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Article

Carbon footprint in choosing the best sustainable mode of intercity passenger transport

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Abstract: The carbon footprint, which measures greenhouse gas emissions, is a good environmental indicator for choosing the best sustainable mode of transportation. The available emission factors depend heavily on the calculation methodology and are hardly comparable. The minimum and maximum scenarios are one way of making the results comparable. The best sustainable passenger transport modes between Rijeka and Split were investigated and compared by calculating the minimum and maximum available emission factors. The study aims to select the best sustainable mode of transport on the chosen route and to support the decision-making process regarding the electrification of the Lika railroad, which partially connects the two cities. In the minimum scenario, ferry transport without vehicles was the best choice when the transportation time factor was not relevant, and electric rail transport when it was. In the maximum scenario, the electric train and the ferry with vehicles were equally good choices. Road transportation between cities was not competitive at all. The comparison of the carbon footprint based on minimum and maximum scenarios gives a clear insight into the ratio of greenhouse gas emissions from vehicles in passenger transport. It supports the electrification of the Lika railroad as the best sustainable transport solution on the route studied.

Keywords: carbon footprint; transportation sustainability; passenger transport; minimum and maximum scenarios; Croatian transport system

1. Introduction

The accumulation of greenhouse gases in the atmosphere contributes to climate change, thus having particular meaning. The most abundant of these gases is carbon dioxide (CO_2), which is released into the environment through the combustion of fossil fuels (Shirley and Gecan, 2022). Effort Sharing Regulation (ESR) from 2018 obliges European Union Member States to reduce greenhouse gas emissions by 40% by 2030 compared to 2005 levels. Amendments from 2023 establish an additional obligation regarding emission reduction by 55% to 2030 compared to 1990 levels (European Commission, 2023a). Carbon footprint is a measure of the total impact of greenhouse gases on global warming (Živković et al., 2020). According to Mike Berners-Lee, it is the sum of all greenhouse emissions, which are the result of the production of a certain product or activity (Mulvaney, 2022). Traffic is the largest source of greenhouse gasses in developed countries, and CO_2 share in the total emission is 97%. For that reason, the value of all greenhouse gas emissions is expressed as the CO_2 coefficient, i.e., equivalent CO_2 emission (VR Group, 2023). CO_2 emission is directly proportional to fuel consumption (European Commission, 2023b). A share of energy-related emission of CO_2 by economic sectors in the USA is shown in **Figure 1**.

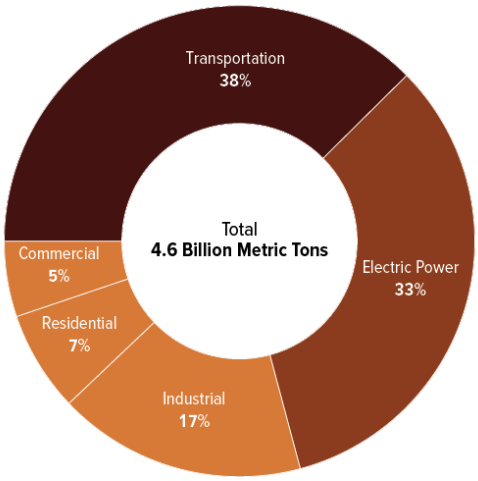

Figure 1. CO_2 emissions from energy by economic sectors in the USA, 2021.
Source: Shirley and Gecan, 2022.

Road transport accounts for the largest share of greenhouse gas emissions. The share of emissions by types of transportation in the USA is shown in **Figure 2**.

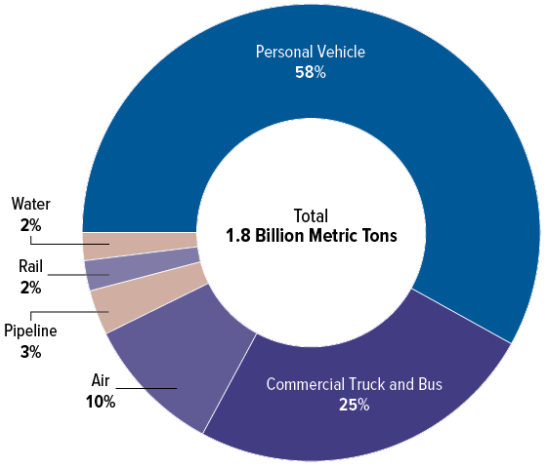

Figure 2. The share of CO_2 emissions by types of transportation in the USA, 2021.
Source: Shirley and Gecan, 2022.

The emissions of the transport system also depend on the average carbon content in the energy production process used to power it, as well as on the load factor of the system (e.g., the average occupancy in passenger traffic) (VR Group, 2023). Electric trains are almost always the best option for medium and short distances (especially when they use electricity from renewable energy sources). Medium-distance transportation by electric train instead of car reduces emissions by approx. 80% (GOV.UK, 2022; Ritchie, 2024). Some sources show that maritime transport is environmentally acceptable, while others show it is very polluting. Different sources use different calculation methods (Shirley and Gecan, 2022). Various methods of carbon footprint calculation led to different values of the conversion factor in certain types of transportation, so there are no universal reference values. The Finnish research institute, VTT, provides 19 different calculation methods, and none of them is flawless. In passenger transport, especially maritime transport, in addition to passengers, a significant amount of cargo is transported as well. European Union's

MRV Standard and the Finnish F-EN 16258 Standard distinguish two basic calculation methods in maritime transport based on the criterion of passenger and cargo weight or the criterion of space designated for passengers and cargo on the ship. The differences in results between those two methods can account for 70% (Tapaninen, 2021a). There is also a financial criterion that divides the load between passengers and cargo based on the profit share (Travel and Climate, 2023). Due to the complexity of such calculations, especially in upstream processes of production and fuel distribution and social status, habits, and behaviors of the passengers, Berners-Lee states that it is never possible to be accurate absolutely but, in most cases, it does not even matter (VR Group, 2023).

Without a doubt, carbon footprint is one of the criteria for choosing the transport mode on a route. Based on this criterion, this research aims to determine the priorities in selecting the most environmentally friendly means of transport in passenger traffic on the intercity line Rijeka—Split in Croatia, but also as a contribution to considering the need for electrification of the Lika railway, which connects the Dalmatian cities with northern Croatia. The outdated rail transport technology on the Lika railway makes passenger transport uncompetitive, and such quality of freight transport is the limiting factor for the ports of Zadar, Šibenik, and Split development (Vukić et al., 2022). The results should influence the decision-makers in the choice of the type of transportation at the individual, public, and management levels.

2. Materials and methods

The research includes the calculation of the carbon footprint in passenger traffic between the cities of Rijeka and Split by bus, train, and ferry. The selected types of vehicles are the inter-city bus (capacity of 51 passengers) on the regular Rijeka—Split line, the MB "Marko Polo" on the canceled long coastal ferry line Rijeka—Split (capacity of 1100 passengers and 270 cars) and the regular train which operates on the Zagreb—Split line (with an average capacity of 270 passengers), given that the cities of Rijeka and Split are not yet connected by a direct railway line. The calculation includes distance, vehicle load (the number of passengers, i.e., the amount of load), and the conversion factor for each transportation type. The results are expressed as the emission of equivalent CO_2 amount by passenger kilometer (gCO_2 e/pkm). The calculation was made according to the following formula:

$$\text{Emission} = \text{distance} \times \text{emission factor} / \text{no. of passengers} \quad (1)$$

The number of passengers (load) means occupancy of 60% of the vehicle's maximum capacity (Čamaj et al., 2022). Vehicle speed significantly increases the value of the emission factor, especially in ferry transportation (Travel and Climate, 2023). The emission factor values are relevant for a specific vehicle on a selected route. The calculation operated with low speeds and highlighted as the travel time.

To make the results of carbon footprint calculation in traffic comparable, the methodologies of calculation of emission factors for transport modes must be compatible. For this reason, in this research, reference values from several different sources will be used to compare the carbon footprint in the calculation with the minimum and maximum values of the conversion factors. Methodologically, the results of total greenhouse gas emissions expressed through CO_2 equivalent emission

units will not be relevant or considered separately. The emphasis will be on emission ratios in different types of transport between the same destinations with methodological conditions of minimum and maximum values. Based on such results, conclusions will be brought out about the advantages of certain types of transport on the selected route according to the carbon footprint criterion.

3. Results

Table 1 shows an overview of the distance of the transport route and the capacity of vehicles in certain types of transport on the examined route.

Table 1. Transport route distance and capacities of transport vehicles on the section Rijeka—Split.

Vehicle	Capacity (no. of passengers)	Distance
Car petrol, diesel	5	415
Electric car	5	415
Bus	51, 80	415
Train[a]	137, 270, 360	453
Ferry	1100	294

Note: "a" means the railway route is divided into an electrified section (Rijeka—Oštarije, 127 km) and an unelectrified section (the Lika railway, Oštarije – Knin—Split, 326 km).
Source: Crobus (2023); HŽŽP (2022); Hina (2022); HŽ Infrastruktura (2022); Jadrolinija (2023); Simović (1990); Udaljenost (2023).

Table 2 shows an overview of emission factors in different types of transportation.

Table 2. Emission factors of greenhouse gases by type of transportation.

Transport mode	Emission factor (gCO_2 e/pkm)
Car petrol, diesel	42, 60
Electric car	5, 15
Bus diesel (average)	89, 97, 109
Bus diesel (long distance, coach)	7[b], 25, 26
Train diesel	84, 91
Train electric	7, 24, 35
Ferry[a] (foot)	18, 19
Ferry[a] (car)	129, 226
Ferry[a] (car, 4 passengers)	44

Note: "a" means LSFO (low-sulfur fuel oil), the listed conversion factors are valid for regular ferries, not fast ferries; "b" means valid for a bus that uses biodiesel.
Source: Shirley and Gecan (2022); Travel and Climate (2023); UK Government (2022); Van der Bij (2022); DEFRA (2007).

Calculation results are shown in **Table 3**.

Table 3. Total greenhouse gas emission by passenger kilometer on the selected route by types of transportation (min; max).

Route Rijeka—Split	Distance/km	Time/h	Capacity 60% no. of passengers	Emission factor gCO_2 e/pkm	TotalgCO_2 e/pkm	
				Min/Max	Min.	Max.
Bus	415	5	31	25/109	334.68	1459.19
Train diesel	453	8	162	84/91	234.89	254.46
Electric train	453	8	162	7/35	19.57	97.87
Ferry	294	13	660	18/226	8.02	100.67
Cars	415	5	3	42/60	5810	8300
Electric cars	415	5	3	5/15	691.67	2075

4. Discussion

The results show that in passenger transport on the Rijeka—Split route at 60% capacity utilization, the smallest carbon footprint in the minimum scenario is caused by passengers without a vehicle on a ferry, followed by the electric railroad. In the maximum scenario, electric rail and ferry traffic (including vehicles on board) have almost identical values. In the same scenario, the carbon footprint per passenger kilometer for electric rail transport is 93.29% lower than for bus transport and 61.54% lower than for diesel rail transport. In this section, 127 km have already been electrified, so the carbon footprint on this part is slightly smaller than shown. However, on the remaining part of the route (the Lika railroad, 326 km), significant ups and downs require additional propulsion and increase the carbon footprint (Vukić et al., 2022). The results obtained should be interpreted in such a context. Considering the significantly shorter transportation time by rail compared to sea transport, electric rail seems to be the best choice on the observed route according to the carbon footprint criterion. Sea transportation of passengers without a car on the same route remains competitive when transportation time is not crucial, e.g. for tourist trips. Transporting cars by ferry with an average load factor is still environmentally friendly. Theoretically, if all passenger vehicles transported by ferry have an electric drive, the carbon footprint of road transport with these cars on the observed route would be 75%–88% lower than that of transport with classic cars, but still not competitive comparing to the maritime and railway transportation. Realistically, the traffic of electric cars on this route is marginal at the moment. Fossil-fueled cars are not competitive with electric rail in passenger or ferry transport on the observed route according to this criterion, as their carbon footprint is more than 98% larger in both scenarios.

Transportation is responsible for about a quarter of global carbon dioxide (CO_2) emissions from energy production (Ritchie, 2015), and calculating the carbon footprint provides a general overview of greenhouse gas emissions (Živković et al., 2020). In 2019, cars, trucks and busses were responsible for 83% of emissions in the transport sector, while at the same time 81% of all passenger kilometers were traveled by car (Shirley and Gecan, 2022). Decisions on transportation infrastructure will affect emissions for decades to come, so they should be considered in the context of global warming (Solomon et al., 2009). Decision makers in the transportation sector should promote infrastructure solutions with the lowest carbon emissions when deciding on

transport between cities, rural and urban areas and public transport (Litman, 2008). Considering the need for quality connections between the cities of Rijeka and Split and other central Dalmatian cities with the hinterland, and in the context of global warming and the commitment to reduce CO_2 emissions, the electrification and reconstruction of the Lika railroad is also a necessity. In addition to high-quality passenger transport connections, the electric railroad would promote the revitalization of the Central Dalmatian ports. The railroad is the most environmentally friendly means of transportation. It has the highest energy efficiency with low pollutant emissions (VR Group, 2023). Investments in rail transport led to a reduction in traffic intensity on the road, and the carbon footprint of electric rail transport is many times lower. Sales of electric vehicles have increased significantly in recent times because battery prices have fallen, their capacity is greater and the number of charging stations has increased (U.S. Department of Energy, 2023). Although electrically powered vehicles do not produce emissions, electricity generation does produce emissions, which must be taken into account (Congressional Budget Office, 2022). Only if the electricity generation comes predominantly or entirely from renewable energy sources could electric road vehicles be competitive under this criterion. The shipping industry has regularly lagged behind in the introduction of environmental protection measures. Their effectiveness is delayed by the long service life of ships, which are not covered by the new measures. Although maritime transport accounts for only 3% of global greenhouse gas emissions, the IMO published ambitious CO_2 reduction guidelines as early as 2018, which were unfortunately weakened in 2021 to reduce the carbon intensity of maritime transport by 11% between 2019 and 2026. (Tapaninen, 2021b) According to the Congressional Budget Office (CBO), the measures set are having an effect, so that CO_2 emissions in the transport sector are lower than in 2005 and a further reduction of 15% is estimated by 2032 compared to the same referent year (Shirley and Gecan, 2022).

5. Conclusion

Carbon footprint is one of the environmental pollution indicators in which the transport sector leads the way and can help to choose the ecologically best transport mode on the transport route. The values of the carbon footprint are very sensitive to the calculation methodology. Displaying the minimum and maximum values is one of the ways to assess the extent of pollution. According to this criterion and all listed calculation elements, the electric railway is the optimal option for connecting Rijeka and Split in passenger traffic. The decision for the Lika railway to electrify follows the reducing CO_2 emissions policy aiming to net zero carbon emissions in the future. Nevertheless, environmental criteria are not the only ones; economic and social criteria are equally significant elements of sustainable transport.

Conflict of interest: The author declares no conflict of interest.

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