Journal of
Marine Science and Engineering

MDPI

Article

Emphasis on Occupancy Rates in Carbon Emission Comparison for Maritime and Road Passenger Transportation Modes

Josip Dujmović [1,*], Tomislav Krljan [1], Nikola Lopac [1,2] and Srđan Žuškin [1,2]

[1] Faculty of Maritime Studies, University of Rijeka, Studentska 2, 51000 Rijeka, Croatia; tomislav.krljan@uniri.hr (T.K.); nikola.lopac@pfri.uniri.hr (N.L.); srdan.zuskin@pfri.uniri.hr (S.Ž.)
[2] Center for Artificial Intelligence and Cybersecurity, University of Rijeka, 51000 Rijeka, Croatia
* Correspondence: josip.dujmovic@pfri.uniri.hr

Abstract: Carbon emissions generated by the transportation sector represent a large part of total greenhouse gas emissions and are thus subject to various policies and initiatives for emission reduction and the development of sustainable transportation networks. Furthermore, passenger transportation generates a significant amount of emissions within this sector, especially in those countries with large and developed tourist sectors. Examples of such countries are Italy and Croatia, located in the Adriatic region, with a large portion of passengers between them being transported utilizing mainly maritime and/or road transportation modes. A proper analysis of the impact of these transportation mode choices on carbon emissions is essential to enable the selection of the optimal transportation mode for the particular transportation route with respect to the generated emissions. Therefore, this study determines the carbon emissions of the maritime and/or road transportation modes on the existing cross-border passenger transportation routes between Italy and Croatia. For the analysis, the Adriatic region was divided into three sections—the Northern, Middle, and Southern regions—each characterized by specific transportation routes defined by geographical features and distances. The results obtained from this research are presented as total carbon emissions for each transportation mode separately, based on each of three chosen routes in different regions. In addition, a carbon emission comparison between each transportation mode in regard to occupancy rate is performed and presented separately for each chosen route based on its specific distances, transportation means, and features. Finally, by providing an analysis of the existing state, this study can serve as a basis for Italy–Croatia cross-border passenger mobility network modernization and the introduction of new, sustainable, and multimodal transportation routes.

Keywords: carbon emissions; occupancy rates; passenger mobility; transportation mode choice; maritime transportation; road transportation

check for updates

Citation: Dujmović, J.; Krljan, T.; Lopac, N.; Žuškin, S. Emphasis on Occupancy Rates in Carbon Emission Comparison for Maritime and Road Passenger Transportation Modes. *J. Mar. Sci. Eng.* **2022**, *10*, 459. https://doi.org/10.3390/jmse10040459

Academic Editor: Mihalis Golias

Received: 4 March 2022
Accepted: 22 March 2022
Published: 24 March 2022

1. Introduction

Between 2013 and 2019, greenhouse gas (GHG) emissions from the European Union's (EU) transport sector increased steadily from 773 to 835 million tons of CO_2 equivalent (Mt CO_2e), representing an increase of 8% [1]. This trend differed significantly from other sectors in the same period [1]. The transport sector causes above 30% of the EU's total GHG emissions, with road transport constituting the highest proportion of the total GHG transport emissions (71.7%) in 2019 [1]. The majority of this percentage in 2019 was attributed to passenger cars (44.3%) [2]. Thus, the most of road transport emissions can be attributed to passenger transportation [3]. Therefore, passenger transportation is responsible for a large portion of total carbon emissions, particularly in countries with large tourist sectors [1]. Typical examples of such countries are Italy and Croatia, located in the Adriatic region. Namely, a total of 17.5 million tourists arrived in Croatia in 2019, with about 1.175 million tourists coming from Italy [4]. Most of these passengers were transported by the existing cross-border routes, utilizing maritime and road transportation modes.

The impact of passenger transportation on carbon emissions is visible from the data provided by the European Environment Agency (EEA) for the period between 2014 and 2018 [5], where the average GHG emissions generated by the motorized passenger transportation mode were 143 g/passenger-kilometer (pkm) for personal cars, 80 g/pkm for public buses, and 61 g/pkm for the maritime transportation mode. If only these data were considered, the maritime transportation mode would be expected to be the most favorable transportation mode from a carbon emissions standpoint. On the other hand, according to the same criteria, personal car-based transportation would represent the least favorable transportation mode choice.

The impact of vessel fuel consumption on emissions is defined within the International Maritime Organization (IMO) guidelines [6,7]. Moreover, the influence of the optimal vessel route on emissions was discussed in a study by Mannarini et al. [8], with the route being selected based on geographical and topological features. In addition, the influence of vessel speed on fuel consumption and consequently on carbon emissions was addressed in the work of Dagkinis et al. [9]. On the other hand, the emission factors for the road transportation modes were defined within the methodology paper from the Department for Environment, Food and Rural Affairs (DEFRA) [10]. Furthermore, an analysis of carbon emissions from the Croatian RO-RO fleet was provided in a study by Ančić et al. [11], while the emissions from the personal car-based road transportation in Croatia were studied in a paper by Rešetar et al. [12].

Furthermore, the sustainability of maritime and/or road transport plays a central role in the strategy of the European Union within the overall context of the EU's strategic long-term vision, expressed in the document "A clean planet for all" [13]. The general framework of reference stands in the strategic approach to maritime transport of the European Union [14], which is a central part of the Integrated Maritime Policy of the European Union (IMP) [15]. Additionally, the strategic goals of the EU in this field can be found in a series of documents, among which are of particular importance:

- The 2011 White Paper from the European Commission, "Roadmap to a Single European Transport Area" [16], where the general premises are set. Among these are mentioned: the reduction of 40% of maritime transport emissions by 2050 compared to 2005, the simplification of procedures for travelers within the "European Blue Belt", and the enhancement of safety, security, and environmental protection through the SafeSeaNet of the EMSA (European Maritime Safety Agency).
- Communication 2009-8 of the EC [17], which highlights, among the rest: the need to improve environmental performance through incentives and taxation measures, to support actions specifically aimed at greener shipping, technological innovation, the enhancement of short-sea transport services, and the promotion of a European Environmental Management System for Maritime Transport (EMS-MT).
- The "European Green Deal" and its annex [18], which defines the agenda and the roadmap for a set of "deeply transformative policies", specifying a long list of prerequisites and targets that development must abide by in order to be effectively "sustainable", in the sense of increasing the social, environmental, and economic capital of the EU member states. Particularly, the EC strategy for the improvement of the environmental performance of maritime transport (COM2009-8 final) specifically mentions a comprehensive approach to reducing greenhouse gas emissions from international shipping, combining technical, operational, and market-based measures.

The ecological aspect in terms of transport-related GHG emissions varies significantly in each individual transport mode in the cross-border area. Additionally, the carbon-neutral EU requires the decarbonization of all sectors. Furthermore, the European Commission proposed to increase the intermediate target for the greenhouse gas emission reduction for 2030 to 55% in its proposal for the Climate Law, which the European Council officially accepted at the end of 2020 (COM (2020) 80 final) [19].

Nevertheless, the process planning for the function of GHG emission reduction is crucial for multi-stakeholder integration in the cross-border area between Italy and Croatia.

This integration is necessary to overcome the limitations of traditional/circumscribed (e.g., local, regional) transport planning models [20], limitations that mainly consist of assuming a centralized and deterministic (i.e., equilibrium-based) process rather than a political one, which is strongly interrelated with socioeconomic implications [21]. The main approach to the transport planning process for the function of environmental protection includes the following steps: analysis of existing conditions, trend forecasts, identification of current and future demand and supply with possible further needs, prioritization of issues, short- and medium-term action plans, an operational strategy, and a financial plan [22]. This complexity is even greater in the specific case of the Italy–Croatia program, in which aspects of intermodality and multimodality between maritime, coastal, and hinterland competences are involved and in which technological aspects have or might have a significant weight in conditioning development programs [23].

Furthermore, many carbon footprint studies have been conducted with a growing understanding of the importance of climate change and its representation in media and policies. The carbon footprint represents the amount of gaseous emissions related to climate change generated by human activities, including production and consumption. The methods to quantify carbon footprint include a broad spectrum of approaches, ranging from direct carbon dioxide (CO_2) emissions to full life-cycle greenhouse gas emissions expressed in CO_2 equivalents [24,25], such as the analysis of the carbon footprints of nations and the corresponding trends and emission reduction options provided in the study by Sarkodie [26].

Carbon footprint analyses are conducted for different sectors and subsectors of human activities, as well as for specific locations or regions. As elaborated above, the transport sector has a significant impact on total greenhouse gas emissions. Therefore, the calculation and analysis of the transport sector's carbon footprint, as well as the carbon footprint of the different transport modes comprised by it, are critical in planning and implementing initiatives and policies to reduce greenhouse gas emissions affecting climate change. Thus, many studies on carbon footprint calculation in the transport sector can be found in the recent scientific literature [27–31].

The study by Ülker et al. [32] provided a comparative analysis of CO_2 emissions produced by road transport and RO-RO and ferry lines in short-sea shipping in the Marmara Region in Turkey. Yang et al. conducted an analysis of ship emissions based on automatic identification system (AIS) data and localized emission factors for Tianjin Port in China [33], while Zhang et al. studied the real-world emissions of rural vehicles on different types of roads in China [34]. Sun et al. [35] used a long short-term memory network to estimate emissions from conventional- and new-energy buses utilized for public transportation. Angelevska et al. provided a categorization of emission reduction measures and a guidance framework for urban air quality in the Republic of North Macedonia [36]. Obaid et al. calculated emissions using a model combining autonomous vehicles with park and ride and electric vehicle transportation policies [37].

Furthermore, a comparative analysis of the emissions produced by maritime and land passenger transportation routes was conducted in several case studies found in the recent literature. Batur et al. assessed CO_2 emissions from urban motorized passenger transportation in Istanbul, Turkey [38]. A study by Zhang et al. [39] investigated the impact of freight and passenger transportation on environmental pollution in BRICS countries for the period between 1990 and 2018, showing a significantly higher impact of freight transportation. A paper by Brewer [40] assessed the impact of black carbon emissions from transportation on climate change and discussed the related regulatory policies. Fridell et al. considered in their study [41] traffic infrastructure in models for calculating emissions from freight transportation. A study by Anenberg et al. [42] provided an overview of the effects of transportation emissions on global public health. Russo et al. presented a methodological framework for estimating emissions from tourism activities, with the framework developed specifically for the case study of Portugal [43]. A paper by Wang et al. [44] discussed the carbon intensity indicator adopted by the IMO in 2021, emphasizing its shortcomings and proposing the development of more advanced models. Skrúcaný et al. provided a comparative analysis of the energy consumption and GHG emissions from the road, railway, and maritime transportation modes [45]. Rivarolo et al. proposed an algorithm for comparative analysis of traditional and innovative energy systems for maritime applications, with generated emissions as one of the considered parameters in the case studies of a small passenger ship for short routes and a large RO-RO cargo ship [46]. Wanke et al. developed the robust Bayesian stochastic frontier analysis of sustainability efficiency for exploring CO_2 emissions from the Chinese freight and passenger transportation sectors concerning the individual transportation modes, including maritime, railway, road, and air transportation [47]. Fridell provided an overview of the fuel use and emissions in the maritime transportation sector and discussed their environmental impact, regulatory policies, and future developments [48]. Finally, Zis et al. studied the impact of several emission reduction measures in the case study of RO-PAX services employed in short-sea shipping [49].

Several studies on the impact of transportation mode occupancy on produced carbon emissions have also been conducted recently. Kang et al. studied the implementation intention of the drivers of single-occupancy vehicles to adopt high-occupancy public bus transport to reduce GHG emissions [50]. A study by Shiraki et al. [51] addressed the impact of vehicle occupancy on CO_2 emissions from private cars in Japan, suggesting the improvement of fuel efficiency and the increase in vehicle occupancy through ridesharing and proper vehicle sizing to be the critical factors in emission reduction. Soukhov et al. assessed the impact of vehicle occupancy on GHG emissions based on the case studies of alternative and traditional transportation technologies, including buses and passenger cars, showing the advantages of using alternative energy sources, public buses, and car-sharing approaches [52]. Amatuni et al. assessed the impact of car-sharing services on GHG emission reduction using an upgraded model that showed more modest values (3–18%) of the life cycle emission reduction than those previously reported [53]. A review paper by Fernando et al. [54] provided a detailed insight into various recent studies on the impact of adopting car-sharing mobility on GHG emissions, comparing these services to private cars and showing reductions in GHG emission of 11-25% for car-sharing, 1-10% for taxis, 50% and more for ride-sourcing, and 26-75% for car-pooling. Chergui et al. investigated the relationship between vehicle occupancy and the aggregate emission rate to obtain an objective function that could be used in optimization problems [55].

Moreover, several studies on carbon emissions from maritime transportation in the Mediterranean region have been conducted recently. Manarini et al. presented a case study of optimizing routes of a medium-size RO-PAX ship in the Adriatic Sea to reduce carbon emissions [8]. Schembari et al. investigated the impact of the European directive on ship emissions on air quality in several Mediterranean harbors [56]. Pseftogkas et al. applied a new lane separation methodology for the maritime transportation emissions in the Mediterranean and Black Sea regions [57]. A paper by Stazić et al. [58] presented an emission inventory of international marine traffic in the Port of Split, the third-largest passenger port in the Mediterranean. Škurić et al. estimated the emissions generated by passenger ferries in the Montenegrin part of the Adriatic Sea called Boka Kotorska Bay [59]. A study by Vidas et al. [60] provided an analysis of the potential measures for CO_2 emission reduction of RO-RO vessels in unprofitable coastline passenger transportation in the Croatian part of the Adriatic Sea. Ančić et al. provided a case study of using alternative power options to reduce carbon emissions of RO-RO passenger transportation along the Croatian coast of the Adriatic Sea [11]. A case study by Degiuli et al. [61] investigated the impact of slow steaming, i.e., sailing at reduced speed, on reducing CO_2 emissions from container ships in the Mediterranean Sea. Finally, Merico et al. provided a comparative analysis of the emissions from maritime transportation in four Adriatic–Ionian port-cities: Brindisi and Venice (Italy), Patras (Greece), and Rijeka (Croatia) [62].

This study presents a methodology to calculate carbon emissions for the maritime and road passenger transportation modes. Subsequently, the presented methodology is tested on the existing cross-border passenger transportation routes in the Adriatic region between Italy and Croatia regarding different unit capacities, distances, and occupancy rates. After an extensive literature overview, we identified a large gap in providing detailed insight into the problem of studying the influence of the occupancy rate θ and choosing an optimal transportation mode in terms of carbon emission efficiency. The results from the research can present a basis for further optimization, introduction, and development of more sustainable, multimodal transportation routes between two cross-border countries.

2. Materials and Methods

The methodology approach to calculate carbon emissions is different for each transportation mode. The main reasons are different technical characteristics and modes of operation, different industry regulations and models for calculating and reporting emissions, and data availability.

2.1. Framework for Calculating Carbon Emissions

The carbon emission calculation for the maritime transportation mode is based on the engine fuel consumption of the reference vessel for the corresponding engine power on the particular route and timetable. Route timetables are based on 2019 data, and the distribution of the vessel operation is determined for each vessel employed on a particular route, as presented in Table 1. The vessel operation distribution is based on the vessel speed calculation and the propulsion machinery load.

Table 1. Operation distribution of a single vessel.

Vessel Operation	Time Period	Relative Period
Navigation $*$ (j_1)	t_1	t_1/S
Port stay origin (j_2)	t_2	t_2/S
Port stay destination (j_3)	t_3	t_3/S
	$S = \sum_{j=1}^{j=3} t_j$	$\sum_{n=1}^{n=3} t_n/S$

* Including maneuvering.

The vessel carbon emission $\xi_{vTotalCO2}$ ($kgCO_2$) is calculated as the product of the F_c and the emission factor (fuel-to-CO_2 conversion factor, $kgCO_2/kg$ fuel) C_f, as defined in [6], for the time period including all vessel operations:

$$\xi_{v(Total)CO2} = C_f \sum_{j=1}^{j=3} F_{ctj} \tag{1}$$

or, in the case that auxiliary engines are not operated during a port stay (operating under "Cold ironing" mode). "Cold ironing" mode is associated with the process of providing shoreside electrical power to a vessel at berth while its main and auxiliary engines are turned off. The mentioned process has two different approaches depending on vessel type:

- If the passenger line is operated by the HSC, "Cold ironing" means that all technical systems on board are turned off.
- If the passenger line is operated by the RO-PAX ferry vessel, "Cold ironing" means that the all engines are turned off, and electrical power must be supplied from shore to vessel with a zero-emission source.

In this case, vessel carbon emission $\xi_{v(wCI)CO2}$ ($kgCO_2$) is calculated:

$$\xi_{v(wCI)CO2} = C_f F_{c_{t1}} \tag{2}$$

In both cases the C_f is taken as 3.206 $kgCO_2/kg$ fuel, as defined in [6]. This value corresponds to the DMA fuel grade, as defined in ISO 8217 [63].

Fuel consumption F_c (kg) for each vessel operation is calculated based on the IMO model presented in [6] and as mentioned in [64,65]:

$$F_{c_{t1}} = \sum_{i=1}^{nME} P_{ME(i)} SFOC_{ME(i)} t_{(j1)} + P_{AE} SFOC_{AE} t_{(j1)} \tag{3}$$

and

$$\sum_{j=2}^{j=3} F_{c_{t(j)}} = \sum_{j=2}^{j=3} P_{AE} SFOC_{AE} t_{(j)} \tag{4}$$

where P_{ME} is the propulsion engine power (kW), P_{AE} is the auxiliary engine power (kW), t is the timeframe within the specific vessel operation mode (h), $SFOC$ is the specific fuel oil consumption (kg/kWh), and nME is the number of propulsion engines. As the auxiliary engines power data were not available, according to [7], it is calculated that the auxiliary engine's power is:

- Auxiliary engine power for RO-PAX ferry vessels—10% of main propulsion engine(s) power.
- Auxiliary engine power for HSC—5% of main propulsion engine(s) power.

The dependency of the propulsion engines' load on the vessel speed for the RO-PAX ferry vessels is calculated using the Admiralty coefficient, as described in [66]:

$$\sum_{i=1}^{nME} P_{ME(i)} = \frac{\sqrt[3]{D^2}}{A_c} {v_{eff}}^3 \tag{5}$$

where D is the vessel displacement (tones), A_c is the Admiralty coefficient, and v_{eff} is the vessel speed (kn).

The A_c for each vessel is calculated based on the maximum service speed versus the propulsion engines' maximum continuous rating (MCR). Afterward, the obtained coefficient is used to further calculate the power point of the propulsion engine(s) based on the actual vessel speed obtained from the vessel timetable.

Considering that HSC is employed, the Admiralty coefficient will not provide the most accurate power-to-speed functional ratio. In this case, the dependency of the propulsion engine load on vessel speed is calculated based on the SES model's research in the water tank, as described in [67].

The specific fuel oil consumption $SFOC$ for diesel engines is taken as a function of the relative engine load P_{REL}, engine speed RPM, and engine utilization, either as a propulsion engine ME or as an auxiliary engine AE:

$$SFOC = f\ (P_{REL},\ RPM,\ ME/AE), \tag{6}$$

and is within the range of 180–340 g/kWh, as defined in [68].

Based on the described models, the following input data are considered for the carbon emission calculation:

- During navigation (j_1), auxiliary engines are considered to be in operation, and carbon emission is calculated according to (3).
- Port stay ship operation ($j_2,\ j_3$) consists of the hoteling phase, where auxiliary engines are operated, and carbon emission is calculated according to (4).
- During the maneuvering phase, the propulsion engine load is estimated as during navigation, and the auxiliary engine load is estimated based on the earlier-mentioned methodology.

The carbon emission calculation of the road transportation mode is based on the publicly available emission factors for average personal cars and public buses. The representative model for personal car is taken as a 5-seat car with an internal combustion engine. The average car age in the EU is taken as 10.7 years as per the Finnish Information Centre of Automobile Sector [69]. Accordingly, the average emission for newly registered cars in 2011 was 135.7 gCO_2/vehicle-km, and this was taken as an average for this study [70], as presented in Figure 1. The obtained value is based on the New European Driving Cycle (NEDC) test methodology for new cars.

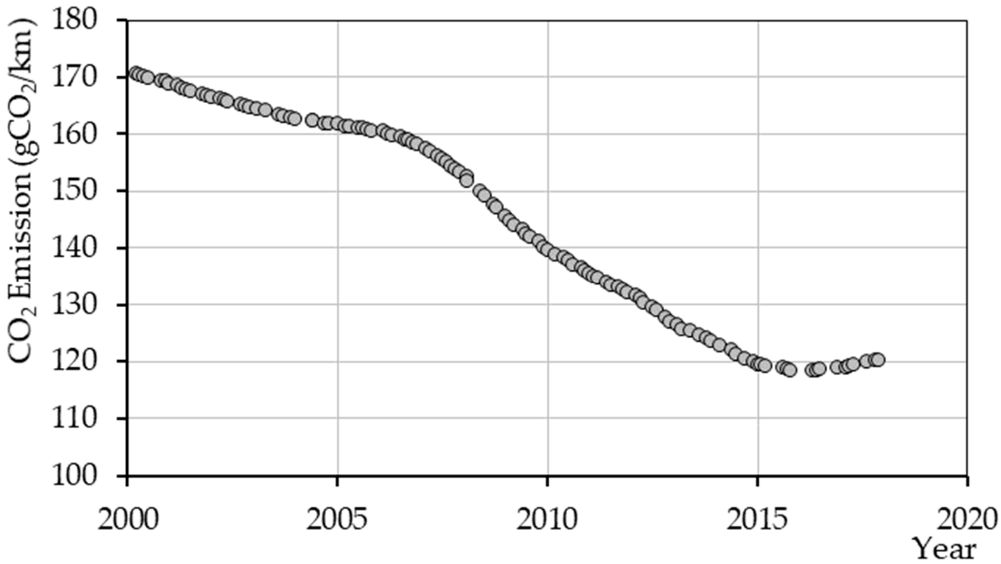


Figure 1. The average carbon footprint of a newly registered car in the EU.

The carbon emission for personal cars ξ_{cCO_2} ($kgCO_2$) on a specific route is then calculated as:

$$\xi_{cCO_2} = \frac{E_{fc}}{1000} l_r \tag{7}$$

where E_{fc} is the average car carbon factor (gCO_2/km) and l_r is the traveled distance on a particular route (km).

The representative public bus is taken as a standard 49-seat bus with a diesel engine. Emission factors in gCO_2/km for buses are different based on the legislation for each EURO class and the different road types [10]. The collected data on the existing public bus fleet (Croatian public bus services) indicates buses in service from EURO III to EURO VI class. After analyzing the available data, we concluded that public buses of EURO V class are the most common in the existing fleet. A model of EURO V class public bus with emission for Highway—Multi-Lane road type is therefore taken as a carbon emission base for this research, with an average of 601 gCO_2/km [10]. In this case, the average emission factor is taken for Highway—Multi-Lane. The carbon emission for a public bus ξ_{bCO_2} ($kgCO_2$) is calculated with the same model as a personal car, except a different emission factor E_{fb} (gCO_2/km) is used:

$$\xi_{bCO_2} = \frac{E_{fb}}{1000} l_r \tag{8}$$

Road distances for personal cars and public buses are estimated to be the same, i.e., it was not considered that public buses on the observed routes might have additional waypoints (public bus stations). Furthermore, the distances on the selected routes are determined by Open CPN 5.0.0 + 9065270, following all navigational rules and good seamanship practice (maritime transportation mode), QGIS software (version 3.16.8-Hannover) and its extension OpenStreetMap query requests (road transportation modes).

2.2. Italy–Croatia Interconnection Network and Chosen Routes

For the purpose of this research, the current state of the Italy–Croatia passenger transportation network is analyzed according to the several main regions identified in the Adriatic Sea area that connects Italy's and Croatia's national borders.

After analyzing the importance of the specific origin and destination transportation pairs defined in the Adriatic Sea area, the considered area is divided into three main regions: Northern, Middle, and Southern Adriatic. The defined regions are depicted in Figure 2.

Figure 2. Main Adriatic regions.

Every defined region is specific regarding the availability of mentioned transportation modes. These specifics are based on the acceptable time–distance proportion where not every transportation mode is preferable for overcoming the particular distances. Furthermore, it should be noted that not all transportation modes are available in each considered region.

Furthermore, the maritime transportation mode represents a reference for selecting the origin–destination pairs. Following this approach, the existing routes have been distributed within the predefined Adriatic regions as shown in Table 2, according to data in [71].

Table 2. Distribution of maritime transportation lines in the defined Adriatic regions.

Northern Adriatic Region	Middle Adriatic Region	Southern Adriatic Region
Pesaro–Mali Lošinj	Split–Ancona	Dubrovnik–Bari
Rab–Cesenatico	Ancona–Zadar	
Pesaro–Zadar	Civitanova–Hvar	
Poreč–Venice	Civitanova–Split	
Venice–Pula		
Pula–Trieste		
Rovinj–Venice		
Rovinj–Cesenatico		
Trieste–Piran–Rovinj		
Pula–Venice		

For the carbon emission calculation and further comparison, several routes from Table 2 have been selected depending on transportation distance, which is identified as a significant factor in route selection. Distances are closely related to calculated carbon emissions. Among various midpoint combinations for achieving specific destination points on routes, finding the shortest path also represents a significant selection factor.

The additional selection factors were also considered, which include transportation entity type (e.g., not all destinations can be reached by the same vessel type), trip/voyage frequency in the considered time period, passenger flow intensity in the considered time period, and average passenger occupancy.

Based on the mentioned factors that affect the route selection in the defined Adriatic regions, the following routes were selected for three case studies:

1. Case study 1: Venice–Pula–Poreč–Venice (R_1).
2. Case study 2: Zadar–Ancona (R_2).
3. Case study 3: Bari–Dubrovnik (R_3).

3. Routes Analysis and Calculation Results

3.1. Venice–Pula–Poreč (R_1)

Route R_1 consists of several major destinations as waypoints, primarily located in Croatia. The route is defined as a closed circled route in the Northern Adriatic region. Due to there being several waypoints, route R_1 is segmented into three major segments: Venice–Pula (R_1S_1), Pula–Poreč (R_1S_2), and Poreč–Venice (R_1S_3).

As the origin/destination point of the selected route, the port of Venice is one of the major Italian passenger ports in the Northern Adriatic. It is located on the northeastern part of the Italian mainland.

As the origin/destination port, the port of Pula is located on the northwestern part of the Croatian mainland at the bottom of the Istrian peninsula.

The port of Poreč, as a virtual waypoint on the route R_1, is located on the northwestern part of the Croatian mainland in the Istrian Peninsula.

From the perspective of maritime passenger transportation lines, all three ports serve existing passenger lines, as taken in this research. According to data in [71], the passenger lines for which the above-mentioned ports represent origins or destinations are listed in Table 3.

Table 3. Existing passenger lines serviced in 2019 between selected route segments.

Passenger Lines (Line Operator)	Vessel Name	Average Passenger Occupancy per Trip in 2019	Number of Vessel Voyages in 2019
Pula–Venice (Venezia Lines LTD)	San Pawl	56%	44
Poreč–Venice (Venezia Lines LTD)	San Pawl	30.6%	88

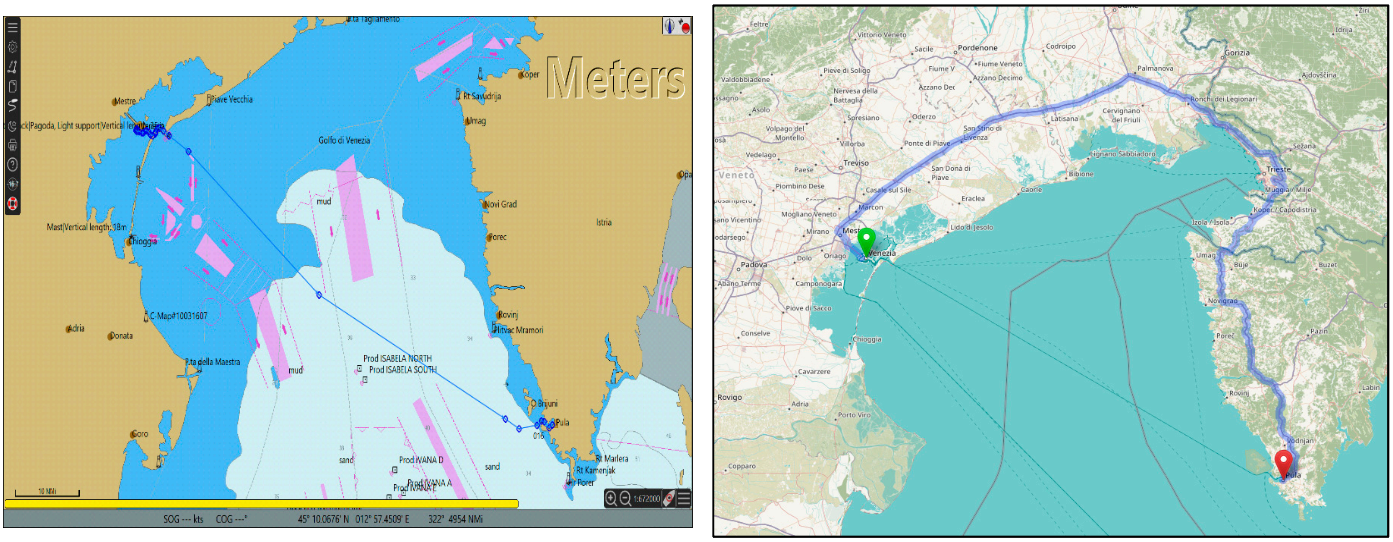
For the maritime transportation mode, the HSC "San Pawl" (IMO Number: 8815932), with 389 GT and a passenger capacity of 330, is used as a reference vessel for carbon emission calculation. According to data in [71,72], the technical characteristics of the reference vessel are presented in Table 4.

Table 4. Technical characteristics of the reference vessel "San Pawl".

Technical Characteristics: Vessel "San Pawl"	
Vessel type	HSC air cushion
Summer DWT	50 t
Length overall (LOA)	35.3 m
Breadth	11.5 m
Draught	2.05 m
Propulsion type	2× fixed pitch propellers
Propulsion power	3358 kW

On the other hand, the carbon emission calculation for the road transportation mode is conducted for either personal car or public bus entities. Road transportation modes consist of transportation on highways and local roads, as well as those described in the further text and presented in Figure 3b. Based on data available from the Croatian Bureau of Statistics [4], for border crossings between Croatia and Slovenia applicable for R_1S_1 and R_1S_3, an average personal car occupancy is calculated. This value is based on the number of passengers, personal cars, public buses, and trucks entering and exiting Croatia during 2019 through border checkpoints Plovanija and Kaštel. The calculated average personal car occupancy in this case is:

- 3.31 passenger/car for R_1S_1 route segment.
- 3.26 passenger/car for R_1S_3 route segment.



(**a**) (**b**)

Figure 3. Route segment R_1S_1: (**a**) maritime transportation; (**b**) road transportation.

Bus occupancy for these route segments, as well as for other routes considered in this study, was not possible to obtain, as it is not made public due to the increasingly privatized nature of national public bus services. Based on calculations with Open CPN 5.0.0 + 9065270 software for the maritime transportation mode and QGIS software (version 3.16.8-Hannover) extension OpenStreetMap query requests for the fastest route on road transportation modes, the total distances determined for route R_1, i.e., segments R_1S_1, R_1S_2, and R_1S_3, are shown in Table 5.

Table 5. Determined distances on route R_1.

	Maritime Transportation Mode Distances (Nm)			Road Transportation Mode Distances (km)	
Route Segment	**Maneuvering**	**Sea Passage**	**Total**	**Road**	**Total**
R_1S_1	12.7	63.5	76.2	283	283
R_1S_2	3.8	26.6	30.4	56	56
R_1S_3	10.7	50	60.7	250	250

The maritime transportation route segment R_1S_1 (Figure 3a) is defined by the distances operated in a specific navigation mode, taking into account the essential port features. The defined navigation modes include maneuvering on departure, sea passage, and maneuvering on arrival. The maritime distances calculated for these navigation modes are presented in Table 6.

Table 6. Distances traveled in the specific navigation mode on the route segment R_1S_1.

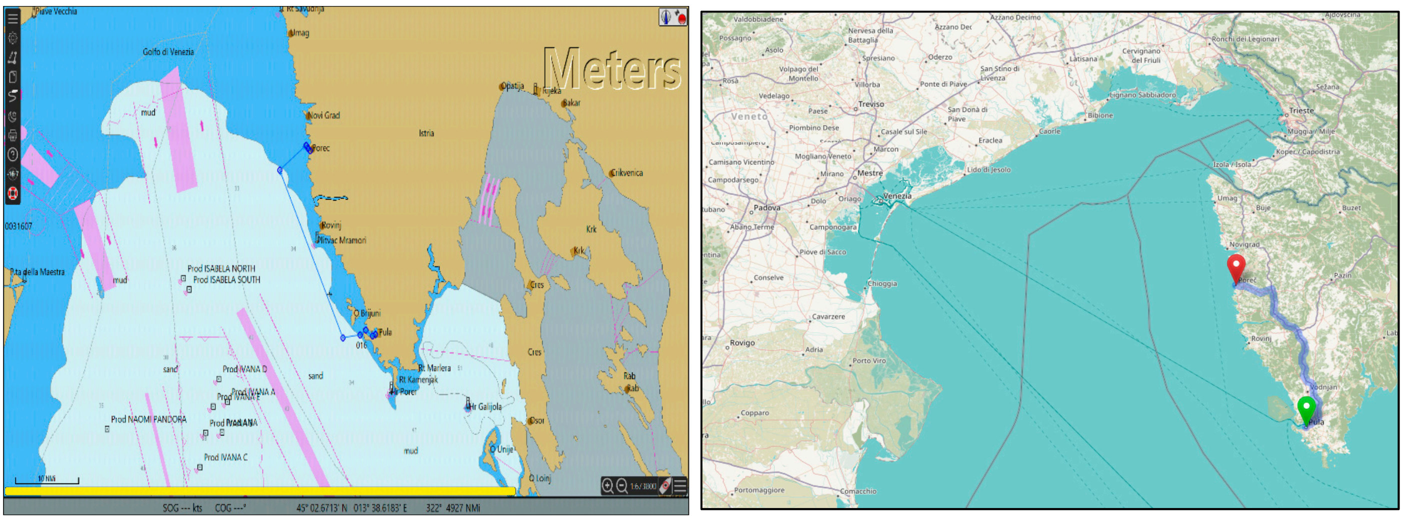
Route Segment: R_1S_1	
Maneuvering on departure	9.8 Nm
Sea passage	63.5 Nm
Maneuvering on arrival	2.9 Nm

The road transportation mode is defined by the distances traveled by personal car or public bus. The R_1S_1 route segment, presented in Figure 3b, includes transportation on the following roads:

- Italy: highway SR11 and motorway A4 (part of European route E70) from Venice to Trieste.
- Slovenia: highways H5 and H6 (part of European route E751) from border crossing Škofija to border crossing Dragonja.
- Croatia: motorway A9 (part of European route E751) from Dragonja to Pula.

In this case, the total calculated road distance for the mentioned route segment is 283 km.

The next route segment, R_1S_2, is a virtual one (not based on the actual route) and is shown in Figure 4. This segment was determined to allow for comparing a circular route with short distances between two destinations.



(**a**) (**b**)

Figure 4. Route segment R_1S_2: (**a**) maritime transportation; (**b**) road transportation.

The maritime distances calculated for this segment are shown in Table 7 for each navigation mode.

Table 7. Distances traveled in the specific navigation mode on the route segment R_1S_2.

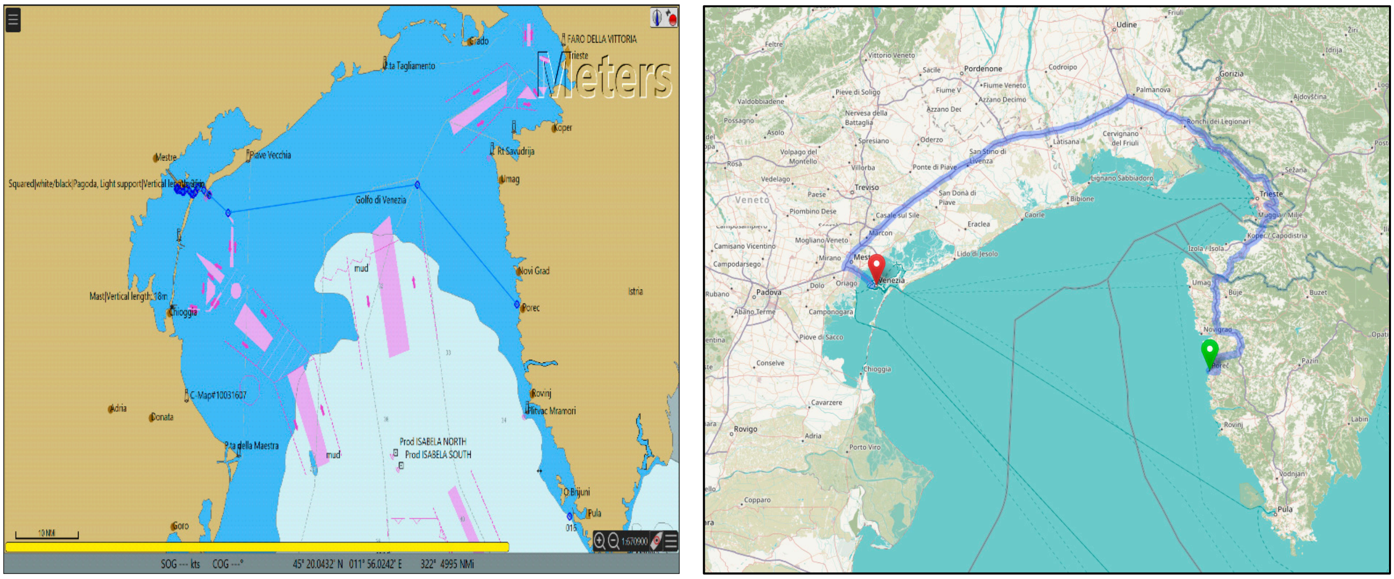
Route Segment: R_1S_2	
Maneuvering on departure	2.9 Nm
Sea passage	26.6 Nm
Maneuvering on arrival	0.9 Nm

The distances traveled by personal car and public bus on the route segment R_1S_2 are shown in Figure 4b and consist of transportation on the following roads:

- Croatia: motorway A9 (part of European route E751) and
- State road D302 from Pula to Baderna and from Baderna to Poreč, respectively.

In this case, the total calculated road distance for the mentioned route segment is 56 km.

The route segment R_1S_3 represents the last segment of this circled route. The maritime distances calculated for this route segment are presented in Figure 5a and provided in Table 8 for each navigation mode.



(**a**) (**b**)

Figure 5. Route segment R_1S_3: (**a**) maritime transportation; (**b**) road transportation.

Table 8. Distances traveled in the specific navigation mode on the route segment R_1S_3.

Route Segment: R_1S_3	
Maneuvering on departure	0.9 Nm
Sea passage	50 Nm
Maneuvering on arrival	9.8 Nm

The distances traveled by personal car and public bus on the route segment R_1S_3 (Figure 5b) consist of transportation on the following roads:

- Croatia: state road D302 and motorway A9 (part of European route E751) from Poreč to Baderna and from Baderna to Dragonja, respectively.
- Slovenia: highway H5 and H6 (part of European route E751) from border crossing Dragonja to border crossing Škofija.

- Italy: motorway A4 and highway SR11 (part of European route E70) from Trieste to Venice.

  In this case, the total calculated road distance is 250 km.

3.2. Zadar–Ancona (R_2)

The port of Zadar (Gaženica), as an actual origin/destination port, is a deepwater port and represents the most significant economic and business zone in Zadar County. It is located at the border between the Northern Adriatic and Middle Adriatic regions.

As an actual origin/destination port, the port of Ancona is located in the middle of the Italian Adriatic coast, in the Gulf of Ancona, at the border between Northern Adriatic and Middle Adriatic regions. These ports serve as a base for the existing passenger line to/from Croatia chosen in this research. According to data in [71], the passenger line for which the ports mentioned above represent the origin or destination are listed in Table 9.

Table 9. Passenger lines serviced in 2019 for the existing Ancona–Zadar route.

Passenger Line (Line Operator)	Vessel Name	Average Passenger Occupancy per Trip in 2019	Number of Vessel Voyages in 2019
Ancona–Zadar (Jadrolinija)	Zadar	28.5%	49

For the maritime transportation mode, the RO-PAX vessel "Zadar" (IMO Number: 9021485) with 9487 GT, passenger capacity of 1300, and vehicle capacity of 280 is used as a reference vessel for carbon emission calculation. According to data in [71,72], the technical characteristics of the reference vessel are shown in Table 10.

Table 10. Technical characteristics of the reference vessel "Zadar".

Technical Characteristics: Vessel "Zadar"	
Vessel type	RO-PAX ferry
Summer DWT	2152 t
Length over all (LOA)	116 m
Breadth	18.9 m
Draught	5.15 m
Propulsion type	2× controllable pitch propellers
Propulsion power	7.000 kW

The carbon emission calculation for the road transportation mode is also conducted for either personal car or public bus entities. The road transportation mode consists of transportation on motorways, highways, and local roads using the fastest route through Rijeka (Bosiljevo junction). The total distance determined for the Ancona–Zadar route is shown in Table 11.

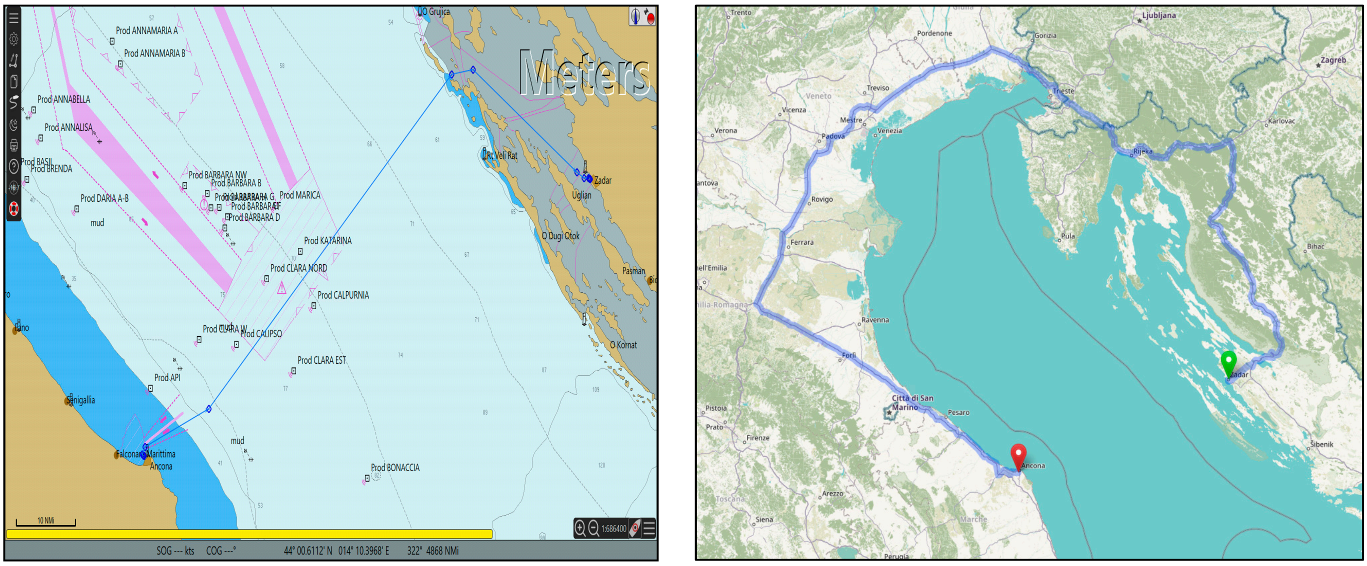
Table 11. Determined distances on route R_2.

	Maritime Transportation Mode Distances (Nm)			Road Transportation Mode Distances (km)	
Route	Maneuvering	Sea Passage	Total	Road	Total
R_2	6.7	84.7	91.4	864	864

As described in the further text and presented in Figure 6b, based on data available from the Croatian Bureau of Statistics [4], an average car occupancy is calculated for the border crossing between Croatia and Slovenia for the R_2 route. This value is based on the number of passengers, personal cars, public buses, and trucks entering and exiting

Croatia during 2019 through border checkpoint Pasjak. The calculated average personal car occupancy in this case is:

- 3.25 passenger/car for entry into Croatia—route Ancona–Zadar,
- 3.28 passenger/car for exiting from Croatia—route Zadar–Ancona.



(a) (b)

Figure 6. Route R_2: (**a**) maritime transportation; (**b**) road transportation.

The maritime transportation distances on the route R_2 (Figure 6a), provided in Table 12, are calculated based on the specific navigation modes, taking into account the specific port features.

Table 12. Distances in the specific navigation modes on the route R_2.

Route: R_2	
Maneuvering on departure	4.2 Nm
Sea passage	84.7 Nm
Maneuvering on arrival	2.5 Nm

The average vessel speed on the route mentioned above is assumed to be 10.11 kn, based on the 2019 operational timetables.

The road transportation mode on the route R_2 is presented in Figure 6b and is realized by personal car or public bus on the following roads:

- Italy: motorway A14 (part of European route E55), A13, A4, and highway SS14 from Ancona to Bologna, from Bologna to Padua, from Padua to Trieste, and from Trieste to border crossing Krvavi Potok, respectively.
- Slovenia: state road G7 from border crossing Krvavi Potok to Starod.
- Croatia: highway D8, motorways A7, A6, A1, and state road D424 from Pasjak to Rupa, from Rupa to Orehovica, from Orehovica to junction Bosiljevo, from junction Bosiljevo to Zadar I, and from Zadar I to port of Zadar (Gaženica), respectively.
- The total calculated road distance for the mentioned route is 864 km.

3.3. *Dubrovnik–Bari (R_3)*

The port of Dubrovnik is located in southern Croatia, in the Southern Adriatic region. Moreover, the port of Dubrovnik is one of the most prominent passenger ports and tourist destinations in the Mediterranean area. On the other end, the port of Bari is located in the southern part of the Italian Adriatic coast, in the Southern Adriatic region. These ports serve as the actual origin/destination points on the considered passenger line. According to data in [71], the passenger line for which the ports mentioned above represent the origins or destinations is listed in Table 13.

Table 13. Passenger lines serviced in 2019 for the existing Dubrovnik–Bari route.

Passenger Line (Line Operator)	Vessel Name	Average Passenger Occupancy per Trip in 2019	Number of Vessel Voyages in 2019
Dubrovnik–Bari (Jadrolinija)	Dubrovnik	30.5%	87 voyages

For the maritime transportation mode, the vessel RO-PAX "Dubrovnik" (IMO Number: 7615048) with 9795 GT, passenger capacity of 1300, and vehicle capacity of 300 is used as a reference vessel for carbon emission calculation. According to data in [71,72], the technical characteristics of the reference vessel are shown in Table 14.

Table 14. Technical characteristics of the reference vessel "Dubrovnik".

Technical Characteristics: Vessel "Dubrovnik"	
Vessel type	RO-PAX Ferry
Summer DWT	1310 t
Length over all (LOA)	113.01 m
Breadth	18.5 m
Draught	4.83 m
Propulsion type	2× controllable pitch propellers
Propulsion power	13,248 kW

The carbon emission calculation for the road transportation mode is performed for transportation on motorways and highways from Bari to Ploče and continuation by the local roads. Reaching the final destination by road requires a border crossing through Bosnia and Herzegovina, which can negatively impact transportation time but not the carbon emission value. For the road transportation mode, the same border crossing between Croatia and Slovenia is used for routes R_2 and R_3, thus resulting in the same occupancy rate values.

The total distance determined for route R_3 is shown in Table 15.

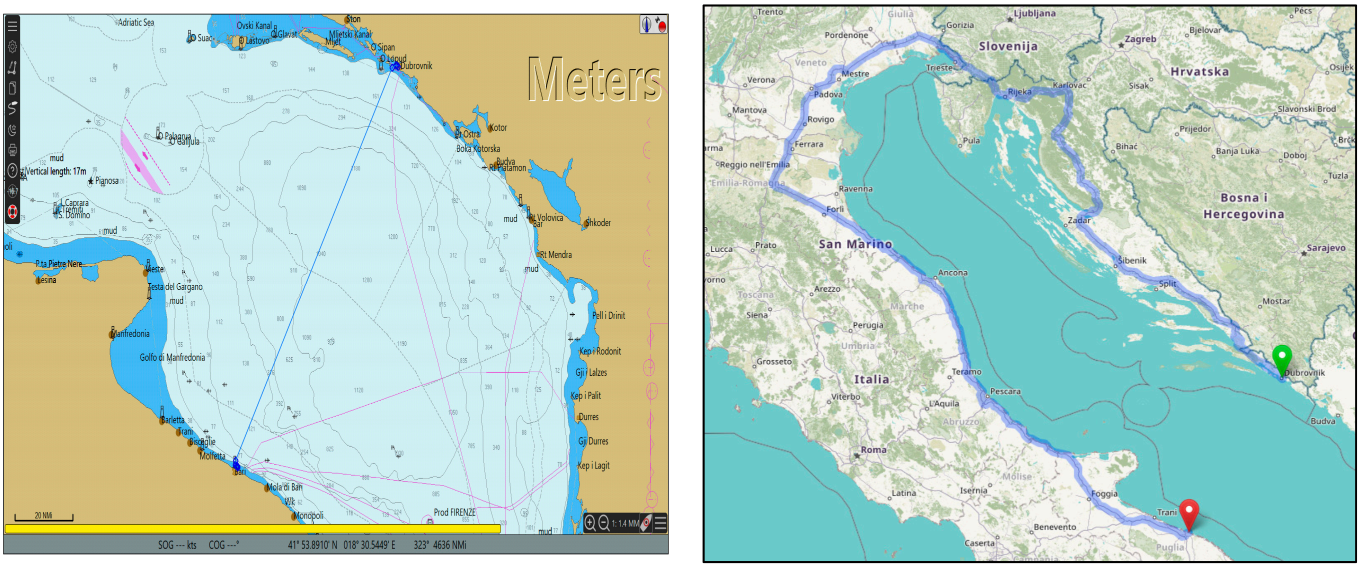
Table 15. Determined distances on route R_3.

	Maritime Transportation Mode Distances (Nm)			Road Transportation Mode Distances (km)	
Route	Maneuvering	Sea Passage	Total	Road	Total
R_3	4.5	104.4	108.9	1633	1633

The maritime transportation distances on the route R_3 (Figure 7a), provided in Table 16, are calculated based on the specific navigation modes, taking into account the port features.

Table 16. Determined distances on the route R_3.

Route: R_3	
Maneuvering on departure	2.1 Nm
Sea passage	104.4 Nm
Maneuvering on arrival	2.4 Nm



(**a**) (**b**)

Figure 7. Route R_3: (**a**) maritime transportation; (**b**) road transportation.

Based on the 2019 operational timetables, the average vessel speed on the route mentioned above is assumed to be 11.6 kn.

The personal car and public bus transportation mode for the selected route (Figure 7b) consists of transportation on the following roads:

- Italy: motorways A14 (part of European route E55), A13, A4, and highway SS14 from Bari to Bologna, from Bologna to Padua, from Padua to Trieste, and from Trieste to border crossing Krvavi Potok, respectively.
- Slovenia: state road G7 from border crossing Krvavi Potok to Starod.
- Croatia: highway D8, motorways A7, A6, A1, highways D425, and D8 from the border crossing Pasjak to the border crossing Rupa, from the border crossing Rupa to Orehovica, from Orehovica to junction Bosiljevo, from junction Bosiljevo to junction Karamatići, from junction Karamatići to Ploče, and from Ploče to the border crossing Klek-Neum I, respectively.
- Bosnia and Herzegovina: highway M2 from the border crossing Klek-Neum I to Neum II.
- Croatia: highway D8 from the border crossing Neum II to the port of Dubrovnik.
- The total calculated road distance for the mentioned route is 1633 km.

4. Results and Discussion

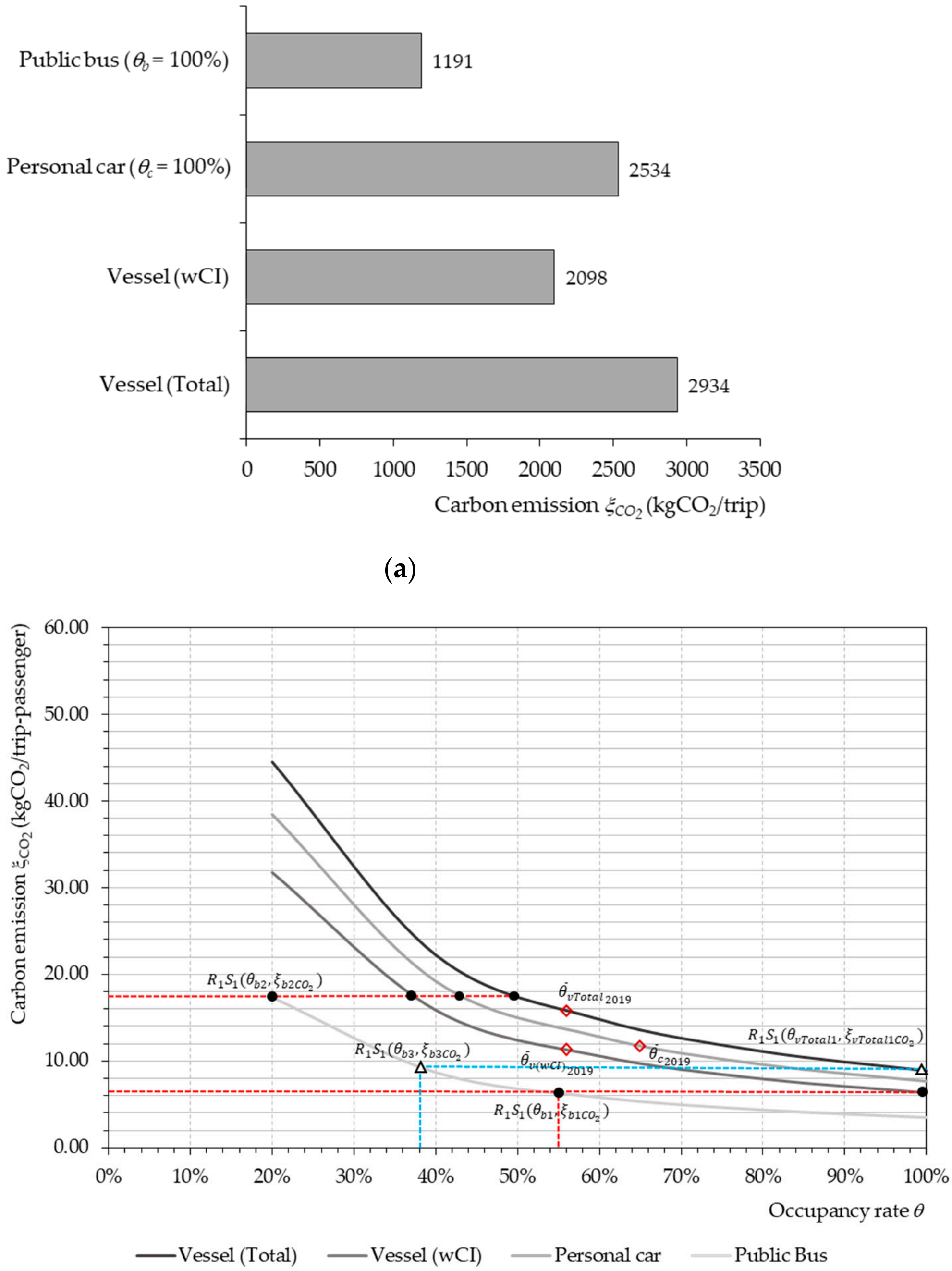
By implementing the presented methodology on each of the individual routes, the calculated carbon emissions in $kgCO_2$/trip passenger are presented as a function of the occupancy rates θ for each transportation mode. The total carbon emission in $kgCO_2$ for each transportation mode is calculated based on the reference number of passengers, which depends on the technical characteristics of the vessels and their capacities employed on each of the considered route segments. In general, the main objectives of interpreting the following results are to present:

- The total carbon emission for each transportation mode based on the reference capacity;
- The calculated carbon emission values per passenger considering different transportation modes;
- The optimal transportation mode choice with respect to the different relative occupancy rates;
- The calculated carbon emission relationship for available actual observed occupancy rates.

4.1. Case Study 1—Venice–Pula–Poreč–Venice (R_1)

4.1.1. Route Segment Venice–Pula (R_1S_1)

According to the results presented in Figure 8a, for the reference capacity of 330 passengers, the calculated carbon emission for transportation by HSC is 2934 $kgCO_2$ per trip when the "Cold ironing" process is not implemented. In the case that the mentioned process is taken into account, carbon emission would be lower by approximately 28%. The large difference is associated with a long port stay period between two consecutive trips, as obtained from line timetables.



(a)

(b)

Figure 8. Calculated carbon emissions on the route segment R_1S_1: (**a**) total carbon emissions per single trip with respect to each transportation mode and based on the reference capacity of 330 passengers; (**b**) comparison of carbon emissions with respect to the θ for each transportation mode choice.

Furthermore, road transportation mode choices are mainly influenced by θ, e.g., in the case that the reference passenger capacity is considered at $\theta_c = 100\%$ (average 5 passengers per car), the total calculated carbon emission is 2534 $kgCO_2$ per trip. This value is slightly lower than the one obtained for transportation by HSC, not considering the "Cold ironing" process. However, if the public buses employed on this route segment are fully occupied ($\theta_b = 100\%$), fewer buses are required, and a significantly lower carbon emission of 1191 $kgCO_2$ per trip is generated. This value is two times lower than the value obtained for transportation by HSC.

Calculating carbon emissions for the first segment of the route R_1S_1 (Figure 8b), transportation by HSC where "Cold ironing" is not implemented is identified as having the highest carbon emission value based on the reference capacity. On the other hand, the lowest calculated carbon emission value is associated with transportation by public bus. Moreover, transportation by HSC when "Cold ironing" is taken into account is slightly more preferable than transportation by personal car.

Since the corresponding curves are relatively close to each other, the difference in θ is not the prevailing factor of the appropriateness of choosing a particular transportation mode in terms of carbon emissions.

Hypothetically, we take the public bus transportation mode as a reference for further analysis, since it is the most favorable transportation mode choice. In that case, it is evident that if $\theta_b > 55\%$ (average 27 passengers per public bus), which represents the point $R_1S_1(\theta_{b1}, \xi_{b1CO_2})$, no other transportation mode can deliver a lower carbon emission per trip passenger. In this case, the calculated carbon emission is 6.4 $kgCO_2$/trip passenger.

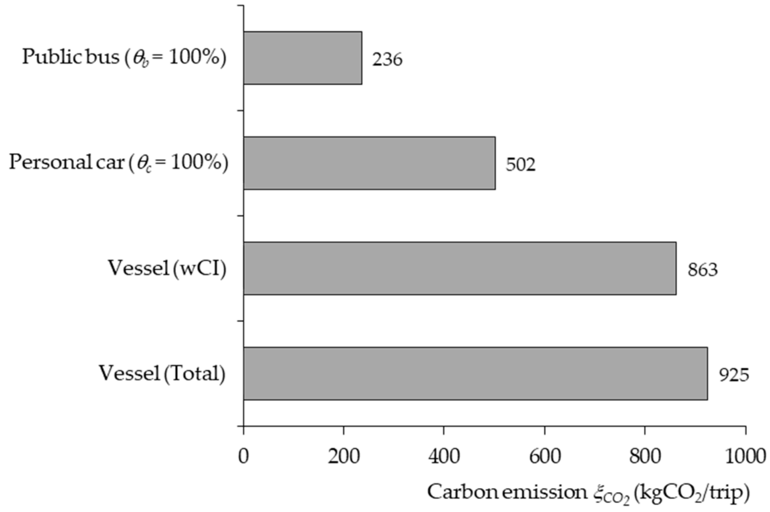
On the other hand, if the highest calculated carbon emission value generated by public bus ($\theta_b = 20\%$, generating 17.4 $kgCO_2$/trip passenger) is used as a reference, as at point $R_1S_1(\theta_{b2}, \xi_{b2CO_2})$, it can be concluded that this value is equivalent to transportation by HCS when "Cold ironing" is taken into account when $\theta_{v(wCI)} = 37.5\%$ (124 passengers) or personal car when $\theta_c = 43\%$ (average 2.2 passengers per personal car), as well as HSC when the "Cold ironing" process is not considered, $\theta_{vTotal} = 49.5\%$ (163 passengers). For the above-mentioned θ_b, transportation by personal car or HSC will offer more acceptable carbon emission values.

Under the theory that transportation by HSC is considered as the least favorable mode choice, if $\theta_{vTotal} = 100\%$ (330 passengers), as at point $R_1S_1(\theta_{vTotal1}, \xi_{vTotal1CO_2})$, it can be concluded that the θ_c of the personal car needs to be less than 84% (average 4.2 passengers per personal car) to be less favorable. Moreover, θ_b for the public bus must be less than 37% (average 18 passengers per public bus) to be less favorable than the maritime transportation mode at point $R_1S_1(\theta_{b3}, \xi_{b3CO_2})$.

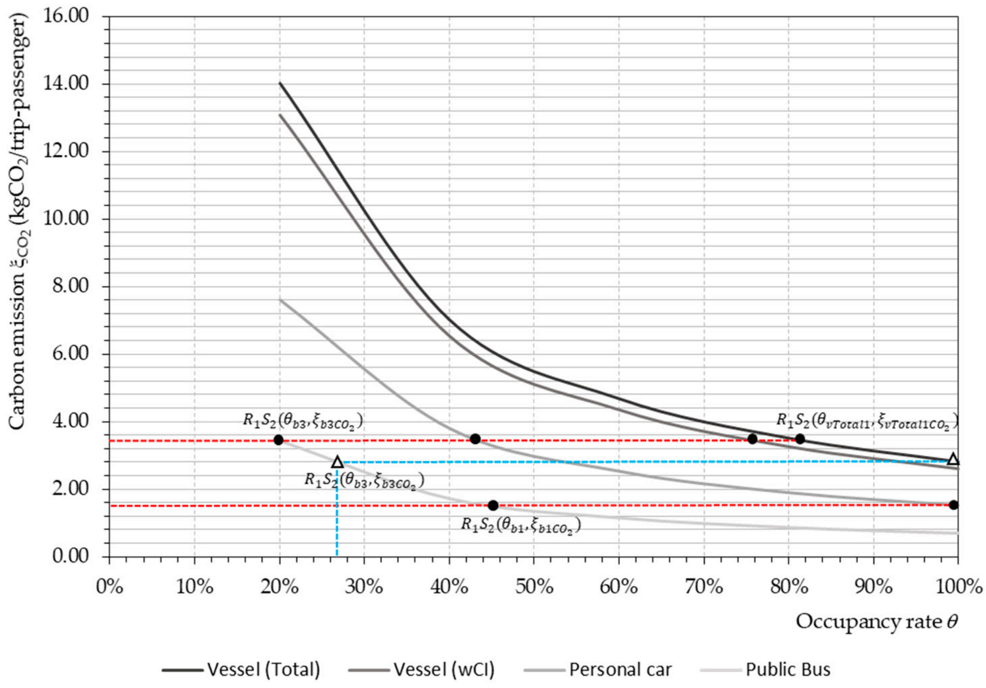
4.1.2. Route Segment Pula–Poreč (R_1S_2)

According to the results presented in Figure 9a, for the reference capacity of 330 passengers, the calculated carbon emission for transportation by HSC is 925 $kgCO_2$ per trip when the "Cold ironing" process is not implemented. In the case that the mentioned process is taken into account, carbon emission is slightly lower due to the fact that the mentioned port presents only a midpoint on the whole route, where the port stay is very short.

Furthermore, the road transportation mode is mainly influenced by θ, e.g., in the case that the reference passenger capacity is considered at $\theta_c = 100\%$ (average 5 passengers per car), the calculated carbon emission is considerably lower: 502 $kgCO_2$ per trip. If the public buses employed on this route segment are fully occupied ($\theta_b = 100\%$), fewer buses are required, and a significantly lower carbon emission of 236 $kgCO_2$ per trip is calculated.



(**a**)



(**b**)

Figure 9. Calculated carbon emissions on the route segment R_1S_2: (**a**) total carbon emissions per single trip with respect to each transportation mode and based on the reference capacity of 330 passengers; (**b**) comparison of carbon emissions with respect to the θ for each transportation mode choice.

Calculating carbon emissions for the second route segment R_1S_2 (Figure 9b), transportation by HSC is definitely the mode with the highest carbon footprint emissions based on the reference capacity whether "Cold ironing" process is implemented or not. On the other hand, the lowest calculated carbon emission value is associated with transportation by public bus transport, generally due to the short distance between origin and destination on this route segment. Moreover, transportation by personal car is more acceptable than transportation by HSC. The appropriateness of choosing a particular transportation mode is influenced by the differences in θ, since the curves are distant from each other.

However, in this case, the public bus mode is taken as a reference; as the most favorable one, the conclusion can be drawn that if $\theta_b > 46\%$ (average 23 passengers per bus), which represents the point $R_1S_2(\theta_{b1}, \xi_{b1CO_2})$, no other mode choice can provide a lower carbon emission per trip passenger. In this case, the calculated carbon emission is 1.5 $kgCO_2$/trip passenger.

Suppose that the worst calculated carbon emission value for transportation by public bus ($\theta_b = 20\%$, generating 3.4 $kgCO_2$/trip-passenger) is used as a reference, as at point $R_1S_2(\theta_{b2}, \xi_{b2CO_2})$. It can be concluded that this value is equivalent to transportation by the personal car when $\theta_c = 43\%$ (average 2.2 passengers per car) or transportation by HSC when $\theta_{v(wCI)} = 76\%$ (251 passengers) when the "Cold ironing" process is taken into account. This corresponds to 5% increase in θ when "Cold ironing" is not involved.

On the other hand, assuming that transportation by HSC vessel is considered as the least favorable transportation mode, if $\theta_{vTotal} = 100\%$ (330 passengers), as at point $R_1S_2(\theta_{vTotal1}, \xi_{vTotal1CO_2})$, it can be concluded that the θ_c of the personal car needs to be less than 54% (average 2.7 passengers per personal car) and that of the public bus less than 27% (average 13 passengers per public bus) to be less favorable than transportation by HSC (point $R_1S_2(\theta_{b3}, \xi_{b3CO_2})$.

4.1.3. Route Segment Poreč–Venice (R_1S_3)

According to the results presented in Figure 10a, for the reference capacity of 330 passengers, the calculated carbon emission for transportation by HSC is 2347 $kgCO_2$ per trip when the "Cold ironing" process is not implemented. In the case that the mentioned process is considered, carbon emission would be lower by approximately 45%. The large difference is associated with a long port stay period between two consecutive trips, as obtained from line timetables.

Furthermore, in the case that the reference passenger capacity is considered to be transported by personal car at $\theta_c = 100\%$ (average 5 passengers per personal car), the total calculated carbon emission is 2239 $kgCO_2$ per trip. This value is almost the same as the one obtained for transportation by HSC without "Cold ironing" being considered. However, if the public buses employed on this route segment are fully occupied ($\theta_b = 100\%$), significantly fewer buses are required, and consequently, a lower carbon emission of 1052 $kgCO_2$ per trip is generated.

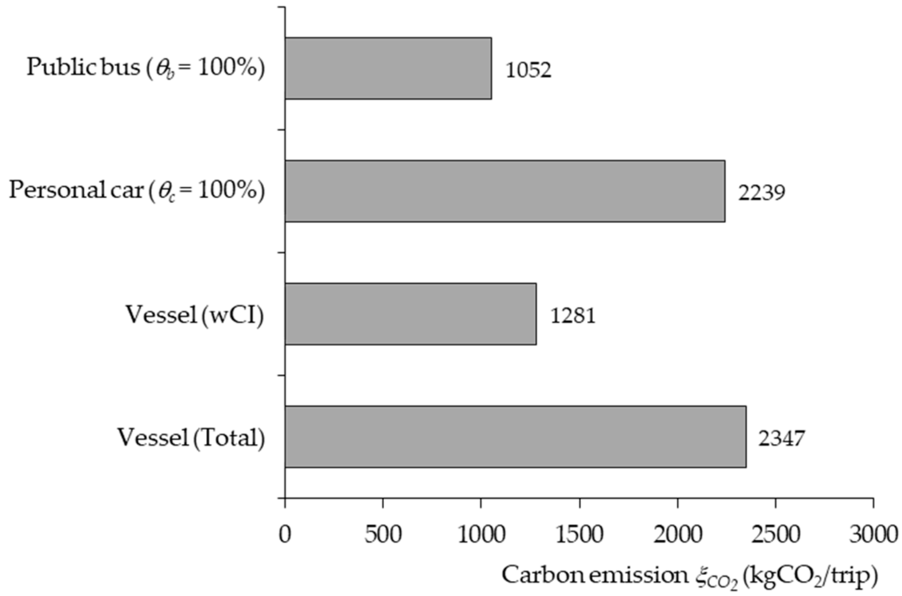
Calculated carbon emission on the third segment of the route R_1S_3 (Figure 10b) implies that the transportation by HSC when "Cold ironing" is not implemented is identified as having the highest carbon emission value based on the reference capacity.

It is interesting to note that the calculated values for personal cars and HSC are almost identical for the same θ and that transportation by HSC when "Cold ironing" is taken into account is considerably more preferable than the personal car but not as much as the public bus.

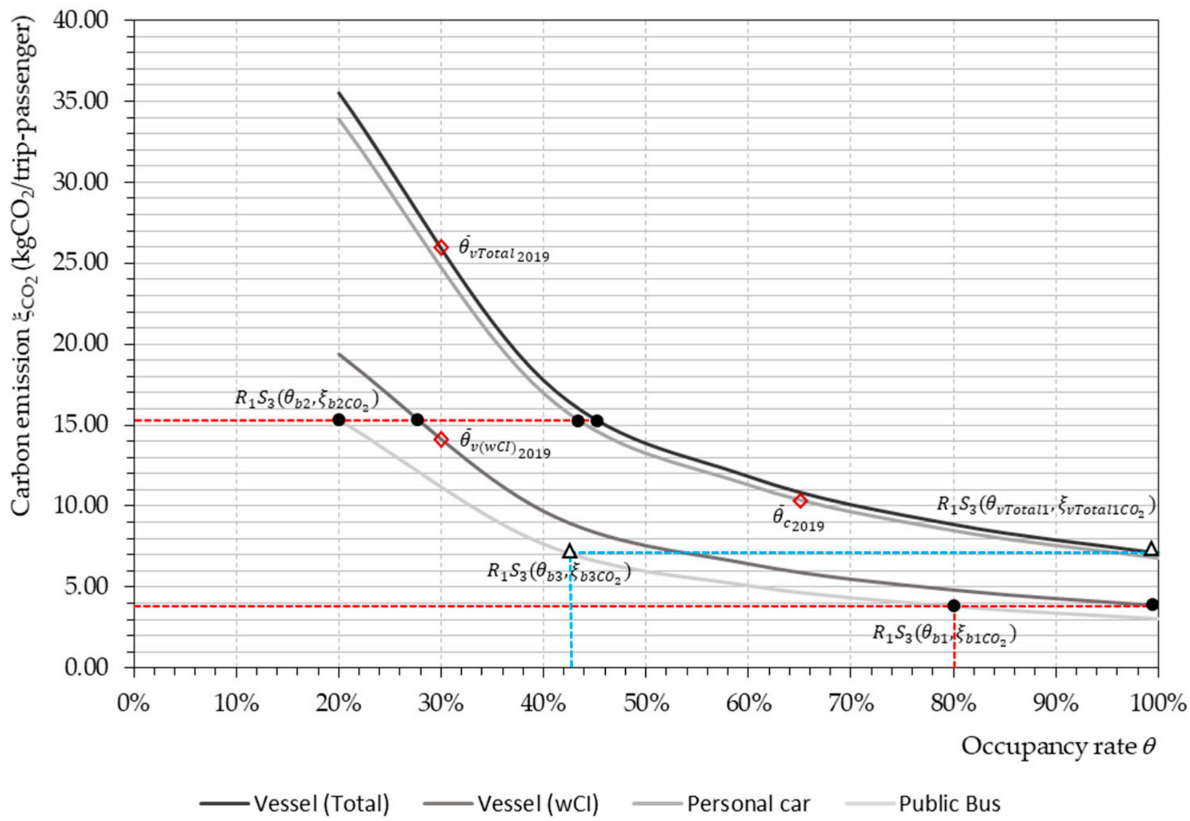
However, if transportation by public bus is taken as a reference, as the most favorable transportation mode choice, the conclusion can be drawn that above $\theta_b > 80.5\%$ (average 39 passengers per public bus), which represents the point $R_1S_3(\theta_{b1}, \xi_{b1CO_2})$, no other transportation mode choice can deliver a lower carbon emission per trip passenger. In this case, the calculated carbon emission is 3.9 $kgCO_2$/trip passenger.

On the other hand, suppose that the worst calculated carbon emission value for public bus ($\theta_b = 20\%$, generating 15.3 $kgCO_2$/trip passenger) is used as a reference, as at point $R_1S_3(\theta_{b2}, \xi_{b2CO_2})$, it can be concluded that this value is equivalent to transportation by HSC when "Cold ironing" is involved when $\theta_{v(wCI)} = 27\%$ (89 passengers) or transportation by personal car $\theta_c = 45\%$ (average 2.25 passengers per personal car), as well as HSC when "Cold ironing" is not considered $\theta_{v(Total)} = 47\%$ (155 passengers). For the above-mentioned θ_b, transportation by personal car or HSC will offer more acceptable carbon emission values per trip passenger.

Otherwise, assuming that transportation by HSC is considered as the least favorable transportation mode, and if $\theta_{v(Total)} = 100\%$ (330 passengers), as at point $R_1S_3\left(\theta_{v(Total)1}, \xi_{v(Total)1CO_2}\right)$, it can be concluded that $\theta_{v(wIC)}$ of the HSC with implemented "Cold ironing" needs to be less than 55% (182 passengers) and θ_b of the public bus needs to be less than 43% (average 21 passengers per public bus) to be less favorable.



(**a**)

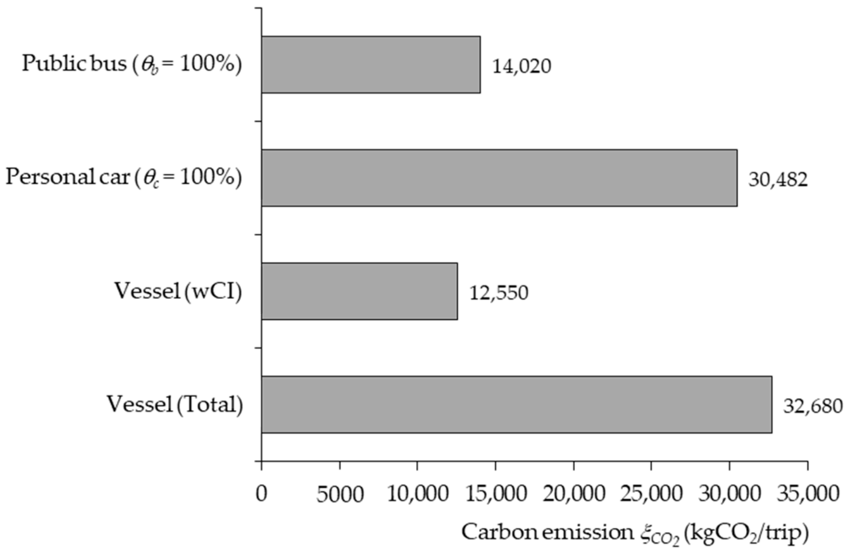


(**b**)

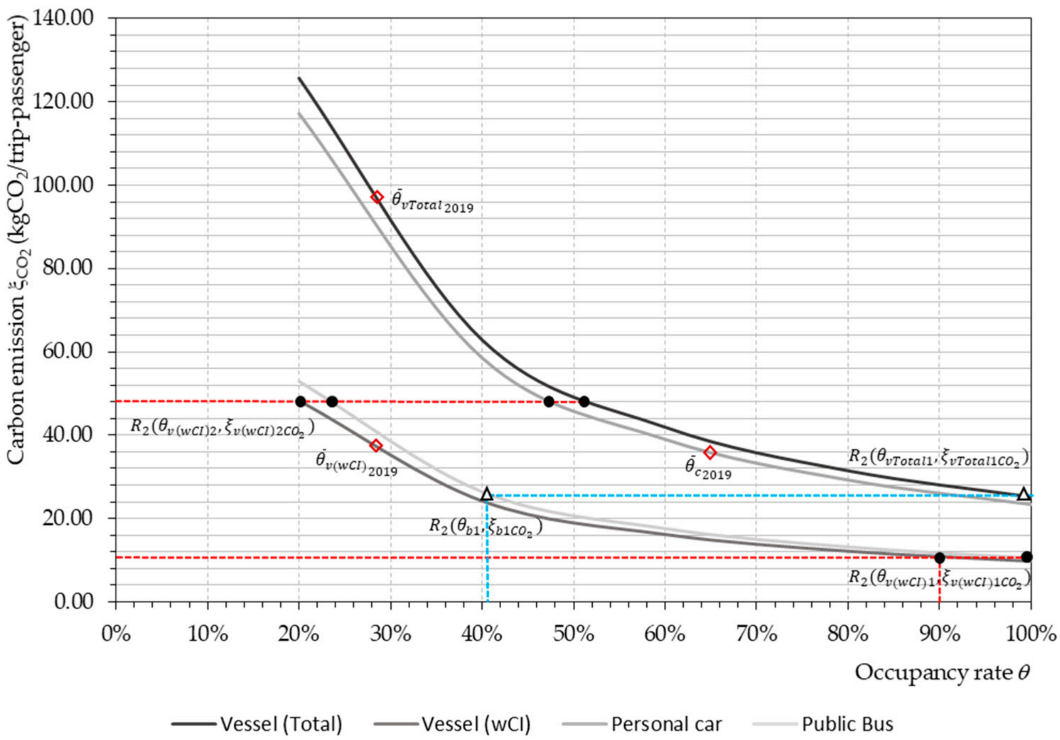
Figure 10. Calculated carbon emissions on the route segment R_1S_3: (**a**) comparison of carbon emissions with respect to the θ for each transportation mode choice; (**b**) total carbon emissions per single trip with respect to each transportation mode and based on the reference capacity of 330 passengers.

4.2. Case Study 2—Ancona–Zadar (R_2)

According to the results presented in Figure 11a, for the reference capacity of 1300 passengers, the calculated carbon emission for transportation by RO-PAX ferry vessel is 32,680 kgCO_2 per trip when the "Cold ironing" process is not implemented. In the case that the mentioned process is taken into account, carbon emission would be significantly lower, by approximately 61.6%. The high difference between these two values is associated with a long port stay period between two consecutive trips, as obtained from line timetables.



(**a**)



(**b**)

Figure 11. Calculated carbon emissions on the route R_2: (**a**) total carbon emissions per single trip with respect to each transportation mode and based on the reference capacity of 1300 passengers; (**b**) comparison of carbon emissions with respect to the θ for each transportation mode choice.

Furthermore, road transportation mode choice is mainly influenced by θ, e.g., in the case that the reference capacity is considered at $\theta_c = 100\%$ (average 5 passengers per car), the total calculated carbon emission is 30,482 $kgCO_2$ per trip. The value is slightly lower than the one obtained for transportation by RO-PAX ferry vessel including carbon emission generated during port stay. Otherwise, if the public buses employed on this route are fully occupied ($\theta_b = 100\%$), a significantly lower carbon emission of 14,020 $kgCO_2$ per trip is generated, which is still slightly higher than transportation by the RO-PAX ferry vessel, not including port stay carbon emission.

Calculated carbon emissions for this route (Figure 11b) show that transportation by RO-PAX ferry vessel is identified as having the highest carbon emission value based on the reference capacity. On the other hand, the lowest calculated carbon emission value is also associated with the RO-PAX ferry vessel, but in the case that port stay carbon emission is not considered. Moreover, transportation by personal car is slightly more acceptable than transportation by RO-PAX ferry vessel when the port stay emission is included.

Since the curves for transportation by personal car and RO-PAX ferry vessel with included port stay carbon emission are relatively close to each other, the difference in θ is not a prevailing factor of the appropriateness of choosing between mentioned transportation modes.

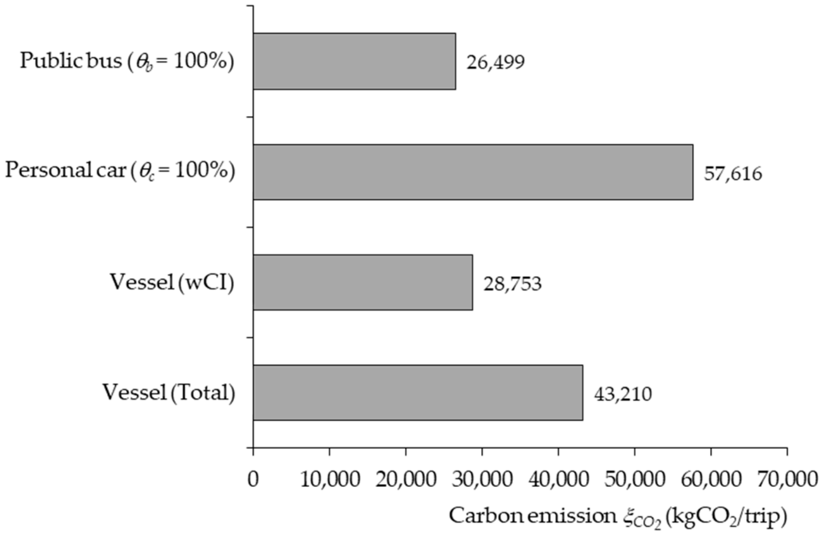
Hypothetically, we take the RO-PAX ferry vessel without port stay carbon emission included as a reference for further analysis, since it is the most favorable mode choice. In that case, it is evident that if $\theta_{v(wCI)} > 90\%$ (1170 passengers), which represents point $R_2\left(\theta_{v(wCI)1}, \xi_{v(wCI)1CO_2}\right)$, no other transportation mode choice can deliver a lower carbon emission per trip passenger. In this case, the calculated carbon emission is 10.6 $kgCO_2$/trip passenger.

On the other hand, suppose that the worst calculated carbon emission generated by the RO-PAX ferry vessel without port stay emission included ($\theta_{v(wCI)} = 20\%$, generating 48.3 $kgCO_2$/trip passenger) is used as a reference, as at point $R_2\left(\theta_{v(wCI)2}, \xi_{v(wCI)2CO_2}\right)$. It can be concluded that this value is equivalent to transportation by public bus with $\theta_b = 24\%$ (average 12 passengers per public bus), personal car with $\theta_c = 47\%$ (average 2.35 passengers per personal car), and RO-PAX ferry with port stay carbon emission included with $\theta_{v(Total)} = 52\%$ (676 passengers).

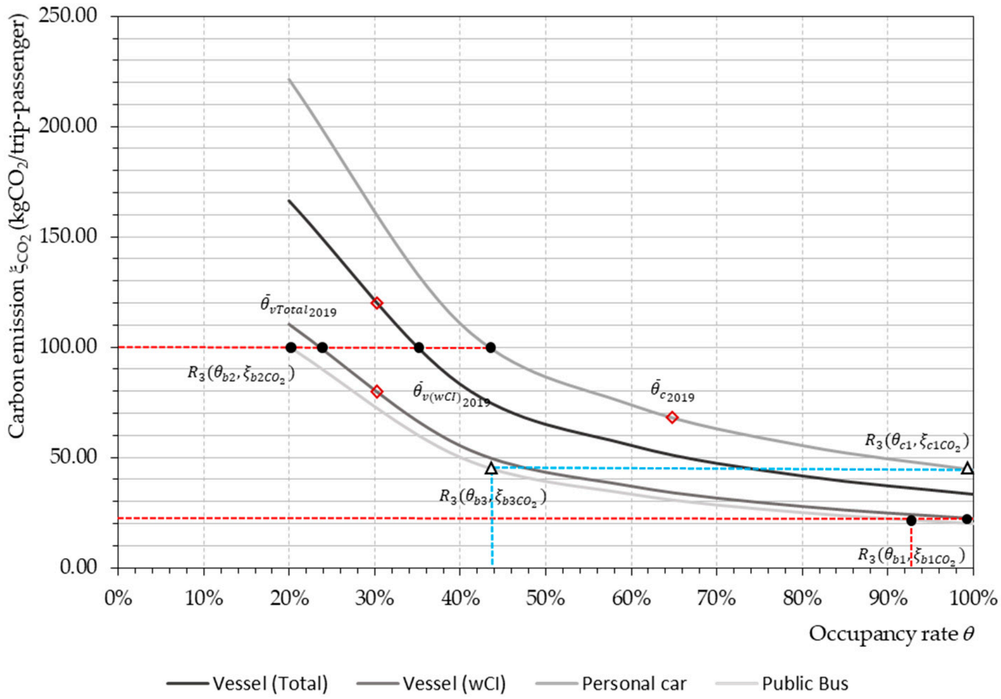
On the other hand, assuming that transportation by RO-PAX ferry vessel with port stay carbon emission included is the least favorable mode choice, when $\theta_{v(Total)} = 100\%$ (1300 passengers), as at point $R_2\left(\theta_{v(Total)1}, \xi_{v(Total)1CO_2}\right)$, it can be concluded that θ_b of the public bus needs to be less than 41% (average 20 passengers per public bus) to be less favorable at point $R_2(\theta_{b1}, \xi_{b1CO_2})$.

4.3. Case Study 3—Dubrovnik–Bari (R_3)

According to the results presented in Figure 12a and for the reference capacity of 1300 passengers, the calculated carbon emission for passenger transportation by RO-PAX ferry vessel is 43,210 $kgCO_2$ per trip when the "Cold ironing" process is not implemented. Alternatively, if the mentioned process is considered, carbon emissions would be more acceptable by approximately 33%.



(a)



(b)

Figure 12. Calculated carbon emissions on the route R_3: (**a**) total carbon emissions per single trip with respect to each transportation mode and based on the reference capacity of 1300 passengers; (**b**) comparison of carbon emissions with respect to the θ for each transportation mode choice.

In case the same number of passengers are transported by personal cars, and with $\theta_c = 100\%$ (5 passengers), the total calculated carbon emission is considerably higher: 57,616 kgCO_2 per trip. However, the most acceptable carbon emission value is obtained for public buses; where $\theta_b = 100\%$, the total calculated carbon emission is 26,499 kgCO_2 per trip.

Calculated carbon emissions (Figure 12b) for the personal car mode are identified as having the highest carbon emission value based on the reference capacity and various θ. On the other hand, the lowest calculated carbon emission value is associated with the public bus mode. In addition, the RO-PAX ferry vessel is more acceptable in terms of carbon emissions than a personal car.

However, if we consider the public bus mode as a reference for further analysis, since it is the most favorable transportation mode, the conclusion can be drawn that if $\theta_b > 93\%$ (average 46 passengers per public bus), as at point $R_3(\theta_{b1}, \xi_{b1CO_2})$, no other transportation mode choice can provide a lower carbon emission per trip passenger. In this case, the calculated carbon emission is 22.1 $kgCO_2$/trip passenger.

On the other hand, if the highest calculated carbon emission value, generated by the public bus mode ($\theta_b = 20\%$, generating 100.2 $kgCO_2$/trip passenger), is used as a reference, as at point $R_3(\theta_{b2}, \xi_{b2CO_2})$, it can be concluded that this value is equivalent to transportation by the RO-PAX ferry vessel when the port stay is not included in the calculation with $\theta_{v(wCI)} = 23\%$ (299 passengers), the RO-PAX ferry vessel when the port stay is included with $\theta_{v(Total)} = 35\%$ (455 passengers) or the personal car mode when $\theta_c = 44\%$ (average 2.2 passengers per personal car). For the above-mentioned θ, transportation by personal car or RO-PAX ferry vessel with or without a port stay included will offer more acceptable carbon emission values.

In contrast, assuming that the personal car mode is considered ($\theta_c = 100\%$ (5 passengers per car)), as it represents the least favorable mode choice at point R_3 $(\theta_{c1}, \xi_{c1CO_2})$, it can be concluded that θ_b for the public bus must be less than 43% (average 21 passengers per bus) to be less favorable at point $R_3(\theta_{b3}, \xi_{b3CO_2})$.

4.4. Discussion

The analysis of the results obtained for the route R_1 shows that public buses generate the lowest carbon emissions regarding transport work performed. The maritime transportation mode, as well as the usage of a personal car, shows higher carbon emissions. The usage of the "Cold ironing" process during port stays might bring some additional reduction in emission levels and change the preferability between the personal car and maritime transportation modes.

For the short route segment R_1S_2, it is especially notable that the maritime transportation mode has the highest carbon emission per trip passenger. Due to the short port stay, even implementing the "Cold ironing" process does not change the preferable choice. However, the emission curves based on the occupancy rate versus transport work are distant from each other, and the differences in occupancy rates between different transportation modes change the mode preferability.

Based on the occupancy rates $\theta_{c_{2019}}$ and $\theta_{vTotal_{2019}}$ for the route segment R_1S_1 in 2019 presented in Figure 8b, it is noticeable that carbon emission per transported passenger was higher for maritime transportation than for a personal car. This can be attributed to relatively high $\theta_{c_{2019}}$ (above 60%). However, by implementing the "Cold ironing" process during port stays (point $\theta_{v(wCI)_{2019}}$), this value is reduced to the level below the one obtained for a personal car. Based on these results, further improvement in reducing carbon emissions on the route segment R_1S_1 can be made through incentives to increase θ_v and to implement technical measures for the "Cold ironing" process.

Furthermore, based on the available and calculated occupancy rates $\theta_{c_{2019}}$ and $\theta_{vTotal_{2019}}$ for the route segment R_1S_3 in 2019 (Figure 10b), the carbon emission per transported passenger was considerably higher than for the personal car. Since the $\theta_{c_{2019}}$ was similar as that for the R_1S_1, the carbon emission difference can be attributed to the relatively lower $\theta_{vTotal_{2019}}$ defined on R_1S_3. By implementing the "Cold ironing" process, carbon emissions are still above that of the personal car per transported passenger. Therefore, considering that $\theta_{vTotal_{2019}}$ on R_1S_3 was 30.6% and that further incentives for increasing θ_v might not bring sufficient results, carbon emission improvement is to be made by focusing on personal car and public bus transportation.

Single lines between two destinations in the Middle and Southern Adriatic regions, which include routes R_2 and R_3, show higher preferability for maritime transportation but are still below public bus transportation. In this particular case, carbon footprint reductions caused by avoiding emissions during port stays would significantly change the preferability. This is especially observable on R_2, where during 2019, $\theta_{vTotal_{2019}}$ was 28.5% (Figure 11b). In this case, avoiding emissions during the port stay would provide a significantly lower carbon emission per transported passenger, even slightly lower than the public bus for the same θ_b. Further increasing θ_{vTotal} might further improve carbon emission per transported passenger. However, low $\theta_{vTotal_{2019}}$ on R_2 might be correlated with cargo transported by RO-RO modality, which might change carbon emission efficiency, but due to data unavailability and the work scope of this research, this case was not examined.

Results on R_3 show higher preferability for maritime transportation than for the personal car for the same occupancy rate, but it is still below public bus transportation. Based on the presented $\theta_{c_{2019}}$ and $\theta_{vTotal_{2019}}$ (Figure 12b), it is noticeable that carbon emissions per transported passenger are higher for maritime transportation than for the personal car mode. This can be attributed to high $\theta_{c_{2019}}$ (above 60%) and relatively low $\theta_{vTotal_{2019}}$, which was around 30%. By implementing the "Cold ironing" process and supplying renewable energy to vessel during the port stay, carbon emission efficiency can be further improved. Low $\theta_{vTotal_{2019}}$ on R_3 might also be correlated with cargo transported by RO-RO modality, which might change carbon emission efficiency. Therefore, by not considering cargo transportation, public bus passenger transportation on R_3 is the most efficient mode choice regarding carbon emission.

Furthermore, results obtained for carbon emissions regarding the maritime transportation mode could be partially compared with the results obtained through research performed within the project "Saving Fuel and Emissions from Maritime Transport in the Adriatic Region" (GUTTA), considering data provided through the THETIS-MRV database [73]. The scope of the GUTTA project was to establish optimal sailing routes to achieve minimal carbon emission in the Adriatic Region. The aggregated results of the research are presented in Mannarini et al. [8]. THETIS-MRV is a system to report CO_2 emissions from ships according to the EU Regulation 2015/757. Verification of the calculated results for the personal car and public bus modes was not performed due to the lack of research on particular routes in Adriatic regions.

For result verification purposes, we extract results and introduce them in Tables 17 and 18. In Table 17, the total calculated carbon emissions for selected routes for single transportation unit per trip are presented. In addition, in Table 18, we distributed calculated carbon emissions generated by the main engines, i.e., propulsion emissions ($\xi_{MEt1CO2}$) and emissions generated by the auxiliary engines on board ($\xi_{AEt1CO2}$). From Table 18, it is clearly visible that a significant portion of the calculated carbon emissions is generated to ensure the safe operation of technical systems on board ($\xi_{AEt1CO2}$) and not directly related to propulsion.

Table 17. Distribution of carbon emissions on selected routes for single transportation unit and vessel operation according to defined time periods (in $kgCO_2$/trip-unit).

	R_1S_1	R_1S_2	R_1S_3	R_2	R_3
$\xi_{vTotalCO2}$	2933.7	924.5	2346.5	32,680.2	43,210.4
$\xi_{v(wCI)CO2}$	2098.1	862.7	1281.1	12,549.8	28,752.5
ξ_{cCO2}	38.4	7.6	33.93	117.24	221.6
ξ_{bCO2}	170.08	33.66	150.25	519.26	981.43

Table 18. Distribution of total carbon emissions generated by main and auxiliary engines during t_1 (in $kgCO_2$/trip).

	R_1S_1	R_1S_2	R_1S_3	R_2	R_3
$\xi_{MEt1CO2}$	1714.3	712.9	965.9	7801.1	19,765.2
$\xi_{AEt1CO2}$	383.8	149.8	315.2	4748.7	8987.3
$\xi_{v(wCI)CO2}$	2098.1	862.7	1281.1	12,549.8	28,752.5

In the sense of data verification, we consider the measured carbon emissions obtained on the route R_2. The obtained carbon emission from the GUTTA project on the selected route was 8900 $kgCO_2$, which, compared to the 7801 $kgCO_2$ ($\zeta_{MEt1CO2}$) presented in Table 18, indicates a difference of 12%. However, the methodology of the conducted research is based on a navigational simulator implementing the ship routing mode (discoVerIng Safe and effIcient Routes—VISIR). In addition, the reference vessel taken for evaluation is a virtual simulation model, and the technical specifications do not fully correspond to the reference vessel considered in our research.

Furthermore, considering result verification through the THETIS-MRV database, annual CO_2 carbon emission for reference vessel "Zadar" employed on route R_2 was 279.3 $kgCO_2$/Nm in 2019, which corresponds to 25,528.02 $kgCO_2$/per trip. This represents a difference of 28% between reported and calculated carbon emissions. However, annually reported carbon emissions between consecutive years vary up to 9%. As this report is based on annual carbon emissions, the differences are to be attributed to unknown vessel operation patterns (number of voyages or navigational distances or even specific routes on which the vessel was actually employed).

5. Conclusions

This work presents a methodology to assess the carbon emissions of the passenger transportation modes between Italy and Croatia. Transportation modes chosen for carbon emission comparison include maritime and road transportation modes. In each of the considered Adriatic regions, example routes were chosen based on the presently available maritime routes, the difference in the destination locations and transport mode availability, the passenger flow history, and the different vessel types in use. Thus, the selected routes are Venice–Pula–Poreč, Ancona–Zadar, and Bari–Dubrovnik.

The methodology used for calculating carbon emissions for each of the selected transportation modes is different due to the different technical characteristics and operation modes, different industry regulations, different industry standards, and data availability. The calculation of the carbon emissions of the maritime transportation mode is based on presently available models for calculating emissions for specific vessels. Moreover, the carbon emission calculation of the road transportation mode utilizes the existing emission factors based on the industry standards and presently available research. The carbon emissions for each route are calculated based on the reference capacity, which is based on the vessel capacity operating on a particular route.

The analysis of the relatively short circled routes in the Northern Adriatic region, consisting of several midpoints, such as Venice–Pula–Poreč, shows that the public bus represents the best choice with respect to the generated carbon emissions. This transportation mode is followed by a personal car, while the maritime transportation mode represents the least preferable choice from the carbon emission standpoint.

Single lines between two destinations in the Middle and Southern Adriatic regions, including the lines Ancona–Zadar and Dubrovnik–Bari, show higher preferability for maritime transportation but are still below public bus transportation. Moreover, the possibility of implementation of the "Cold ironing" process significantly impacts the preferability of the transportation mode choice. However, considering that carbon emission curves per transported passenger between different transportation modes are more distant than on shorter routes in the Northern Adriatic region, the differences in occupancy rate change the preferability.

This study provided a more detailed insight into the influence of the occupancy rate θ on the selection of the optimal transportation mode with respect to carbon emission efficiency, which is not sufficiently addressed in the existing literature at the present moment. The transportation units involved in maritime and road modes have different passenger capacities, and therefore, it is very challenging to adequately compare generated carbon emissions, as they are strongly influenced by the passenger demand and occupancy rates.

Furthermore, the study presented in this paper represents a basis for possible future modernization and optimization of the passenger transportation network in the Italy–Croatia cross-border region, with a special emphasis on introducing and developing modern, sustainable, and multimodal passenger transportation routes. The main goal of introducing such solutions is carbon emission reduction in the Adriatic region, with these solutions also being proposed and discussed within this study. Moreover, future research might include more detailed models into the carbon emission calculation framework and the analysis of transportation route options based on graph models.

Author Contributions: Conceptualization, J.D., T.K. and N.L.; methodology, J.D.; software, T.K.; validation, J.D., T.K. and N.L.; formal analysis, J.D.; investigation, J.D. and T.K.; resources, J.D., T.K. and N.L.; data curation, J.D. and T.K.; writing—original draft preparation, J.D., T.K., N.L. and S.Ž.; writing—review and editing, J.D., T.K., N.L. and S.Ž.; visualization, T.K.; supervision, N.L.; project administration, S.Ž.; funding acquisition, S.Ž. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the Interreg Italy—Croatia CBC Programme, project Maritime and Multimodal Sustainable Passenger Transport Solutions and Services (MIMOSA), ID number 10249002.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: This research was supported by the European Regional Development Fund within the Interreg Italy–Croatia MIMOSA project. The authors would especially like to thank Capt. Robert Jurić for sharing his expertise on vessel voyage and route planning and for his contribution in this field during research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. European Environment Agency (EEA). Greenhouse Gas Emissions from Transport in Europe. Available online: https://www.eea.europa.eu/ims/greenhouse-gas-emissions-from-transport (accessed on 6 February 2022).
2. European Environment Agency (EEA). Share of Transport Greenhouse Gas Emissions. Available online: https://www.eea.europa.eu/data-and-maps/daviz/share-of-transport-ghg-emissions-2/#tab-googlechartid_chart_13 (accessed on 6 February 2022).
3. European Environment Agency (EEA). Passenger and Freight Transport Demand in Europe. Available online: https://www.eea.europa.eu/data-and-maps/indicators/passenger-and-freight-transport-demand/assessment-1 (accessed on 6 February 2022).
4. Croatian Bureau of Statistics. Available online: https://www.dzs.hr/default_e.htm (accessed on 15 November 2021).
5. European Environment Agency (EEA). Rail and Waterborne—Best for Low-Carbon Motorised Transport. Available online: https://www.eea.europa.eu/publications/rail-and-waterborne-transport (accessed on 2 December 2021).
6. International Maritime Organization (IMO). Guidelines for Voluntary Use of the Ship Energy Efficiency Operational Indicator (EEOI). MPEC.1/Circ.684. Available online: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Circ-684.pdf (accessed on 2 December 2021).
7. International Maritime Organization (IMO). Guidelines on Survey and Certification of the Energy Efficiency Design Index (EEDI), as Amended (Resolution MEPC.254(67), as Amended by Resolution MEPC.261(68) and Resolution MEPC.309(73)). MPEC.1/Circ.855/Rev.2. Available online: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/MEPC.1-Circ.855-Rev.2.pdf (accessed on 2 December 2021).
8. Mannarini, G.; Carelli, L.; Orović, J.; Martinkus, C.P.; Coppini, G. Towards Least-CO_2 Ferry Routes in the Adriatic Sea. *J. Mar. Sci. Eng.* **2021**, *9*, 115. [CrossRef]
9. Dagkinis, I.; Nikitakos, N. Slow Steaming Options Investigation Using Multi Criteria Decision Analysis Method. In Proceedings of the Conference ECONSHIP2015, Chios, Greece, 24–27 June 2015.
10. Department for Environment, Food and Rural Affairs (DEFRA). Passenger Transport Emission Factors—Methodology Factor. Available online: https://www.carbonindependent.org/files/passenger-transport.pdf (accessed on 17 November 2021).
11. Ančić, I.; Perčić, M.; Vladimir, N. Alternative Power Options to Reduce Carbon Footprint of Ro-Ro Passenger Fleet: A Case Study of Croatia. *J. Clean. Prod.* **2020**, *271*, 122638. [CrossRef]
12. Rešetar, M.; Pejić, G.; Lulic, Z. Road Transport Emissions of Passenger Cars in the Republic of Croatia. In Proceedings of the 8th European Combustion Meeting, Dubrovnik, Croatia, 18–21 April 2017.

13. European Commission (EC). A Clean Planet for All—A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy. COM(2018) 773 Final. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773 (accessed on 21 November 2021).
14. European Parliament. Maritime Transport: Strategic Approach. Available online: https://www.europarl.europa.eu/factsheets/en/sheet/124/maritime-transport-strategic-approach (accessed on 21 November 2021).
15. European Parliament. Integrated Maritime Policy of the European Union. Available online: https://www.europarl.europa.eu/factsheets/en/sheet/121/integrated-maritime-policy-of-the-european-union (accessed on 21 November 2021).
16. European Commission (EC). Roadmap to a Single European Transport Area—Towards a Competitive and Resource Efficient Transport System. White Paper. COM(2011—144 Final). Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0144:FIN:EN:PDF (accessed on 21 November 2021).
17. European Commission (EC). Strategic Goals and Recommendations for the EU's Maritime Transport Policy until 2018. COM (2009-8 Final). Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM%3A2009%3A0008%3AFIN%3AEN%3APDF (accessed on 21 November 2021).
18. European Commission (EC). The European Green Deal. COM (2019—640 Final). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN (accessed on 21 November 2021).
19. European Commission (EC). Sustainable and Smart Mobility Strategy. (COM/2020/789 Final). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789 (accessed on 21 November 2021).
20. Kane, L.; Del Mistro, R. Changes in Transport Planning Policy: Changes in Transport Planning Methodology? *Transportation* **2003**, *30*, 113–131. [CrossRef]
21. Zuidgeest, M.; Maarseveen, M.F.A.M. Transportation Planning for Sustainable Development. In Proceedings of the 19th South African Transport Conference (SATC 2000), Pretoria, South Africa, 17–20 July 2000.
22. Litman, T. *Introduction to Multi-Modal Transportation Planning*; Victoria Transport Policy Institute: Victoria, BC, Canada, 2017.
23. Sirotić, M.; Žuškin, S.; Rudan, I.; Stocchetti, A. Methodology for the Sustainable Development of the Italy-Croatia Cross-Border Area: Sustainable and Multimodal/Cross-Border Passenger Services. *Sustainability* **2021**, *13*, 11895. [CrossRef]
24. Wiedmann, T.; Minx, J. A Definition of 'Carbon Footprint'. In *Ecological Economics Research Trends*; Nova Science Publishers: Hauppauge, NY, USA, 2008; pp. 1–11.
25. Pandey, D.; Agrawal, M.; Pandey, J.S. Carbon Footprint: Current Methods of Estimation. *Environ. Monit. Assess.* **2011**, *178*, 135–160. [CrossRef]
26. Sarkodie, S.A. Environmental Performance, Biocapacity, Carbon & Ecological Footprint of Nations: Drivers, Trends and Mitigation Options. *Sci. Total Environ.* **2021**, *751*, 141912. [CrossRef]
27. Lenzen, M.; Sun, Y.-Y.; Faturay, F.; Ting, Y.-P.; Geschke, A.; Malik, A. The Carbon Footprint of Global Tourism. *Nat. Clim. Change* **2018**, *8*, 522–528. [CrossRef]
28. Osorio-Tejada, J.L.; Llera-Sastresa, E.; Hariza Hashim, A. Well-to-Wheels Approach for the Environmental Impact Assessment of Road Freight Services. *Sustainability* **2018**, *10*, 4487. [CrossRef]
29. Ma, F.; Wang, W.; Sun, Q.; Liu, F.; Li, X. Ecological Pressure of Carbon Footprint in Passenger Transport: Spatio-Temporal Changes and Regional Disparities. *Sustainability* **2018**, *10*, 317. [CrossRef]
30. Kitamura, Y.; Ichisugi, Y.; Karkour, S.; Itsubo, N. Carbon Footprint Evaluation Based on Tourist Consumption toward Sustainable Tourism in Japan. *Sustainability* **2020**, *12*, 2219. [CrossRef]
31. Wang, S.; Ge, M. *Everything You Need to Know About the Fastest-Growing Source of Global Emissions: Transport*; World Resources Institute: Washington, DC, USA, 2019.
32. Ülker, D.; Bayırhan, İ.; Mersin, K.; Gazioğlu, C. A Comparative CO_2 Emissions Analysis and Mitigation Strategies of Short-Sea Shipping and Road Transport in the Marmara Region. *Carbon Manag.* **2021**, *12*, 1–12. [CrossRef]
33. Yang, L.; Zhang, Q.; Zhang, Y.; Lv, Z.; Wang, Y.; Wu, L.; Feng, X.; Mao, H. An AIS-Based Emission Inventory and the Impact on Air Quality in Tianjin Port Based on Localized Emission Factors. *Sci. Total Environ.* **2021**, *783*, 146869. [CrossRef] [PubMed]
34. Zhang, S.; Peng, D.; Li, Y.; Zu, L.; Fu, M.; Yin, H.; Ding, Y. Study on the Real-World Emissions of Rural Vehicles on Different Road Types. *Environ. Pollut.* **2021**, *273*, 116453. [CrossRef] [PubMed]
35. Sun, Z.; Wang, C.; Ye, Z.; Bi, H. Long Short-Term Memory Network-Based Emission Models for Conventional and New Energy Buses. *Int. J. Sustain. Transp.* **2021**, *15*, 229–238. [CrossRef]
36. Angelevska, B.; Atanasova, V.; Andreevski, I. Urban Air Quality Guidance Based on Measures Categorization in Road Transport. *Civ. Eng. J.* **2021**, *7*, 253–267. [CrossRef]
37. Obaid, M.; Torok, A.; Ortega, J. A Comprehensive Emissions Model Combining Autonomous Vehicles with Park and Ride and Electric Vehicle Transportation Policies. *Sustainability* **2021**, *13*, 4653. [CrossRef]
38. Batur, İ.; Bayram, I.S.; Koc, M. Impact Assessment of Supply-Side and Demand-Side Policies on Energy Consumption and CO_2 Emissions from Urban Passenger Transportation: The Case of Istanbul. *J. Clean. Prod.* **2019**, *219*, 391–410. [CrossRef]
39. Zhang, H.; Razzaq, A.; Pelit, I.; Irmak, E. Does Freight and Passenger Transportation Industries Are Sustainable in BRICS Countries? Evidence from Advance Panel Estimations. *Econ. Res.—Ekonomska Istraživanja* **2021**, *0:0*, 1–21. [CrossRef]
40. Brewer, T.L. Black Carbon Emissions and Regulatory Policies in Transportation. *Energy Policy* **2019**, *129*, 1047–1055. [CrossRef]
41. Fridell, E.; Bäckström, S.; Stripple, H. Considering Infrastructure When Calculating Emissions for Freight Transportation. *Transp. Res. Part D Transp. Environ.* **2019**, *69*, 346–363. [CrossRef]

42. Anenberg, S.; Miller, J.; Henze, D.; Minjares, R. *A Global Snapshot of the Air Pollution-Related Health Impacts of Transportation Sector Emissions in 2010 and 2015*; International Council on Clean Transportation: Washington, DC, USA, 2019.
43. Russo, M.A.; Relvas, H.; Gama, C.; Lopes, M.; Borrego, C.; Rodrigues, V.; Robaina, M.; Madaleno, M.; Carneiro, M.J.; Eusébio, C.; et al. Estimating Emissions from Tourism Activities. *Atmos. Environ.* **2020**, *220*, 117048. [CrossRef]
44. Wang, S.; Psaraftis, H.N.; Qi, J. Paradox of International Maritime Organization's Carbon Intensity Indicator. *Commun. Transp. Res.* **2021**, *1*, 100005. [CrossRef]
45. Skrúcaný, T.; Kendra, M.; Kalina, T.; Jurkovič, M.; Vojtek, M.; Synák, F. Environmental Comparison of Different Transport Modes. *NAŠE MORE* **2018**, *65*, 192–196. [CrossRef]
46. Rivarolo, M.; Iester, F.; Massardo, A.F. An Algorithm for Comparative Analysis of Power and Storage Systems for Maritime Applications. *E3S Web Conf.* **2022**, *334*, 06001. [CrossRef]
47. Wanke, P.; Chen, Z.; Zheng, X.; Antunes, J. Sustainability Efficiency and Carbon Inequality of the Chinese Transportation System: A Robust Bayesian Stochastic Frontier Analysis. *J. Environ. Manag.* **2020**, *260*, 110163. [CrossRef]
48. Fridell, E. Emissions and Fuel Use in the Shipping Sector. In *Green Ports: Inland and Seaside Sustainable Transportation Strategies*; Bergqvist, R., Monios, J., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 19–33. ISBN 978-0-12-814054-3.
49. Zis, T.P.V.; Psaraftis, H.N.; Tillig, F.; Ringsberg, J.W. Decarbonizing Maritime Transport: A Ro-Pax Case Study. *Res. Transp. Bus. Manag.* **2020**, *37*, 100565. [CrossRef]
50. Kang, A.S.; Jayaraman, K.; Soh, K.-L.; Wong, W.-P. Tackling Single-Occupancy Vehicles to Reduce Carbon Emissions: Actionable Model of Drivers' Implementation Intention to Try Public Buses. *J. Clean. Prod.* **2020**, *260*, 121111. [CrossRef]
51. Shiraki, H.; Matsumoto, K.; Shigetomi, Y.; Ehara, T.; Ochi, Y.; Ogawa, Y. Factors Affecting CO_2 Emissions from Private Automobiles in Japan: The Impact of Vehicle Occupancy. *Appl. Energy* **2020**, *259*, 114196. [CrossRef]
52. Soukhov, A.; Mohamed, M. Occupancy and GHG Emissions: Thresholds for Disruptive Transportation Modes and Emerging Technologies. *Transp. Res. Part D Transp. Environ.* **2022**, *102*, 103127. [CrossRef]
53. Amatuni, L.; Ottelin, J.; Steubing, B.; Mogollón, J.M. Does Car Sharing Reduce Greenhouse Gas Emissions? Assessing the Modal Shift and Lifetime Shift Rebound Effects from a Life Cycle Perspective. *J. Clean. Prod.* **2020**, *266*, 121869. [CrossRef]
54. Fernando, C.; Soo, V.K.; Compston, P.; Doolan, M. *The Impact of Car-Based Shared Mobility on Greenhouse Gas Emissions: A Review*; Social Science Research Network: Rochester, NY, USA, 2022.
55. Chergui, S.; Agoujil, S. Implementation of Vehicle Occupancy and Aggregate Emission Rate. In Proceedings of the 3rd International Conference on Smart City Applications, Tetouan, Morocco, 10–11 October 2018; Association for Computing Machinery: New York, NY, USA, 2018; pp. 1–5.
56. Schembari, C.; Cavalli, F.; Cuccia, E.; Hjorth, J.; Calzolai, G.; Pérez, N.; Pey, J.; Prati, P.; Raes, F. Impact of a European Directive on Ship Emissions on Air Quality in Mediterranean Harbours. *Atmos. Environ.* **2012**, *61*, 661–669. [CrossRef]
57. Pseftogkas, A.; Koukouli, M.-E.; Skoulidou, I.; Balis, D.; Meleti, C.; Stavrakou, T.; Falco, L.; van Geffen, J.; Eskes, H.; Segers, A.; et al. A New Separation Methodology for the Maritime Sector Emissions over the Mediterranean and Black Sea Regions. *Atmosphere* **2021**, *12*, 1478. [CrossRef]
58. Stazić, L.; Radonja, R.; Pelić, V.; Lalić, B. The Port of Split International Marine Traffic Emissions Inventory. *Pomorstvo* **2020**, *34*, 32–39. [CrossRef]
59. Škurić, M.; Maraš, V.; Radonjic, A.; Gagić, R.; Nikolić, D. Some Results of Air Pollution from Passenger Ferries in the Boka Kotorska Bay. In *The Montenegrin Adriatic Coast*; The Handbook of Environmental Chemistry; Springer International Publishing: Cham, Switzerland, 2021; ISBN 978-3-030-77628-2.
60. Vidas, S.; Cukrov, M.; Šutalo, V.; Rudan, S. CO_2 Emissions Reduction Measures for RO-RO Vessels on Non-Profitable Coastal Liner Passenger Transport. *Sustainability* **2021**, *13*, 6909. [CrossRef]
61. Degiuli, N.; Martić, I.; Farkas, A.; Gospić, I. The Impact of Slow Steaming on Reducing CO_2 Emissions in the Mediterranean Sea. *Energy Rep.* **2021**, *7*, 8131–8141. [CrossRef]
62. Merico, E.; Gambaro, A.; Argiriou, A.; Alebic-Juretic, A.; Barbaro, E.; Cesari, D.; Chasapidis, L.; Dimopoulos, S.; Dinoi, A.; Donateo, A.; et al. Atmospheric Impact of Ship Traffic in Four Adriatic-Ionian Port-Cities: Comparison and Harmonization of Different Approaches. *Transp. Res. Part D Transp. Environ.* **2017**, *50*, 431–445. [CrossRef]
63. *ISO 8217 2017*; Fuel Standard for Marine Distillate Fuel. World Fuel Services Corporation: Miami, FL, USA, 2017. Available online: https://www.wfscorp.com/sites/default/files/ISO-8217-2017-Tables-1-and-2-1-1.pdf(accessed on 5 November 2021).
64. Trivyza, N.L.; Rentizelas, A.; Theotokatos, G. A Comparative Analysis of EEDI Versus Lifetime CO_2 Emissions. *J. Mar. Sci. Eng.* **2020**, *8*, 61. [CrossRef]
65. Tran, T.A. Calculation and Assessing the EEDI Index in the Field of Ship Energy Efficiency for M/V Jules Garnier. *J Mar. Sci Res Dev* **2016**, *6*, 212. [CrossRef]
66. Babicz, J. *Wartsila Encyclopedia of Ship Technology*, 2nd ed.; WÄRTSILÄ Corporation: Helsinki, Finland, 2015.
67. Waters, J. Atlantic Center for the Innovative Design and Control of Small Ships: Surface Effect Ship (Ses) Test Program. In Proceedings of the 2004 American Society for Engineering Education Annual Conference & Exposition, Salt Lake City, UT, USA, 20–23 June 2004; pp. 9.242.1–9.242.10.
68. Ančić, I.; Vladimir, N.; Cho, D.-S. Determining Environmental Pollution from Ships Using Index of Energy Efficiency and Environmental Eligibility (I4E). *Mar. Policy* **2018**, *95*, 1–7. [CrossRef]

69. Finnish Information Centre of Automobile Sector (Autoalan Tiedotuskeskus). ACEA Statistics. *Average Age of Passenger Cars in European Countries*. Available online: https://www.aut.fi/en/statistics/international_statistics/average_age_of_passenger_cars_in_european_countries (accessed on 15 November 2021).
70. European Environment Agency (EEA). Average CO2 Emissions from Newly Registered Motor Vehicles in Europe. Available online: https://www.eea.europa.eu/data-and-maps/indicators/average-co2-emissions-from-motor-vehicles/assessment-1 (accessed on 2 December 2021).
71. Interreg Italy-Croatia Maritime and Multimodal Sustainable Passenger Transport and Services (MIMOSA). O.3.5. Cross-Border Transport Sustainability Action Plan. Available online: https://edu.pfri.hr/mimosa/ (accessed on 5 January 2022).
72. MarineTraffic: Global Ship Tracking Intelligence. Available online: https://www.marinetraffic.com/en/ais/home/centerx:-12.0/centery:25.0/zoom:4 (accessed on 23 December 2021).
73. EMSA\THETIS-MRV. Available online: https://mrv.emsa.europa.eu/#public/eumrv (accessed on 17 January 2022).