sustainability

MDPI

Review

Carbon Intensity of Passenger Transport Modes: A Review of Emission Factors, Their Variability and the Main Drivers

Michel Noussan *, Edoardo Campisi and Matteo Jarre

Decisio S.r.l., Corso Marconi 34, 10125 Turin, Italy
* Correspondence: m.noussan@decisio.nl

Abstract: The transport sector is responsible for a significant amount of global carbon emissions, and several policies are being implemented at different levels to reduce its impact. To properly assess the effectiveness of planned measures, analysts often rely on average emission factors for different transport modes. However, average values often hide significant variability that stems from factors along the entire supply chain of transport modes. This review presents a comprehensive overview of research on this topic, comparing emission factors for different passenger transport modes and discussing the main drivers and parameters that affect their variability. The results are useful for researchers and policymakers to properly understand the reliability of carbon intensity indicators when evaluating the impact and effectiveness of sustainable transport policies.

Keywords: transport; energy; emissions; emission factors; transport modes

Citation: Noussan, M.; Campisi, E.; Jarre, M. Carbon Intensity of Passenger Transport Modes: A Review of Emission Factors, Their Variability and the Main Drivers. *Sustainability* **2022**, *14*, 10652. https://doi.org/10.3390/su141710652

Academic Editor: Lei Zhang

Received: 9 August 2022
Accepted: 24 August 2022
Published: 26 August 2022

1. Introduction

Decreasing carbon emissions is one of the main goals of mobility strategies worldwide, given the rising concerns associated with climate change [1]. The implementation of effective policies to limit global warming requires effective and reliable estimation of the carbon emissions associated with transport modes, solutions and scenarios [2]. However, accurate assessment of these emissions often requires the measurement or calculation of several parameters, which are often unavailable in real-world applications due to lack of data or to time or resource limitations.

As a result, carbon emissions are often estimated by considering emission factors, a reference value of emissions associated with specific quantities that are relatively easy to measure. The use of emission factors is a common practice in multiple applications, including research [3,4], policy assessments [5,6] and impact evaluations [7]. However, while emission factors are an easy and quick method to estimate carbon emissions, it is important to remember that the result only represents a preliminary estimation, since the potential variability and uncertainty related to the parameters is not considered.

The proper choice of relevant emission factors for a specific application should take into account the largest number of appropriate parameters, such as the relevant type of vehicles, traffic conditions, load factors, etc. [5]. While researchers in this field are well aware of such limitations [3], this is, unfortunately, not always the case in other applications. We believe that raising awareness of the complexity of choosing a proper set of emission factors and on the importance of including variability and uncertainty in the results is of utmost importance to improve the effectiveness of innovative mobility strategies.

This paper presents a comprehensive review of the use of carbon emission factors in transportation in order to help the readers understand the complexity associated with emission factors. Such complexity includes multiple dimensions:

- The type of emissions, either limited to carbon dioxide or also including other gases using global warming potential (GWP) methods;

- The boundaries that are considered, which can include or exclude the various stages of the transport systems, such as operation, fuel extraction, manufacture and distribution, or vehicle and infrastructure manufacture and decommissioning;
- A large number of parameters and aspects that may affect the emission factors, such as transport mode, vehicle characteristics, load factors, technology, average speed and other relevant features of each trip.

Relevant references for the emission factors associated with the main transport modes are discussed to provide the readers with median values as well as indications of the level of uncertainty and variability associated with the main factors.

The results of this work may be of interest for different stakeholders, as emission factors are widely used in applications and studies dealing with the climate emissions of transportation and potential decarbonization solutions. The subject is also central for policy-makers, as the sector is vital for the economy, and the use of reliable emission factors is the basis for the design of effective transport decarbonization strategies at global, national and local levels.

2. Methodologies for Calculation of CO_2 Emission Factors

GHGs are emitted at different stages of the supply chain of transport modes, as discussed below. The largest part of GHG emissions in transport consist of carbon dioxide, although in some stages other gases may be emitted as well. These other gases (mostly CH_4 and N_2O) are generally converted to CO_2-equivalent units in terms of global warming potential (GWP) to provide a single emission factor to account for climate impact.

2.1. Direct, Indirect and LCA Emissions

The main stages considered in a life-cycle perspective of the emissions of transport modes are:

- Direct emissions (also called tailpipe emissions or tank-to-wheel (TTW)) are emitted directly by the vehicle during its use and are related to fuel consumption, e.g., the combustion of gasoline in an internal combustion engine. Thus, knowledge of the amount of fuel consumed is sufficient to estimate emissions. Unfortunately, while total fuel consumption is often available from energy statistics, its precise allocation to different vehicle types is often missing [8]. Moreover, in many applications, emissions need to be assessed for specific locations, times and transport modes. For this reason, most analyses rely on CO_2 emission factors that are estimated based on distance in addition to several parameters that are discussed below (including vehicle type, fuel, size, etc.).
- Indirect emissions (or well-to-tank (WTT)) are associated with the fuel supply chain (including extraction, transformation, transportation, storage, etc.) or, in the case of electric vehicles, the emissions caused by the generation of electricity.
- Manufacturing emissions are caused by the production of the vehicle, including the manufacturing of batteries for electric vehicles, which, in some cases, represents the largest fraction of total manufacturing emissions [9].
- End-of-life emissions stem from the possible recycling or reuse of components and materials. This stage is often responsible for a minor fraction of the total emissions over the lifetime of the vehicles, and end-of-life emissions are thus often calculated together with the manufacturing emissions.

A study presenting a life-cycle assessment (LCA) of one or multiple transport modes includes all the aforementioned stages. Many studies provide only direct emissions or, in some cases, well-to-wheel (WTW) emissions, which is the combination of well-to-tank (WTT) and tank-to-wheel (TTW) emissions.

2.2. Additional Emissions Sources

In addition to the four stages previously described, some scholars include additional emissions sources, especially for specific transport modes:

- Services: in some cases, the impact of specific services that are needed for the operation of transport modes are also considered. These services may include support operations for shared mobility systems (such as relocating and charging e-bikes or e-scooters) or the operation of airports or train stations.
- Infrastructure: important impacts stem from the construction and maintenance of transport infrastructure such as roads and rails. However, these impacts are generally overlooked on the basis that infrastructure is often shared by different transport modes and over a very long lifetime, making emissions allocation very complex and uncertain. Nevertheless, in some cases, infrastructure impacts are included in LCAs, such as for high-speed rail projects, for which the infrastructure is not shared with other transport modes.

2.3. Other Aspects

In this work, we consider several recent studies providing data on emission factors for different passenger transport modes; we compare them with the aim of obtaining average indicators of carbon intensity per passenger-km. We focus on works based on LCA emission factors, which provide more complete figures of the real impacts associated with each transport mode, but we also include WTW emission factors due to their diffusion in the literature and transport emissions evaluations.

Most emission factors are calculated on a national basis, and they are always based on average annual figures, although some scholars point out that some parameters may show additional variability over time, such as the carbon intensity of electricity generation. However, as described below, this additional layer of complexity is difficult to include given the already large number of parameters and drivers that are considered when evaluating emission factors for different transport modes.

From the same perspective, the use of average emission factors may not be appropriate for some specific contexts where a marginal approach is needed. A common example is estimation of the modal shift from private cars to public transport. In the short term, if no additional buses are scheduled, additional passengers shifting modes avoid emissions from cars without adding additional emissions from buses (the additional energy consumption caused by the added weight of passengers being negligible). This phenomenon cannot be correctly estimated with average emission factors, which would instead depict increased emissions from buses. However, from a medium-term perspective, public transport schedules will adapt to increased ridership, and the variations may be incorporated into average emission factors with higher occupancy. Nevertheless, these aspects are seldom addressed in the literature, and for such specific analyses a dedicated assessment is preferred over the use of average emission factors.

The analyses and charts presented in this paper have been carried out using R environment [10] and the tidyverse collection of R packages [11].

3. CO_2 Emission Factors by Transport Mode

Emission factors are often grouped by transport mode, despite the relevant differences that exist within each mode in terms of technology, trip distances, energy source and other aspects. This section presents a literature review of the main factors influencing emissions for each transport mode. The results are based on analysis of multiple literature sources, including research papers, reports from research institutions and industry analyses [5,6,12–53].

Through this literature review, a database with more than one thousand emission factors for different transport modes and life-cycle stages has been constructed, and it is available to the readers as Supplementary Materials. Around 29% of these records represent total LCA impact, another 19% are WTW impact, while the remaining part provides information on specific stages (e.g., manufacture, operation, fuel processing, etc.).

The results of our analysis are summarized in Figure 1, showing boxplots of both LCA and WTW emission factors for different transport modes. The chart is based on almost 500 different data points, and it aims to report median results while also highlighting the variability of the emission factors for each transport mode.

Such variability is particularly relevant for emission factors of passenger cars, since the number of available studies is much larger than for other transport modes. Moreover, as we explain later, the wide range of results is a consequence of the large number of different technologies that are available.

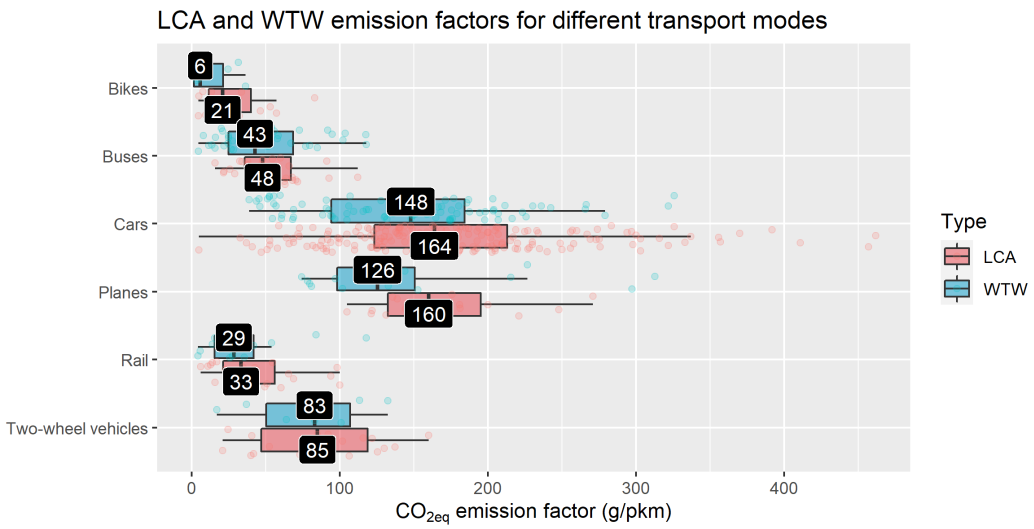

Figure 1. Distribution of LCA emission factors by mode.

When comparing LCA and WTW emission factors in Figure 1, it is important to remember that some studies report both values, while in other cases, only WTW or LCA values are available. For this reason, some of the distributions may not be directly comparable, especially those relying on a limited number of studies.

The next sections report additional information on the emission factors of these six groups of transport modes. A very limited number of studies include LCA emission factors for ferries [6,50], which were thus excluded from this analysis, also due to their limited importance for passenger transport (while their importance is significant for freight transport).

3.1. Cars

The car is the transport mode that is mostly addressed in the literature when computing emission factors, both for its dominance in current global mobility demand and for the wide range of available technologies. At the same time, as already presented in Figure 1, the emission factors that are calculated for cars show significant variability due to a number of factors that must be properly understood to choose the right indicator for each specific context.

Figure 2 shows LCA emission factors for cars based on different technologies, differentiated as fossil fuel-based (CNG, diesel, gasoline, hybrid and LPG), electricity-driven (BEVs and FCEVs) or both (PHEV). While the boxplots show total LCA emissions, it is important to remember that the impact of internal combustion engine (ICE) cars is mostly due to direct (tailpipe) emissions, whereas electricity-driven vehicles have no direct emissions, and their impact is mostly related to indirect emissions for the generation of electricity.

Figure 2 shows that median values for traditional fossil-based technologies are generally higher than those of electrified options, although in many cases, the ranges of the values across technologies may overlap. Wider ranges are also seen for gasoline cars and BEVs due to the fact that these two technologies are the ones that are most often compared in the LCA studies that were considered for this work (with 15% and 45%, respectively, of the total data points in this chart).

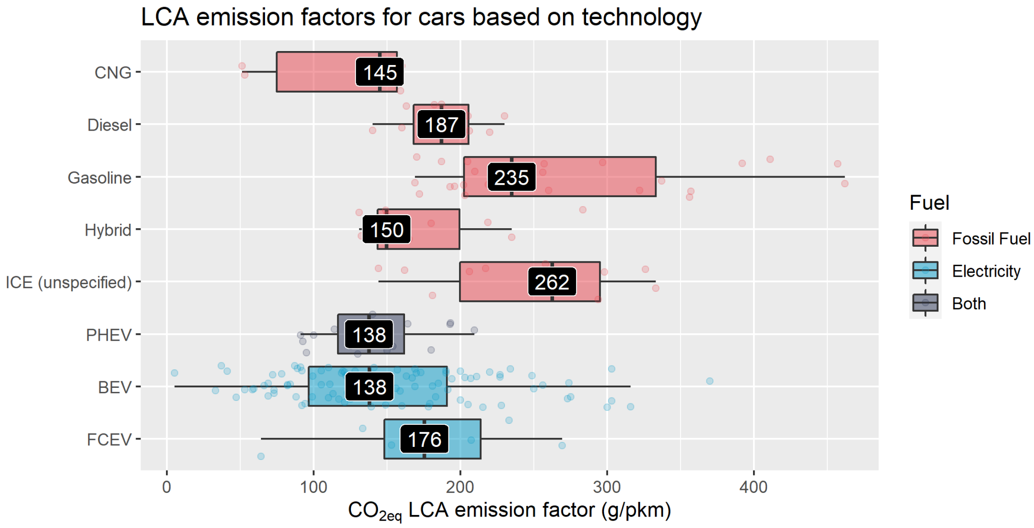

Figure 2. Distribution of LCA emission factors for private cars.

The variability of fossil-based emission factors is due to hypotheses on vehicle and engine size (with American studies usually considering larger vehicles than European studies), occupancy, vehicle age, annual driving range and lifetime. As seen in the plot, while the median value for gasoline cars is 235 g/pkm, the range spans from 169 to 462 g/pkm (−28% to +97% of the median). Diesel cars show both a lower median value and lower variability thanks to fewer cases considered and due to the fact that American cars, which are generally bigger, only run on gasoline, while diesel is mostly used in other areas (including Europe).

The range for BEVs varies from 5 to 370 g/pkm, corresponding to −96% to +191% of the median value of 138 g/km. In addition to aforementioned aspects, such significant variability for BEVs is strongly related to the electricity generation considered in the analysis.

The chart also shows that PHEV cars have median values that are comparable to those of BEVs (although the range is much narrower, 91 to 209 g/pkm); however, this figure is based on only 18 data points, while BEV emission factors come from 99 data points. On the one hand, the low LCA emissions of PHEVs can be explained by the lessened impact of battery manufacturing, which is smaller than for BEVs; on the other hand, it can also be caused by optimistic estimates of the range driven using electricity vs. fossil fuels. Recent research [54] shows that real-world fuel consumption of PHEVs is often much higher than the values expected from tests, suggesting users cover less distance on electricity and more on traditional fuel than forecast. This aspect should be carefully considered when assessing the potential benefits of PHEVs.

Finally, the median LCA emission factor from FCEVs is 176 g/pkm (range 64 to 269 g/km, based on eight data points), suggesting higher a impact than BEVs due to the less-efficient supply chain for the generation and storage of hydrogen [55]. Further, while the global stock of BEVs and PHEVs surpassed 16 million in 2021 [56], the global FCEV fleet remains limited to around 50 thousands units.

In Figure 3, specific focus is presented on BEVs due to their importance in the literature and their potential role for the decarbonization of transportation. The use of reliable metrics to estimate their potential benefits is paramount for effective and reliable strategies and policies. Figure 3 shows the effect of different electricity generation options on the LCA emission factors of BEVs, together with the (minor) contribution of different years considered in the analysis (with a general decarbonization trend over the years that is noticeable in studies).

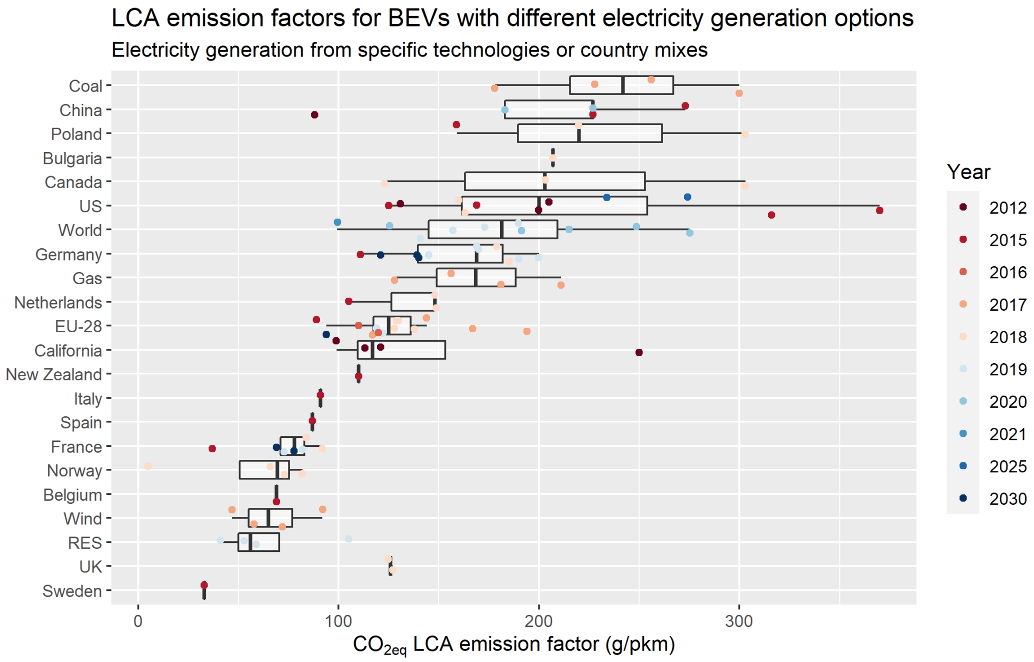

Figure 3. Distribution of LCA emission factors for BEVs with different electricity generation options.

Nevertheless, it is interesting to note that the electricity mix and the year do not explain the whole variability, which means there are still other factors at play (as mentioned above for traditional cars). For BEVs, manufacturing of batteries is an important fraction of the total life-cycle impact, and thus, the electricity mix considered for battery manufacturing may represent an additional key parameter. Since batteries are often manufactured in specific countries (mostly in China), this electricity mix seldom corresponds to that of the country where the BEV is driven.

In addition to the parameters we have already discussed, a crucial point is vehicle occupancy. While most of the considered studies are based on average occupancy levels for passenger cars (generally in the range of 1.2–1.5), this parameter can have important variation in specific contexts, and it obviously has a significant contribution to the calculation of emission factors per pkm. Data show that occupancy can vary based on the purpose of the trip: while the average occupancy for British cars in 2020 was 1.49, commuting trips had on average 1.14 occupants, while for holiday trips this value increased to 1.96 [57]. This parameter is even more relevant when evaluating the specific effect of measures that aim to increase vehicle occupancy, such as carpooling schemes. Proper assessment of the effect of these schemes requires the possibility of separating the effect of vehicle occupancy on emission factors [58].

Another aspect that is seldom addressed in the literature (making up only a few of the studies in our analysis, especially [5]) is the role of taxi and ride-hailing services. In addition to their potential effect on average vehicle occupancy (of course without considering the driver), these solutions often show very high impact on deadweight loss, i.e., the distance driven by empty cabs between trips. Different studies highlight that this increased driving contributes significantly to congestion in large cities (together with a significant modal shift from transit) [59,60]. In [5], the total LCA emission factors are 98–114% higher for taxis and 53–70% higher for ride-hailing services compared to private cars. These figures show the importance of using dedicated emission factors that are focused on these specific transport modes for analyses.

3.2. Two-Wheelers

The two-wheelers category includes a range of different modes, such as mopeds and motorbikes, but also electric scooters, which are seeing increasing success in many cities worldwide thanks to sharing schemes.

ICE mopeds show LCA emission factors of 73 to 92 g/pkm (average and median of 83 g/pkm), while a single study [6] shows an LCA emission factor for motorbikes of 137 g/pkm due to their larger size. The largest contribution comes from direct emissions, with a minor share from manufacturing and WTT. Emission factors are lower than those presented for ICE cars in the previous section due to lower weights of two-wheelers, which causes lower energy consumption both in operation and in manufacturing. As previously mentioned, however, increasing the number of passengers in cars can lead to comparable (or even lower, when at full-capacity) emission factors.

Private electric mopeds are considered in only three studies [5,6,37] and show LCA emission factors of 21 to 41 g/pkm. When considering the contribution of each stage, these studies provide mixed results: two studies suggest a larger impact of manufacturing over operation, while the third study suggests the opposite.

Shared electric mopeds are also included in [5], with an LCA emission factor of 79 g/pkm. The higher impact compared to private mopeds is due to the additional emissions from services (including trips for charging/relocation) and the shorter estimated lifetime (in terms of total km driven over the life of the vehicle). This value is higher than the results of another dedicated study [34], which reports an emission factor of 53 g/pkm (with the largest part associated with battery swapping and charging), but comparable to another work [37] that reports a value of 77 g/pkm.

An additional two-wheel transport mode that is gaining momentum in cities, and has also been the focus of a number of research studies in recent years, is shared electric scooters. Research on this mode [5,6,35,36] reports total LCA emission factors in the range 102 to 160 g/pkm, with a median value of 122 g/pkm (and an average value of 123 g/pkm). While electricity consumption has a marginal impact, the production phase is the most critical (up to 80% of the total emissions) due to the short lifetime of e-scooters, which can be both a consequence of misuse by customers and low-quality materials. Another significant impact is due to the relocation of scooters for charging; in fact, analyses of private e-scooters show much lower impact, from 25 to 42 g/pkm of total LCA emissions. Operators of electric scooter sharing systems are trying to improve this performance through better construction quality and swappable batteries.

3.3. Bikes

Figures on emission factors of private bikes show a range of 5 to 17 g/km, with a median value of 9 g/km and an average value of 10 g/km. Most of the impact is related to manufacturing, with a minor share related to maintenance. Bike-sharing systems show higher impact, with emission factors varying from 10 to 58 g/km (median of 46 g/km and average of 38 g/km). Both the higher impacts and the variability are mostly related to the services supporting bike-sharing system, such as bike relocation.

Electric bikes generally have higher emission factors, mainly due to more complex manufacturing and only secondarily due to the impact of electricity consumption during their operation. Private e-bikes show emission factors in the range of 21 to 34 g/km (median 22 g/km, average 25 g/km), with emissions related to their operation accounting for 14% to 35% of the total. As seen with scooters, bike sharing increases the impact, as shared e-bikes emit 53 to 83 g/km due to the significant impact of different services of the system, since, in addition to relocation for optimizing the system, e-bikes also need to be charged. In this case, services account for 30–58% of the total emissions, depending on the study.

Some authors also consider the effect of additional food consumption in active mobility. Others even suggest that additional breathing leading to CO_2 emissions should be considered, although it is clear that emissions from breathing are part of a natural closed cycle and are thus net zero emissions. However, the considerations related to food consumption are still a debated topic and are affected by significant uncertainties.

A research report on cycling benefits published in 2011 and focused on the European Union [61] estimated an impact of 16 g_{CO2e}/km related to food consumption. This result is based on the assumption that a cyclist consumes on average 11 kcal/km, and the average diet in the EU leads to the emission of 1.44 g_{CO2e}/kcal.

A recent report [62] estimates that the potential impact of food consumption is 140 g_{CO2e}/km (with an uncertainty interval (UI) between 60 and 280 g/km) by considering additional energy expenditure to cycle one km to be between 25 and 40 kcal and assuming energy expenditure is fully compensated for with increased energy intake based on the average global diet. The report also remarks that the impact of food varies significantly around the world based on different diets and the related GHG impact. Moreover, the authors provide additional results based on the hypothesis that only 57% (UI 19–96%) of additional energy expenditure is compensated for by additional food intake (based on other studies), leading to emissions of 80 g_{CO2e}/km (UI 30–130 g/km) in developed countries.

However, Bell et al. [63] report the incidence of obesity for users switching from bikes to motorized vehicles, suggesting they maintain their caloric intake even when reducing exercise. This challenges the assumption of a one-to-one relationship between energy requirements for cycling and caloric intake. Moreover, other scholars suggest that active mobility often substitutes for other forms of physical activity (running, gym, etc.) that would have been done, thus having marginal or null effects on food consumption by the users.

Due to these significant unsolved elements, we believe that these emissions should not be compared to the other emissions related to the different stages of transport modes.

3.4. Buses

The climate impact of buses depends on a number of aspects, including average occupancy, powertrain technology and urban/intercity operation.

In the works considered for this analysis, traditional urban buses running on diesel have emission factors in the range 55 to 112 g/pkm (average 87 g/pkm, median 93 g/pkm). Long-distance buses and coaches show better performance, with emission factors in the range of 33–38 g/pkm due to better occupancy and less frequent starts and stops compared to urban buses.

Hybrid solutions provide some improvements, with hybrid diesel buses emitting 66–70 g/pkm and PHEV buses 38–68 g/pkm (also depending on the electricity mix). The use of fuels other than diesel may show benefits in some cases, as selected studies show hydrotreated vegetable oil (HVO) leading to 34 g/pkm [42], and LPG and LNG having 47 g/pkm and 63 g/pkm, respectively [43].

Electric buses show promising benefits, with emission factors from 16–72 g/pkm (median 48 g/pkm, average 43 g/pkm), especially when operated in countries that have low emission intensity for electricity generation (TTW emissions account for between 28% and 82% of the total, depending on the electricity mix).

3.5. Rail

This section includes mostly electrified transport modes, although non-urban trains may also include a share of diesel-powered vehicles in some locations. Compared to buses, all these transport modes are much less standard in terms of length and capacity, which adds a layer of complexity when comparing different systems. At the same time, the fact that they mostly rely on electricity leads to lower emissions than for other transportation modes.

An additional point of uncertainty is the impact of infrastructure: while roads are considered without taking into account the impact of construction and maintenance based on the fact that their use is shared across several different modes, rail transport often has dedicated infrastructure, which should be taken into account. However, this infrastructure usually has a long lifetime, complicating the extrapolation of meaningful values.

Few studies include different rail modes, and their results are not always comparable. For instance, two studies focus on urban rail (i.e., trams and metro) considering the LCA [5,6], with emission factors from 11 to 66 g/pkm (average 40 g/pkm, median 43 g/pkm), while other studies present WTW values from 29 to 84 g/pkm (average 56 g/pkm, median 54 g/pkm) for the same modes [12–14]. Moreover, none of these studies specifically address rail transport modes, which are instead included in broader comparisons of urban mobility options.

Considering national and regional trains (excluding high-speed trains), WTW emission factors are from 14 to 42 g/pkm (average 30 g/pkm, median 35 g/pkm), although one specific study [12] reports values as low as 6 g/pkm and as high as 118 g/pkm, which represent the boundaries for electricity-driven trains with very low carbon electricity mixes and for diesel trains, respectively. LCA emission factors of national and regional trains, obtained from five different studies [6,44,45,47,53], range from 6–100 g/pkm, with an average value of 59 g/pkm and a median of 55 g/pkm. The lowest value is from a study in Mumbai that shows a very high occupancy rate [44] and that may therefore be less representative of the performance of this transport mode in other locations.

Finally, high-speed rail (HSR) is quite different compared to other rail transport modes due to the dedicated infrastructure. Some studies considering high-speed rail report 13 to 94 g/pkm for LCA emission factors (average of 36 g/km), although they do not always consider the impact of infrastructure. A specific analysis on the HSR infrastructure in Spain [53] estimates its impact to be between 12 and 60 g/pkm depending on the region, with a national value of 18 g/pkm. As previously mentioned, the choice of considering the impact of infrastructure remains debated, especially when comparing HSR with road transport modes.

3.6. Aviation

Airplanes are one of the worst transport modes, together with private cars, when considering GHG emissions. It is true that emissions for cars are often higher, but it also should be considered that their average occupancy is usually around 1.5 people (corresponding to a 30% load factor), while planes often show average load factors of 80–85% of their maximum capacity.

Moreover, when considering aviation's impact on climate change, it is important to remember that the operation of airplanes at high altitude has different impacts on global warming in addition to carbon dioxide emissions, including contrail cirrus and NO_X emissions. Recent research [64] confirms that aviation operations are currently warming the climate at approximately three times the rate associated with aviation CO_2 emissions alone. However, due to the uncertainty of these effects and to make aviation emissions comparable across studies and with other modes, we excluded non-CO_2 climate impacts in our analyses.

Recent LCA analyses of air transport, mostly focusing on narrow-body and wide-body aircraft, report emission factors of 105 to 271 g/pkm (with a median of 160 g/pkm and an average of 170 g/pkm). Other studies estimate WTW emission factors from 74 to 313 g/pkm (median 126 g/pkm, average 145 g/pkm). The higher maximum values compared to LCA studies are related to allocating emissions across different classes based on the space dedicated to passengers. As a result, business and first classes show very high WTW emission factors, even higher than LCA emission factors calculated without this allocation.

Considering aircraft operations, a crucial aspect is the occupancy rate, which had been continuously increasing in the years leading up to the COVID-19 pandemic. Together with technological improvements, this led to lower specific emissions [65]. However, the pandemic had a disruptive impact on the sector, and it is still too early to draw a reliable future outlook for the evolution of aviation. Nevertheless, as already discussed above, while most reports for aviation focus on direct CO_2 emissions, it is crucial to remember that these only account for a marginal share of the actual climate impact of traveling by plane.

3.7. Other Transport Modes

The analysis has compared the transport modes that are most diffused, which are also those most considered in the literature. However, there are other transport modes that may be relevant for specific applications but that have not been included due to the limited number of available studies.

The most notable example is passenger transport on ferries, either on maritime routes or internal waterways. There are two studies that provide LCA analyses [6,50], with LCA emission factors of 152 and 2044 g/pkm, respectively, for diesel ferries. Research studies evaluate the advantages of electrifying passenger ferries [66], but this technology is still limited to a few applications, and most LCA comparisons are focused on vessels, without considering the number of passengers that are actually transported. Other studies [67,68] are limited to CO_2 emissions during the operational phase.

Other passenger transport modes may be relevant for some specific regions but are not distributed globally and have not been included in this study. Some notable examples are the use of three-wheelers in southeastern countries, also referred to as "tuk-tuks" [69], or the use of cargo bikes to transport children [70].

4. Discussion

The results of this work display a comprehensive picture of the LCA and WTW emission factors that are used to assess the carbon intensity of different transport modes. The values that emerge from the literature show important variability of emission factors across transport modes, but also within each mode. Such variability is driven by multiple aspects, including vehicle type, energy source, technology, average speed and occupancy. For this reason, an accurate choice of proper emission factors based on the conditions being analyzed is paramount for reliably estimating transport emissions.

Moreover, the lack of a coherent framework on the perspective to be considered when addressing mobility emissions emerges. Considering direct, WTW or LCA emissions may lead to very different results, which may, in some cases, even lead to different policies. In general, shifting towards a more comprehensive approach may benefit the applicability and usefulness of emission factors; at the same time, attention must be paid to the reliability of LCA hypotheses and calculations. In particular, although the LCA methodology is clearly codified, there seems to be a lack of comparability regarding the inclusion of different stages: some studies (such as [5,6]) include the impact associated with the infrastructure or services needed to operate specific transport modes (such as shared mobility systems, airports and rail infrastructure), while other studies neglect these altogether. A common evaluation framework is needed to determine comparable and effective indicators.

In addition, LCA analyses highlight how different stages influence the emission factors differently across transport modes; the impacts during the operation phase (i.e., direct emissions) are lower for lighter vehicles such as two-wheeler and electric bikes, and they are the most significant factors for ICE cars, buses and rail modes (particularly for urban and metro trains). On the other hand, emissions during manufacture constitute a significant fraction of the overall emissions for electric vehicles in particular, whether it is bikes or cars. In addition, the impact of infrastructure construction and maintenance is less relevant for cars and buses; it is significant for two-wheelers and bikes (also non-electric ones), and it can be a significant factor for the overall impact of high-speed trains in particular [53]. Knowledge about the relevant impact of each stage within the total climate impact of a transport mode is fundamental because it can help direct reduction efforts in a more efficient way. This is particularly true for those modes in which direct emissions, which are more often the focus of much attention, are less relevant than manufacturing or infrastructure-related emissions.

In the current trend of transport electrification, particularly prominent in some countries and some modes, a conceptual shift of CO_2 emissions from transport modes to the power sector emerges. Thus, while many policies and regulation have historically focused on transport emissions, it should be recommended to shift at least towards a WTW approach to correctly allocate emissions, and to an LCA approach when possible. At the same time, it is important to avoid double-counting of emissions across sectors; an LCA typically includes emissions that are currently allocated to other sectors, such as industry.

The electricity mix is a crucial parameter to assess the carbon intensity of transport modes, and several papers have shown its role through dedicated sensitivity analyses on emission factors. The mix of technologies used for power generation shows significant variations both over space and time. Current research generally uses annual country-level electricity mixes, although in some cases, specific single technologies are considered for comparison. However, daily and monthly variations of emission factors may be significant [71,72], and although recent research shows that the use of average annual values is generally acceptable [73], increasing shares of variable renewables may increase the volatility of electricity emission intensity. In addition, most studies consider average emission intensities, but in some cases it is better to use marginal emission factors, which are seldom available.

Many decarbonization policies currently focus on electrifying transport [30,56], but these solutions should be coupled with a deep decarbonization of the power sector. The results of this work highlight the variability of LCA impact of electrified transport modes, emphasizing the fact that without a strong shift towards low-carbon power generation, emission reductions compared to traditional fossil-fueled options remain limited.

One additional aspect that emerged clearly from the results is the role of sharing systems and their impact on carbon emissions: when comparing non-shared vehicles with shared alternatives, the former emits significantly less than the latter per passenger-km across different modes [5]. This is mainly due to the additional services that are implemented within a sharing system, in particular vehicle relocation, such as in (e-)bike and e-scooter sharing systems. In one way, this conclusion might seem to suggest that sharing systems should be discarded in favor of the equivalent non-shared mode, but we believe this conclusion is misguided. In fact, the use of sharing systems not only substitutes for the use of the same non-shared modes (e.g., shared e-scooter vs. non-shared e-scooter), but they represent an alternative to several transport modes, including ones whose emission factors are higher (e.g., shared e-scooter vs. private car). Therefore, the comparison should be drawn between sharing systems and all the transport modes for which they might substitute.

Finally, the importance of promoting active and collective mobility clearly emerges from the analysis of emission factors. Active modes, even including electric bikes, show very low or null emissions, making them particularly suitable to decrease mobility impact, especially over short distances. On the other hand, since occupancy emerges as a critical driver of many emission factors, optimized use of collective transport can further decrease total emissions. From this perspective, an even more effective measure may be to increase the average passengers carried by private cars [58].

While this study provides a good representation of emission factors presented in the literature, its quality and comprehensiveness have been affected by some limitations. The results of several research works have not been included due to the fact that they were focused on different functional units, making them impossible to compare to other modes. For example, many LCA analyses of urban buses or rail systems only provided total emissions or emissions per vehicle, and without the allocation of emissions to pkm it was not possible to exploit these results. Finally, several studies did not clearly report all the hypotheses and parameters, complicating the analysis of methodological differences and similarities in a coherent and systematic way.

5. Conclusions

Transport decarbonization strategies need to be based on a simple but reliable estimation of their potential impact, which is often performed by emission factors coupled with information on mobility demand and modal share. While emission factors for the main transport modes are widely available in the literature, significant variability is hidden behind the average values that are generally used.

This work presents a comprehensive review of emission factors available in the literature, comparing them across transport modes, technologies, fuels and perspectives (mainly WTW vs. LCA). Emission factors are generally computed per passenger-km and used with data on mobility demand to estimate the total emissions of a transport mode.

The results of this work show the clear difference in GHG emissions when comparing different transport modes, especially private motorized vehicles against active and collective mobility solutions. At the same time, significant variability of emission factors arises within most of the modes presented in this work. The most important drivers of this variability are the technology used by the transport mode and the occupancy. For electrified vehicles, the carbon intensity of the electricity consumed is often the most significant parameter. Other aspects include the size of the vehicle, its age, driving cycles and weather conditions, but they mostly have marginal impact, especially when considering average vehicle fleets.

Given such variability, we recommend that average emission factors are selected after a preliminary check of the main hypotheses related to the chosen value to verify if these hypotheses are suitable to represent the specific conditions of the case study at hand. Available data on the types of vehicles that are in use, such as private car fleet distribution by powertrain, and on the average occupancy of transport modes can significantly improve the quality of the results. In some cases, sensitivity analysis of some emission factors may improve the reliability of the results and the policy choices that they support.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su141710652/s1, Dataset with all the emission factors discussed in the paper.

Author Contributions: conceptualization: M.N., E.C. and M.J.; methodology: M.N., E.C. and M.J.; formal analysis: M.N. and E.C.; data curation: E.C. and M.N.; writing—original draft preparation: M.N. and E.C.; writing—review and editing: M.N. and M.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All the data presented in this study are available in the dataset included in the Supplementary Material.

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

Abbreviations

The following abbreviations are used in this manuscript:

BEV	battery electric vehicle
CNG	compressed natural gas
FCEV	fuel cell electric vehicle
GHG	greenhouse gas
GWP	global warming potential
HSR	high-speed rail
HVO	hydrotreated vegetable oil
ICE	internal combustion engine
LCA	life-cycle assessment
LNG	liquefied natural gas

LPG	liquefied petroleum gas
PHEV	plugin hybrid electric vehicle
RES	renewable energy source
TTW	tank-to-wheels
UI	uncertainty interval
WTT	well-to-tank
WTW	well-to-wheels

References

1. International Energy Agency. World Energy Outlook 2021. Technical Report. 2021. Available online: https://www.iea.org/reports/world-energy-outlook-2021 (accessed on 2 August 2022).
2. Eyring, V.; Gillett, N.; Achuta Rao, K.; Barimalala, R.; Barreiro Parrillo, M.; Bellouin, N.; Cassou, C.; Durack, P.; Kosaka, Y.; McGregor, S.; et al. Human Influence on the Climate System. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021; pp. 423–552. [CrossRef]
3. Bigazzi, A. Comparison of marginal and average emission factors for passenger transportation modes. *Appl. Energy* **2019**, *242*, 1460–1466. [CrossRef]
4. Seo, J.; Park, J.; Park, J.; Park, S. Emission factor development for light-duty vehicles based on real-world emissions using emission map-based simulation. *Environ. Pollut.* **2021**, *270*, 116081. [CrossRef] [PubMed]
5. International Transport Forum. Good to Go? Assessing the Environmental Performance of New Mobility. Technical Report, ITF, 2020. Available online: https://www.itf-oecd.org/good-to-go-environmental-performance-new-mobility (accessed on 12 January 2022).
6. Travel and Mobility Tech. The Environmental Impact of Today's Transport Types. Technical Report. 2021. Available online: https://tnmt.com/infographics/carbon-emissions-by-transport-type/ (accessed on 12 January 2022).
7. van Essen, H.; van Wijngaarden, L.; Schroten, A.; Sutter, D.; Bieler, C.; Maffii, S.; Brambilla, M.; Fiorello, D.; Fermi, F.; Parolin, R.; et al. Handbook on the External Costs of Transport—Version 2019. Technical Report. 2019. Available online: https://cedelft.eu/publications/handbook-on-the-external-costs-of-transport-version-2019/ (accessed on 2 August 2022). [CrossRef]
8. Eggleston, S.; Walsh, M. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Emissions: Energy, Road, Transport. Technical Report. Available online: https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/2_3_Road_Transport.pdf (accessed on 12 January 2022).
9. International Energy Agency. Global EV Outlook 2020. Technical Report. 2020. Available online: https://www.iea.org/reports/global-ev-outlook-2020 (accessed on 4 August 2022).
10. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2022.
11. Wickham, H.; Averick, M.; Bryan, J.; Chang, W.; McGowan, L.D.; François, R.; Grolemund, G.; Hayes, A.; Henry, L.; Hester, J.; et al. Welcome to the tidyverse. *J. Open Source Softw.* **2019**, *4*, 1686. [CrossRef]
12. International Energy Agency. GHG Intensity of Passenger Transport Modes, 2019. Technical Report. 2020. Available online: https://www.iea.org/data-and-statistics/charts/ghg-intensity-of-passenger-transport-modes-2019 (accessed on 12 January 2022).
13. Doll, C.; Brauer, C.; Köhler, J.; Scholten, P. Methodology for GHG Efficiency of Transport Modes—Final Report. Technical Report. 2020. Available online: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccn/2021/Methodology%20for%20GHG%20Efficiency%20of%20Transport%20Modes.pdf (accessed on 12 January 2022).
14. UK Government-Department for Business, Energy & Industrial Strategy. Greenhouse Gas Reporting: Conversion Factors 2021. Technical Report. 2021. Available online: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021 (accessed on 12 January 2022).
15. Balpreet, K. Life Cycle Analysis of Electric Vehicles—Quantifying the Impact. Technical Report. 2018. Available online: https://sustain.ubc.ca/sites/default/files/2018-63%20Lifecycle%20Analysis%20of%20Electric%20Vehicles_Kukreja.pdf (accessed on 12 January 2022).
16. Nealer, R.; Reichmuth, D.; Anair, D. Cleaner Cars from Cradle to Grave—How Electric Cars Beat Gasoline Cars on Lifetime Global Warming Emissions. Technical Report. 2015. Available online: https://www.ucsusa.org/sites/default/files/attach/2015/11/Cleaner-Cars-from-Cradle-to-Grave-full-report.pdf (accessed on 12 January 2022).
17. Hawkins, T.R.; Singh, B.; Majeau-Bettez, G.; Strømman, A.H. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *J. Ind. Ecol.* **2013**, *17*, 53–64. [CrossRef]
18. Pero, F.D.; Delogu, M.; Pierini, M. Life Cycle Assessment in the automotive sector: A comparative case study of Internal Combustion Engine (ICE) and electric car. *Procedia Struct. Integr.* **2018**, *12*, 521–537. [CrossRef]
19. Volkswagen Group News. Electric Vehicles with Lowest CO_2 Emissions. Technical Report. 2019. Available online: https://www.volkswagen-newsroom.com/en/press-releases/electric-vehicles-with-lowest-co2-emissions-4886 (accessed on 12 January 2022).

20. Brennan, J.W.; Barder, T.E. Battery Electric Vehicles vs. Internal Combustion Engine Vehicles—A United States-Based Comprehensive Assessment. Technical Report. 2016. Available online: https://www.adlittle.de/sites/default/files/viewpoints/ADL_BEVs_vs_ICEVs_FINAL_November_292016.pdf (accessed on 12 January 2022).
21. Helms, H.; Kämper, C.; Biemann, K.; Lambrecht, U.; Jöhrens, J.; Meyer, K. Klimabilanz von Elektroautos. Einflussfaktoren und Verbesserungspotenzial. Technical Report. 2019. Available online: https://www.agora-verkehrswende.de/fileadmin/Projekte/2018/Klimabilanz_von_Elektroautos/Agora-Verkehrswende_22_Klimabilanz-von-Elektroautos_WEB.pdf (accessed on 12 January 2022).
22. Ager-Wick Ellingsen, L.; Hammer Strømman, A. Life Cycle Assessment of Electric Vehicles. Technical Report. 2017. Available online: https://www.concawe.eu/wp-content/uploads/2017/03/Ellingsen-LCA-of-BEVs_edited-for-publication.pdf (accessed on 12 January 2022).
23. Hall, D.; Lutsey, N. Effects of Battery Manufacturing on Electric Vehicle Life-Cycle Greenhouse Gas Emissions. Technical Report. 2018. Available online: https://theicct.org/sites/default/files/publications/EV-life-cycle-GHG_ICCT-Briefing_09022018_vF.pdf (accessed on 12 January 2022).
24. Hausfather, Z. Factcheck: How Electric Vehicles Help to Tackle Climate Change. Technical Report. 2019. Available online: https://www.carbonbrief.org/factcheck-how-electric-vehicles-help-to-tackle-climate-change/ (accessed on 12 January 2022).
25. Arup, Verdant Vision. Life Cycle Assessment of Electric Vehicles—Final Report. Technical Report. 2015. Available online: https://www.eeca.govt.nz/assets/EECA-Resources/Research-papers-guides/ev-lca-final-report-nov-2015.pdf (accessed on 12 January 2022).
26. Qiao, Q.; Zhao, F.; Liu, Z.; He, X.; Hao, H. Life cycle greenhouse gas emissions of Electric Vehicles in China: Combining the vehicle cycle and fuel cycle. *Energy* **2019**, *177*, 222–233. [CrossRef]
27. Evtimov, I.; Ivanov, R.; Kadikyanov, G.; Staneva, G. Life cycle assessment of electric and conventional cars energy consumption and CO2 emissions. *MATEC Web Conf.* **2018**, *234*, 02007. [CrossRef]
28. NGVA Europe. Going beyond Well-to-Wheel: Life Cycle Emissions. Technical Report. 2019. Available online: https://www.ngva.eu/medias/going-beyond-well-to-wheel-life-cycle-emissions/ (accessed on 12 January 2022).
29. Tagliaferri, C.; Evangelisti, S.; Acconcia, F.; Domenech, T.; Ekins, P.; Barletta, D.; Lettieri, P. Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach. *Chem. Eng. Res. Des.* **2016**, *112*, 298–309. [CrossRef]
30. International Energy Agency. Global EV Outlook 2019. Technical Report. 2019. Available online: https://www.iea.org/reports/global-ev-outlook-2019 (accessed on 12 January 2022).
31. Messagie, M. Life Cycle Analysis of the Climate Impact of Electric Vehicles. Technical Report. 2014. Available online: https://www.transportenvironment.org/wp-content/uploads/2021/07/TE%20-%20draft%20report%20v04.pdf (accessed on 12 January 2022).
32. ADAC. Klimabilanz: Entscheidend ist der Lebenszyklus. Technical Report. 2021. Available online: https://www.adac.de/verkehr/tanken-kraftstoff-antrieb/alternative-antriebe/klimabilanz/ (accessed on 12 January 2022).
33. Bouter, A.; Melgar, J.; Ternel, C. LCA Study of Vehicles Running on NGV and bioNGV. Technical Report. 2019. Available online: https://www.afgaz.fr/wp-content/uploads/afg_rapport_afg_vf_en.pdf (accessed on 12 January 2022).
34. Schelte, N.; Severengiz, S.; Schünemann, J.; Finke, S.; Bauer, O.; Metzen, M. Life Cycle Assessment on Electric Moped Scooter Sharing. *Sustainability* **2021**, *13*, 8297. [CrossRef]
35. Severengiz, S.; Schelte, N.; Bracke, S. Analysis of the environmental impact of e-scooter sharing services considering product reliability characteristics and durability. *Procedia CIRP* **2021**, *96*, 181–188. [CrossRef]
36. Hollingsworth, J.; Copeland, B.; Johnson, J.X. Are e-scooters polluters? The environmental impacts of shared dockless electric scooters. *Environ. Res. Lett.* **2019**, *14*, 084031. [CrossRef]
37. Felipe-Falgas, P.; Madrid-Lopez, C.; Marquet, O. Assessing Environmental Performance of Micromobility Using LCA and Self-Reported Modal Change: The Case of Shared E-Bikes, E-Scooters, and E-Mopeds in Barcelona. *Sustainability* **2022**, *14*, 4139. [CrossRef]
38. Huang, Y.; Jiang, L.; Chen, H.; Dave, K.; Parry, T. Comparative life cycle assessment of electric bikes for commuting in the UK. *Transp. Res. Part Transp. Environ.* **2022**, *105*, 103213. [CrossRef]
39. Hendriksen, I.; van Gijlswijk, R. Fietsen is Groen, Gezond en Voordelig. Technical Report. 2010. Available online: http://resolver.tudelft.nl/uuid:85559746-1929-4bb9-8735-9989c3e074dc (accessed on 27 July 2022).
40. Cherry, C.R.; Weinert, J.X.; Xinmiao, Y. Comparative environmental impacts of electric bikes in China. *Transp. Res. Part Transp. Environ.* **2009**, *14*, 281–290. [CrossRef]
41. D'Almeida, L.; Rye, T.; Pomponi, F. Emissions assessment of bike sharing schemes: The case of Just Eat Cycles in Edinburgh, UK. *Sustain. Cities Soc.* **2021**, *71*, 103012. [CrossRef]
42. Nordelöf, A.; Romare, M.; Tivander, J. Life cycle assessment of city buses powered by electricity, hydrogenated vegetable oil or diesel. *Transp. Res. Part Transp. Environ.* **2019**, *75*, 211–222. [CrossRef]
43. Chang, C.C.; Liao, Y.T.; Chang, Y.W. Life Cycle Assessment of Carbon Footprint in Public Transportation - A Case Study of Bus Route NO. 2 in Tainan City, Taiwan. *Procedia Manuf.* **2019**, *30*, 388–395. [CrossRef]
44. Shinde, A.M.; Dikshit, A.K.; Singh, R.K.; Campana, P.E. Life cycle analysis based comprehensive environmental performance evaluation of Mumbai Suburban Railway, India. *J. Clean. Prod.* **2018**, *188*, 989–1003. [CrossRef]

45. Landgraf, M.; Horvath, A. Embodied greenhouse gas assessment of railway infrastructure: The case of Austria. *Environ. Res. Infrastruct. Sustain.* **2021**, *1*, 025008. [CrossRef]
46. Lewis, T. A Life Cycle Assessment of the Passenger Air Transport System Using Three Flight Scenarios. Technical Report. 2013. Available online: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/235319/654869_FULLTEXT01.pdf (accessed on 28 July 2022).
47. Horvath, A.; Chester, M. Environmental Life-cycle Assessment of Passenger Transportation An Energy, Greenhouse Gas, and Criteria Pollutant Inventory of Rail and Air Transportation. Technical Report. 2008. Available online: https://escholarship.org/uc/item/6m5865v5 (accessed on 28 July 2022).
48. Cox, B.; Jemiolo, W.; Mutel, C. Life cycle assessment of air transportation and the Swiss commercial air transport fleet. *Transp. Res. Part Transp. Environ.* **2018**, *58*, 1–13. [CrossRef]
49. Jordão, T.C. Life Cycle Assessment oriented to climate change mitigation by aviation. In Proceedings of the 15th International Conference on Environmental Economy, Queenstown, New Zealand, 11–15 February 2013.
50. Nordtveit, E. Life Cycle Assessment of a Battery Passenger Ferry. Master's Thesis, University of Adger, Kristiansand, Norway, 2017.
51. Dreier, D.; Silveira, S.; Khatiwada, D.; Fonseca, K.V.; Nieweglowski, R.; Schepanski, R. Well-to-Wheel analysis of fossil energy use and greenhouse gas emissions for conventional, hybrid-electric and plug-in hybrid-electric city buses in the BRT system in Curitiba, Brazil. *Transp. Res. Part Transp. Environ.* **2018**, *58*, 122–138. [CrossRef]
52. Jones, H.; Moura, F.; Domingos, T. Life cycle assessment of high-speed rail: A case study in Portugal. *Int. J. Life Cycle Assess* **2017**, *22*, 410–422. [CrossRef]
53. Kortazar, A.; Bueno, G.; Hoyos, D. Environmental balance of the high speed rail network in Spain: A Life Cycle Assessment approach. *Res. Transp. Econ.* **2021**, *90*, 101035. [CrossRef]
54. Plötz, P.; Moll, C.; Bieker, G.; Mock, P.; Li, Y. Real-World Usage of Plug-In Hybrid Electric Vehicles Fuel Consumption, Electric Driving, and CO_2 Emissions. Technical Report. 2020. Available online: https://theicct.org/wp-content/uploads/2021/06/PHEV-white-paper-sept2020-0.pdf (accessed on 26 July 2022).
55. Noussan, M.; Raimondi, P.P.; Scita, R.; Hafner, M. The Role of Green and Blue Hydrogen in the Energy Transition—A Technological and Geopolitical Perspective. *Sustainability* **2021**, *13*, 298. [CrossRef]
56. International Energy Agency. Global EV Outlook 2022. Technical Report. 2022. Available online: https://www.iea.org/reports/global-ev-outlook-2022 (accessed on 12 July 2022).
57. UK Department for Transport. Data on Vehicle Mileage and Occupancy. Technical Report. 2021. Available online: https://www.gov.uk/government/statistical-data-sets/nts09-vehicle-mileage-and-occupancy#car-or-van-occupancy (accessed on 26 July 2022).
58. Noussan, M.; Jarre, M. Assessing Commuting Energy and Emissions Savings through Remote Working and Carpooling: Lessons from an Italian Region. *Energies* **2021**, *14*, 7177. [CrossRef]
59. Diao, M.; Kong, H.; Zhao, J. Impacts of transportation network companies on urban mobility. *Nat. Sustain.* **2021**, *4*, 494–500. [CrossRef]
60. Erhardt, G.D.; Roy, S.; Cooper, D.; Sana, B.; Chen, M.; Castiglione, J. Do transportation network companies decrease or increase congestion? *Sci. Adv.* **2019**, *5*, eaau2670. [CrossRef]
61. Blondel, B.; Mispelon, C.; Ferguson, J. Cycle More Often 2 Cool Down the Planet!-Quantifying CO_2 Savings of Cycling. Technical Report. 2011. Available online: https://ecf.com/files/wp-content/uploads/ECF_BROCHURE_EN_planche.pdf (accessed on 27 July 2022).
62. Mizdrak, A.; Cobiac, L.; Cleghorn, C.; Woodward, A.; Blakely, T. Fuelling walking and cycling: Human powered locomotion is associated with non-negligible greenhouse gas emissions. *Sci. Rep.* **2020**, *10*, 9196. [CrossRef]
63. Bell, A.C.; Ge, K.; Popkin, B.M. The Road to Obesity or the Path to Prevention: Motorized Transportation and Obesity in China. *Obes. Res.* **2002**, *10*, 277–283. [CrossRef]
64. Lee, D.; Fahey, D.; Skowron, A.; Allen, M.; Burkhardt, U.; Chen, Q.; Doherty, S.; Freeman, S.; Forster, P.; Fuglestvedt, J.; et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos. Environ.* **2021**, *244*, 117834. [CrossRef]
65. Graver, B.; Rutherford, D.; Zheng, S. CO_2 Emissions from Commercial Aviation—2013, 2018, and 2019. Technical Report. 2020. Available online: https://theicct.org/wp-content/uploads/2021/06/CO2-commercial-aviation-oct2020.pdf (accessed on 28 July 2022).
66. Anwar, S.; Zia, M.Y.I.; Rashid, M.; Rubens, G.Z.d.; Enevoldsen, P. Towards Ferry Electrification in the Maritime Sector. *Energies* **2020**, *13*, 6506. [CrossRef]
67. Mannarini, G.; Carelli, L.; Salhi, A. EU-MRV: An analysis of 2018's Ro-Pax CO2 data. In Proceedings of the 2020 21st IEEE International Conference on Mobile Data Management (MDM), Versailles, France, 30 June–3 July 2020; pp. 287–292. [CrossRef]
68. Jenu, S.; Baumeister, S.; Pippuri-Mäkeläinen, J.; Manninen, A.; Paakkinen, M. The emission reduction potential of electric transport modes in Finland. *Environ. Res. Lett.* **2021**, *16*, 104010. [CrossRef]
69. Karunarathne, E.; Wijesekera, A.; Samaranayake, L.; Binduhewa, P.; Ekanayake, J. On the implementation of hybrid energy storage for range and battery life extension of an electrified Tuk-Tuk. *J. Energy Storage* **2022**, *46*, 103897. [CrossRef]
70. Thomas, A. Electric bicycles and cargo bikes—Tools for parents to keep on biking in auto-centric communities? Findings from a US metropolitan area. *Int. J. Sustain. Transp.* **2022**, *16*, 637–646. [CrossRef]

71. Vuarnoz, D.; Aguacil Moreno, S. Dataset concerning the hourly conversion factors for the cumulative energy demand and its non-renewable part, and hourly GHG emission factors of the Swiss mix during a one-year period (2016 and 2017). *Data Brief* **2020**, *30*, 105509. [CrossRef]
72. Noussan, M.; Roberto, R.; Nastasi, B. Performance Indicators of Electricity Generation at Country Level—The Case of Italy. *Energies* **2018**, *11*, 650. [CrossRef]
73. Noussan, M.; Neirotti, F. Cross-Country Comparison of Hourly Electricity Mixes for EV Charging Profiles. *Energies* **2020**, *13*, 2527. [CrossRef]