Energy Consumption and Carbon Dioxide Emissions of a Suburban Coastal Transport System

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ENERGY CONSUMPTION AND CARBON DIOXIDE EMISSIONS OF A SUBURBAN COASTAL TRANSPORT SYSTEM

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ABSTRACT. This paper explores energy consumption and carbon dioxide (CO_2) emissions of a coastal transport system envisioned as a substitute for road transport. Past work investigating the economics of coastal passenger transport via high-speed small passenger dolphin-type ferries has shown that the most profitable sea itinerary is achieved when fewer mid stops and the highest ticket price is applied. Road and maritime distances, fuel consumption and CO_2 emissions were calculated for typical passenger cars and marine vessels. Although a ferry is a massive consumer of energy and emitter of CO_2 compared to a single passenger car, the capacity of a ferry is much larger. The reduction that must be achieved in the number of cars per ferry trip in order to overcome the increase in CO_2 emissions due to the ferry was estimated for various occupancy levels up to a capacity of 250 persons. Depending on the number of mid stops, high occupancy levels of the ferries must be achieved in order to realize a negative CO_2 contribution to the atmosphere.

INTRODUCTION

Transport is responsible for one fifth of worldwide energy use (Ortmeyer and Pillay, 2001) and one third of final energy consumption in the European Union (Beggs, 2002). After electricity generation, the transport sector is the most rapidly developing sector regarding energy consumption and carbon dioxide (CO_2) emissions, composing about 20% of global CO_2 emissions (Ellis and Treanton, 1998). The main cause of this increase in energy use is growth in road transport (European Environment Agency, 2001). In 1997, road energy consumption was about three fourths of the total for the transport sector (Ortmeyer and Pillay, 2001) and, in 1998, road transport accounted for 84% of emissions (Mourelatou and Smith, 2002). Passenger transport in particular, increased by an average 2.8% annually between 1970 and 1997 (European Environment Agency, 2001) and, in 2004, about 84% of total passenger kilometers were performed by road, namely by passenger cars, powered two wheelers, buses and coaches (Eurostat, 2007). Passenger cars expanded their share of passenger transport from about two thirds in 1970 (European Environment Agency, 2001) to about three fourths in 2007 (Eurostat, 2007). Today, a typical European Union citizen travels 36 km daily, 27 of which in a car (Eurostat, 2007).

The growth rate of maritime transport between 1990 and 2000 was estimated at about 2.5% per year (Kageson, 2001) and now accounts for approximately 2% of global anthropogenic emissions of CO_2 (Eurostat, 2002). About two thirds of European Union's boundaries face the sea and its network of numerous ports formulate "motorways of the sea" and constitute a valuable alternative to land transport (Eurostat, 2007). Short sea shipping in particular is the only intermodal mode of transport that keeps pace with the fast growth of road transport. Within the EU, maritime passenger transport between 1970 and 1995 increased by 107.6%

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reaching 27 Mpkm, although its share remained equal to about 0.5% of total demand for passenger transportation. Passenger transport by sea in the European Union is particularly high in Denmark (8954 passengers per 1000 inhabitants), Greece (8720 passengers per 1000 inhabitants), Croatia (5090 passengers per 1000 inhabitants), Estonia (4782 passengers per 1000 inhabitants), Sweden (3705 passengers per 1000 inhabitants) and Finland (3215 passengers per 1000 inhabitants) with all other countries having less than 1500 passengers per 1000 inhabitants (2004 data; Eurostat, 2006). Most passenger ferry lines are offered by main seaports. The highest number of main sea ports in Europe are found in the United Kingdom (46) and Italy (43) while the lowest in Bulgaria (2), Malta (2), Lithuania (1) and Iceland (1). Greece possesses 26 main seaports with Piraeus being the top ranking port in the country. Many of these ports along with their suburbs, such as Piraeus, are areas of concentrated economic activity with corresponding high demand for transportation most of which is fulfilled with traditional means (mostly passenger car and public transportation).

Sambracos (2000 and 2001) explored the economics of an interesting albeit unusual option of providing coastal passenger transport in the Piraeus area of Greece via high-speed small passenger ferries and showed that the most profitable sea itinerary was achieved when fewer mid stops and the highest ticket price were applied. This work estimates and compares the environmental impact (i.e. energy consumption and CO_2 emissions) of the proposed coastal transport system to those of the traditional road link.

BACKGROUND

CO_2 emissions constitute the majority (81%) of greenhouse gas (GHG) emissions of Greece, with the the transport sector accounting for 21% of total carbon dioxide (CO_2) emissions (Lalas et al, 2002). Transport CO_2 emissions and their increase are primarily attributed to road transport since emissions from railways and air transport are much smaller and remained constant during the 1990s. The Athens wider metropolitan area (Attica prefecture) is a huge urban conurbation that is permanent residence of over 4 million people (in a total population of about 11 million) and is located in a basin of approximately 450 km^2 surrounded by low mountains and the sea (Saronic Bay) to the south west (Mantis et al., 2005). Latest statistical data of the National Statistical Service of Greece (ESYE) show that, in 2005, the Greek private car fleet consisted of about 4.3 million passenger cars, half of which (2.2 million) belong to the Athens metropolitan area. Car ownership has increased from below 30 cars per 100 people in 1990 to 66 cars per 100 people in 2005. Travel times have increased by 26% in the last 12 years which, along with the insufficient urban road network in the central areas, has led to a deterioration of traffic conditions in the capital (Golias, 2002) with very long travel times (Stathopoulos and Karlaftis, 2003). The ever increasing rates of vehicle ownership, especially around Athens, lead to even more serious congestion and environmental problems (Kourtidis et al. 1999; Kamarianakis and Prastacos, 2005; Kassomenos et al. 2006). What is more important, passenger car ownership in Greece is projected to increase to almost 50 cars per 100 people by 2010 (Paravantis and Georgakellos, 2007) and fuel consumption and CO_2 emissions will follow suit (Ntanos, 2004).

Greece has 59 main ports which handle over 80% of total cargo traffic (Eurostat, 2003). Piraeus, the main passenger port, is the second biggest municipality in Attica (after Athens), and constitutes the place of residence of about half a million people. As a large urban area and the largest port of Greece, Piraeus attracts many people from the suburbs for purposes of work, leisure, and sea travel. Until now, the only possible way to move from Piraeus to the coastal suburbs has been the existing coastal road, a major three lane per direction seashore drive.

Unfortunately this drive suffers from severe congestion, mostly from private car traffic; this has been exacerbated by the fact that a tram track is situated next to the road oftentimes narrowing its cross section. As a result, the usual time of private car travel for a distance of about 20 km (for example from the city of Pireaus to the Vouliagmeni resort) often exceeds one and a half hour.

Although suburban coastal systems are quite uncommon, there exist systems that have been used with success e.g. the Bluewater Network in New York (Bluewater Network, 2003). Several feasibility studies are currently investigating RO–RO fast ferries and high-speed ferries serving a dual role of passenger service during the summer months and freight transport during the winter, a trend that is likely to continue as demand for shorter transit and delivery times is ever present (Cooper, 2001). Sambracos (2000 and 2001) looked into the economics of passenger transport from and to Piraeus via high-speed small passenger ferries; the number of stops, number of ships and ticket price were examined. Sambracos notes that an economic viability analysis for such a maritime suburban transport system between Piraeus and the coastal suburbs has already been performed by the Greek Bank of Industrial Development in 1995. The only criterion of Sambracos' analysis was the maximization of total profit of the investment, considering possible loan levels; it was concluded that the optimum economic solution is accomplished when the smallest number of mid stops (i.e. one) and the higher ticket price level are applied.

In this paper, the proposed system of coastal passenger transport for the port of Piraeus is assessed from an environmental perspective. Energy consumption and CO_2 emissions of a typical coastal shipping system are estimated and compared to those of the traditional road link with the objective of testing whether the coastal shipping alternative, which may help to alleviate traffic congestion, is also friendlier to the environment than private cars.

METHODOLOGY

The stated goal of this research is to compare the existing system of passenger transportation via private cars for the coastal driveway of Piraeus against a hypothetical passenger transportation system via high-speed sea vessels from an energy consumption and GHG emissions perspective. To achieve this objective, the authors break down the work into the following steps:

1. Road and sea distances between areas of interest are calculated.
2. Fuel consumption and CO_2 emissions for private car transportation are estimated.
3. A typical high-speed sea vessel is assumed and fuel consumption and CO_2 emissions for the routes proven economically viable by Sambracos (2000 and 2001) are estimated.
4. The authors then compare the two systems in terms of energy consumption and CO_2 emissions. The authors also calculate the minimum number of passengers per ship (i.e. loading factor), required in order to realize an environmental benefit in terms of CO_2 emissions.
5. Finally, exogenous benefits from the use of such a system are discussed.

The MS Autoroute software package (MS Autoroute, 2001) was utilized to draw maps and estimate distances and SYSTAT (version 10.2), a general purpose statistical package was used for graphing.

RESULTS

Analysis commences with the calculation of distances for road and sea routes to be studied.

Calculation of distances

The southwestern coastline of Attica includes many urban and suburban municipalities that may generate demand for a coastal sea transport system. These locations constitute places of residence for an important part of the population of Attica and include the City of Piraeus, the port of Zea and the coastal suburbs of Paleo Faliro, Kalamaki, Elliniko and Glyfada that define the study area for this analysis. Most trips are generated in Piraeus and have a destination in any of the other four cities (or vice versa). The existing road link (Poseidonos Avenue) among these locations is shown in Figure 4 (thick gray line).

Although there exist numerous alternative combinations of sea routes and intermediate stops between origins and destinations that a system of marine transport could employ (assuming that demand is generated at all locations), several of these routes may in fact be excluded from the analysis because Sambracos (2000 and 2001) has shown that more intermediate stops require a greater number of ships, increase the total cost of the system and thus make the coastal transport system more inefficient and less attractive compared to the road transport alternative. Furthermore, Sambracos argues that the biggest demand for sea transportation exists between Pireaus and Glyfada.

The most profitable scenarios of the Sambracos studies concern two, one or zero intermediate stops. Maps of the study area with sea routes corresponding to these most profitable scenarios are presented in Figures 1, 2 and 3 correspondingly. The distance of each leg of the trip is also indicated at the end further away from Piraeus.

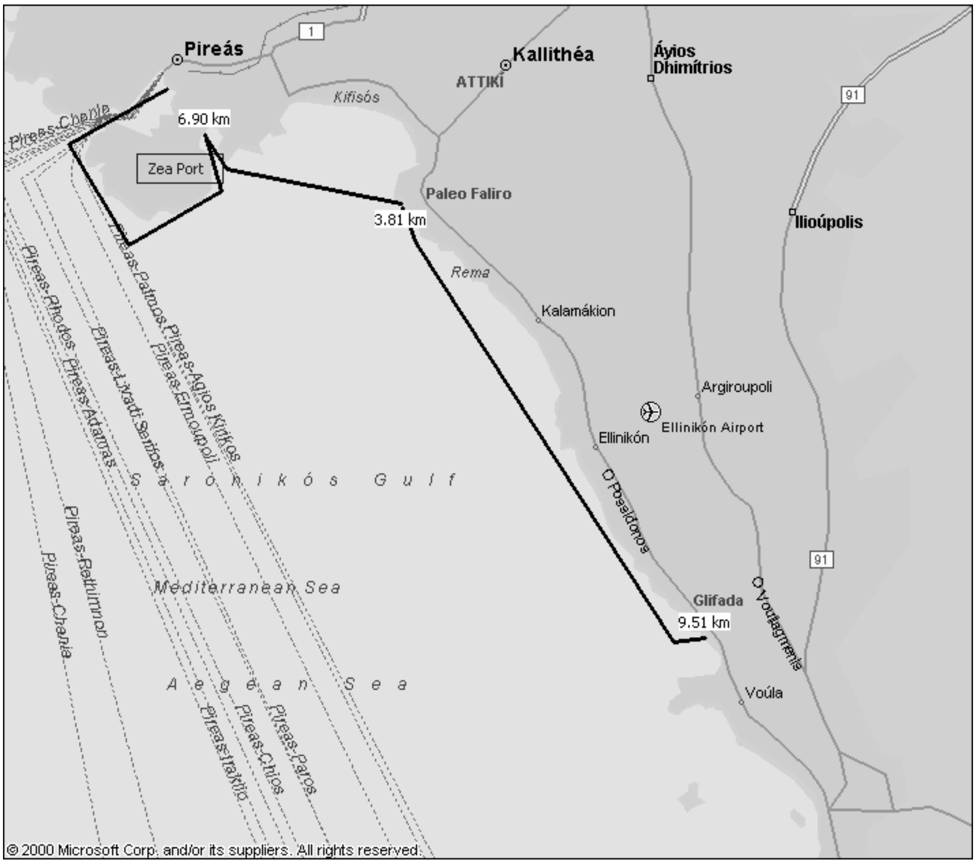

Figure 1. Proposed sea route with 2 mid stops (Pireaus – Zea - P.Faliron -Glyfada)

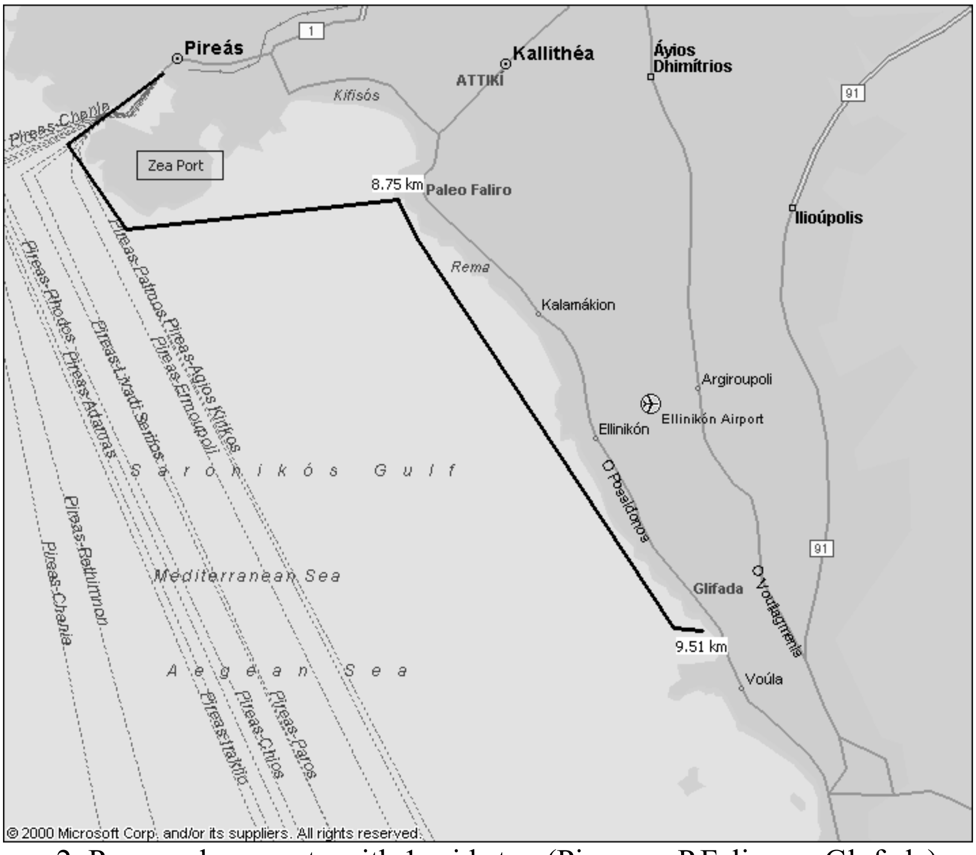

Figure 2. Proposed sea route with 1 mid stop (Pireaus - P.Faliron – Glyfada)

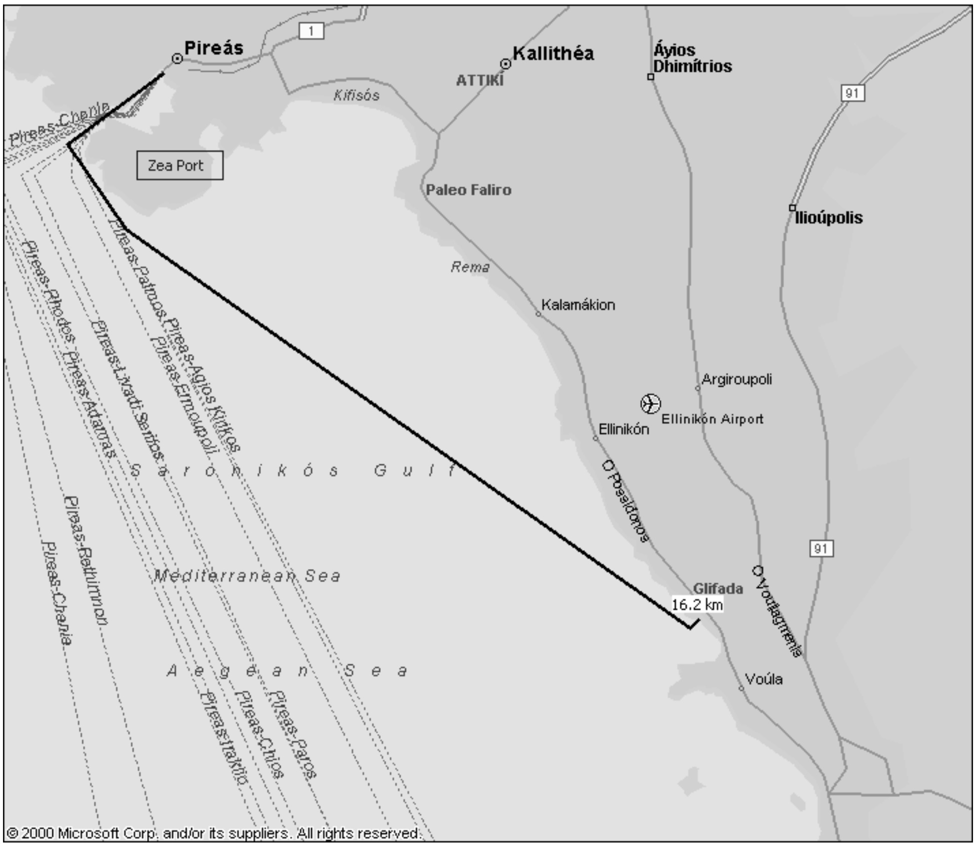

Figure 3. Proposed sea route with no mid stops (Pireaus – Glyfada)

While estimating the length of alternative sea routes, it was found that overall distance increases as more intermediate stops are added to the system, an effect caused by the geographical configuration of the harbors (as shown in Figures 1, 2 and 3). Alternative scenarios, number of mid stops and total trip length are listed in Table 1.

Table 1. Most profitable sea route scenarios, mid stops and distance.

Scenarios	*Route*	*Number of mid stops*	*Naval distance (km)*
1	Piraeus - Glyfada	0	16.2
2	Piraeus - Palaio Faliro - Glyfada	1	18.26
3	Piraeus -Zea - Palaio Faliron - Glyfada	2	20.22

It is noted that sea distance between Piraeus and Glyfada varies from 16.2 km (no mid stops) to a 20.22 km (with mid stops at Zea and Paleo Faliro).

In comparison, Figure 4 shows the existing road system between Piraeus and Glyfada with a total distance estimated at 15.5 km.

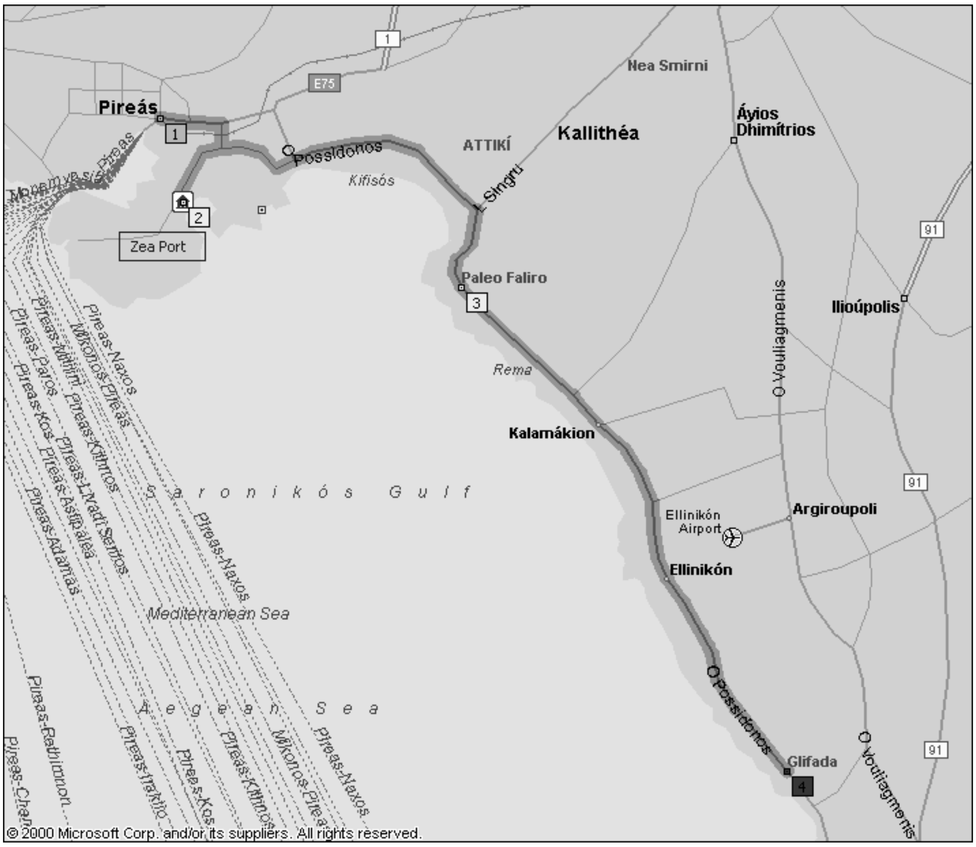

Figure 4. Proposed road route (Pireaus – Zea - P.Faliron -Glyfada)

It is clear that traveling by sea is longer than by road, because of the geographic configuration of the Saronikos bay and the location of the harbors of Piraeus and Zea that access to them somewhat laborious (as shown in Figure 1). Although this is a disadvantage of the marine alternative, as it will become evident later in this work, it is compensated by the higher mean speed that the ships may develop compared to passenger cars traveling in congested conditions.

Fuel and emissions for private car transportation

In the next step, fuel consumption and CO_2 emissions for the road transport alternative are estimated.

As mentioned before, the Piraeus-Glyfada road trip represents a distance of 15.5 km and is shown in Figure 4. In order to estimate energy consumption and CO_2 emissions over than trip, the authors assumed a mean speed of 25 km/h, a value consistent with the movement of a passenger car in congested conditions. The average consumption of a typical new three-way catalyst car (1400 cc) has been estimated to be about 90 gr/km (Andre and Hammarstorm, 2000). Converting gr/km into liters per km (L/km) via the ratio mentioned in Environment Canada (2003), an average gasoline consumption of 0.123 L/km is obtained.

Total fuel consumption for a trip traveled by a specific transport medium may be calculated in a simple manner as in Schipper and Marie-Lilliu (1999):

$$TFC_i = d \times SFC_i \quad (1)$$

where

TFC_i total fuel consumption of transport medium i (liters or L)
d total distance between origin and destination (km)
SFC_i specific fuel consumption of transport medium i (L/km)

and the medium refers to either passenger cars or passenger ships.

By substituting for d (15.5 km) and the SFC of a typical passenger car (0.123 L/km), TFC_{car} of a single passenger car is found to be equal to 1.907 L.

Next, based on fuel consumption, the authors estimate carbon dioxide emissions per car trip. The CO_2 emission factor equals about 2400 gr CO_2 per liter of gasoline burned by a typical car, as calculated from 2002 data of the Association of Motor Vehicles Importers. The total CO_2 emissions of a single car for the trip, may be calculated as follows:

$$TCDE_i = TFC_i \times CDEF_i \quad (2)$$

where

$TCDE_i$ total CO_2 emissions from transport medium i (gr)
$CDEF_j$ CO_2 emission factor for fuel j (gasoline or diesel) (gr CO_2/L)

and fuel refers to either gasoline (in the case of cars) or diesel (in the case of ships). By multiplying TFC_{car} with the CO_2 emission factor of gasoline, $TCDE_{car}$ is found equal to 4.577 kg CO_2.

Fuel and emissions for high-speed ferry transportation

In the context of this analysis, the authors disregard the effect of cargo weight and vessel stops of fuel consumption and proceed to calculate carbon dioxide emissions based on emission factors (Cooper, 2001).

A ferry vessel is selected for coastal transport, of the flying dolphin type mainly because of its high speed and small dimensions (MTU Friedrichshafen, 2007). An emission factor of 2698.74 gr CO_2 per liter of diesel is estimated, based on the value of 3200 kg/t of diesel reported by Kesgin and Vardar (2001). Vessel characteristics are presented in Table 2.

Table 2. Specifications of the chosen high-speed ship

Characteristic	*Value*	*Measurement units or type*
Number of engines	4	MTU Friedrichshafen
Power	788	KW
Total power	3152	KW
Fuel consumption	209	gr/KWh
Passenger capacity	250	Passengers
Average speed	30	Knots
Average speed	55.56	km/h
Fuel consumption (per time)	778.68	L/h
Fuel consumption (per distance)	14.01	L/km
CO_2 emission factor	2698.74	gr/L of diesel
Diesel density	0.846	kg/L

According to Table 2, the average speed of the selected ferry is 30 knots, equivalent to 55.5 km/h, while its fuel consumption per distance (i.e. specific fuel consumption) achieved under the specified average speed equals 14.01 L/km. Using these values with equation (1), the authors calculate total fuel consumption of a single ferry trip for each of the three sea-route scenarios and compare the results in Figure 5.

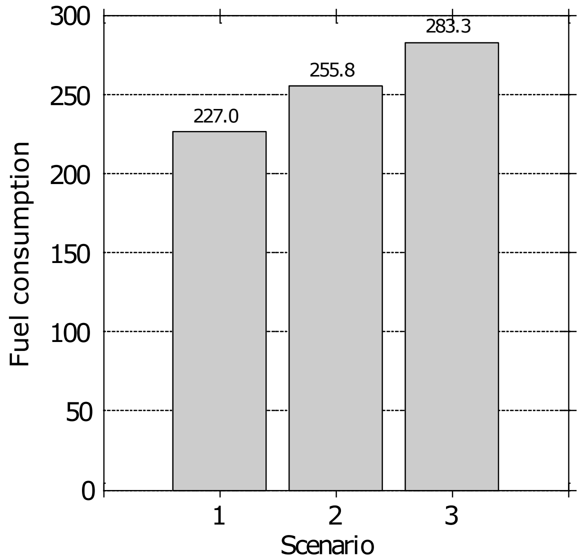

Figure 5. Total fuel consumption of the passenger ferry per trip and scenario

Based on fuel consumption, the authors use equation (2) to calculate carbon emissions of a single ferry trip for each of the three sea routes and tabulate the results in Table 3.

Table 3. High-speed passenger ferry, fuel consumption and CO_2 emissions per trip for the three alternative scenarios

Scenarios	Fuel consumption per trip (L)	Ship emission factor (gr CO_2/l)	Total emissions per trip (kg)
1	227.0	2698.74	612.51
2	255.8	2698.74	690.40
3	283.3	2698.74	764.51

Environmental evaluation of the two transportation systems

The authors are now in a position to compare the two alternative transportation systems, car versus ferry, using the criterion of CO_2 emissions per trip. This is appropriate because fuel consumption figures are not directly comparable (in terms of environmental impact) since different types of fuel are used by each transportation system (cars use gasoline while ferries use diesel). Incidentally, it is assumed that total travel demand remains at its previous level even after the introduction of the sea transport system.

Compared to a single passenger car, a ferry is a massive consumer of energy and emitter of CO_2 (Table 3); on the other hand, the capacity of a ferry is 250 persons (Table 2), much larger than that of a car. One goal of this research is to calculate the reduction that must be achieved in the number of cars per ferry trip (due to car users shifting to ferries), in order to overcome the increase in CO_2 emissions due to the ferry.

To do this, the authors calculate the number of cars that correspond to different occupancy levels of the ferry. Occupancy values are grouped into 25 classes of 10 persons each (up to the maximum occupancy of 250) and the number of cars that may be substituted at each occupancy level is calculated. In order to do this though, one must have data on average vehicle occupancy. In a recent study, the mean vehicle occupancy for the area of Athens was found to be around 1.4 persons per vehicle, excluding trips for vacation purposes (Ntanos, 2004). Utilizing this value, the authors calculate the number of cars that may be substituted at each occupancy level for a single ferry trip and then estimate the total CO_2 emissions into the atmosphere in order to arrive at an optimum ship occupancy level. For instance, the total number of cars that correspond to a ship occupancy of 250 persons is 179 (at a vehicle occupancy of 1.4). The number of cars that correspond to each occupancy level of the ship are similarly calculated.

Because the road trip distance between Piraeus-Glyfada is fixed at 15.5 km, fuel consumption and CO_2 emissions by cars remain constant. On the other hand, since sea distance increases with the number of mid-stops, total ship fuel consumption and CO_2 emissions increase from one scenario to another. Total CO_2 emissions at each occupancy level of the ferries for both road and ship transport are calculated thus, assuming that users that board ferries do not use cars anymore. It is also assumed that a ferry emits a fixed amount of CO_2 regardless of the number of passengers on board.

Figure 6 graphs total CO_2 emissions, released into the atmosphere when the two alternate transportation systems (passenger cars and ferry) are used simultaneously.

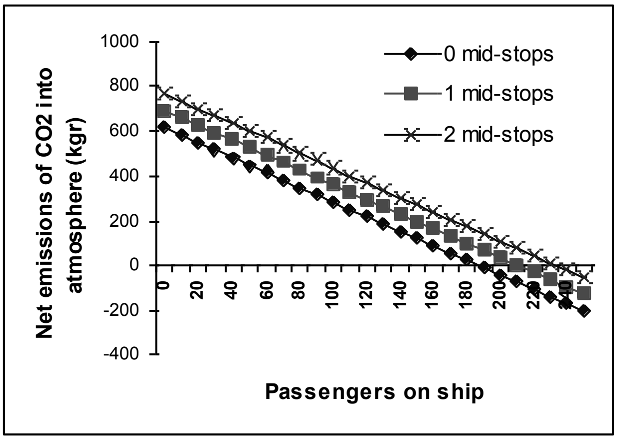

Figure 6. Emissions that are added or avoided at different ship occupancy levels and number of mid-stops as car trips are replaced by ferry tripe (negative values indicate mean reduction in the CO_2 released to the atmosphere).

It may be noted for example, that when a ferry makes the trip with two mid stops but zero occupancy (i.e. no passengers board the ferry), an additional 765 kg of CO_2 are emitted; on the other hand, if the same trip is made at full ship occupancy, around 52 kg of CO_2 emissions are in fact avoided, in other words forgoing the use of 179 cars (that would transport 250 persons) leads to a smaller volume of CO_2 emissions.

It is easily understood that high occupancy levels of the ferries must be achieved in order to realize a negative CO_2 contribution to the atmosphere, i.e. a large number of passengers must decide to switch from passenger cars to ferry. One may also observes that the increase in the number of intermediate stops makes sea transport consume more energy because of the increase in overall distance. The authors note that the target ship occupancy is set at quite a high value for the scenario of 2 mid stops (i.e. at least 234 to realize a benefit in CO_2 emissions); on the other hand, the zero mid-stop scenario requires a minimum occupancy of 188 persons (75% occupancy), in order to start realizing a benefit in total CO_2 emitted to the atmosphere.

Clearly, the challenge is to make ferries a more attractive medium by offering a ticket price low enough for passengers to decide to switch to ferries. Given that fuel cost for the road trip is more that 1.5 euros if a car is used (assuming a consumption of 1.906 L per trip), the ferry ticket price must be (significantly) less than that for people to switch. Naturally, a ferry of capacity 250 that consumes diesel is much cheaper to operate than 178 cars using gasoline that would be required to transport the same number of people. Ferries are also faster because of their higher average speed especially when there are zero or one mid stop(s). The average speed of the selected ferry is 30 knots (or 55.5 km/h) while the average speed of cars is 25 km/h (due to congested conditions). This means that a ferry can perform the trip between Piraeus and Glyfada in 18.7 minutes, while a car requires 37 minutes. Thus, for a 12-hour test period, a high-speed ferry can perform 38.5 trips while the car only 19.4.

CONCLUSIONS AND RECOMMENDATIONS

In this work, the authors calculated fuel consumption and CO_2 emissions for transportation by (a) passenger cars and (b) high speed ferries for the Piraeus-Glyfada route. It was found that with fewer mid stops and high occupancy rates, ferries achieve a net reduction in CO_2 emissions.

The importance of this analysis may be put into the proper perspective if one considers that the burden sharing agreement for 6 GHG emissions from EU member countries that was finalized in June 1998 at the Environment Council, set the upper limit for Greece at +25% compared to 1990 emission levels. Such emission saving measures may prove to be important in helping Greece control CO_2 emissions successfully and meet its target.

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