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Multi-Modal Life Cycle Assessment of Journeys by Aircraft, Train or Passenger Car

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Abstract: To reduce the carbon footprint of transport, policymakers are simultaneously stimulating cleaner vehicles and more sustainable mobility choices, such as a shift to rail for short-haul flights within Europe. The purpose of this study is to determine the climate impact of a journey within Europe by aircraft, train or passenger car, and to better understand what factors drive this impact in order to make smarter and more sustainable fact-based mobility choices. The study consists of a life cycle inventory (LCI) and life cycle impact assessment (LCA) of greenhouse gas emissions of specific vehicles in five case study travel scenarios in Europe. The energy and resulting direct emissions (including non-CO_2) of the aircraft scenarios were calculated for the purpose of this study using the Mission Aircraft and Systems Simulation tool developed by the Royal Netherlands Aerospace Centre NLR. For other LCA phases and other modes of transport, the study relies on emission factors from public literature. A trip by train results in three to five times less emissions than a comparable trip by aircraft. In most scenarios, the passenger car with two people onboard emits significantly more than a train but slightly less than an aircraft. The study also shows what drives the climate impact of such a trip and how this is very different for different modes of transport. The study further highlights a lack of high-quality data, especially in the areas of indirect emissions and infrastructure, poor consistency among studies and a general under-documentation and lack of transparency regarding assumptions.

Keywords: climate impact of transportation; comparative LCA; direct and indirect emissions; infrastructure emissions; non-CO_2 effects; multi-modal transportation

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1. Introduction

Transport is an important contributor to air pollution and climate change. In 2019, transportation was responsible for 23% of the CO_2 emissions [1,2]. Transport is, therefore, an important component of the European Green Deal and the European Commission's vision of a net-zero society. In order to reduce to the climate impact of transportation and enable sustainable policy and mobility choices, one needs to understand the 'true' climate impact, including both direct and indirect and infrastructure emissions. An LCA is an established method to gain this understanding.

This study is far from the first to compare the life cycle greenhouse gas emissions of multiple transportation modes and it uses previous literature for finding credible emission factors, especially for the trains, cars and infrastructure, which are not the core expertise of the NLR.

In 2021, the research and consultancy group CE Delft released their "*Kosten externe ketenemissies*" (English: Cost of indirect emissions) [3], which focuses on the impact of indirect emissions, such as production, maintenance, end-of-life and supporting infrastructure. Together with previous studies [4,5], it provides a complete set of emission factors for both direct and indirect emissions of passenger transport by road, rail and air, including an impact assessment for multiple travel scenarios originating from The Netherlands. It is also one of the few studies that provides emission factors for specific European airports and includes local terrain factors in determining emissions of road and rail infrastructure. Limitations of the study are a reliance on fleet averages of relatively old (2014) vehicles and a lack of transparency on certain underlying assumptions. Despite these shortcomings, the study provided a good starting point and reference, and was the main source for airport emissions and the emissions for railway construction.

The findings from *Kosten externe ketenemissies* align with a 2012 study for the European Commission by a consortium led by AEA (now part of Ricardo) and, among others, CE Delft [6], on the impact of indirect and infrastructure emissions. The emission factors for road construction were used in this study. Notably, Hill refers to both Chester and Simonsen (both discussed below) for aircraft emissions.

A study that is often cited or proves to be the original source of specific LCA data is the 2008 dissertation by Mikhail Chester [7]. The study provides a complete LCI and LCA of both road, rail and air transportation, including indirect emissions and infrastructure. By now, the information is a bit dated and US-centric, and some underlying assumptions can be improved. For example, it is assumed that in aircraft production with the maintenance emissions scale with list price, an aircraft that is 20% more expensive than a Boeing 737 will have 20% higher emissions. Despite its limitations, the study is still relevant for its completeness. This study uses the emissions factors for passenger car maintenance and railway maintenance. A study that can be considered an update of the Chester dissertation is the 2016 study by Liu and others [8]. The study shares the main limitations of the previous study, with newer numbers. This study uses the emission factors for aircraft manufacturing and maintenance.

What can be considered a European alternative to Chester's study for aircraft emissions is the Norwegian 2010 study by Simonsen [9]. The study is less accessible, as it is written in Norwegian, but it contains data from the Norwegian airport operator Avinor and the Norwegian airlines SAS and Norwegian. Similar to Chester's work, the study is frequently cited or proves to be the original source of information.

In terms of aircraft end-of-life studies, there is only one credible source, which is the 2010 master's thesis by Lopes [10] on an LCA for the Airbus A330. The emission factors for end-of-life are based on findings from the Airbus PAMELA study and are used here.

A comparison of the environmental impact of conventional and high-speed rail by AEA [11] provides a complete LCI of the direct, indirect and infrastructure emissions for specific train models. Even though the study contains relatively old information (2009), it remains one of the few studies that assesses specific train models. As such, this study uses (scaled) emission factors for rail vehicle emissions (both direct and indirect) and station operations.

Similar to trains and aircraft, few studies assess the life cycle emissions of specific passenger cars. Volvo is one of the manufactures who publish LCA's of their own vehicles, including indirect emissions. The LCA for the C40 and XC40 [12] provided the emission factors for the passenger car vehicle emissions in this study. While this cannot be considered an independent source, an independent study by Bieker [13] showed that the emission factors provided by Volvo are at least more conservative than average.

The study that is presented here adds to the existing body of knowledge in three areas: by including new vehicle emission figures for the Airbus A320neo that have not been found in other studies, by comparing the aircraft emissions to specific, modern examples of trains and passenger cars, and by being transparent about the methodology and underlying assumptions.

The goal of the study is to compare the climate impact of choosing a certain mode of transport as an individual when travelling across Europe. The study aims to create a high-level understanding of the relative impact of the individual life cycle components on the total climate impact of a certain mode of transport and a better understanding of the strengths and weaknesses of current options for intra-European travel. Finally, the study contributes to the creation of a framework by NLR in which the life cycle impact of future aircraft can be assessed and compared to alternative modes of transport.

2. Materials and Methods

This study consists of a comparative life cycle assessment of the climate impact of passenger transport. The study follows the template provided by ISO 14044-2006. The methodology used in the four phases of the LCA is provided below. A spreadsheet containing numbers and calculations is provided as Supplementary Material.

2.1. Goal and Scoping

The goal of this study is to determine the differences in the climate impact of different modes of transport under 5 different case study scenarios and to gain a high-level understanding of the factors driving the outcome. The 5 case studies all originate from Amersfoort Central Station, The Netherlands, and range from 400 to 1300 km. The destinations are London King's Cross, UK; Paris Gare du Nord, FR; Strasbourg Station, FR; Berlin Hbf, DE; Roma Termini, IT.

For each vehicle, both direct and indirect emissions were assessed, including emissions from producing fuel or energy and emissions from supporting infrastructure. Specifically for the aircraft, the climate impacts of non-CO_2 emissions were included. Cost and depletion of materials were not included in the assessment, nor were time or passenger comfort. Energy consumption was considered when required to calculate carbon emissions. The system boundaries are shown in Table 1 below.

Table 1. System boundaries of the study.

Cost	Materials	Energy	'Indirect' Emissions				'Direct' Emissions
			Vehicle (V)		Infrastructure (I)		Vehicle (V)
			Fixed	*Variable*	*Fixed*	*Variable*	*Variable*
			V. Manufacturing	V. Maintenance	I. Construction	I. Operation	V. TTW [1] emissions
			V. End-of-life		I. End-of-life	I. Maintenance	V. WTT [2] emissions

[1] TTW, Tank-to-Wake; [2] WTT, Well-to-Tank.

The impact was assessed based on the emissions of the greenhouse gasses (GHG), including carbon dioxide (CO_2), nitrogen oxide (NO_X), ammonia (NH_4) and water vapour (H_2O). The results are presented as CO_2-equivalents, or CO_2eq, and the functional units are kg per journey per passenger, kg per passenger-kilometres-travelled (PKT) and kg per vehicle-kilometres-travelled (VKT).

As the study was performed by an aerospace research institute, there is an inherent knowledge bias towards aviation. This was mitigated by relying on publicly available emission factors that are applied to specific scenarios and aiming for a high level of internal consistency for all life cycle phases and modes of transportation. Only the direct aircraft emissions were specifically calculated for the purpose of this study, as this is a key area of expertise of the authors. Table 1 notes the system boundaries in this study.

2.2. Inventory Analysis

The vehicle fleets assessed in the study represent modern examples of the vehicles that are typically used under the assessed scenarios. For the aircraft, this was the Airbus A320neo, a modern single-aisle aircraft. For the train, this included both regular 'intercity' (IC) and high-speed trains (HST). The first was represented by the 2022 Alstom Coradia Stream, a modern commuter train. The latter was represented by 3 models: the 1998 TGV Thalys PKB(A), the 1999 Siemens class 403 ICE-3 and the 2016 Siemens class 374 Eurostar. For the passenger car, the study assessed two versions of the Volvo XC40, an internal combustion engine (ICE) version and a Battery Electric Vehicle (BEV). The XC40 represents a modern vehicle in a crossover-body style that is very popular today. Table 2 notes the fleet assumptions in this study.

Table 2. Fleet assumptions used in this study.

Assumption	Aircraft	Train		Passenger Car	
	Single Aisle	IC	HST	Petrol	Electric
Service life (km)	92,100,000 [8]	12,000,000 [5]	15,000,000 [5]	200,000 [12]	200,000 [12]
No. of seats	180	417	Thalys: 377 ICE: 441 Euro: 902	5	5
Occupancy	86% [5]	36% [4]	66% [4]	2	2

2.2.1. Direct Vehicle Emissions—Aircraft

Direct vehicle emissions of the aircraft were calculated specifically for this study based on the flight distance and the number of passengers (95 kg per passenger, including baggage) using the Mission Aircraft and Systems Simulation (MASS) tool developed by NLR [14]. All flight distances have been determined using a great circle distance calculator and have been corrected for route inefficiencies, with a correction factor of 97% based on the mean 2017 horizontal flight efficiency for Europe applied to the segment length [15]. Unless otherwise stated, the aircraft was assumed to operate on regular jet fuel (Jet-A) without any biofuel or synthetic fuel blended in.

Aircraft are unique in emitting NO_X and H_2O into the stratosphere, which can subsequently lead to contrail-induced cloud (CiC) formation. To account for the global warming potential of these 'non-CO_2' emissions, the following distance-based formulas were applied to the calculated CO_2 emissions [16]:

$$CO_{2eq}^{CO_2} = 1.0 \quad (1)$$

$$CO_{2eq}^{NOX} = 2.3\arctan(3.1D) - 2.0 \quad (2)$$

$$CO_{2eq}^{CiC} = 1.1\arctan(0.5D) \quad (3)$$

$$CO_{2eq}^{H_2O} = 0.2\arctan(D) \quad (4)$$

where D is the flown distance in thousand km.

The fuel was assumed to be regular Jet-A kerosene with a WTT emission factor of 0.016 kg per MJ [17,18]. This resulted in the emission factors shown in Table 3. WTT emissions represent the emissions involved in producing and moving the fuels or energy, whereas TTW emissions refer to direct, tailpipe emissions.

Table 3. Aircraft direct emission factors per vehicle-kilometres-travelled (VKT).

Aircraft Emission Factors	Emissions per VKT
Energy	141–207 MJ
Tank-to-Wake (TTW) CO_2 emissions	10.4–15.3 kg CO_2eq
TTW non-CO_2 emissions	4.2–19.7 kg CO_2eq
Well-to-Tank (WTT) emissions	2.3–3.3 kg CO_2eq

2.2.2. Direct Vehicle Emissions—Train

The energy consumption of the IC and HST trains was based on a 2009 LCA study by AEA that provided data on a number of specific train models [11]. As some of the models in the AEA study are no longer used, the energy consumption figures have been scaled to better represent the performance of the newer models. The scaling was based on the delta in passenger capacity. In addition, a 2% annual increase in efficiency based on the year of entry into the market was assumed [4]. The study assumed a carbon intensity of 70.3 kg CO_2eq per MJ or the mean carbon intensity of the EU27+UK in 2019 [19]. This resulted in the emission factors shown in Table 4.

Table 4. Train direct emission factors per vehicle-kilometres-travelled (VKT).

Train Emission Factors per VKT	IC All Scenarios	HST Paris and Strasbourg	HST Berlin and Rome	HST London
Energy	33.8 MJ	46.9 MJ	53.8 MJ	83.7 MJ
Tank-to-Wheel (TTW) emissions	0	0	0	0
WTT emissions	2.37 kg CO_2eq	3.30 kg CO_2eq	3.78 kg CO_2eq	5.88 kg CO_2eq
AEA reference model used for scaling	Alstom Class 390 Pendolino	TGV Reseau	-	Alstom 'class 373' Eurostar 300

2.2.3. Direct Vehicle Emissions—Passenger Car

Vehicle economy figures were based on manufacturer claims for the XC40 B4 and XC40 Recharge and were 0.864 MJ per km and 7.33 L/100 km, respectively [12]. The petrol was assumed to be regular e5 petrol without additives and with a WTT emission factor of 0.651 kg CO_2eq per litre [20]. The study assumed a carbon intensity of 70.3 kg CO_2eq per MJ, similar to that for the trains. This resulted in the emission factors shown in Table 5.

Table 5. Passenger car direct emission factors per vehicle-kilometres-travelled (VKT).

Passenger Car Emission Factors per VKT	Electric Car	Petrol Car
Energy	0.864 MJ	7.33 L/100 km
TTW emissions	0	0.163 kg CO_2eq
WTT emissions	0.061 kg CO_2eq	0.048 kg CO_2eq

2.2.4. Indirect Vehicle Emissions—Aircraft

No emission factors for indirect emissions of the A320neo where found. Based on recommendations by Liu et al. [8], the emissions factor for the similar, albeit older, Boeing 737 was scaled using the assumptions of the manufacturing emissions scale with list price. The Boeing 737–700 currently lists for USD 89.1 M [21]. For the A320neo, the 2018 list price was USD 110.6 M [22]. Assuming a 2% annual price increase, this would correspond to a 2022 list price of USD 118.2 M. This results in a scaling factor of 1.33.

The Boeing 737 emission factors for production found in the literature ranged from 19.2 to 32.6 million kg, with an average value of 23.9 million kg CO_2eq [6–9]. Applying the scaling factor of 1.33, A320neo production would result in 31.8 million kg CO_2eq.

Literature data on Maintenance Repair and Overhaul (MRO) emissions were even more limited than those for vehicle manufacturing. Chester [7] estimated MRO emissions for the Boeing 737 to be 19.9 million kg CO_2eq. Assuming again based on the MRO emissions scale with list price, maintenance of the A320neo would emit 26.3 million kg CO_2eq.

All data on aircraft end-of-life emissions seem to originate from a single study by Airbus. Using findings from the Airbus Project for Advanced Management of End-of-life of Aircraft (PAMELA), the authors of [10] estimated that 26.3% of the emissions during production were compensated by recycling at the vehicle's end-of-life. For the A320neo, this would amount to a compensation of 8.36 million kg CO_2eq at the end-of-life. This resulted in the emission factors shown in Table 6.

Table 6. Aircraft indirect emission factors.

Emission Factor	Per Aircraft
Production	31.8 million kg CO_2eq
Maintenance	26.3 million kg CO_2eq
End-of-life	−8.36 million kg CO_2eq

2.2.5. Indirect Vehicle Emissions—Train

AEA [11] estimated manufacturing emissions for a number of different models. AEA noted that while model-specific information is lacking, no fundamental differences in manufacturing among train types are expected. Therefore, the reference values have been scaled to fit the vehicles assessed in the study based on empty weight (tare mass) or, when mass was unknown, train length.

In the literature, maintenance is often included with manufacturing and end-of-life in a single figure for indirect vehicle emissions. Different studies show a wide range of GHG emissions during maintenance, especially for IC trains. Due to the lack of insight into assumptions in these studies, it is not possible to explain these differences. However, it is determined that the type of train does not have a substantial influence on the materials and maintenance of trains. AEA [11] includes a separate figure for maintenance of 1 kWh per km. At 69.4 g CO_2 per MJ, this equals 250 g CO_2eq per km. AEA states that this indication applies to both IC and HST. As the Eurostar is nearly twice as long as the other trains, maintenance emissions are doubled for that train type in this study. For all other types, the AEA figure is used.

End-of-life emissions of the trains are included in vehicle manufacturing based on the mid-level recycling assumption, in which 50% of materials are recycled and the rest goes to landfill [11]. This resulted in the emission factors shown in Table 7.

Table 7. Train indirect emission factors.

Emission Factor	IC All Scenarios	HST Paris and Strasbourg	HST Berlin and Rome	HST London
Production	1,444,651 kg CO_2eq	1,293,865 kg CO_2eq	1,381,699 kg CO_2eq	2,417,208 kg CO_2eq
Maintenance	0.25 kg CO_2eq per VKT	0.25 kg CO_2eq per VKT	0.25 kg CO_2eq per VKT	0.50 kg CO_2eq per VKT
End-of-life	Incl. in production	Incl. in production	Incl. in production	Incl. in production

2.2.6. Indirect Vehicle Emissions—Passenger Car

Based on the Bill of Materials (BOM) containing the material composition and weight, Volvo estimates carbon emissions of both the petrol and the electric version of the XC40: 15,700 and 26,400 kg CO_2eq, respectively. In this study, the refinement and production of the materials were taken into account, including the batteries for the electric XC40 (7000 kg CO_2eq per vehicle). Transport from Tier 1 suppliers (inbound) and to the dealers (outbound) have been included as well [12].

Compared to an independent, global LCA study by Bieker [13], the Volvo estimates appear to be conservative. A possible explanation could be that Volvo's study does not include avoided emissions due to recycling, whereas Bieker's does. This resulted in the emission factors shown in Table 8.

Table 8. Passenger car indirect emission factors.

Emission Factor	Electric Car	Petrol Car
Production	26,400 kg CO_2eq	15,700 kg CO_2eq
Maintenance	4 g CO_2eq per km	5 g CO_2eq per km
End-of-life	500 kg CO_2eq	600 kg CO_2eq

2.2.7. Infrastructure Emissions—Aircraft

In contrast to rail and road transport, air transport requires most physical infrastructure at the origin and destination (point-based) and limited infrastructure in between. This study includes the emissions for the construction of the terminal, runways and aprons, and the operation, including lighting, de-icing, Ground Service Equipment and Air Traffic Control, and maintenance of the airport building, runways and aprons are included in the assessment.

Public data on EU airport emissions are scarce. CE Delft [3] managed to estimate the total infrastructure emissions of a number of European airports by multiplying the mean emissions per area from the Mobitool database [23] with the total area of an airport and accounting for the share of passenger transport in the total operation (including cargo), as shown below. In this study, a lifetime of 100 years was assumed for airport infrastructure. The selection of airports included Amsterdam Schiphol (AMS), Paris Charles de Gaulle (CDG), London Heathrow (LHR) and Rome Fiumicino (FCO). Berlin (BER) and Strasbourg (SXB) were not included in the CE Delft study.

While CE Delft continued the calculation by assigning total airport emissions to specific routes, this study chose a simpler approach. The total airport emissions were divided by the lifetime of the airport (100 years) to determine the annual emission. This figure was then multiplied by the share of passenger transport in the operation and divided by the number of passengers in 2019. This resulted in emissions between 3 and 5 kg per passenger, as shown below. For Berlin and Strasbourg, airport emissions of 5 kg per passenger were assumed. This resulted in the emission factors shown in Table 9.

Table 9. Airport emission factors.

Airport	Amsterdam	Paris CDG	London Heathrow	Rome FCO	Berlin Branden-Burg	Strasbourg
GHG per year (PAX-only)	320.6 MT CO_2eq	296.9 MT CO_2eq	259.1 MT CO_2eq	181.9 MT CO_2eq	Unknown	Unknown
No. of passengers (2019)	71.7 million	76.2 million	80.1 million	43.5 million	35.6 million	1.3 million
GHG per PAX	4.47 kg CO_2eq	3.90 kg CO_2eq	3.23 kg CO_2eq	4.18 kg CO_2eq	5.00 kg CO_2eq (assumed)	5.00 kg CO_2eq (assumed)

2.2.8. Infrastructure Emissions—Train

Rail infrastructure consists of many different elements along the route. In this study, railway tracks and stations were considered. The International Union of Railways (UIC) assessed a number of HST routes. Carbon emissions for constructing the routes ranged from 58 to 176 tonnes of CO_2eq per year per km of track [24], with the main driver being the number of tunnels and bridges. The previously mentioned AEA study estimated a number as high as 270 tonnes of CO_2eq per year, yet it is unclear what the underlying case studies were. Based on a number of studies, including that by AEA [11], CE Delft managed to differentiate infrastructure emissions depending on the type of track (IC or HST) and terrain (flat, hills or mountainous) [3]. Assuming a fixed 35-year lifetime of the infrastructure, GHG emissions ranged from 113 to 258 tonnes of CO_2eq per km per year.

AEA [11] estimated that the operation of stations requires 45 Wh per passenger on average. At 70.3 g CO_2 per MJ, this results in 11 g CO_2eq per passenger. The emissions of rail traffic management and other supporting operational activities are unknown. Chester [7] presented 57,000 MJ per km per year for the California High-Speed Rail. At 70.3 g CO_2 per MJ, this results in 4007 kg CO_2 per km per year for track maintenance. This resulted in the emission factors shown in Table 10.

Table 10. Rail infrastructure emission factors.

Emission Factor	IC	HST
Construction on flat	113.3 tonnes of CO_2eq per km per year	156.7 tonnes of CO_2eq per km per year
Construction on hill	131.4 tonnes of CO_2eq per km per year	181.6 tonnes of CO_2eq per km per year
Construction on mountain	149.4 tonnes of CO_2eq per km per year	206.6 tonnes of CO_2eq per km per year
Construction of Eurotunnel	-	257.9 tonnes of CO_2eq per km per year
Operation	11.4 g of CO_2eq per passenger	11.4 g of CO_2eq per passenger
Maintenance	4006 kg of CO_2eq per km per year	4006 kg of CO_2eq per km per year

A dominant factor in the impact of construction emissions on rail transport is how intensively the railway tracks are used. In The Netherlands, the average intensity is 64 trains a day [25]. However, on busy routes with 4 to 6 trains per hour, the intensity can be higher.

Some busy HSTs have an intensity as high as 110 trains per day [24]. For this study, an intensity of 75 trains per day was assumed on all routes.

2.2.9. Infrastructure—Passenger Car

Similar to rail infrastructure, road infrastructure consists of many different elements along the route. In this study, roads, lighting and traffic systems (such as traffic lights) were considered. Secondary infrastructure such as petrol or charging stations were not considered.

Hill [6] reported the kilograms of CO_2eq per year per metre for roads. The numbers in this study were converted to g CO_2eq per km, assuming an average 40-year lifespan for a road. The study considered various types of roads, such as hot and cold asphalt, concrete and overlays, with a large variability in emission factors. For this study, the average value was used for all scenarios.

The operation of infrastructure includes the operation and energy use of traffic systems and lighting. It is estimated that lighting consumes 95% of the total energy for road operation. Hill [6] estimated emissions from operation at 12,400 kg CO_2eq per km per year.

Hill [6] also reported the maintenance for road surfaces, including all preventive and corrective maintenance. Again, there is great variation depending on the type of road and construction. For this study, the average value of 3300 kg CO_2eq per km per year was used. This resulted in the emission factors shown in Table 11.

Table 11. Road infrastructure emission factors.

Emission Factor	Highway
Construction on flat	56,257 kg CO_2eq per km per year
Construction on hill	87,657 kg CO_2eq per km per year
Construction on mountain	119,086 kg CO_2eq per km per year
Construction of Eurotunnel	257,943 kg CO_2eq per km per year
Operation	12,400 kg CO_2eq per km per year
Maintenance	3,300 kg CO_2eq per km per year

The TEN-T performance report provides data on the traffic load and total length of highways in a country, which is used to calculate the annual average daily traffic (AADT) on motorways of a certain highway [26]. Unfortunately, not all data are complete for all countries. The AADT of the UK has been derived from the figure on page 50 of the TEN-T report. Data for France were missing altogether, though it is assumed that France has a similar AADT to Germany. The numbers that are available have been reported in Table 12 below.

Table 12. Road infrastructure utilisation.

	VKT per Year (km $\times$ 10^9)	Total Length of Motorway	Annual Average Daily Traffic on Motorway (AADT) (Both Directions)
The Netherlands	49.60	1886 km	72,000
Belgium	21.79	820 km	72,000
France	-	-	50,000
Germany	189.23	10,341 km	50,000
Austria	25.99	1735 km	41,000
Italy	-	7943 km	7000
United Kingdom	-	2727 km	90,000
Average motorway			38,200

2.3. Impact Assessment

All scenarios cover a multi-modal trip originating from the central station of Amersfoort, The Netherlands—a mid-sized town centrally located in The Netherlands—and terminating at the central station of another European city. In terms of distance, the set covers journeys between 385 and 1260 km (great circle distance, GCD). The actual travelled ground distance of a journey is often significantly longer and varies depending on the mode of travel, as is shown in the table below. For the aircraft, all flight distances were determined using a great circle distance calculator and have been corrected for route inefficiencies, and a correction factor of 97% based on the mean 2017 horizontal flight efficiency for Europe was applied to the segment length [15]. Ground distances for the train were calculated by hand using the most direct route shown in Google Maps. Similarly, ground distances for the passenger cars were based on the Google Maps' route planner. This resulted in the distances shown in Table 13.

Table 13. Distances per scenario and mode of transport.

	London	Paris	Strasbourg	Berlin	Rome
Ground distance by aircraft (airport to airport)	384 km	411 km	480 km	616 km	1337 km
Ground distance by aircraft (incl. first and last mile, station to station)	466 km	493 km	550 km	705 km	1419 km
Ground distance by train	588 km	524 km	632 km	581 km	1950 km
Ground distance by car	525 km	483 km	567 km	616 km	1669 km

Each trip was divided into a first leg towards the nearest travel hub (except for scenarios by car), main leg from the origin hub to the travel hub near the destination, and finally, the last leg to the destination. The scenarios by air assumed a first leg by intercity train and last leg by intercity train. When no intercity connection was available from the travel hub near the destination, the last leg was assumed by ICE taxi. The scenarios by rail assumed a first leg by intercity train towards the travel hub. From there, the main leg was by HST. If the final destination was unreachable by HST, the last leg was assumed by intercity train. For the distance by train, the shortest route in terms of time was selected. The scenarios by car only involved a main leg from the starting point at Amersfoort CS to the final destination. All destinations could be covered with a single flight, even Strasbourg, although the direct service to this city is limited to twice a day on weekdays. GHG emissions were calculated based on the actual distance travelled.

Tables A1–A3 in Appendix A detail the scenario assumptions per mode of transport.

3. Results

The results show the climate impact of the modes of transport using five example travel scenarios. Each scenario started in Amersfoort, the geographical centre of The Netherlands, but five different destinations were determined within Europe up to 1300 km. The destinations were London, Paris, Strasbourg, Berlin and Rome. For both the origin and destinations, the city central station was the exact starting and end point. The results are shown in GHG emissions in kg CO_2eq per passenger per trip. The results can be divided into three parts.

3.1. Results per Scenario

Figure 1 shows the total GHG emissions per passenger per trip in kg CO_2eq for all scenarios. Please refer to Table A2 in Appendix A for the numerical values. Table 14 shows the relative outcome compared to the modality with the lowest GHG emissions, the train.

Table 14. GHG emissions per passenger per trip relative to the emissions of a similar trip by train.

	London	Paris	Strasbourg	Berlin	Rome
Aircraft	4.7	3.1	2.9	5.2	3.4
Train	1.0	1.0	1.0	1.0	1.0
Car, electric	3.5	2.0	1.8	2.7	2.0
Car, petrol	5	2.8	2.6	3.9	2.8

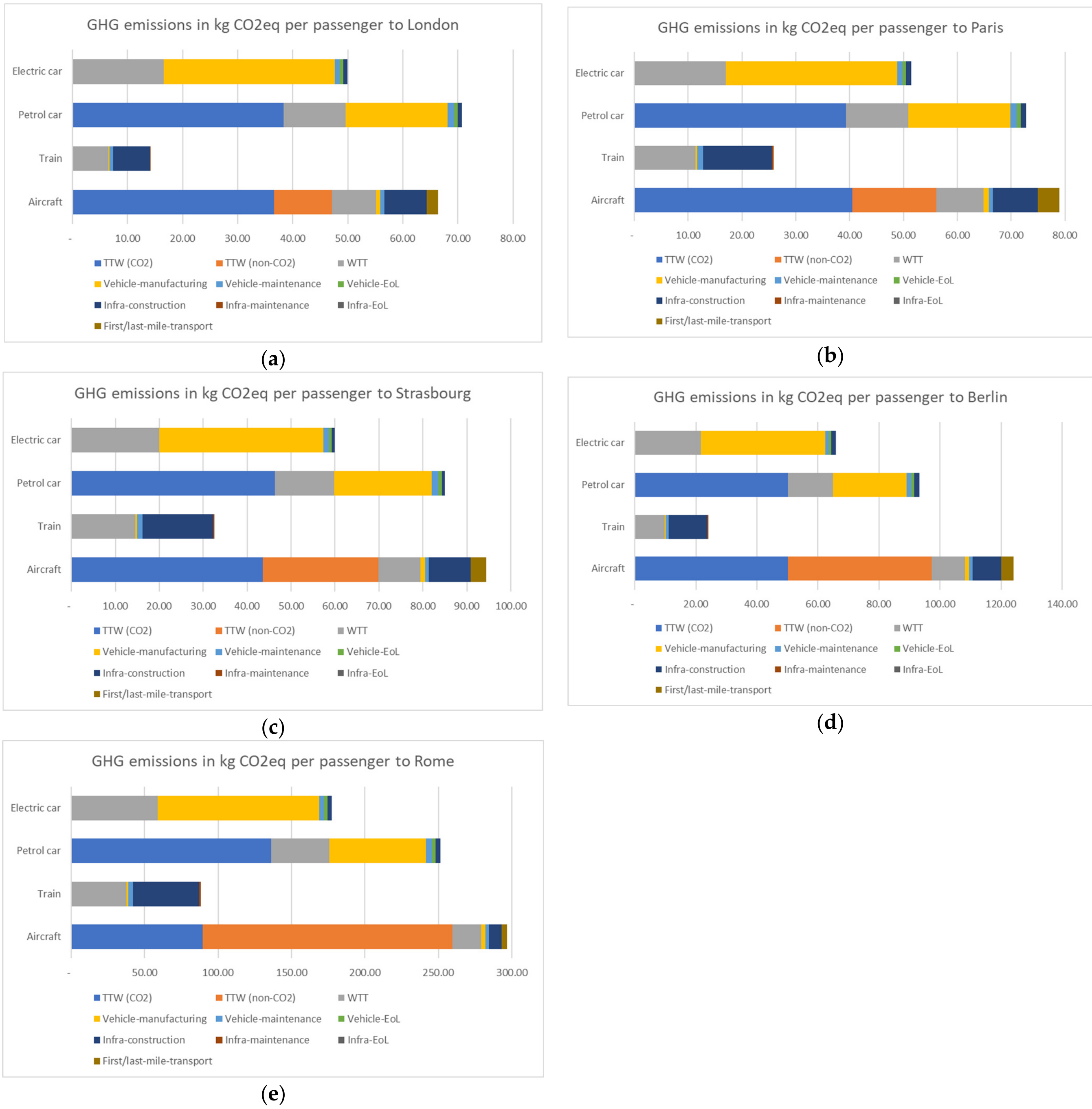

Figure 1. Total GHG emissions per passenger per trip in kg CO_2eq to: (**a**) London, (**b**) Paris, (**c**) Strasbourg, (**d**) Berlin, and (**e**) Rome.

Each scenario shows similar results compared to other destinations. In all scenarios, the train was the mode of transport with the lowest GHG emissions per passenger by a factor up to 5, in comparison to other modes. If a journey by train is not feasible, the electric passenger car is the best alternative, even with the current carbon intensity levels. The petrol car is the third-best modality based on GHG emissions, with the exception of the trip between Amersfoort and London due to the Canal Tunnel. In this scenario, the aircraft is the third-best modality. The use of the tunnel also ensures that the petrol and electric passenger car have limited savings over the aircraft due to the Canal Tunnel. Lastly, the aircraft emits the most GHG emissions in these five scenarios.

3.2. Origins of Emissions

In terms of the origins of life cycle emissions, there are profound differences per mode of transport, as shown in Figure 2. Aircraft-related emissions are dominated by direct vehicle emissions (85%, both from burning fuel during the operation and producing said fuel). Train emissions are dominated by emissions from the generation of electricity, accounting for more than 80% of the total emissions. For passenger cars, it depends on the powertrain. Emissions from the petrol car are dominated by direct vehicle emissions (>70%) and vehicle production (>25%). For the electric car, vehicle production accounts for >60% of the trip emissions. Approximately 30% of the trip emissions is due to the generation of electricity.

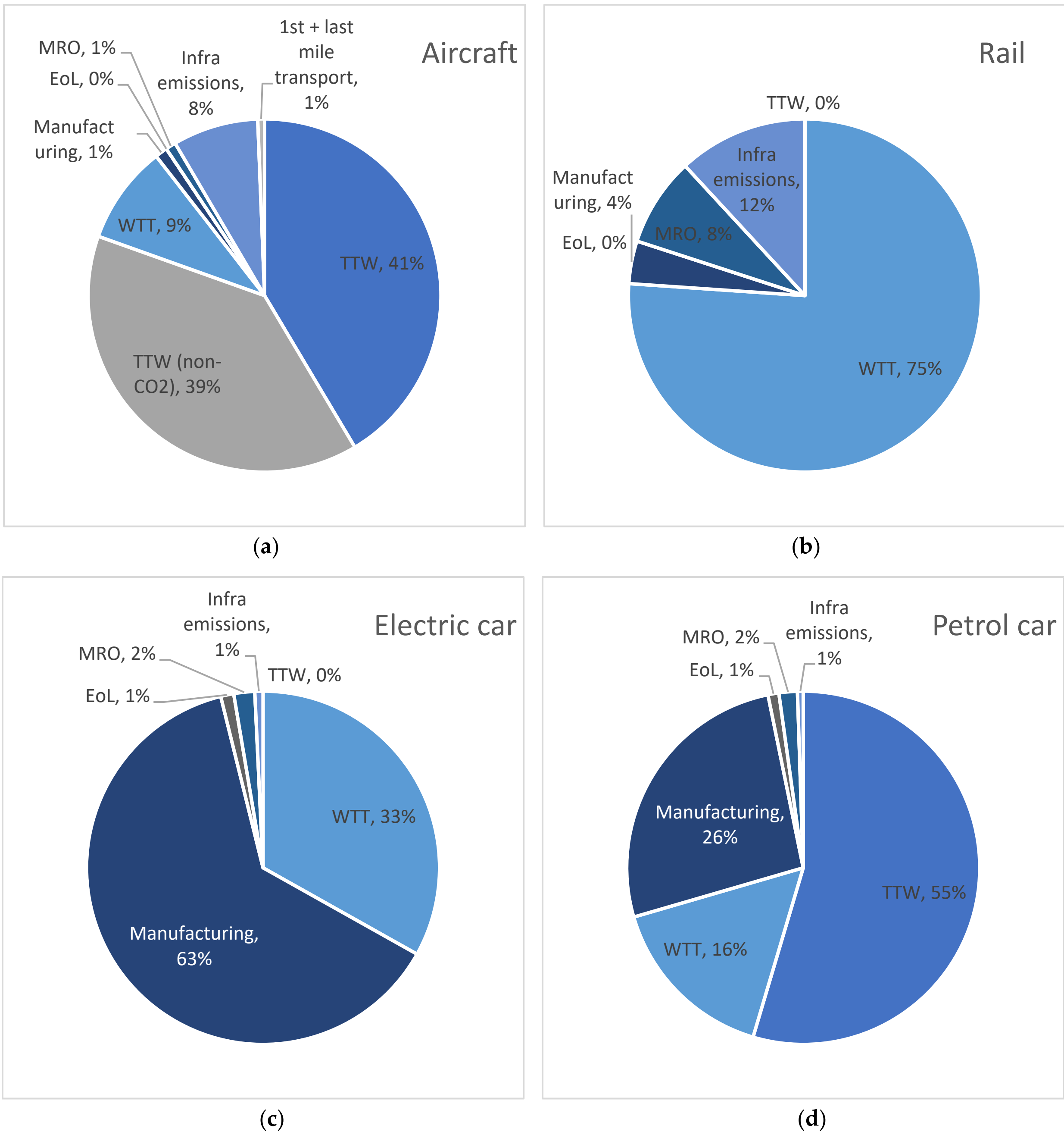

Figure 2. Origin of GHG emissions per transportation mode: (**a**) aircraft, (**b**) train, (**c**) electric passenger car, and (**d**) petrol passenger car.

3.3. Results Infrastructure

When looking at the indirect emissions in more detail, it is striking that the share of emissions for airport and train infrastructure is relatively high. Within infrastructure, this mainly concerns the construction. However, during the extensive literature study on emissions, it has been noticed that the ranges of data input vary widely, which causes a wide range of results, especially for train infrastructure. Relatively little life cycle assessment research has been carried out on trains, and not all studies are equally transparent about the various assumptions (such as service lives, occupancy rates, etc.) that have been made. In addition, the level of detail (e.g., bridges and tunnels) also differs per study, making it difficult to compare the different LCAs. The wide range of results has been highlighted by several researchers. For example, Bueno, Hoyos and Capellán-Pérez [27] showed how wide the differences are in the emissions of infrastructure construction in different LCA studies.

4. Discussion

Multiple parameters were used in this research. The assumptions of the multiple parameters are discussed in this section.

4.1. Assumption for Direct Vehicle Emissions

Fuel or energy consumption drives the amount of fuel or energy that is required for a certain scenario. For the vehicles that use fossil fuel, the amount of fuel drives both TTW and WTT emissions. For electric vehicles, the amount of energy only determines TTW emissions, as WTT emissions are non-existent. The production of fossil fuels is considered an established process, with little variation in the amount of GHG that is released during production. The carbon intensity of electricity, on the other hand, is highly variable depending on the energy source that is used to produce the energy.

A 20% decrease in efficiency can increase the total emissions by as much as 15% for a trip to Berlin for the same passenger load factor. Similar to the aircraft, a train's energy efficiency is an important parameter. A change of 10% in energy efficiency can affect the LCA emissions by 9% for a trip to Berlin. Passenger car emissions are less sensitive to changes in energy efficiency, as 'fixed' LCA categories, such as vehicle production and end-of-life, are more significant than with aircraft or trains. A 10% change in efficiency leads to a 7% impact on LCA emissions for ICE passenger cars and only a 3% impact on LCA emissions for BEV passenger cars. Similar to fossil fuel vehicles, electric vehicles emit GHG with the production of fuel or energy. Different GHG intensities of the generation of electricity have a large impact on LCA emissions. For a train trip to Berlin, a 25% change in GHG intensity leads to a 22% change in emissions per passenger. If the GHG intensity would be zero (fully sustainable generation of energy), trip emissions would drop by 89% compared to the baseline. For a car trip to Berlin, a 25% change in GHG intensity leads to an 8% change in emissions per passenger. If the GHG intensity would be zero (fully sustainable generation of energy), trip emissions would drop by 30% compared to the baseline.

4.2. Assumption for Passenger Load Factor

The passenger load factor is an important assumption that can drive the emissions per passenger. The aircraft load factor used in this study (86%) is typical for an efficient airline in pre-COVID times. Currently, the average load factors are historically low, and the future is uncertain. Lower load factors of 75% or 50% can increase trip GHG emissions by 11% and 55%. The train load factor used in this study (IC: 36%, HST: 66%) is a typical average value for pre-COVID times. Especially, trains used for commuting can have highly volatile load factors. As for aircraft, the average load factors are currently historically low, and the future is uncertain. Changes in the load factor have a high impact on total trip emissions. For the passenger car, an occupancy rate of 2 was assumed, rounded up based on a study conducted by CE Delft [4]. With four passengers on board, both the BEV and ICE passenger cars became more sustainable than the aircraft.

4.3. Uncertainties and Data Quality

The significant differences in the origin of emissions mean that scoping is a very important factor in comparing transportation modes. Selective, incomplete scoping can significantly skew the results in favour of a certain mode. A thorough review of available literature indicated that there are major shortcomings in the available data, particularly related to indirect vehicle emissions, infrastructure emissions and infrastructure utilisation. For road and rail, GIS data for specific routes are often lacking or not readily accessible. Moreover, some of the more accessible and frequently quoted publications are vague on their exact methodology and assumptions.

The wide range in data for rail infrastructure found in the literature has been noted by several researchers. For example, the authors of [27] showed, as in Figure 3, how wide the differences are in the emissions of infrastructure construction in different LCA studies.

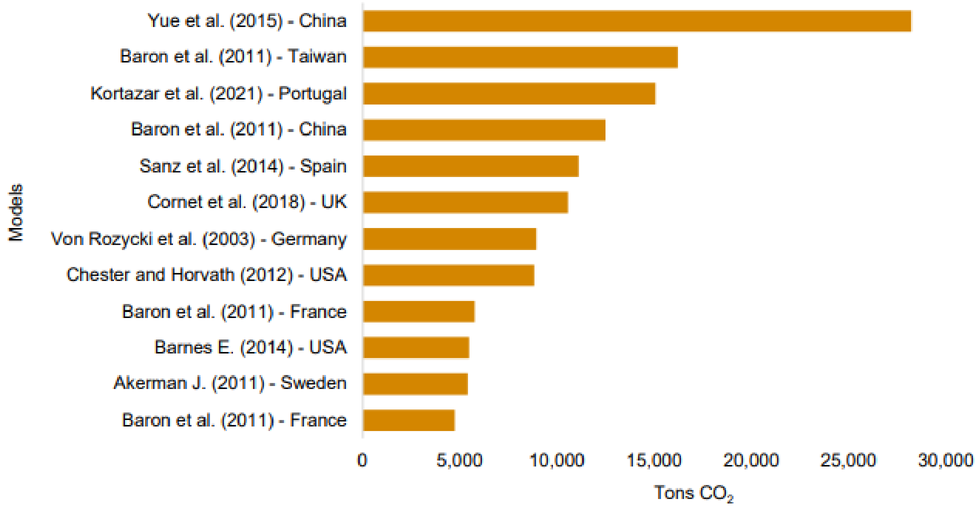

Figure 3. Construction emission models in tCO_2/km [27].

5. Conclusions

Based on all available information and taking into account both direct and indirect emissions from the vehicles and supporting infrastructure, the train is the mode of transport with the smallest climate impact for the kind of travel scenarios that were assessed in this study. The electric passenger car is usually the second-best option in terms of climate impact, even if it is a relatively inefficient model and when factoring in the increased manufacturing emissions and the current carbon intensity levels for electricity in the EU. This is assuming that there are at least two people in the car. When travelling solo, the passenger car has the largest climate impact of all modes of transport, even when it is an electric vehicle. Of the two fossil fuel options, that which has the lowest climate impact depends on the distance travelled. As expected, the direct emissions per kilometre from the aircraft decreased as the distance increased, as the aircraft is most efficient during cruise. However, this benefit is diminished by the climate impact of non-CO_2 emissions, such as NOx and water vapour. These non-CO_2 effects increased with increasing distance. This resulted in the surprising finding that the aircraft is more efficient on shorter routes compared to the petrol-powered passenger car, but not on longer routes (assuming at least two people in the car).

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Appendix A

Tables A1–A3 detail the scenario assumptions per mode of transport.

Table A1. Aircraft scenario details.

	London	Paris	Strasbourg	Berlin	Rome
GCD	372.0	399.0	466.0	597.0	1297.0
Corrected GCD	**383.5**	**411.3**	**480.4**	**615.5**	**1337.1**
First leg	53.6	53.6	53.6	53.6	53.6
Last leg	28.6	28.5	15.5	35.4	28.6
Indicative flight time	0:45	0:46	0:51	1:00	1:46

Table A2. Train scenario details.

	London	Paris	Strasbourg	Berlin	Rome
IC distance	115.8	133.2	50.6	581.2	444.6
HST distance	471.9	391.1	581.7	0.0	1503.4
Total distance	**587.7**	**524.3**	**632.3**	**581.2**	**1949.9**
% flat IC	17%	21%	4%	30%	9%
% hills IC	3%	4%	4%	70%	12%
% mountainous IC	0%	0%	0%	0%	3%
% flat HST	61%	63%	40%	0%	29%
% hills HST	11%	12%	52%	0%	40%
% mountainous HST	0%	0%	0%	0%	9%
% Canal Tunnel	8%	0%	0%	0%	0%
Indicative travel time	4:28	3:36	5:57	5:49	13:55

Table A3. Passenger car scenario details.

	London	Paris	Strasbourg	Berlin	Rome
Distance NL	92.7	149.4	144.5	104.8	36
Distance BE	157.5	120.1			
Distance FR	102.3	213.3	70.7		
Distance DE			352.1	511.5	703.6
Distance AT					209.5
Distance IT					720.3
Distance UK	118.4				
Eurotunnel	53.8				
Total distance	**524.6**	**482.8**	**567.4**	**616.3**	**1669.4**
Indicative travel time	6:39	5:32	6:12	6:14	17:15

Table A4 shows the GHG emissions in kg CO_2eq per passenger per destination, which is also depicted in Figure 1.

Table A4. Detailed overview of GHG emissions per passenger per trip in kg CO_2eq for all scenarios.

London	Aircraft	Train	Petrol Car	Electric Car
TTW (CO_2)	36.63	-	38.37	0.00
TTW (non-CO_2)	10.48	-	0.00	0.00
WTT	7.97	6.50	11.24	16.55
Vehicle, manufacturing	0.85	0.22	18.48	31.08
Vehicle, maintenance	0.71	0.60	1.18	0.94
Vehicle, EoL	-	-	0.71	0.59
Infrastructure, construction	7.71	6.76	0.79	0.79
Infrastructure, maintenance	-	0.17	0.00	0.00
Infrastructure, EoL	-	-	0.00	0.00
First/last mile transport	1.99	-	0.00	0.00
Total direct	**55.08**	**6.50**	**49.61**	**16.55**
Total indirect	**11.26**	**7.74**	**21.15**	**33.39**
Grand total	**66.34**	**14.24**	**70.76**	**49.94**
Paris	**Aircraft**	**Train**	**Petrol Car**	**Electric Car**
TTW (CO_2)	40.51	-	39.35	0.00
TTW (non-CO_2)	15.57	-	0.00	0.00
WTT	8.82	11.34	11.52	16.97
Vehicle, manufacturing	0.92	0.36	18.95	31.86
Vehicle, maintenance	0.76	1.02	1.21	0.97
Vehicle, EoL	-	-	0.72	0.60
Infrastructure, construction	8.37	12.77	1.00	1.00
Infrastructure, maintenance	-	0.34	0.00	0.00
Infrastructure, EoL	-	-	0.00	0.00
First/last mile transport	4.05	-	0.00	0.00
Total direct	**64.90**	**11.34**	**50.87**	**16.97**
Total indirect	**14.09**	**14.50**	**21.88**	**34.44**
Grand total	**78.99**	**25.84**	**72.75**	**51.40**
Strasbourg	**Aircraft**	**Train**	**Petrol Car**	**Electric Car**
TTW (CO_2)	43.63	-	46.24	0.00
TTW (non-CO_2)	26.25	-	0.00	0.00
WTT	9.50	14.54	13.54	19.94
Vehicle, manufacturing	1.07	0.42	22.27	37.45
Vehicle, maintenance	0.89	1.27	1.42	1.13
Vehicle, EoL	-	-	0.85	0.71
Infrastructure, construction	9.47	15.99	0.69	0.69
Infrastructure, maintenance	-	0.38	0.00	0.00
Infrastructure, EoL	-	-	0.00	0.00
First/last mile transport	3.56	-	0.00	0.00
Total direct	79.38	14.54	59.78	19.94
Total indirect	14.99	18.06	25.23	39.98
Grand total	94.37	32.60	85.01	59.93
Berlin	**Aircraft**	**Train**	**Petrol Car**	**Electric Car**
TTW (CO_2)	50.08	-	50.23	0.00
TTW (non-CO_2)	47.14	-	0.00	0.00
WTT	10.90	9.72	14.71	21.66
Vehicle, manufacturing	1.37	0.38	24.19	40.68
Vehicle, maintenance	1.14	0.94	1.54	1.23
Vehicle, EoL	-	-	0.92	0.77
Infrastructure, construction	9.47	12.61	1.59	1.59
Infrastructure, maintenance	-	0.37	0.00	0.00
Infrastructure, EoL	-	-	0.00	0.00
First/last mile transport	3.91	-	0.00	0.00

Table A4. *Cont.*

Berlin	Aircraft	Train	Petrol Car	Electric Car
Total direct	108.13	9.72	64.94	21.66
Total indirect	15.89	14.30	28.25	44.27
Grand total	124.02	24.02	93.18	65.93
Rome	**Aircraft**	**Train**	**Petrol Car**	**Electric Car**
TTW (CO_2)	89.43	-	136.06	0.00
TTW (non-CO_2)	170.13	-	0.00	0.00
WTT	19.47	37.45	39.84	58.68
Vehicle, manufacturing	2.98	1.19	65.53	110.18
Vehicle, maintenance	2.47	3.37	4.17	3.34
Vehicle, EoL	-	-	2.50	2.09
Infrastructure, construction	8.65	45.18	3.09	3.09
Infrastructure, maintenance	-	1.10	0.00	0.00
Infrastructure, EoL	-	-	0.00	0.00
First/last mile transport	3.72	-	0.00	0.00
Total direct	279.03	37.45	175.90	58.68
Total indirect	17.82	50.85	75.30	118.70
Grand total	296.85	88.30	251.20	177.38

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