle. An assumption is made that all three-axis vehicles weigh 12 t and all multi axis 18 t. In Table 6, the total annual CO_2 emissions ($grCO_2$ tkm^{-1}) is using the conversion factor of 3.06 kg CO_2 per diesel liter (Dynapac Sustainable Way Final).

From the above analysis, an average amount of carbon emissions from the road axis operation is about of 80 $grCO_2$ pkm^{-1} for passenger transport and about of 270 $grCO_2$ tkm^{-1} for multi-axis vehicles and 110 $grCO_2$ tkm^{-1} for three-axis.

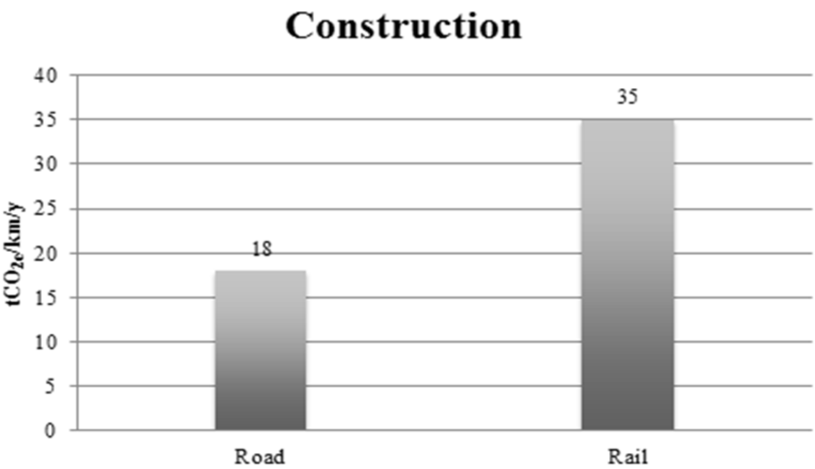

Fig. 2. Comparison of CO_{2e} emissions from road and rail construction (average value from literature review).

Table 3. Average daily annual traffic of Egnatia Odos (Egnatia Odos Observatory).

Year	2004	2005	2006	2007	2008	2009	2010	2011
Annual average daily traffic vehicles/day	112200	117023	132704	120222	129032	139380	132592	124847
Average heavy vehicle percentage (%)	12%	13.7%	17.2%	17.6%	15.5%	14.8%	15.6%	17.1%

Table 4. CO_2 emissions (gr km^{-1}), fuel consumption (lt 100 km^{-1}) and CO_2 emission factor (gr lt^{-1}) for petrol engine vehicles based on data from Greek vehicle manufacturing companies.

Vehicle Category	Interurban Cycle Average Fuel Consumption (lt 100 km^{-1})	CO_2 Conversion Factor (gr lt^{-1})	Interurban Cycle CO_2 Emissions (gr km^{-1})
I	4.33	2320.40	100.36
II	5.53	2379.86	131.62
III	7.62	2336.33	177.93

Table 5. Annual emissions in gr CO_2 pkm^{-1}.

Year	Total CO_2 emissions (tn)	Total Daily Recorded Vehicles	Calculated Annual Passengers	Passenger-kilometers (pkm)	Annual Emissions $grCO_2$ pkm^{-1}
2004	122,971	112,200	68,391,510	1,534,097,739	80.16
2005	126,101	117,023	71,331,248	1,572,521,817	80.19
2006	141,167	132,704	80,889,723	1,760,508,542	80.19
2007	128,355	120,222	73,281,076	1,601,737,232	80.13
2008	138,633	129,032	78,651,151	1,729,509,705	80.16
2009	107,358	139,380	84,959,201	1,916,303,911	80.02
2010	140,381	132,592	80,821,697	1,750,670,248	80.19
2011	126,949	124,847	76,100,733	1,584,410,432	80.12
Total (average value)					80.0

Table 6. Total annual CO_2 emissions ($grCO_2$ tkm^{-1}) for freight road transport.

Year	Recorded Heavy Vehicles	Recorded Three-axis Vehicles	Recorded Multi-axis Vehicles	Three-axis tkm	Multi-axis tkm	Total annual $grCO_2$ tkm^{-1} emissions for multi-axis vehicles	Total annual $grCO_2$ tkm^{-1} emissions for three-axis vehicles
2004	15,300	12,586	2,714	506,977,798	180,000,523	170	71
2005	18,537	15,248	3,288	603,659,077	214,326,841	202	85
2006	10,253	8,434	1,819	329,645,122	117,039,236	111	46
2007	25,722	21,159	4,563	830,526,910	294,875,394	278	117
2008	23,669	19,470	4,199	768,838,866	272,973,291	258	108
2009	24,102	19,826	4,276	803,053,931	285,121,219	269	113
2010	24,460	20,121	4,339	782,686,520	277,889,847	262	110
2011	25,813	21,234	4,579	793,891,802	281,868,240	266	111
Total (average value)						270	110

LCA OF RAILWAY OPERATION

The CO_2 emissions estimation from the passenger rail operation takes into account the carbon footprint due to the operation of the railway. In Table 7, average emission conversion factors, namely gr CO_2 per passenger kilometer (pkm), proposed by different European Institutions are presented.

The annual reports of International Union of Railways (UIC) publication mention that the carbon footprint due to the operation lies in the range of 5.7–42.9 $grCO_2$ pkm^{-1}, depending on the type of train. Considering, Eurostar's series published figure is 7.71 $grCO_2$ pkm^{-1}. This value of this factor is based on a passenger-km weighted average of the emission factors for the Eurostar London-Brussels and London-Paris routes and the emission factors for electricity (in $kgCO_2$ per kWh) for the UK and France/Belgium journey sections. However, Defra/DECCGHG Conversion Factors differ from the above factor as they are calculated using the individual conversion factors as specified by each electricity supplier across each network section upon which they operate, rather than the grid average. According to the Baseline energy statement (2007) of Association of Train Operating Companies the amount of CO_2 emissions per pkm is 74 gr. This amount is based on that a diesel train consumes 0.0276 litres per passenger km and the produced CO_2 emissions are 2695 gr $litre^{-1}$.

The length of the infrastructure of the rail line Thessaloniki - Alexandroupolis is 440 km and contains 72 railway stations.

For the estimation of carbon emissions, the following

Table 7. CO_2 emission factors per passenger km proposed in different sources.

	$grCO_{2e}$ pkm^{-1}
Department of Energy and Climate change, 2010 Guidelines to Defra (UK)	15.1 (international rail) 56.5 (national rail) 77.3 (light rail systems)
International Union of Railways-UIC (France)	5.7–42.9
Association of Train Operating Companies	74

assumptions have been made:

- The whole line is divided into smaller sections (Li) (from station to station), where their length and the average gradient of the vertical alignment are known.
- Delays (the average speed is reduced in some sections, due to the presence of narrow curves or other factors) are not taken into account.
- The journey is considered as non- stop.
- Passenger trains are hauled by ADtranz locomotives, which have two MTU engines of 1050 kw power each.

The simplified equation of fuel consumption is given by Eq. (1), whereas Eq. (2) presents the relation between the engine power and the number of rotations.

$$fc = 0.2378 \times e^{0.0021 \times U} \tag{1}$$

$$U = 467.85 \times \ln(P) - 1459 \tag{2}$$

where,
U: the number of motor rotations (600–800 rpm);
f_c: fuel consumption (kg min^{-1});
P: power.

The journey's average speed is defined 60 km h^{-1}. Due to the lack of international data concerning the response of the motor in relation to the speed and the average gradient of line, the following assumptions are being made: Motor's charge is assumed to be 100% (the whole power) when the average speed is 60 km h^{-1} and the average gradient is +3,5%, whereas it is assumed to be 25% when the average speed is 60 km h^{-1} and the average gradient is 0%.

According to Eq. (3), the factor of motor's charge is estimated in relation to route's gradient whereas the required power P(i) for the development of a speed of 60 km h^{-1} at each section is given by Eq. (4).

$$\varphi(\%) = 0.25 + 0.75 \times \frac{i}{0.035} \tag{3}$$

$$Pi(KW) = 1050 \times \varphi(\%) \tag{4}$$

Subsequently, the total fuel consumption (fc,tot) is given by Eq. (5).

$$fc.tot = \sum_{i=1}^{n} \frac{Li}{V} \times 0.2378 \times e^{0.982485 \times \ln(Pi) - 3.2529} \tag{5}$$

where
n: the number of traffic sections;
Li/V: running time along each section.

Applying Eq. (5), that the total fuel consumption is estimated at 1371 lt diesel, which corresponds to a consumption rate of 3.12 lt km^{-1}.

In the railway line Thessaloniki - Alexandroupolis, the train set composed of five wagons, where each one has a capacity of 75 seats, operates on this specific corridor every day. The route's length is 440 km and the average train's transport capacity occupancy is 75%, namely 280 passengers make this trip every day. According to engine's characteristics, CO_2 emissions are estimated at 3.06 kg lt^{-1} or 4195 kg for the whole route of 440 km or 34.05 $grCO_2$ pkm^{-1}, expressing this value in passenger kilometers.

Freight trains are hauled by electric and diesel locomotives, but the vast majority is diesel trains. According to 2010 Defra/DECCGHG Conversion Factors the rail freight emission factor is 31.6 $grCO_2$ tkm^{-1}.

In the railway line Thessaloniki - Alexandroupolis, a freight train is hauled by a locomotive MLW500, which has a sixteen-cylinder engine of 3100 HP. Data relating the motor response with the maximum hauled load, the truck gradient and the commercial speed are provided by the manufacturer.

For emissions estimates, the following assumptions have been made:

- The whole line is divided into the same smaller sections (Li) where their length and the average incline of the vertical alignment are known.
- Commercial speed is defined in relation to the vertical alignment's gradient and the engine's potential. The maximum permitted speed in each section is 80 km h^{-1}.
- The train's hauled load is 1000 tn
- MLW's maximum fuel consumption is 0.349 gal HP^{-1} h^{-1}
- Engine's power is 3100 HP.
- Special fuel consumption is estimated at 0.349 × 3100/1.9 = 569.4 lt h^{-1}

Following base assumptions, the total fuel consumption (fc'.tot) is given by the following Eq. (6),

$$fc'.tot = \sum_{i=1}^{n} e \times \varphi \times P \times Li / Vi \tag{6}$$

where
n: the number of track sections;
e: special fuel consumption (lit HP^{-1} h^{-1});
φ: the factor of motor's charge (φ = 1000 tn $Fmax^{-1}$);
Fmax is estimated for each track section by figure, where gradient and speed are known;
Li/V: travel time at each section.

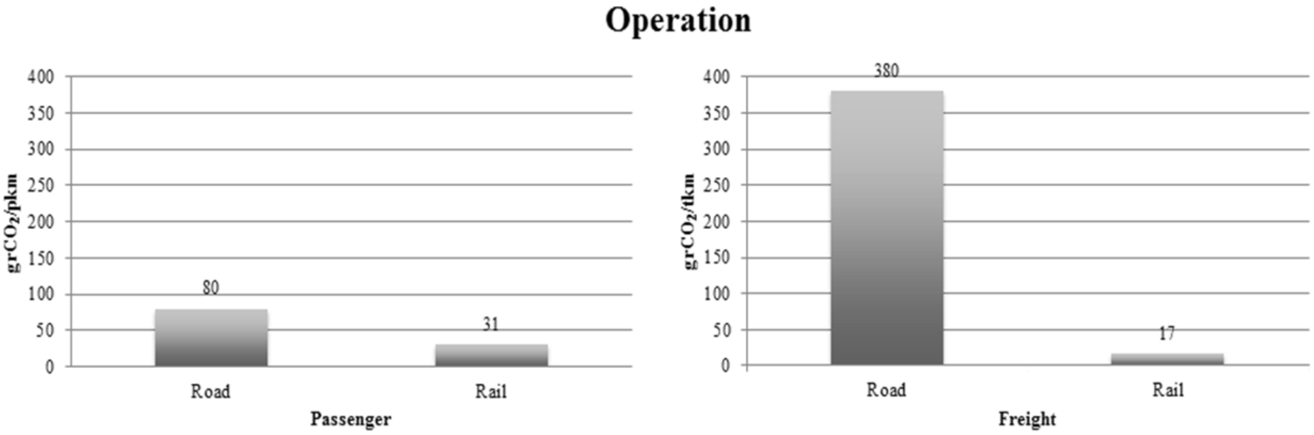

Fig. 3. Comparison of CO_{2e} emissions from road and rail operation in the axis Thessaloniki - Alexandroupolis (Greece).

Applying Eq. (5), it is estimated that the total fuel consumption is 2683 lt diesel and the total estimated emissions are 8210 kg CO_2.

A freight train with maximum load 1200 tn runs every day on the railway line Thessaloniki - Alexandroupolis. Total CO_2 emissions for the whole route of 440 km are estimated at 16.96 $grCO_2$ tkm^{-1}.

In Fig. 3, the estimated amount of CO_2e from road and railway operation in the axis Thessaloniki - Alexandroupolis is presented.

CONCLUSIONS

The results from the comparison of the road and rail transport systems highlight many interesting issues. The present study shows that the environmental impact due to the highway construction is smaller than that of the railway construction. However, the railway system operation is more environmentally friendly than the highway system operation.

Carbon footprint analysis would provide tools for sustainable development of infrastructure construction as well as deciding on alternate models of construction. The choice of materials and techniques in transport construction is dictated not only by structural requirements and economic aspects but also by environmental factors that have also gained in importance due to ecological considerations in politics and society.

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