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Life Cycle Assessment of Transport Infrastructure
A Comparative Analysis of Transport Infrastructure

MASTER'S THESIS

to achieve the university degree of
Diplom-Ingenieur

Master's degree programme:
Civil Engineering - Infrastructure

submitted to
Graz University of Technology

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Graz, August 2021

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Abstract

The life cycle emissions of the transport modes rail and road are examined in many studies worldwide. But these studies differ in their objectives, approaches and methods. For this reason, the life cycle assessments are difficult to compare with each other.

In order to check existing life cycle assessments for their reproducibility and to generate data for a comparison, their contents and characteristics are analysed. The emissions related to the provision of the infrastructure identified in the studies are allocated to one passenger-kilometre and one kilometre of line. Firstly, they are compared with studies of the same mode of transport. Then, based on the previously evaluated emissions per kilometre, a transport performance-dependent comparison of rail and road infrastructure is carried out using the Austrian western line between Vienna and Salzburg as an example.

The master's thesis ends with a description of recommendations for a more uniform structure of life cycle assessments. These are based on the literature research carried out, in which the lack of description of background data causes considerable difficulties.

Kurzfassung

Die Lebenszyklusemissionen der Verkehrsträger Schiene und Straße werden in vielen Studien untersucht. Allerdings unterscheiden sich diese in ihren Zielsetzungen, den Herangehensweisen und Methoden. Deshalb sind die verschiedenen Lebenszyklusanalysen nur schwer miteinander vergleichbar.

Um bestehende Lebenszyklusanalysen auf deren Reproduzierbarkeit zu überprüfen und daraus Daten für einen Vergleich der Verkehrsträger zu generieren, werden deren Inhalte und Eigenschaften analysiert. Die in den Studien ermittelten Emissionen der Infrastrukturbereitstellung werden auf einen Personenkilometer und einen Streckenkilometer umgelegt und danach zunächst Studien desselben Verkehrsträgers gegenübergestellt. Anschließend wird, ausgehend von den zuvor ermittelten Emissionen pro Streckenkilometer, ein transportleistungsabhängiger Vergleich der Schienen- und Straßeninfrastruktur am Beispiel der Weststrecke zwischen Wien und Salzburg durchgeführt.

Abschließend werden Empfehlungen für einen einheitlicheren Aufbau von Lebenszyklusanalysen beschrieben. Diese leiten sich aus der durchgeführten Literaturrecherche ab, in der erhebliche Schwierigkeiten durch die unzureichende Beschreibung der Hintergrunddaten der Studien entstehen.

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1 Introduction

1.1 Problem Description

A comparison of the emissions of individual modes of transport is usually limited to the emissions of vehicle operation. In order to create a holistic picture, it is necessary to consider not only the emissions from vehicle operation, which are sufficiently well known, but also the emissions that occur during the life cycle of the operating vehicles and the infrastructure.

A life cycle assessment (LCA) allows taking into account the environmental impacts which arise during the entire life cycle of a product. This includes all processes, ranging from the extraction of raw materials, over production and use to the disposal of the products at the end of their service life. This provides information regarding the environmental impact of individual products up to large systems.

The majority of existing life cycle assessments concerning the infrastructure provision of individual modes of transport are difficult to compare with each other. This is mainly due to the different assumptions made, the different geographical conditions considered and the respective calculation methods.

In this thesis, the environmental impacts of the infrastructure provision of the transport modes road and rail are considered. The aim of this work is to review and examine existing literature for its comparability within one mode of transport as well as against each other. Subsequently, life cycle assessments for segments of the Austrian rail and road network will be prepared.

1.2 Task Description

This work aims to answer the following questions:

- Can the data of existing LCAs be compared with each other?
- What are the difficulties in standardising the implementation of LCAs?
- What has to be defined in the LCAs to enable comparability?
- Can road and rail networks be compared?

To answer these questions, the first step is to conduct a literature review to analyse existing LCAs of transport modes. Based on these findings, the obstacles in the standardization of LCAs will be described. Additionally, existing LCAs of transport modes will be assessed with respect to their transparency, reproducibility and comparability. The comparison of existing literature illustrates why the emission values determined in each case differ.

Furthermore, this work deals with the preparation of a comparison of segments of the Austrian rail and road network.

By using the findings of the literature research, life cycle assessments are prepared for parts of the Austrian rail and road network. A detailed preparation of the life cycle inventories would exceed the analysis effort of this work.

1.3 Limitations of this work

At the beginning of this paper, it should be noted that the comparisons which have been drawn reflect only a certain part of the aforementioned systems. For this reason, the comparisons made should not be understood as holistic comparisons of the transport modes. They rather represent a first step towards a holistic comparison.

Due to the fact that assumptions have to be made in order to draw a comparison, a number of uncertainty factors (as can be seen in chapter 2.2.4) arise. Finally, these can have a strong influence on the result of the comparison. The comparisons only consider emissions caused by production, construction and partly by maintenance as well as service life of components and systems. The considered life cycle phases are documented as such within the specific analyses. However, end-of-life scenarios are not included within this thesis.

2 Analysis of Railway Life Cycle Emissions

At the beginning of this thesis, literature is reviewed in order to find out whether existing life cycle assessments of emissions of the infrastructure of the transport modes that have already been carried out are comparable with each other, and whether their results are reproducible. Based on the findings of these existing literature reviews, an investigation is made to establish correlations and possible comparisons between the emissions calculations of the considered studies.

2.1 Existing Literature Reviews on Life Cycle Emissions

In this chapter, the contents of literature comparisons already carried out for the rail mode of transport are depicted. Subsequently, their results, advantages and disadvantages as well as their findings will be discussed. Based on these conclusions, a separate literature analysis is employed which aims at comparing the emission values determined in the studies and questioning the transparency and reproducibility of the considered studies. Finally, this results in recommendations for a better comparability in future studies.
The reviewed literature for rail is listed and described hereafter.

- Olubanjo, Olugbenga et al: *Embodied emissions in rail infrastructure: a critical literature review*, Environmental Research Lett. 14, 18.11.2019 [4]

This study attempts to capture the current state of research regarding greenhouse gases GHG emissions from rail infrastructure. The aim is to identify the GHG emissions per kilometre of infrastructure of the different considered studies and to classify them (at-grade, tunnelled, elevated). Fifty-seven case studies are used. In this literature review, *Olugbenga et al.* [4] do not introduce a time reference. [4]
In *Olugbenga et al.* [4] only embodied emissions of the infrastructure are taken into account, although most of the considered studies analyse the construction, operation and maintenance phases. In this study, only the infrastructure emissions per line-kilometre, differentiated in diverse types of track bound transportation (metro, light rail, high-speed rail (HSR), etc.), are compared. Table 1 shows the considered case studies as well as their contents and boundary conditions.
The used case studies differ strongly in the applied LCA methods, the applied functional unit (FU), the scope and the boundary conditions. [4]
"This heterogeneity is the key challenge in developing a generalized model for estimating the embodied GHG emissions in rail infrastructure projects." [4]

Author (Ab)	Type	Construction phase			Infrastructure analyzed				System boundaries			
		Proposed	Under-construction	Constructed	Trackbeds	Stations	Bridges	Tunnels	Construction	Operation	Maintenance	Disposal
Lave (1978)	HRT								x	x	x	
National Rail (2009)	Intercity	x			x	x		x	x	x	x	x
Chester and Horvath (2010)	3*HSR, 3*HRT	x			x	x			x	x	x	
Chang and Kendall (2011)	HSR	x			x			x	x			
Paris and de Silva (2010)	Metro			x	x	x		x	x	x	x	
Westin and Kågeson (2012)	HSR	x			x	x		x	x	x	x	
Chester *et al* (2012)	2*Light			x	x	x			x	x	x	
Chester *et al* (2013)	2*Light			x	x	x			x	x	x	
Morita *et al* (2013)	Light		x		x	x		x	x	x	x	
Hanson *et al* (2016)	5*Commuter			x	x		x	x	x			
Lederer *et al* (2016)	Light			x	x	x			x	x	x	
Miyoshi and Givoni (2014)	HSR	x			x	x		x	x	x	x	
Yue *et al* (2015)	HSR			x	x	x	x	x	x			
Infraestructuras (2015)	HSR			x	x		x		x			
Jones *et al* (2017)	HSR	x			x	x			x	x	x	
Li *et al* (2016)	Metro			x	x	x		x	x	x	x	x
Chester and Cano (2016)	Light			x	x	x	x		x	x	x	
International Union of Railways (2016)	HSR,			x	x	x	x	x	x	x	x	
International Union of Railways (2016)	Intercity			x	x	x	x		x	x	x	
International Union of Railways (2016)	Freight			x	x	x	x	x	x	x	x	
Dimoula *et al* (2016)	Commuter			x	x	x	x	x	x	x	x	
Bueno *et al* (2017)	HSR		x		x	x		x	x	x	x	
Saxe *et al* (2017)	Metro			x	x	x		x	x	x	x	
Shinde *et al* (2018)	Commuter			x	x	x			x	x	x	

Table 1: Considered studies in *Olugbenga et al.* [4]

Olugbenga et al. [4] compare the embodied GHG emissions of the individual case studies separately by rail type. Figure 1 shows the distribution of emissions per kilometre for the different types of rail bound transportation.

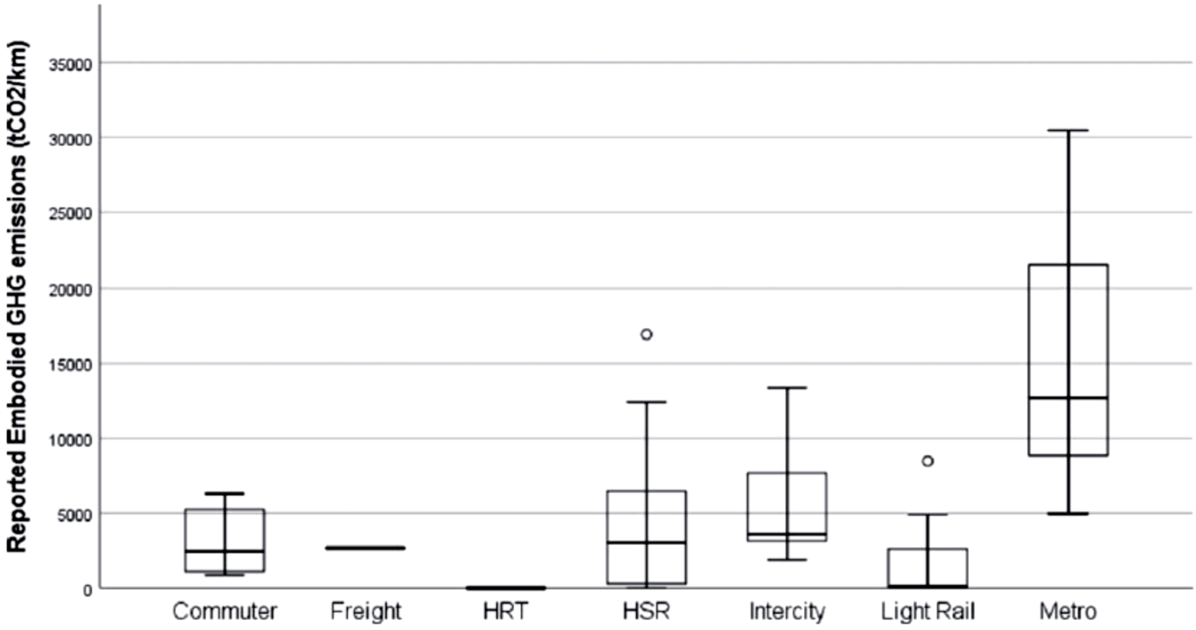


Figure 1: Reported embodied GHG emissions [4]

At first, this figure shows that the sample number of the freight as well as heavy rail transit (HRT) lines is equal to one and therefore, no comparative value is available. In addition, the large scatter in reported GHG emissions by rail type can be seen.

There are several reasons for the large variation. As described earlier, the studies differ in many respects. Furthermore, the share of civil engineering structures (e.g. tunnels and bridges) is not taken into account in this approach. Based on the findings of the literature research, these structures should be considered separately, since they have a significantly higher emission potential than the open section.

In order to eliminate the effects of these structures from the GHG emissions analysis, *Olugbenga et al.* [4] convert the found GHG emissions to equivalent at-grade kilometres. This is done by using a scaling factor for tunnels, which is given as 27. Other structures, such as bridges or stations, are not removed from the calculation. [4]

The following figure shows the converted GHG emissions per equivalent at-grade kilometre.

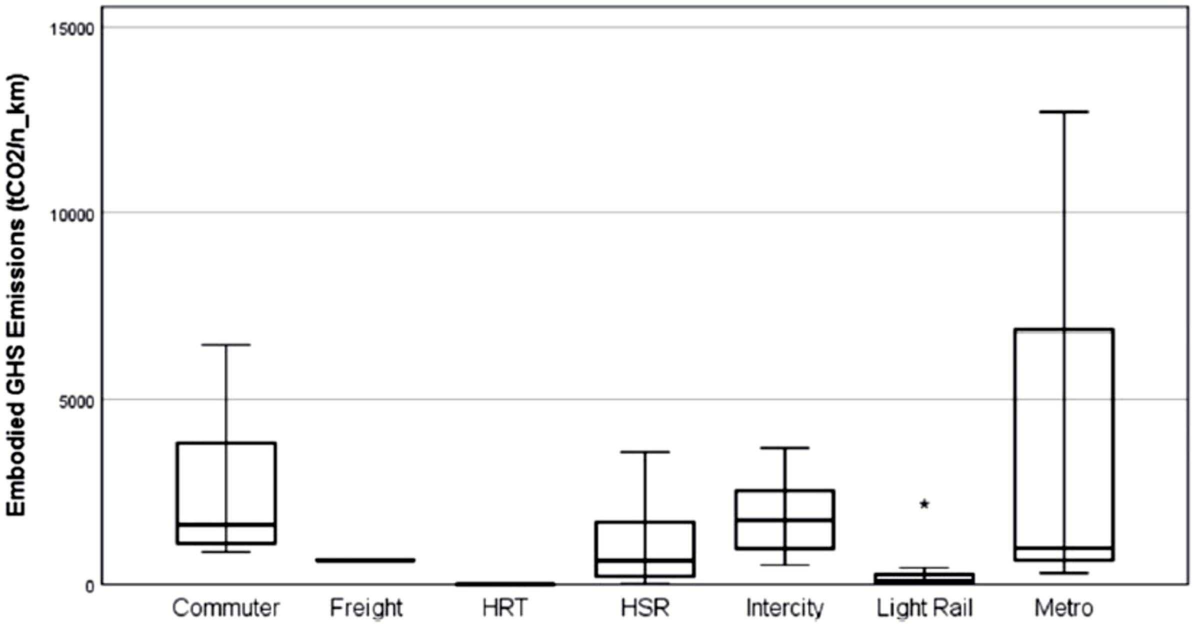


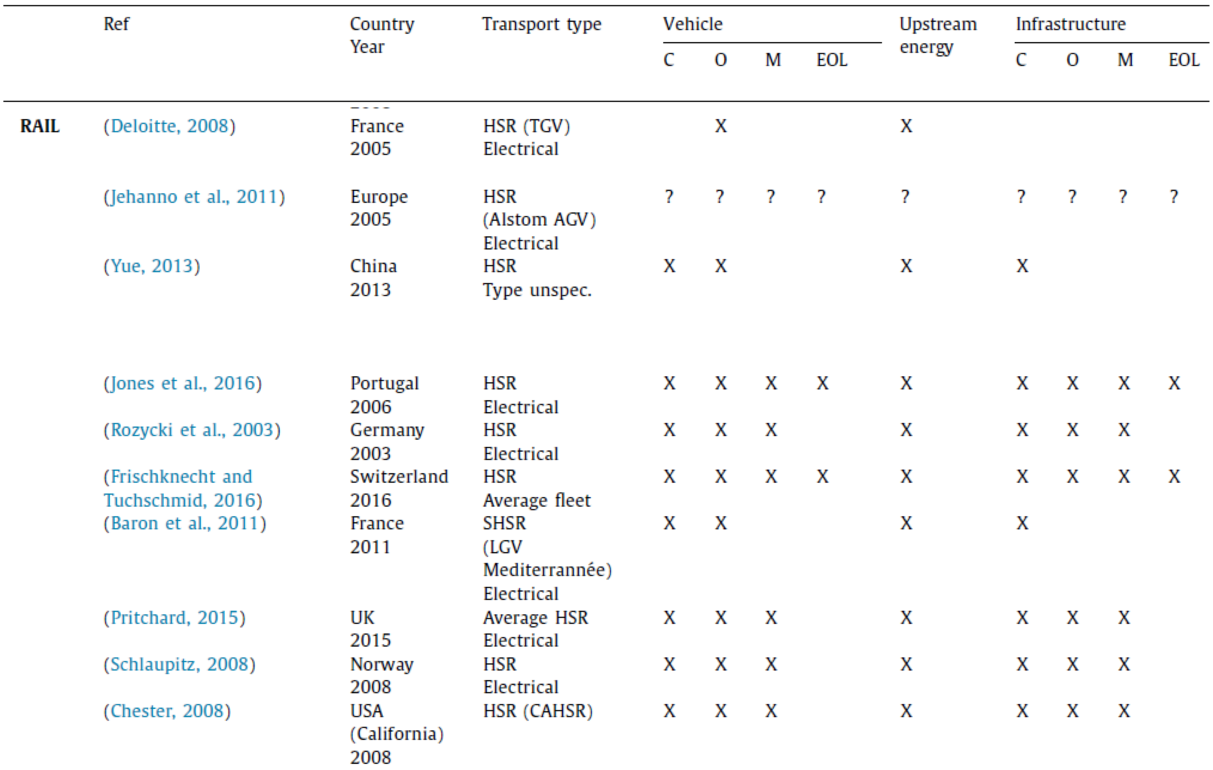
Figure 2: Embodied GHG emissions converted to equivalent at-grade impacts [4]

It can be seen that the adjusted representation shows a reduced range of GHG emissions per kilometre. Nevertheless, the variation within one type is still significant. For HSR routes, the reported at-grade emissions approximately range from 5 to 3500 tons of CO_2 per kilometre. The median is about 500 tons CO_2/at-grade-km. [4]

- Lucile, Trevisan; Mélanie, Bordignon: *Screening Life Cycle Assessment to compare CO2 and Greenhouse Gases emissions of air, road, and rail transport: An exploratory study*, Procedia CIRP, 2020 [3]

Trevisan and Bordignon [3] note that there is still no literature analysis of the results of mode comparisons. To identify the hotspots of emissions, this work analyses the CO_2 and GHG emissions per passenger-kilometre (pkm) of various studies. In addition to road and rail, these include aviation. While some of the considered studies compare the environmental impacts of HSR with other modes of transportation, it can be said that these are rarely based on the ISO standards for preparing LCAs. In addition to the finding that in many cases only tailpipe emissions are identified, it is also stated that the studies differed in a number of ways.
"Consequently, variable results can be found in the literature since most of the studies are based on different scopes, geographic perimeters, assumptions and calculation methods." [3]

The following studies in the field of railways are considered. Table 2 shows the applied life cycle phases (C – construction, O – operation, M – maintenance) of each study.



	Ref	Country Year	Transport type	Vehicle				Upstream energy	Infrastructure			
				C	O	M	EOL		C	O	M	EOL
RAIL	(Deloitte, 2008)	France 2005	HSR (TGV) Electrical		X			X				
	(Jehanno et al., 2011)	Europe 2005	HSR (Alstom AGV) Electrical	?	?	?	?	?	?	?	?	?
	(Yue, 2013)	China 2013	HSR Type unspec.	X	X			X	X			
	(Jones et al., 2016)	Portugal 2006	HSR Electrical	X	X	X	X	X	X	X	X	X
	(Rozycki et al., 2003)	Germany 2003	HSR Electrical	X	X	X		X	X	X	X	
	(Frischknecht and Tuchschmid, 2016)	Switzerland 2016	HSR Average fleet	X	X	X	X	X	X	X	X	X
	(Baron et al., 2011)	France 2011	SHSR (LGV Mediterrannée) Electrical	X	X			X	X			
	(Pritchard, 2015)	UK 2015	Average HSR Electrical	X	X	X		X	X	X	X	
	(Schlaupitz, 2008)	Norway 2008	HSR Electrical	X	X	X		X	X	X	X	
	(Chester, 2008)	USA (California) 2008	HSR (CAHSR)	X	X	X		X	X	X	X	

Table 2: Considered studies in *Trevisan and Bordignon* [3]

A number of similarly prepared life cycle assessments are analysed. It is highly important to ensure that the studies meet the same boundary conditions. The results of the studies show a strong heterogeneity due to the different assumptions that have been made. A direct comparison of the results is not possible due to the different underlying data. Therefore, the relative distribution of the emissions is taken into consideration, as shown in the following figure. [3]

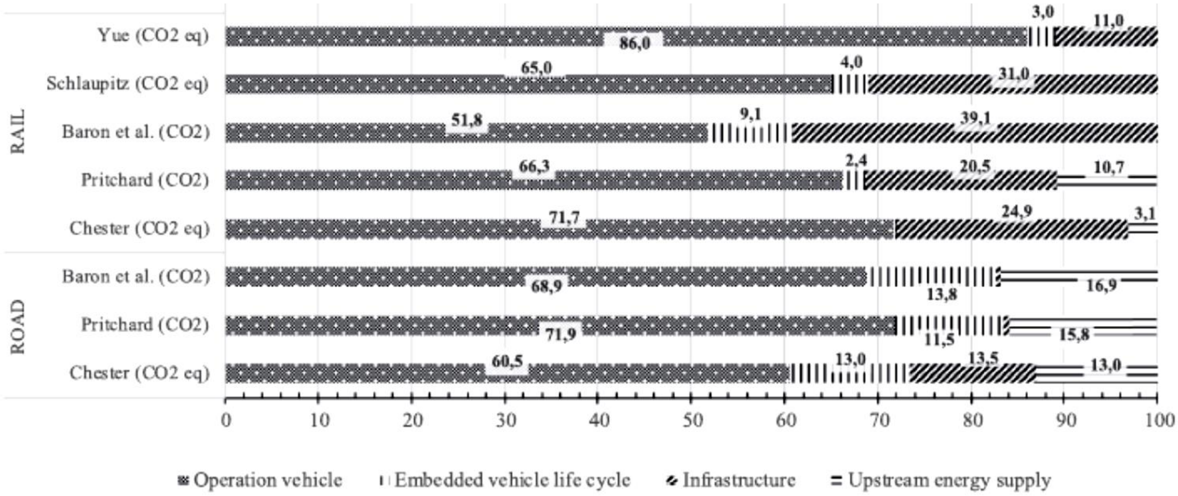


Figure 3: Relative contributions to the total emissions of CO_2 or of GHG (CO_2-eq.) from the reviewed literature [3]

Disregarding the fact that CO_2 and CO_2-eq. emissions are considered together, it can be seen that the emissions follow a similar pattern. Individual outliers can be explained by the fact that additional components are taken into account in individual studies, or that it is not possible to divide them into the four listed categories.

In this distribution, rail infrastructure only accounts for a small share of total emissions. The operation of the mode of transport represents the biggest share, at over two-thirds. However, this is again dependent on many different factors, such as the electricity mix or local conditions. [3]

2.1.1 Findings from the Existing Literature Reviews

Existing literature reviews that address the comparability of emissions between modes of transport usually limit their discussion to simply describing the difficulties such comparison introduces. Existing studies are difficult to compare due to many different reasons. This includes the following:

An analysis of the life cycle emissions separated by types of track bound transportation is reasonable, since they differ to a significant extent from one another. Life cycle assessments are available for most types. However, it is not meaningful to consider emissions per kilometre without distinguishing between components with high emissions like tunnels and bridges. This would influence the result per kilometre too much. Additionally, studies are used in this comparison that vary widely in their scope, objective, and methods. The exclusion of tunnel structures alone is not sufficient in this respect to significantly reduce the scatter of the results of the individual studies.

A separate consideration of railway types should be aimed at. A further refinement of the system into subsystems is found to be more appropriate. A possible subdivision is described in a later chapter.

The different electricity mixes of studies from different countries may have a significant impact on the level of emissions. In countries with a high share of renewable energy sources, the construction phase has a significant share of the system's total emissions. [3] *"Energy and electrical mixes are probably the most influencing factor for the absolute value of CO_2 and GHG levels of emissions, but also for their relative contributions of the process."* [3]

If the operation phase is included, further parameters arise that have an influence on the distribution of life cycle emissions. An operational consideration of the emissions has the advantage that a later combination of operational emissions of vehicles and the emissions of the infrastructure is simplified. There are also large differences in the distribution of emissions when including traffic performance and different occupancy rates. Precise knowledge of traffic performance and occupancy levels is necessary to ensure a meaningful comparison of ecological analyses. Not knowing vehicle occupancy levels accurately carries a high risk of biased results.

To obtain a holistic picture of the emissions, it is not enough to select only one emission indicator. It is important to look at several, which is already the case in many studies.
"The main limitation of the proposed review is its focus on a single type of indicator of impact. […] the ranges of contributions could strongly differ when integration other important environmental indicators, such as biodiversity, eutrophication (due to emissions of nitrous oxides), noise, etc." [3]

To ensure a later reproducibility, the most important data concerning the system has to be presented. This concerns lengths, (standard) cross-sections, construction materials, assumptions made, data sources and calculation methods. Recommendations on how uniform LCAs should be prepared and which content they should contain are described in more detail in chapter 5.

In summary, the level of determined emissions from LCAs is influenced by a large number of variables. In order to ensure standardization and subsequent comparability, all of these aspects have to be defined uniformly.

2.1.2 Further Procedure Based on the Findings

The literature comparisons that have already been carried out provide a basis for the preparation of an own literature analysis. The recommendations and gained insights will be implemented in the process. In order to go further into the details of *Olugbenga et al.* [4], the aim is to differentiate emissions according to system components.

In the following chapters, the search for suitable literature from the rail sector, its contents and components as well as the characteristics regarding transparency and reproducibility of the results are discussed. Subsequently, a comparison of the described emissions is carried out. This is firstly done on the basis of routes and then on a higher level of detail on the component level.

This work mainly focuses on the construction phase, which also includes the production phase in the considered studies. Besides the construction phase, the maintenance phase is often taken into account. In cases in which these two life cycle phases are considered together, this is noted.

2.2 Analysis of Considered Literature

In this section, a literature analysis based on the findings of the previously reviewed literature comparisons will be carried out. The considered literature is primarily collected from the scientific online databases of *ScienceDirect* [1] and *Mendeley* [2]. Furthermore, the Institute of Railway Engineering and Transport Economy of Graz University of Technology provided internal studies. Concerning the railways, 35 studies are selected for further preparation (for a detailed analysis see chapter 2.3).

Although several studies have been conducted regarding the LCA of road and rail infrastructure construction, they differ in various aspects, which are described in the subsequent chapters. A detailed list of the contents of the considered studies in the railway sector can be found in Appendix 1. This table lists addressed components and life cycle phases of the reviewed studies. Moreover, it contains comments on the contents and the implementation of the individual studies.

2.2.1 Goal, Scope and Functional Unit

Life cycle assessments can have a wide variety of objectives, contents and scopes of tasks, depending on the desired purpose. Therefore, studies differ greatly in this respect. The definition of a functional unit is a key issue of any LCA. Only with the introduction of a proper functional unit, different products with competitive functions can be compared. It is critically used to normalise the greenhouse gas (GHG) emissions of similar products. If the compared products have similar functions but different service lives, these products cannot be compared over their entire lifetime. To get them in a comparable condition, a time-based function has to be added. [4]

"However, in the case of rail infrastructure which can be built in many different ways in many different conditions (e.g. soil types, elevation changes), it is challenging to clearly define and capture a well defined and complete function." [4]

For different questions, a suitable functional unit has to be selected. If, for example, only the provision of infrastructure is considered, a functional unit of e.g. "provision of one km of infrastructure for one year" is recommended. If, however, the operation of the mode of transport is also considered, a functional unit related to the transport performance, such as "emissions per passenger-kilometre" or "emissions per vehicle-kilometre" or, for freight transport, "emissions per gross tonne-kilometre", must be defined. Most studies (looked at in this work) consider the operation of the modes of transport in the LCAs and usually use the functional unit "emissions per passenger-kilometre" or "emissions per kilometre of track/line".

Due to the requirement of comparability between the modes of transport, the functional unit should be defined in a way that the considered components fulfil the same functions.
In the case of the per passenger-kilometre performance-based functional unit, the occupancy rate of the vehicle has a major influence on emissions but is also a major uncertainty factor. These occupancy rates can usually only be determined statistically and have a drastic effect on the distribution of pollutant emissions. [8]
For example, life cycle assessments for the entire route network (e.g. *Schmied and Mottschall* [11]; *Tuchschmid et al.* [12]) or for very specific routes (*The Follo Line* [17]; *The Bothnia Line* [10]) have been carried out. This can influence both the level of detail of the implementation and the components treated. The definition of these aspects has a significant influence on the structure and procedure of a life cycle assessment. In the studies considered here, it can be seen that most of them deal with a high-speed line. In addition, there are studies that have conducted LCAs for networks in different countries. In order to enable a later comparison based on the data of the literature analysis, HSR lines are primarily examined here.

2.2.2 System Boundaries and Life Cycle Phases

In order to ensure a correct allocation of environmental impacts due to infrastructure provision and transport services, both direct and indirect processes have to be considered. This includes not only the construction but also the processing of raw materials, the production, operation, maintenance and end-of-life of vehicles, infrastructure and fuels.
Many studies on emissions from transportation services consider only the tailpipe emissions resulting from the operation of a vehicle. They neglect the emission potential of the infrastructure and vehicle production as well as maintenance, although these contribute considerable to the total emissions. [8]

To create comparable systems, it is necessary to define boundary conditions that are the same for all processes. Furthermore, it must be defined which processes still fall within the scope of the analysis and are therefore taken into account, and which are no longer directly related to the product and can be neglected (“cut off”) due to the scope of the analysis. In order to gain a better understanding of which emissions occur in which phase of a product's life cycle, it is advisable to consider the “cradle-to-grave” or “cradle-to-cradle” approach. These considerations probably best reflect the intention of a life cycle assessment. An illustration of the different life cycle approaches can be seen in Figure 4. In the “cradle-to-grave” approach, all life cycle phases, from the extraction of the raw material to the disposal of the materials are considered, whereas in the “cradle-to-cradle” approach all materials are reused.

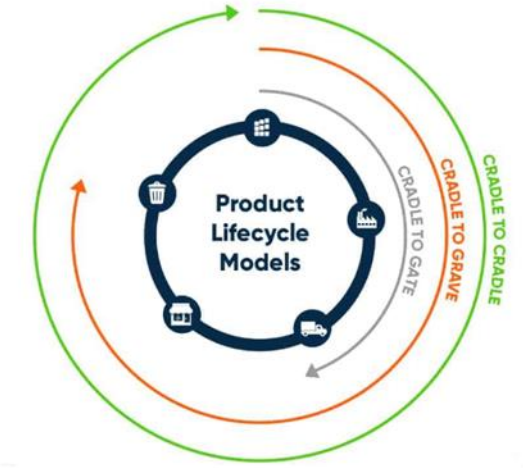


Figure 4: Life cycle approaches [55]

The different studies consider different life cycle phases, depending on the purpose of the investigation, and thus introduce different system boundaries. All of them have in common that they deal with the emissions of the infrastructure. For a comparison between different studies, a uniform definition of the system boundaries is necessary. [4]

While some studies (e.g. *Schmied and Mottschall* [11]; *Tuchschmid et al.* [12]; *Chester and Horvath* [7]) at least consider the life cycle phases of construction, operation and maintenance of the infrastructure, there are studies (e.g. *Grossrieder* [18]) which do not consider these three life cycle phases.

This different consideration of life cycle phases makes a comparison complicated.

This thesis primarily focuses on the construction phase and the maintenance phase. The emissions of the production phase are accounted for in the construction phase. Each life cycle phase will be shortly described in the following. Not every depicted life cycle phase will be addressed in the comparison in this work.

Production Phase

The production phase includes all activities to produce the required materials - beginning with the extraction and processing of raw materials, considering the transformation processes and transports [22]. According to the findings of the reviewed literature, this phase is often accounted for in the construction phase.

Construction Phase

The emissions occurring in this phase depend strongly on the requirements for the infrastructure and thus on the construction method. This phase includes all work necessary for the construction of the infrastructure. This includes earthworks as well as all other construction activities and transport activities for the construction of the track and associated buildings and facilities.
"The construction phase includes transportation from raw-material processing plants to the construction site, as well as the machinery operations and activities carried out to build the track." [22]
Due to the long construction period of infrastructure projects, significant pollutant emissions are generated by the use of machinery.

Operational Phase

The operational phase of an infrastructure system includes all activities that are necessary to maintain an operational infrastructure system and that in turn cause emissions. These activities include power supply for all types of structures, lighting or traffic control systems, as well as other activities such as de-icing roads or heating switches. The cleaning of railway stations or road embankments can also be counted under this heading. The emissions occurring in this life cycle phase will not be considered in the further work. In some of the considered studies, the emissions of the maintenance phase are accounted for in the operational phase to avoid double-counting.

Maintenance Phase

The maintenance phase includes all activities needed to keep the infrastructure in a useable condition. In this phase, higher emissions occur due to the use of machinery. During the estimated lifespan of a product, several maintenance actions and even the replacement of components have to be executed. The maintenance for railway infrastructure includes railway track, electric power and signal systems and station maintenance. The road maintenance includes road surface, road basement, tunnel maintenance and similar activities. [20]

End-of-Life Phase

The end-of-life phase represents all activities to dismantle the infrastructure, like crushing of concrete, transportation of materials to recycling plants or landfill of non-recyclable materials [22]. These removal activities are usually done by diesel-powered machines, which produce significant amounts of emissions [14]. In the case of the "end-of-life" phase, it should be mentioned that individual reuse purposes of components of the infrastructure systems are difficult to determine. The findings from the reviewed literature show that this phase is often not taken into account in LCAs due to the inaccessibility of reliable data. Due to the lack of data, this life cycle phase will not be addressed in the further work.

2.2.3 Considered Components

The choice of system boundaries has a considerable influence on the course of an LCA. If the boundaries are set too narrowly, the result does not correspond to a complete analysis. However, if the boundaries are set too widely, the effort of data acquisition increases rapidly. [12]

A clear definition of the components which are taken into account when mapping the system is necessary to ensure later comparability. The different definitions of the components considered in the reviewed studies make it even harder to compare them. According to *Tuchschmid* et al. [12], the track system can be broken down into the following components: normal track, bridges, tunnels, embankments, catenary equipment, substations, signals and communication. Depending on the objective of the study, all or only some of these components are considered. Furthermore, associated structures such as railway stations, maintenance centres, terminals, administration buildings and parking facilities are of interest, although these structures are only partially taken into account (e.g. *Schmied and Mottschall* [11]; *Tuchschmid et al.* [12]; *Chester and Horvath* [7]).

2.2.4 Other Influencing Parameters

In addition to the described sections in the previous subchapters, there are a number of different input parameters that have an influence on the level and distribution of emissions of the transport modes. This chapter lists some of the found parameters and describes how they should be dealt with to enable comparison. The parameters can roughly distinguish between the areas of infrastructure provision and operation, but there is generally a strong interaction between these areas.

Routing of the Line

Civil engineering structures like bridges, tunnels and also earthworks like excavations and material accumulation have a high impact on the emissions of infrastructure lines. For this reason, routing has a great potential for emissions because a different routing may avoid or require such engineering structures.

The route gradient also has an indirect effect on the level of emissions of a transport infrastructure. Here, both the routing and the operation have an influence. On the one hand, the route gradient is influenced by the chosen alignment, and on the other hand, the operating vehicles affect the route gradient, since heavier vehicles require a lower route gradient (or additional traction locos leading to higher demands). These lower gradients in turn lead to an increasing length of the line.

Furthermore, when considering the operation of the vehicles, a higher energy demand and thus higher emissions can be observed for steep gradients.

Due to the high number parameters that finally determine the route alignment and the fact that the infrastructure is considered in an analysis of the existing infrastructure anyway, the alignment of a route is mentioned here for the sake of completeness, but it will be considered as a given in the further process.

Ground Conditions and Earthworks

Different subsurface conditions have an influence on the extent of earthworks. If, for example, soil improvement is carried out with cement, the identified emissions increase due to the inclusion of cement production. Since a consideration of different subsoil conditions has an influence but would exceed the scope of the LCAs, the subgrade shall be considered as a system boundary. Another issue that also affects the range of the alignment is the gradient of the line. Earthwork in the cut or embankment area creates additional emissions compared to alignment at grade. [13]

Construction Methods and Used Materials

The materials used in different construction methods obviously also have a major influence on emissions. The level of detail with which various materials are taken into account, impacts the analysis effort. For the transport mode road, at least a differentiation between asphalt pavement, concrete pavement and different construction types is required. For the transport mode rail, a distinction between several aspects, such as slab track versus ballasted track, type of sleepers used etc. is reasonable. A detailed differentiation between different ballast materials should not be performed due to the complexity of the data acquisition.

Energy and Electricity Mix

"Energy and electrical mixes are probably the most influencing factor for the absolute value of CO_2 *and GHG levels of emissions, but also for their relative contributions of the process."* [2] In Austria the electricity mix of the traction power is 100 % renewable [52]. However, one has also to consider the energy needed to produce and transport materials, to illuminate tracks and similar activities.

Transport Distances of the Materials

Looking at the transport distances of different components like rails or ballast, these distances have an impact on the emissions of the products on a local level, but are difficult to capture in a network-wide view.

Service Life

Different components in the system obviously have different service lives. The service life of various components is influenced by many boundary conditions. In addition to operation (tonnage/number of vehicles), the routing (tight radii), the choice of components and external conditions (heat, frost) also have an influence. In turn, the required external maintenance work depends on the service life. Since a differentiation of such a large number of aspects in this work is not regarded expedient, guide values from the literature are used.
To enable comparability of the individual components, it is a suitable approach to consider them over a period of one year.

Traffic Performance and Occupancy Rates

If operation is included, further parameters arise that have an influence on the distribution of life cycle emissions. An operational consideration of the emissions has the advantage that a later combination of operational emissions of vehicles and the emissions of the infrastructure is simplified. Precise knowledge of traffic performance and occupancy levels is necessary to ensure a meaningful comparison of ecological analyses. Not knowing vehicle occupancy levels accurately carries a high risk of biased results.

2.2.5 Environmental Indicators

The most common environmental indicator for assessing an environmental impact is the global warming potential, expressed in CO_2-equivalents. In principle, carbon dioxide is a natural component of the air. However, the combustion of fossil fuels increases the amount of CO_2 in the atmosphere, which consequently increases the greenhouse effect and thus contributes to global warming.

The greenhouse effect is mainly caused by the emission of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), wherein CO_2 is the largest component of the transport sector’s contribution to the greenhouse effect. [12]

This indicator is shown in the vast majority of studies. In addition, there are other environmental indicators that can be used to quantify the environmental impact of a project. A significant number of studies also take other indicators besides CO_2 and CO_2-eq. into account. Some of these other environmental indicators are described hereafter.

Primary Energy

This indicator includes the direct energy consumed by the train operation, energy used for upstream energy processes and losses from electric power generation. Every single process to extract the energy form the environment is within the scope of this indicator. [12]

However, if only the provision of infrastructure and not the operation is considered, this indicator is not suitable for classification.

Particulate Matter

Particulate matter in the air can appear in different sizes. They are so fine that they float in the air and do not immediately sink to the ground. Besides natural sources, these air pollutants are man-made, due to traffic (all types of abrasion, internal combustion engines), combustion of wood, power generation and thermal power stations. Particulate matter negatively affects human health through inhalation and toxic substances, depending on their concentration. [12]

Non-methane Volatile Organic Compounds (NMVOC)

NMVOCs are a precursor of ground-level ozone and can be carcinogenic. The gas methane is excluded from this group. *"Volatile organic compounds are organic materials that vaporize easily (i.e. they are volatile) and exit in gaseous form at low (e.g. ambient) temperatures. […] NMVCOs are emitted into the atmosphere by a wide range of anthropogenic bioprocesses." [12]*

During the construction of infrastructure buildings, these compounds are mainly emitted when the diluent volatilizes during asphalt paving [7].

The combustion engine also produces volatile organic compounds, which together with NOx can lead to smog [12].

Nitrogen Oxides (NOx)

Nitrogen oxides can cause respiratory diseases when inhaled. They can also contribute to the formation of acid rain, smog and ground level ozone [12]. The main emission of NOx in traffic occurs in the operating phase through combustion engines. But there is also a non-negligible part, which is mainly caused by electricity generation for production and material transport. Furthermore, these emissions are caused by truck transport of materials in the construction phase of infrastructure components. The high energy demand in cement production contributes significantly to the level of emissions, which is reflected in the construction of tunnels. [8]

Sulphur Dioxide (SO_2)

In high concentrations, sulphur dioxide can be harmful to the environment and cause acid rain. The emission of SO_2 occurs when burning fossil fuels contain sulphur. [59] Thus, it can be stated that wherever (electrical) energy that originates from non-renewable sources is used, SO_2 is emitted. In the infrastructure sector, these are the processes of material production, construction and operation (e.g. lighting).

In the operation of electrified railways more SO_2 is emitted if the electricity originates from fossil fuels. The operation of automobiles, in contrast, produces lower levels of SO_2, as sulphur is removed from their fuels. [7]

Nitrogen oxides, the use of cement, due to its high energy demand, and the transport of materials have a major impact on SO_2 emissions.

Carbon Monoxide (CO)

Carbon monoxide is released during incomplete combustion and is respiratory poison for humans, preventing the absorption of oxygen. It also contributes to the formation of ground-level ozone.
In the infrastructure sector, cement production is again a major source of emissions of this pollutant. Due to the use of large quantities of cement in stations and tunnels, CO emissions rise significantly.

Water Consumption

Another indicator of environmental effect that is not taken into consideration in the reviewed studies is water consumption. This is of great importance at a local level. Currently, this is no issue in Austria.
Future LCAs should include this indicator for impact assessment, particularly in countries with low water supply. [8]

Land Consumption

A comparison of the land consumption of road and rail modes of transport over the last 30 years shows that the land consumption of road transport has risen significantly, whereas for rail transport it has declined for Austrian boundary conditions [51].

To sum up, it can be said that a large number of pollutants occur which can be used to evaluate projects. In order to provide a holistic view, it is usually not sufficient to highlight solely individual indicators. Therefore, many different impact indicators should be considered. Some indicators only lead to local problems, such as particulate matter. Ground-level ozone and smog are also mainly local issues. Water depletion can quickly become a problem in areas with little water availability. On a global scale, other pollutants have to be considered. The most important global indicator is CO_2. It promotes the greenhouse effect and, therefore, leads to climate change and global warming. Most of the considered LCAs quantify based on CO_2 emissions. A consistent quantification based on CO_2 emissions allows an easier comparison of different analyses. An advantage of using CO_2 or CO_2-equivalents for quantification is the availability of considerable emission databases.

2.2.6 Transparency and Reproducibility

To provide the best possible transparency and reproducibility of the studies’ results, the infrastructure details and the GHG calculations should be well communicated. If this is not

the case, subsequent recalculation and reproducibility becomes impossible. Basically, all the points described above should be accurately addressed before preparing an LCA.
Olugbenga et al. [4] describes the data required for a standardised investigation procedure as follows:
"[…] clear description of (1) the kilometres of tunnelled, elevated, and at-grade construction included in the case study, (2) the range of the ground conditions and elevations, (3) boundaries of assessment (specific communication of the embodied emissions in each studied element (track beds, tunnels, elevated sections/bridges and stations) to allow for comparability between studies), (4) a description of all stations." [4]

Among the considered studies in this paper, there are only some which are fully transparent and which have reproducible results. In most of them, no or sparse information on infrastructure or other details is provided. For example, the allocation of emissions to passenger and freight traffic was mostly done using statistical records. However, such data should also be listed in a study to provide a clear idea of the underlying data. For further information concerning the reproducibility of the reviewed studies, Appendix 1 provides information.

2.3 Analysis of Reported CO_2-eq. Emissions

Most of the studies considered here refer to the functional unit of one kilometre of distance or one passenger-kilometre. The first part of the analysis of the results of the studies is to relate their emissions to one kilometre of line and put into context with the particular circumstances. Initially, no distinction is made by component and therefore the various circumstances of the individual routes can lead to strong differences. However, by taking a closer look at the individual routes or networks, it is often possible to determine why the results per kilometre differ. Secondly, the emissions per passenger-kilometre are considered and put into context with the previously determined emissions per kilometre of line.

2.3.1 Comparisons in the Field of Railways

The majority of studies report emissions per passenger-kilometre. At this point, an attempt is made to use the respective transport performance and the length of the route or network to convert emissions per passenger-kilometre back to emissions per kilometre and year. However, this requires knowledge of the underlying transport performance. For studies that do not report the respective transport performance, values from the *UIC statistical database* [53] are used. It should also be mentioned that these values must be known as precisely as possible otherwise the results can be heavily distorted.
Due to the fact that not all studies contain a precise description of the used data, route lengths and transport services are taken from the *UIC statistics* [53] of the appropriate year. In cases where specific routes are analysed, for example in *Chester and Horvath* [7], the database of *Wikipedia* [54] is used in order to gain additional data about the lines.

As already mentioned in the description of the literature, the considered and subsequently compared studies differ in significant respects. For example, the fact that life cycle phases are analysed in combination leads to a less accurate comparison. Additionally, the routes are composed of different components, which are not considered in the same way in all studies. This fact makes a direct comparison even more difficult.

"In PCR for Railways (EPD, 2009) a lifespan of 60 years for civil engineering constructions as bridges, tunnels, viaducts and stations is declared." [12]
Following this recommendation, most studies designed the engineering structures for a service life of 60 years. However, since these civil engineering structures may well have longer service lives, the service life taken in some studies is 100 years. Since the present work considers the emissions of the infrastructure in order to achieve a better comparability, the emissions of the engineering structures were uniformly converted to a service life of 60 years in this chapter.

In one of the later chapters, the analysis of components, a sensitivity analysis for both 60 and 120 years is executed. A detailed table concerning the emission data of the systems can be found in Appendix 2.

2.3.1.1 High-Speed Lines

High-speed lines are the subject in most of the considered studies. For this reason, a comparison between them is made and explained here. The following table lists these studies and their specific HSR routes.

Literature	Country	Line
Chester, Horvath 2007	USA	CAHSR
Schmied, Mottschall 2010	Germany	DB-AG HSR
UIC (Baron et al.) 2011	France	South Europe Atlantic HSR
UIC (Baron et al.) 2011	France	LGV Mediterranee HSR
UIC (Baron et al.) 2011	China	Beijing - Tianjin HSR
UIC (Baron et al.) 2011	Taiwan	Taipei - Kaohsiung HSR
Chang, Kendall 2011	USA	Californian HSR
Bueno et al. 2017	Spain	Basque-Y
Lee et al. 2020	Japan	Osong-Gwangju
Kortazar (in Press)	Spain	Andalusia
Kortazar (in Press)	Spain	Northern
Kortazar (in Press)	Spain	Catalonia
Kortazar (in Press)	Spain	Levante
Cheng et al. 2020	China	Beijing - Tianjin HSR

Table 3: Considered HSR lines in this work

By taking a look at the local conditions and including the proportion of bridges and tunnels on the routes in the analysis, it becomes apparent why some routes have significantly higher emissions per kilometre of line. Figure 5 shows the CO_2-eq. emissions of the routes per line-kilometre and year with their corresponding share of tunnels and bridges. Studies, which also account for the maintenance phase are marked with an asterisk "*".

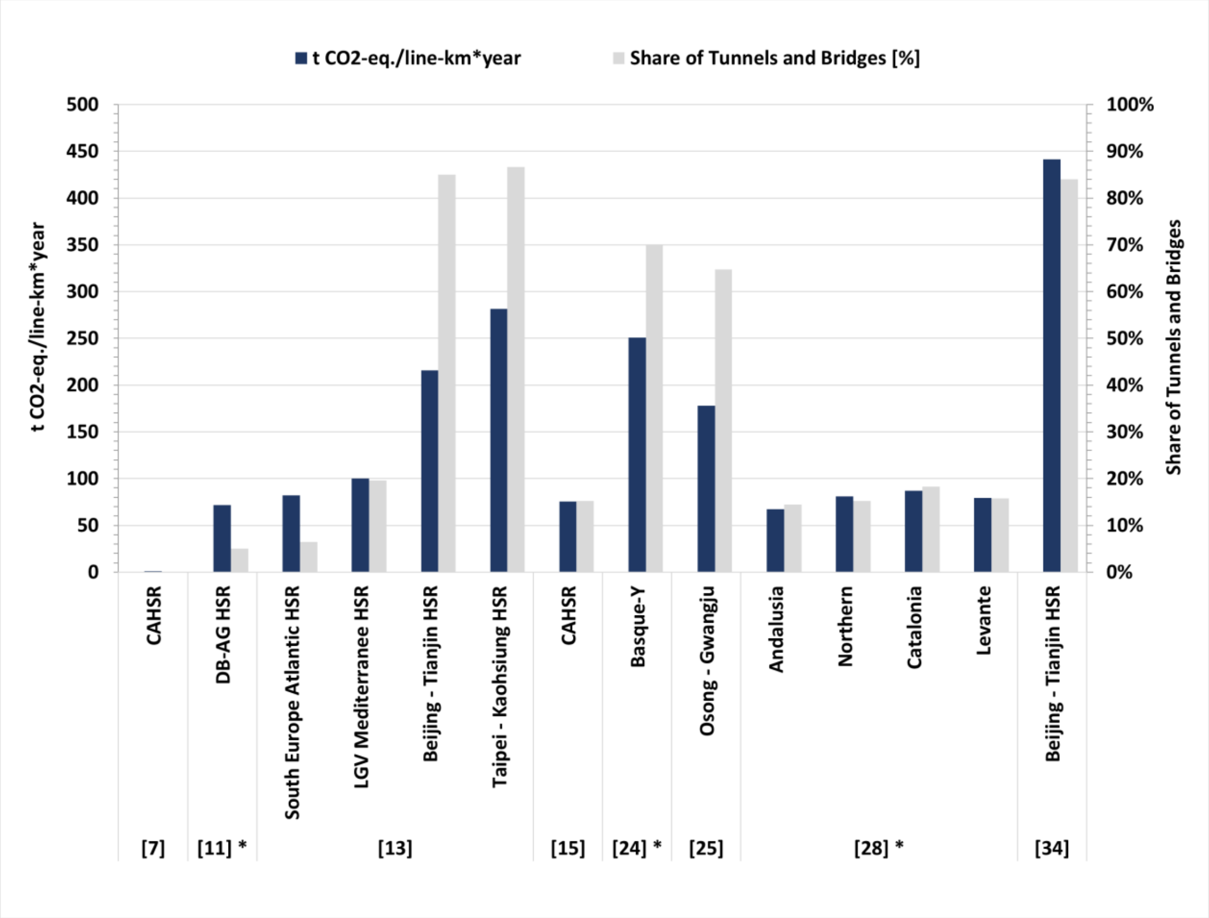


Figure 5: CO_2-eq. emissions per line-kilometre and year with corresponding share of tunnels and bridges

As expected, the higher the proportion of civil engineering structures, the higher the average emissions per line-kilometre. Two routes are particularly notable: In the first place the Californian high speed rail CAHSR in *Chester and Horvath* [7], and secondly the Beijing-Tianjin HSR in *Cheng et al.* [34].

In the study of *Chester and Horvath* [7] on the CAHSR, it must be mentioned that this is a planned line. Solely a part of it is operational. Furthermore, *Chester and Horvath* [7] only consider the emissions of the construction of the track, the power equipment and the stations. A section of the planned route (725 km) is also examined in another study. *Chang und Kendall* [15] determine the emissions per line-kilometre and year at 75.41 t CO_2-eq. They take into account the construction of the track bed, tunnel, aerial structures, electrification and cut-and-fill processes. The estimated service lives are 30 years for the track bed and 60 years for the remaining components.

The study of the Beijing-Tianjin HSR by *Cheng et al.* [34] shows a high emission value per line-kilometre and year. Although this route has a very high proportion of engineering structures (84 %), *Baron et al.* [13] also looked at this route and only determined less than the half of *Cheng's* emissions - and this despite the fact that stations are not taken into account in *Cheng's* calculation. *Cheng's* lifecycle inventory shows that very high emission values are used for the individual infrastructure components in this study. For example, a kilometre of bridge structure is assumed to emit 397 t CO_2-eq. per kilometre and year (with a service life of 60 years). This value is extremely high, which can be seen in the component-specific differentiation that follows in chapter 2.3.2.

In addition to the emissions per line-kilometre, the emissions per passenger-kilometre can also be shown. These are illustrated in Figure 6.

The higher the transport performance on a route, the lower the emissions per passenger-kilometre. For this reason, routes with a high emission value per kilometre can have a lower emission value in this figure.

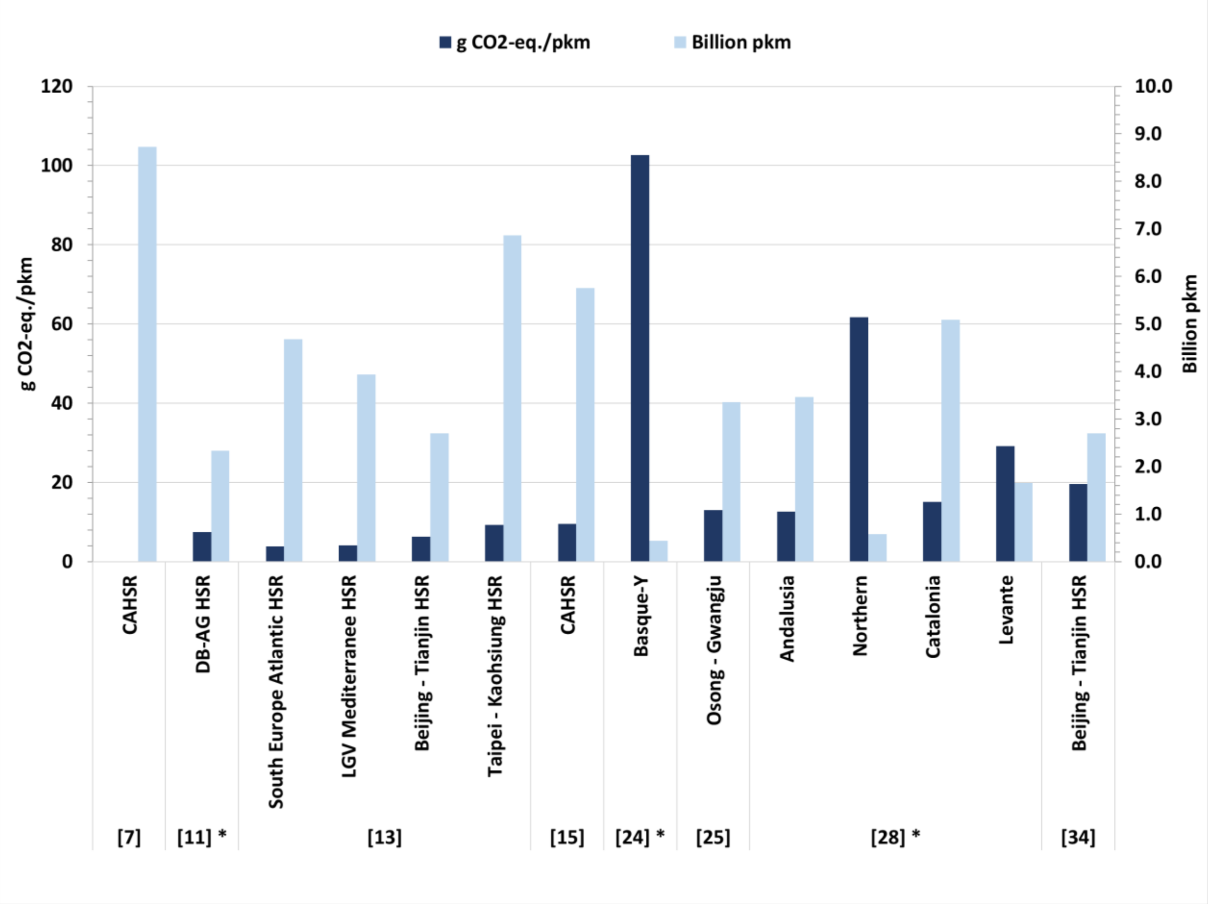


Figure 6: CO_2-eq. emissions per passenger-kilometre

The first remarkable aspect in the figure above is the CAHSR done by *Chester and Horvath* [7]. Due to the fact that emissions per line-kilometre are already set extremely low and combined with a high projected transport performance of 14 billion passenger-miles-travelled (pmt) (equivalent to approx. 8.7 billion pkm), the emissions of 0.11 g CO_2-eq./pkm practically disappear.

The next notable study deals with the planned *Basque-Y* and was conducted by *Bueno et al.* [24]. In this study, the applied transport performance is as low as the emissions per pkm are enormously high. *"[…] it must be stressed that a volume of transport of 2.45 million passengers per annum over the entire infrastructure layout is a magnitude significantly lower than those measured in other railway infrastructures. […] To improve its environmental balance, the Basque Y would have to increase considerably passengers transport diverted from other modes."* [24]

After a sensitivity analysis of the environmental performance, the authors of the *Basque-Y* study realised that even in the most optimistic environmental payback scenario, there would be no compensation of CO_2 emissions from construction and maintenance. For this reason, they recommend that the emission reduction potential and energy savings should not be used as an argument for an investment in HSR infrastructure. [24]

A similar problem is identified in the study by *Kortazar et al.* [28]. The transport performance was estimated by the authors, as no data was provided. The *Levante* and the *Northern* corridor in particular show low demand, which is reflected in high emissions per pkm.

2.3.1.2 National Networks

By using two studies which investigate nationwide networks, an attempt is made to compare them and subsequently question how the emissions of the countries relate to those of their HSR routes.

The data for the following comparison is partly taken from *Schmied and Mottschall* [11], who deal with the German rail network. Primarily, data from *Tuchschmid et al.* [12] is used, who assess the networks of nine countries in Europe and Asia. Both studies address the maintenance phase, therefore, they are marked with an asterisk "*" in Figure 7. Due to the fact that these studies quantify emissions in terms of CO_2, a conversion factor of f=1.04 is used in this work to convert to CO_2-eq. emissions. This factor is derived from the ratio between the calculated CO_2 and CO_2-eq. emissions of studies that consider both.

The averaged values per line kilometre are composed of emissions for earthworks, track, bridges, tunnels, equipment for signals, telecommunication and electricity transport, and stations and substations.

Figure 7 shows the CO_2-eq. emissions per route kilometre for the respective countries. In addition to these, the share of tunnels and bridges in the total route length, as well as the share of HSR routes in the total network are shown.

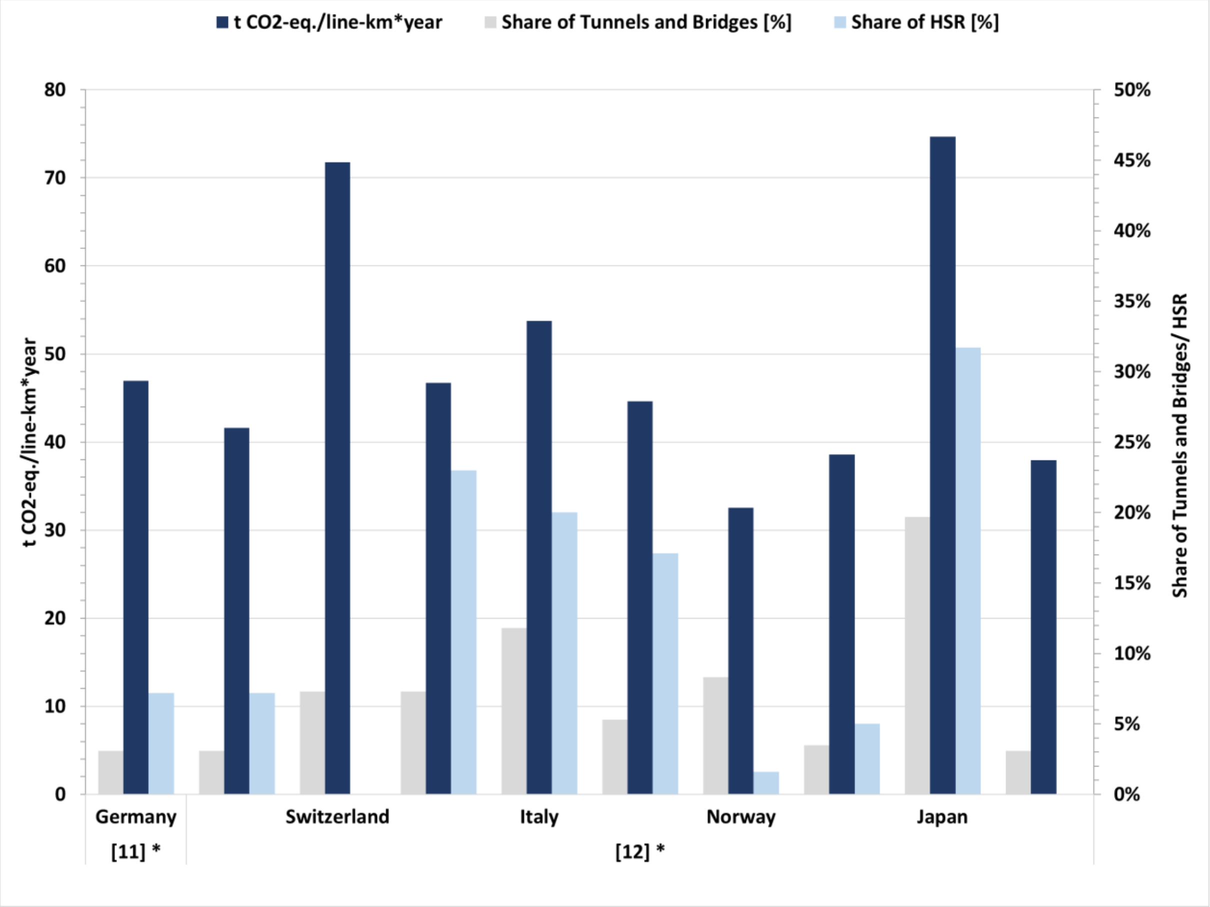


Figure 7: Nationwide CO_2-eq. emissions per kilometre of line with corresponding share of tunnels and bridges and share of HSR lines

Tuchschmid et al. [12] make assumptions about local conditions for the individual countries in this study. For example, the properties or construction methods in some countries are assumed to be the same as those in Germany.

In Figure 8, it is noteworthy that Switzerland, although only 7.3 % of the total length is accounted for by civil engineering structures and there are no HSR lines, has very high CO_2-eq. emissions per kilometre of line. The level of emissions is almost identical to that of Japan, although there are more than 20 % of the lines as tunnels or bridges and more than 30 % of the lines as HSR. *Tuchschmid et al.* [12] justify these high emissions in Japan with the proportion of bridges and tunnels, as well as the two-lane route expansion. The high emissions in Switzerland are not discussed in detail.

Figure 8 shows the emissions per passenger-kilometre and the corresponding transport performance. The passenger-kilometres are plotted logarithmically.

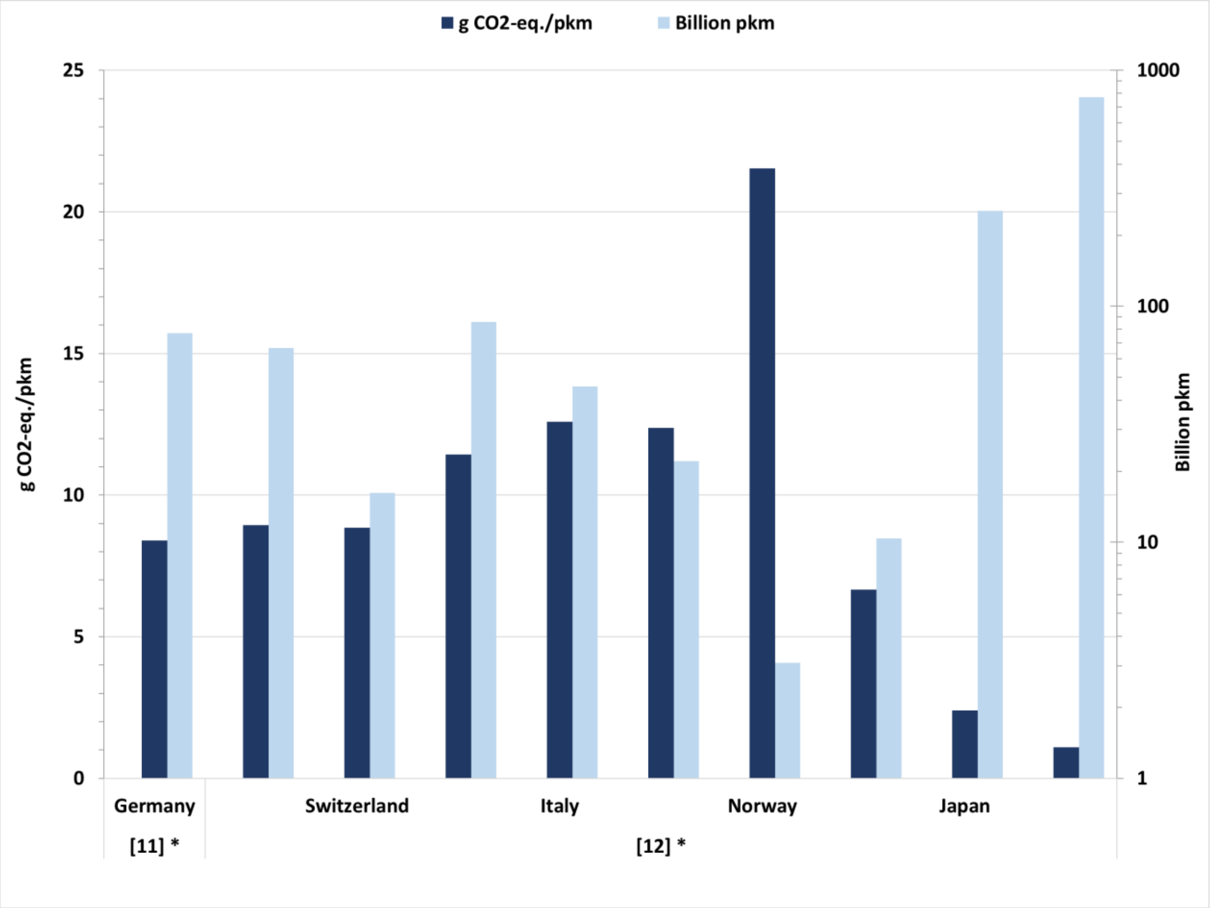


Figure 8: Nationwide CO_2-eq. emissions per passenger-kilometre

In the case of Norway, passenger transport has high emissions per passenger-kilometre. According to *Grossrieder* [18], this is due to Norwegian conditions.

"[…] it is important to note that Norwegian conditions are very specific. A low Norwegian share of tunnels and bridges correspond to an average European share of tunnels and

bridges. Furthermore, a high Norwegian number of pday [passengers per day] per line correspond to a low European numbers pday per line." [18]

The two Asian countries Japan and India show a very low emission value per passenger-kilometre due to their high occupancy rates.

It is also of interest that in the case of Switzerland, although the emissions per kilometre of line are significantly higher than, for example, in Germany, the passenger-kilometre-related representation shows a lower value despite lower transport performance.

2.3.1.3 National Networks and their High-Speed Lines

The following figure shows the level of CO_2-equivalent emissions per kilometre of line and year for the total networks of the countries and selected HSR routes of these countries. In addition to the HSR share of the total route length, the share of engineering structures is also illustrated. As HSR lines obviously have a share of 100 % of HSR, these shares are not plotted in Figure 9.

By comparing the emissions of a country network with those of the HSR lines there, it becomes apparent that, as expected, the emissions of the countries are lower than those of the HSR lines there. Additionally, there is hardly any difference in the emissions per kilometre of the total network of the three considered countries France, Germany and Spain, although they have different shares of HSR lines and civil engineering structures. The study on the planned *Basque-Y* stands on its own in this presentation.

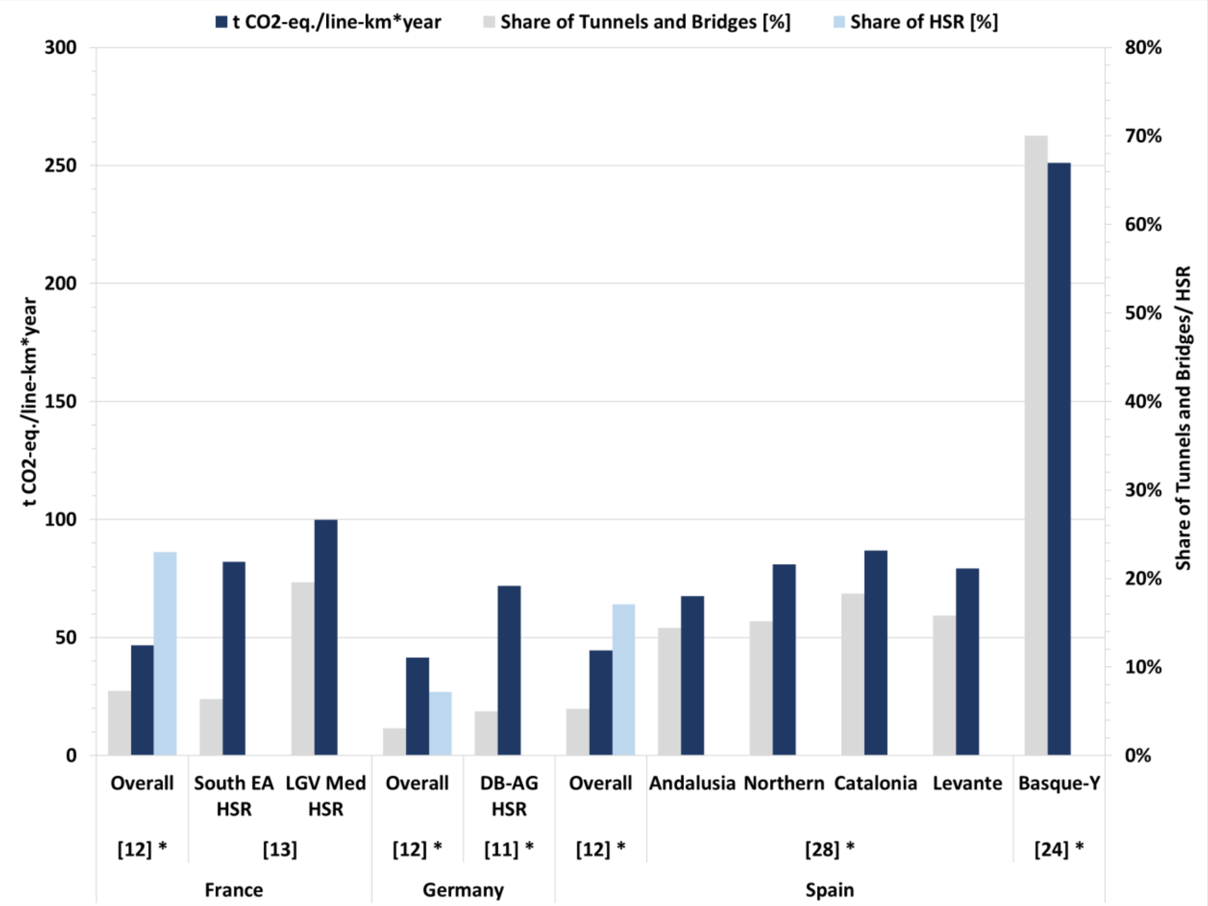


Figure 9: Comparison of CO_2-eq. emissions per kilometre of line: Countries and their HSR lines

The transport performance-related emissions can be seen in Figure 10. In addition to the emissions, the passenger-kilometres are shown in relation to one kilometre of line. This normalisation is chosen in order to reduce the large impact of the route length on this type of presentation. Thus, conclusions about the calculated CO_2-eq. emissions can be made with this derived parameter. The situation is as follows:

In France and Germany, the emissions per passenger-kilometre on the total network are higher than those of the HSR lines. This is mainly due to the fact that national networks have large extensions. The HSR lines there show a very high transport performance and a very short length. Therefore, the emissions per passenger-kilometre are low. However, emissions of HSR lines per kilometre are higher than the overall network when not related to transport performance.

In Spain, the emissions per passenger-kilometre of the overall network are lower than the ones of the HSR lines there. This is due to the very low demand for transport in the north of Spain which leads to an increase in emissions per passenger-kilometre, especially for Northern and the Basque-Y HSR line.

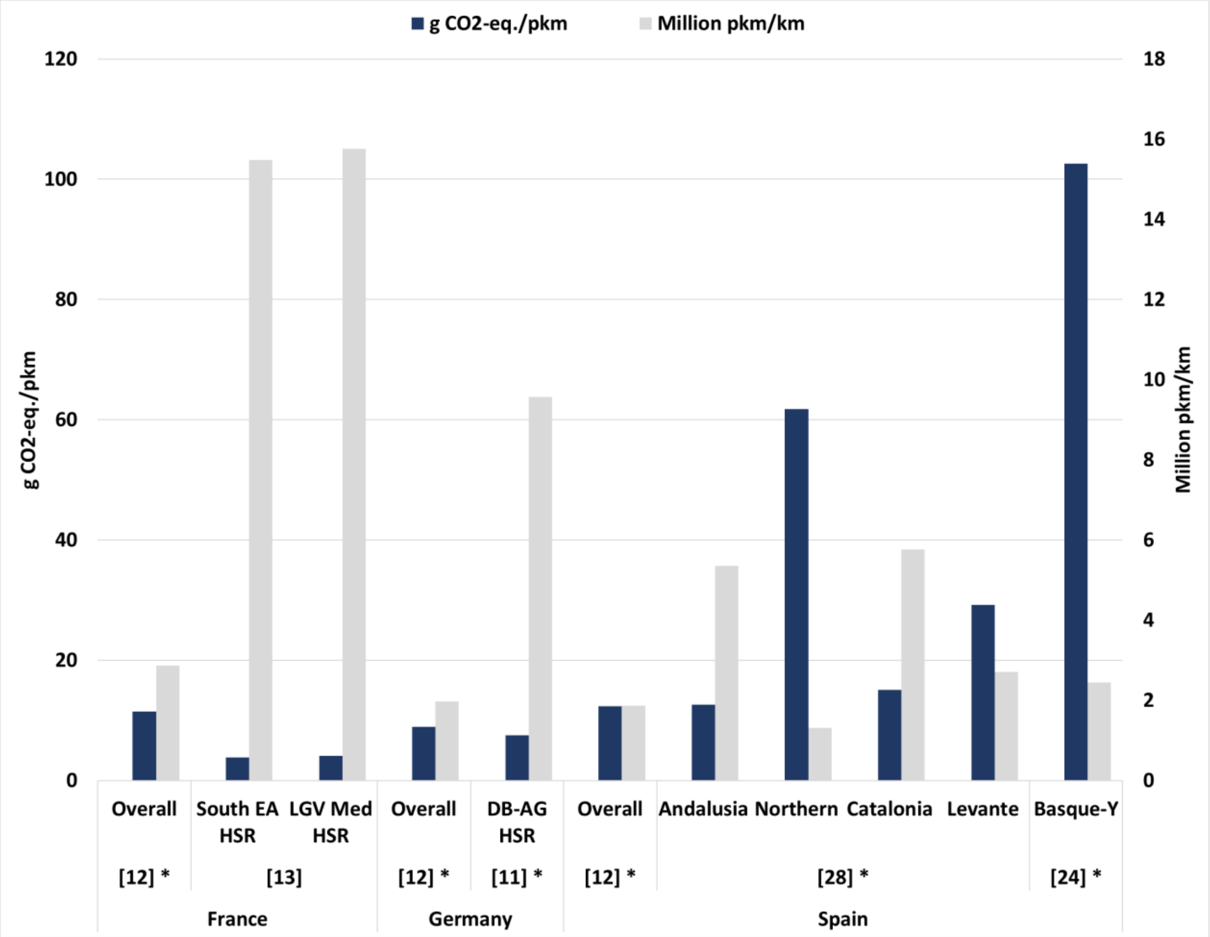


Figure 10: Comparison of CO_2-eq. emissions per passenger-kilometre: Countries and their HSR Lines

2.3.2 Component-based Analysis

The comparison carried out in chapter 4 deals with the superstructure of the modes of transport. This is the component where they differ most, as tunnels and bridges are considered in a similar way at both transport modes. Nevertheless, the underlaying emission data of these engineering structures will be examined here. This is done to give a sense of the magnitude of these emissions compared to the open track. The track itself will be examined in more detail in chapter 2.4.

The CO_2-eq. emissions of the different components, distinguished in the life cycle phases construction and maintenance, are compared on a per kilometre-basis. During the analysis of the literature, it became apparent that only a few studies make an explicit distinction between different components. *Schmid and Mottschall* [11], *Tuchschmid et al*. [12] and *Baron et al.* [13] provide a good breakdown of emissions by different components. These three studies show very similar results for the individual components, as their compilations are closely related and partly build on each other.

2.3.2.1 Tunnel

According to the findings from the literature review, tunnels have an even greater emission potential per kilometre than open tracks. This is due to the high material requirements for steel and concrete, the logistics behind the construction work and the energy consumption of the used machines. The actual emissions depend not only on the construction method used but also to a large extent on the geotechnical conditions. Basically, a differentiation can be made between two construction methods that are the cut-and-cover method and the mined tunnel. Due to the high emission driving potential of tunnels, precise knowledge of their number, length, construction method and assumptions are particularly important in the emission calculation. These data should be listed in detail for later reproducibility of the results. In fact, they are often not shown in the considered studies. For example, it is frequently unclear whether a tunnel is built as a double-track tunnel or two single-track tunnels.

In addition to HSR lines, the considered studies also analyse a single-track freight line (*Bothnia Line* [10]) and a mixed route with Austrian conditions (*Landgraf and Horvath* [35]).

The results of studies quantifying in CO_2 are converted to CO_2-equivalent emissions by using a conversion factor of f=1.04. For studies, which do not specify the construction methods or characteristics, the emission values are listed under n/a.

Tunnel Service Life of 60 Years		t CO_2-eq./km*year						
		Mined		Cut-and-Cover		n/a		
		single	double	single	double	single	double	n/a
[10]	EPD - Bothnia Line 2014							
	Construction	43.33						
[11]	Schmied, Mottschall 2010							
	Construction	168.30	280.50	263.20	438.60			
[12]	Tuchschmid 2011							
	Construction + Maintenance	176.40	294.01	296.76	494.61			
[13]	UIC (Baron) 2011							
	Construction		298.13		421.20			
[18]	NTNU, Grossrieder 2011							
	Construction	167.00	278.00					
[24]	Bueno et al. 2017							
	Construction + Maintenance						296.40	
[25]	Lee et al. 2020							
	Construction							250.43
[27]	Åkerman 2011							
	Construction + Maintenance						123.40	
[35]	Landgraf et al. 2021							
	Construction	45.98	91.94	445.24	633.82			

Table 4: Reported CO_2-eq. emissions of tunnels for a service life of 60 years

The emissions of the tunnels are determined for two different service lives. On the one hand, a service life of 60 years is considered, on the other hand, a service life of 120 years is also considered in order to create a more realistic picture. In studies that report emissions for other service lives, these are converted to the assumed service life. Table 4 and Table 5 below show the emission values for the two applied service lives. In studies that also included maintenance work, these are estimated at five percent of the emissions. This is based on an evaluation by *Hill et al.* [31]. In that study, the maintenance phase is estimated to account for three to seven percent of CO_2-eq. emissions of the infrastructure.

Tunnel Service Life of 120 Year		t CO$_2$-eq./km*year						
		Mined		Cut-and-Cover		n/a		
		single	double	single	double	single	double	n/a
[10]	EPD - Bothnia Line 2014							
	Construction	21.67						
[11]	Schmied, Mottschall 2010							
	Construction	84.15	140.25	131.60	219.30			
[12]	Tuchschmid 2011							
	Construction + Maintenance	92.61	154.35	155.80	259.67			
[13]	UIC (Baron) 2011							
	Construction		149.07		210.60			
[18]	NTNU, Grossrieder 2011							
	Construction	83.50	139.00					
[24]	Bueno et al. 2017							
	Construction + Maintenance						155.61	
[25]	Lee et al. 2020							
	Construction							125.22
[27]	Åkerman 2011							
	Construction + Maintenance						64.78	
[35]	Landgraf et al. 2021							
	Construction		56.73	223.26	317.69			

Table 5: Reported CO$_2$-eq. emissions of tunnels for a service life of 120 years

The emissions for mined tunnels with two tracks are illustrated in Figure 11.
It should be noted that *Bueno et al.* [24], *Tuchschmid et al.* [12], and *Åkerman* [27] include the maintenance of the structures. These studies are marked with an asterisk "*" in Figure 11.
The *Bothnia Line* [10] is a single-track line; hence, only values for single-track tunnels are available. To allow a comparison with other double-track lines, as can be seen in Figure 11, the reported emissions of the *Bothnia Line* [10] are multiplied by two.
The emissions of the *Bothnia Line*, *Åkerman* [27] and *Landgraf and Horvath* [35] are significantly lower than in other studies. This aspect can be explained because the *Bothnia Line* values are used in both, *Åkerman* and *Landgraf and Horvath,* via a conversation factor.

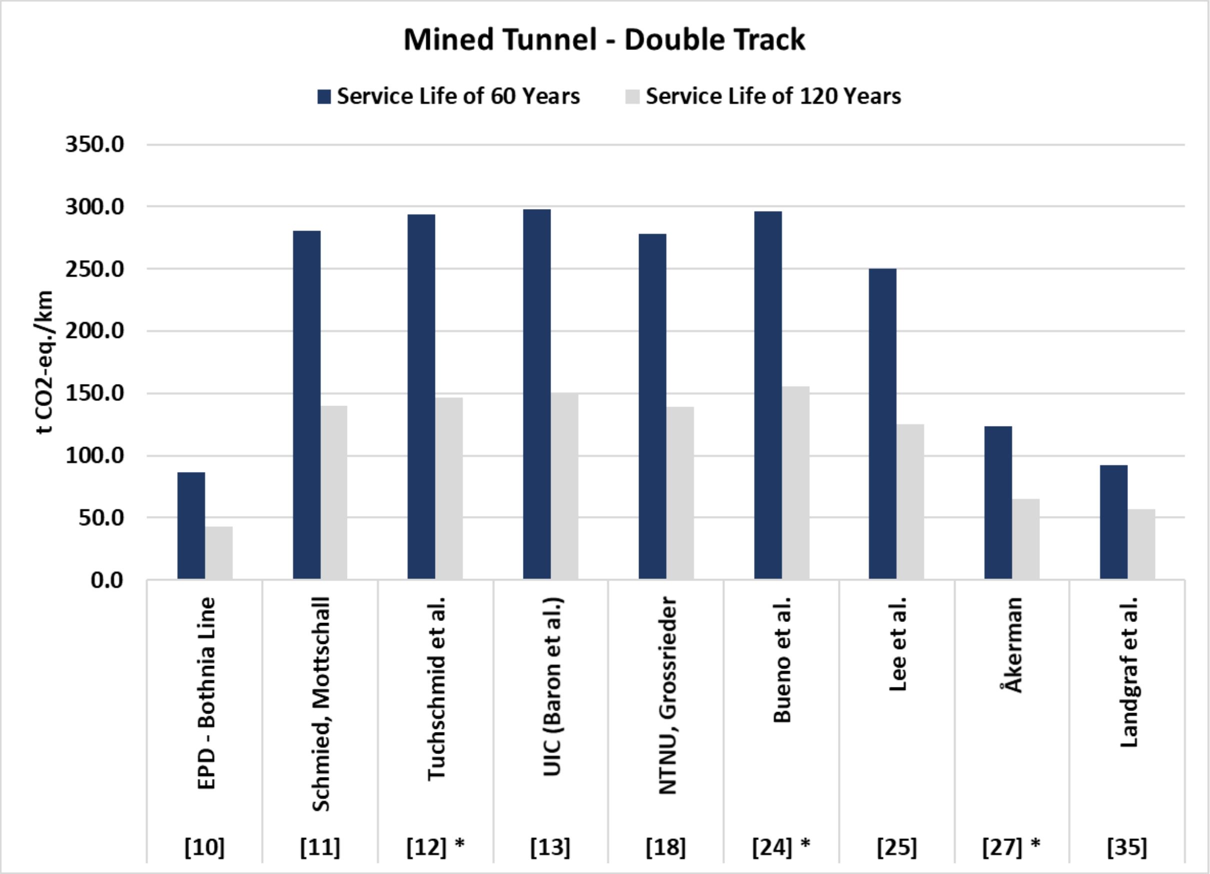


Figure 11: CO_2-eq. emissions of mined tunnels per kilometre and a service life of 60 and 120 years

Data of four studies is considered for the cut-and-cover construction method. It is shown in Figure 12. Basically, it can be stated that this construction method has higher emissions than the mining method. Thus, it is noteworthy that the tunnelling method plays a decisive role, and that significant differences in the level of emissions can therefore arise.

Of the four studies considered here, *Tuchschmid et al.* [12] report the emissions of the construction phase together with the emissions of the maintenance phase (marked with an asterisk "*").

The emissions of this infrastructure component in *Landgraf and Horvath* [35] are significantly higher than those in other studies, even though this study illustrates one of the lowest emission values for mined tunnels. The strong dependency on regional production processes of the used concrete and reinforcement steel might be the reason why the values for cut-and-cover tunnels are that high.

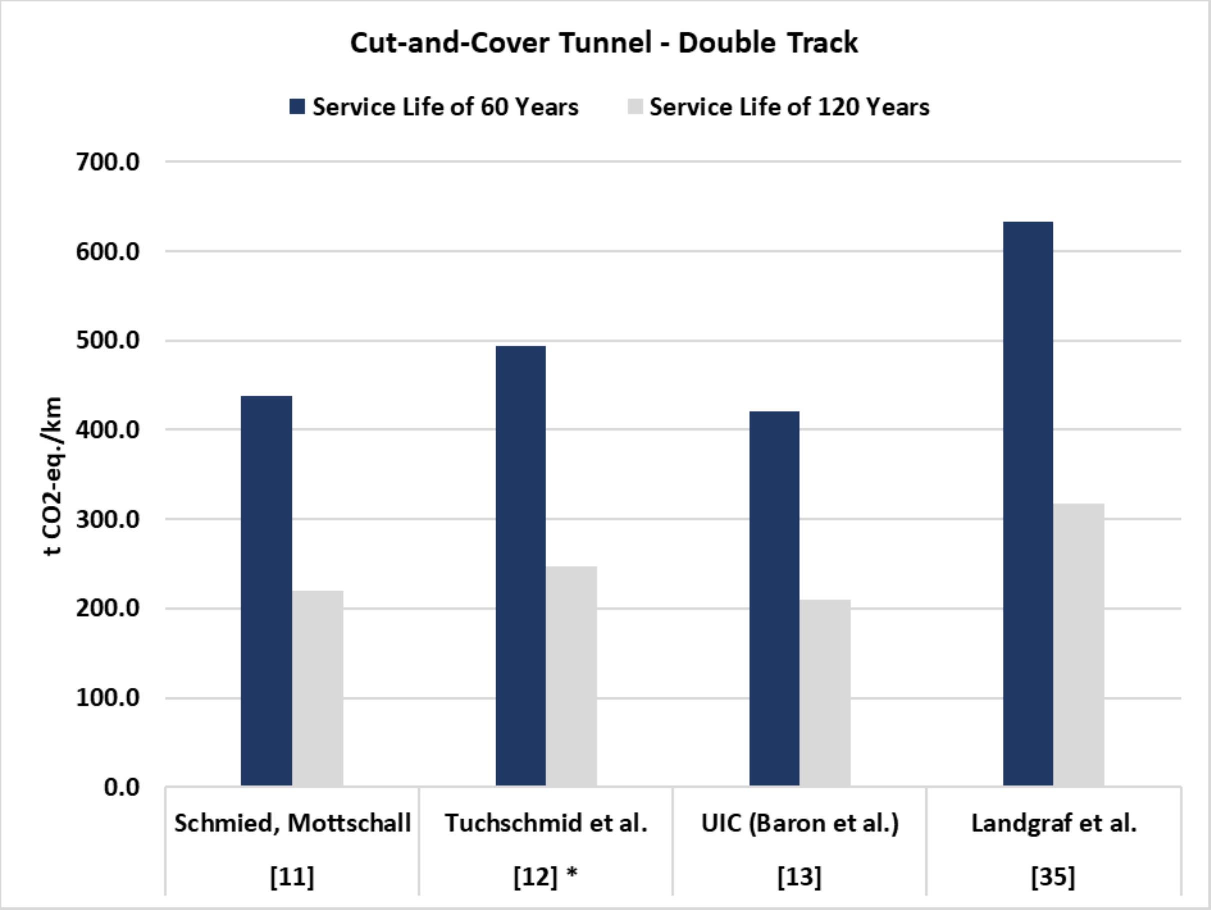


Figure 12: CO_2-eq. emissions of cut-and-cover tunnels per kilometre and a service life of 60 and 120 years

2.3.2.2 Bridges

In the emission calculation of bridges, it is of utmost importance to have precise knowledge of their number, lengths and construction methods.

Ten studies provide data on their underlying emissions per kilometre of bridge construction. These are listed in the following table. Again, it can be seen that some studies define values for bridge structures, whereas others do not mention construction methods nor characteristics. Such emission values are listed in the table under n/a. The results of studies that quantify in CO_2 were converted to CO_2-equivalent emissions using a conversion factor of f=1.04. Table 6 and Table 7 list the determined CO_2-eq. emissions per bridge kilometre.

Bridges Service Life of 60 Years		t CO_2-eq./km*year								
		Concrete Big		Concrete Small		Steel		n/a		
		single	double	single	double	single	double	single	double	n/a
[10]	EPD - Bothnia Line 2014									
	Construction							126.79		
[11]	Schmied, Mottschall 2010									
	Construction	162.00	270.00	70.50	117.50	147.40	245.70			
[12]	Tuchschmid 2011									
	Construction + Maintenance	161.13	268.54	70.23	117.06	141.87	236.44			
[13]	UIC (Baron) 2011									
	Construction		213.20		117.86		294.66			
[18]	NTNU, Grossrieder 2011									
	Construction							161.00	230.00	
[24]	Bueno et al. 2017									
	Construction + Maintenance									317.20
[25]	Lee et al. 2020									
	Construction									440.75
[27]	Åkerman 2011									
	Construction + Maintenance								223.08	
[34]	Cheng et al. 2020									
	Construction								398.66	
[35]	Landgraf et al. 2021									
	Construction	106.26	212.51			118.14	236.29			

Table 6: Reported CO_2-eq. emissions of bridges for a service life of 60 years

The emissions of bridges are also considered for a service life of 60 and 120 years. In some studies, emissions of the maintenance phase have to be estimated because no explicit calculation is carried out. The emissions of the maintenance phase are therefore, following Hill *et al.* [31], assumed to account for five percent of the emissions.

Bridges Service Life of 120 Years		t CO_2-eq./km*year								
		Concrete Big		Concrete Small		Steel		n/a		
		single	double	single	double	single	double	single	double	n/a
[10]	EPD - Bothnia Line 2014									
	Construction							63.39		
[11]	Schmied, Mottschall 2010									
	Construction	81.00	135.00	35.25	58.75	73.70	122.85			
[12]	Tuchschmid 2011									
	Construction + Maintenance	84.59	140.98	36.87	61.46	74.48	124.13			
[13]	UIC (Baron) 2011									
	Construction		106.60		58.93		147.33			
[18]	NTNU, Grossrieder 2011									
	Construction							80.50	115.00	
[24]	Bueno et al. 2017									
	Construction + Maintenance									166.53
[25]	Lee et al. 2020									
	Construction									220.38
[27]	Åkerman 2011									
	Construction + Maintenance								117.12	
[34]	Cheng et al. 2020									
	Construction								199.33	
[35]	Landgraf et al. 2021									
	Construction	53.23	106.45			59.08	118.15			

Table 7: Reported CO_2-eq. emissions of bridges for a service life of 120 years

In Figure 13 and Figure 14, the values of the previous tables are plotted for the different bridge types and the applied service lives. A distinction is made between small concrete bridges, large concrete bridges with intermediate piers, and large steel bridges.

Emission values of studies, which do not describe the addressed types of bridges, are plotted under n/a. The *Bothnia Line* [10] is a single-track line; hence, only values for single-track bridges are available. To allow a comparison with other double-track lines, as can be seen in Figure 13, the reported emissions of the *Bothnia Line* [10] are multiplied by two.

It can be seen that large concrete and steel bridges differ only slightly in the level of emissions from construction. In studies, in which it is not possible to draw a conclusion about the construction method, it can be assumed on the basis of the level of emissions that these are bridges with large spans.

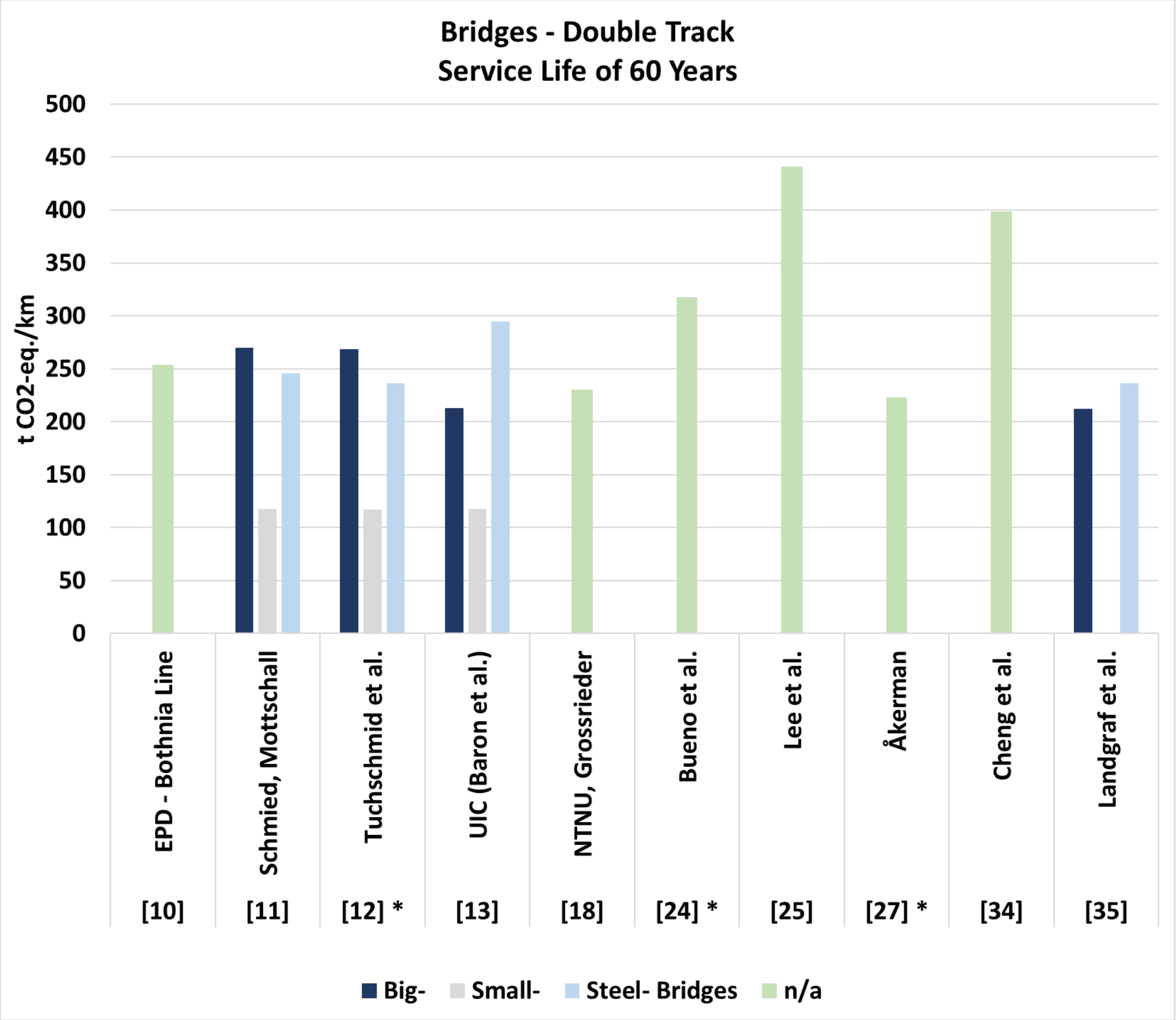


Figure 13: CO_2-eq. emissions of different types of bridges per kilometre and a service life of 60 years

Figure 13 illustrates that large concrete and large steel bridges have similarly high emissions. For studies that do not indicate the bridge type, it can be concluded from the level of emissions that these are bridges with large spans.

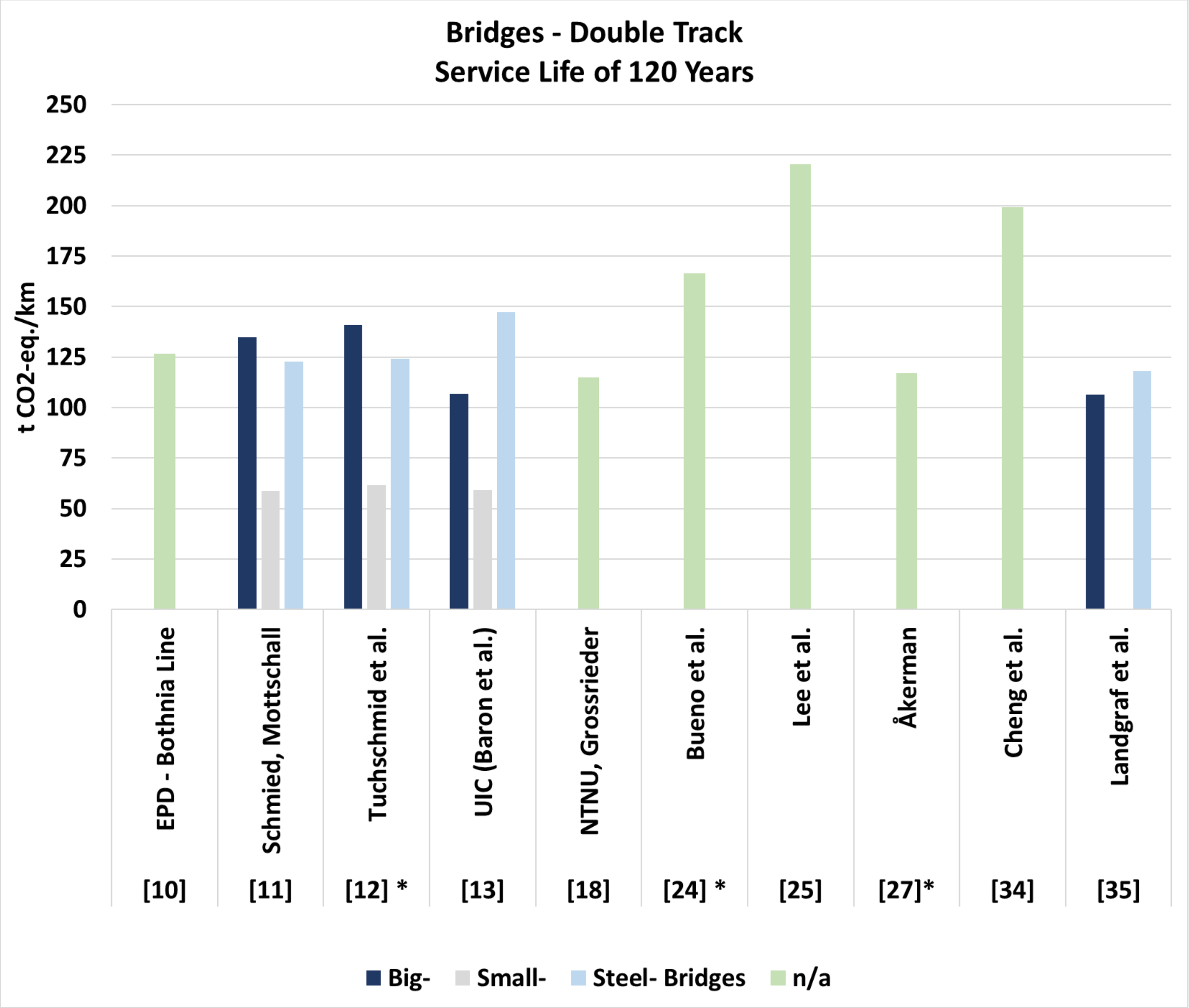


Figure 14: CO_2-eq. emissions of different types of bridges per kilometre and a service life of 120 years

In general, the emissions from a 120-year apportionment correspond to about half of the 60-year consideration. In studies that also include maintenance work, these were estimated at five percent of the emissions. This is done based on an evaluation by *Hill et al.* [31].

2.4 Detailed Analysis of Track Construction

In order to be able to compare the two modes of transport, rail and road, for the purpose of this thesis, the data for the superstructure of the lines will be analysed in more detail. On the one hand, the emissions are related to one kilometre of line and, on the other hand, to the transport performance of the respective line.

In general, the components ballast with sleepers or slab track, rails and any fasteners are considered for this comparison. However, it must be mentioned (as in previous analyses) that the definitions used in the studies are not uniform. In the case of the reported emissions, attention must be paid to the different nomenclature of the components. In *Baron et al.* [13], for example, the ballast, the rail, the sleepers, the fastening, the cable canal and fences are summarised with the term *Rail*. *Chester and Horvath* [7], as another example, show the emissions of the track solely together with those of the power equipment.

Depending on local conditions, the superstructure components have widely differing service lives in reality. The service lives of the components used in the studies are determined differently. *Chester and Horvath* [7], *Schmid and Mottschall* [11] and *Mottschall and Bergmann* [16] apply different service lives for the various superstructure components. In studies that do not report service lives or only total emissions without a time reference, the emissions of the superstructure components are converted to a service life of 30 years in this work. For studies that indicate a service life of 60 years for the track system (*Bueno* [24], *Åkerman* [27], *Kortazar* [28], *Cheng et al*. [34]), it is assumed in this thesis that the superstructure is being renewed after 30 years.

In studies relating emissions to passenger-kilometres, the transport performance and the route length are used to calculate emissions per kilometre. In exactly the opposite way, emissions per route kilometre are converted to emissions per passenger-kilometre by using the route length and the transport performance. Data on route lengths and transport performance, which cannot be obtained directly from the studies, are taken from the *UIC statistics database* [53]. A distinction between passenger and freight traffic is made on the basis of the corresponding gross tonne-kilometres.

The considered lines are national networks, specific lines and HSR lines. The study of *Tuchschmid et al.* [12] is not included here because it is not explicitly stated which transport performance is used to allocate emissions to passenger and freight transport.

For the emissions of *Kortazar* [28] it is assumed that the superstructure causes 30 % of the emissions of the entire system. This is done according to the gained information of the ratio of the emissions of the considered studies.

The table of the assessed emissions can be found in Appendix 3.

2.4.1 Emissions per Kilometre of Line

Figure 15 shows the CO_2-equivalent emissions, wherein emissions are related to one kilometre of line and one year. Studies marked with an asterisk "*" report the emissions of the construction phase and the ones occurring during the maintenance phase.

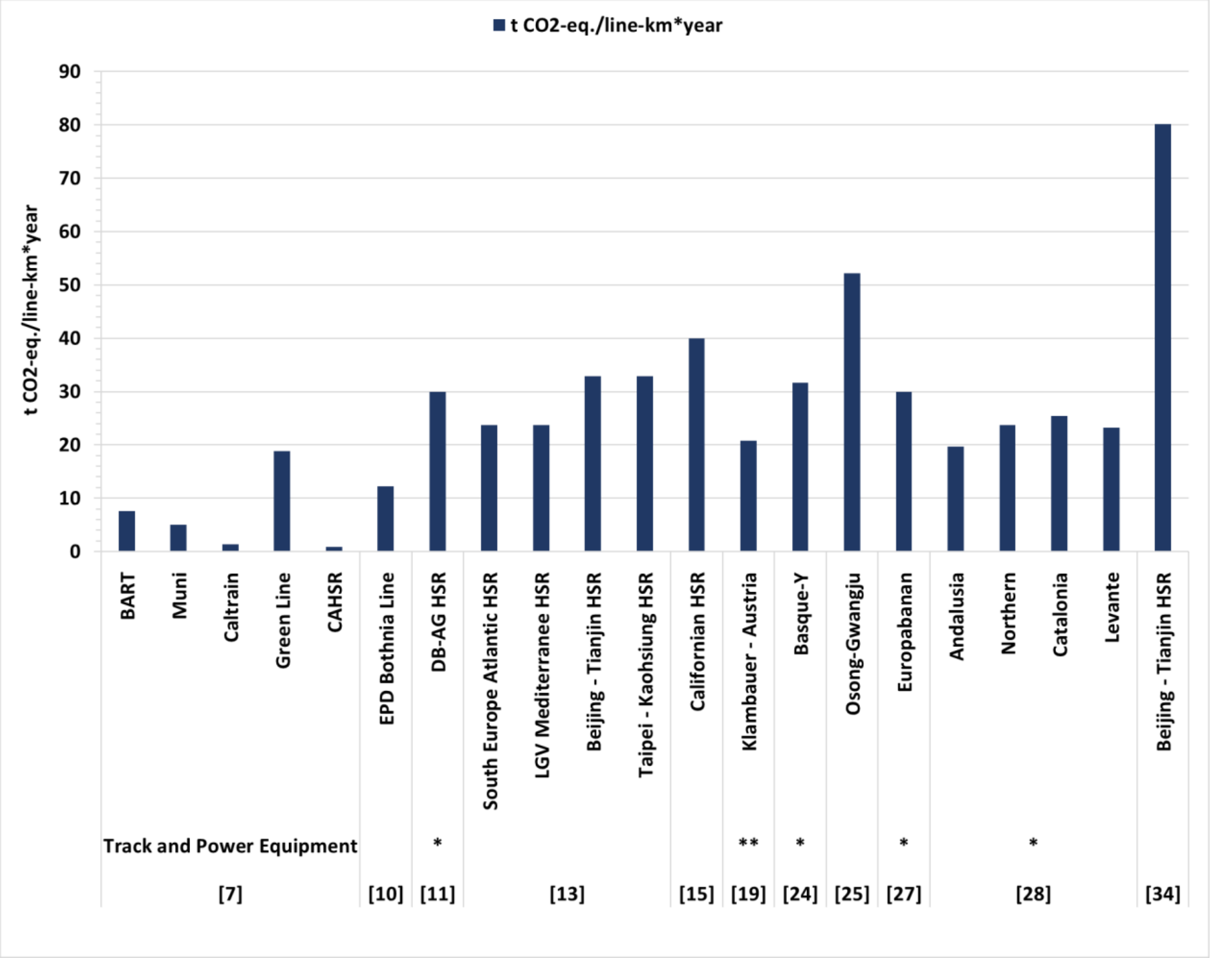


Figure 15: CO_2-eq. emissions of track per line-kilometre

In the case of *Klambauer* [19] it should be mentioned that a highly specific track element is extrapolated onto the Austrian network. This study represents a double-track line with a radius larger than 3000 metres and a load per track of 45,000 to 70,000 tons per day. In addition to the construction phase, this study also considers the maintenance and end-of-life phases. This study is marked with two asterisks "**".

As already seen in the comparison of the HSR routes, it is recognizable that *Cheng* [34] sets extremely high emission values for the superstructure. This study shows a five times higher emission value for the superstructure components than the study of *Baron et al.* [13] which deals with the same route. Besides that, it is noticeable that the values given by *Chester and Horvath [7]*, except the *Green Line*, are immensely low, even though the power equipment is also included.

To get a first overview, the reported CO_2-eq. emissions of all considered types of railways (e.g. HSR, mixed lines, etc.) are averaged and assumed to all be double-track lines. The average CO_2-eq. emissions are 27.41 tons per kilometre of line for one year. Since the *Bothnia Line* [10] is a single-track line, the reported CO_2-eq. emissions are multiplied by two to get an equal number of tracks. This approach does not distinguish between studies that address the emissions of the construction phase or maintenance phase together.

Figure 16 considers the HSR lines exclusively.

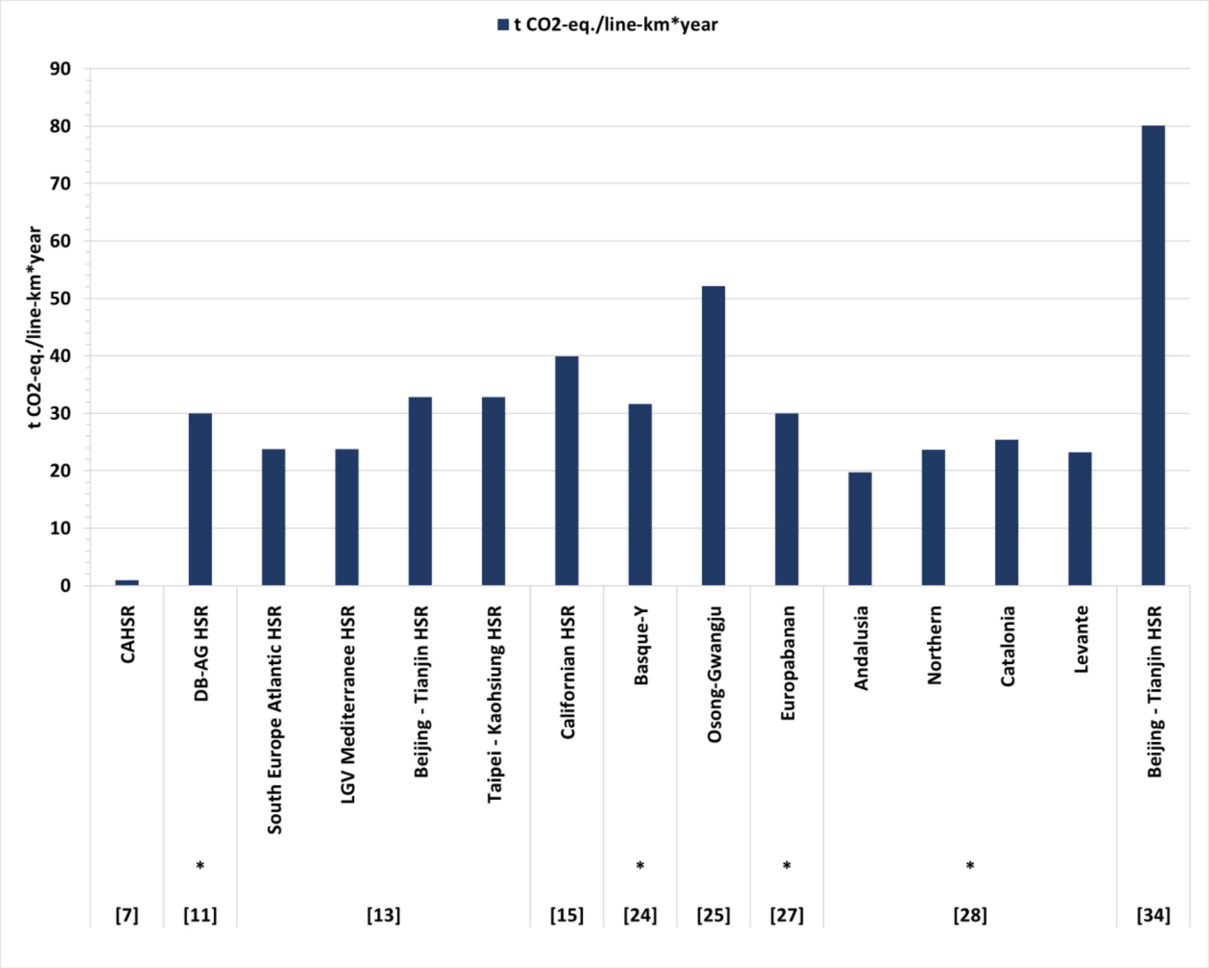


Figure 16: CO_2-eq. emissions of track per line-kilometre for HSR lines

The average value of the HSR lines is equal to 31.32 tons CO_2-eq. per kilometre of line per year. This average value includes studies which consider the emissions of maintenance works as well as studies which do not consider these emissions.

The average emissions of studies, which solely look at the construction phase is equal to 32.59 tons CO_2-eq. per kilometre of line per year. This value is higher than the average emissions of all considered HSR lines. Likely this is due to the fact that some of the studies, which include the maintenance phase, show lower values. The high emission value of the *Beijing-Tianjin HSR* has an even greater impact if less studies are considered. Therefore, the average emissions are calculated separately without this line. The average emissions without considering the *Beijing-Tianjin HSR* are equal to 27.84 tons CO_2-eq. per kilometre of line per year. This value is considered for the comparison with the road mode of transport in chapter 4.2.

2.4.2 Emissions per Passenger-Kilometre

In this section, the emissions of the superstructure are related to the respective transport performance. The distribution of emissions is similar to that of all components of the track as analysed in chapter 2.3.

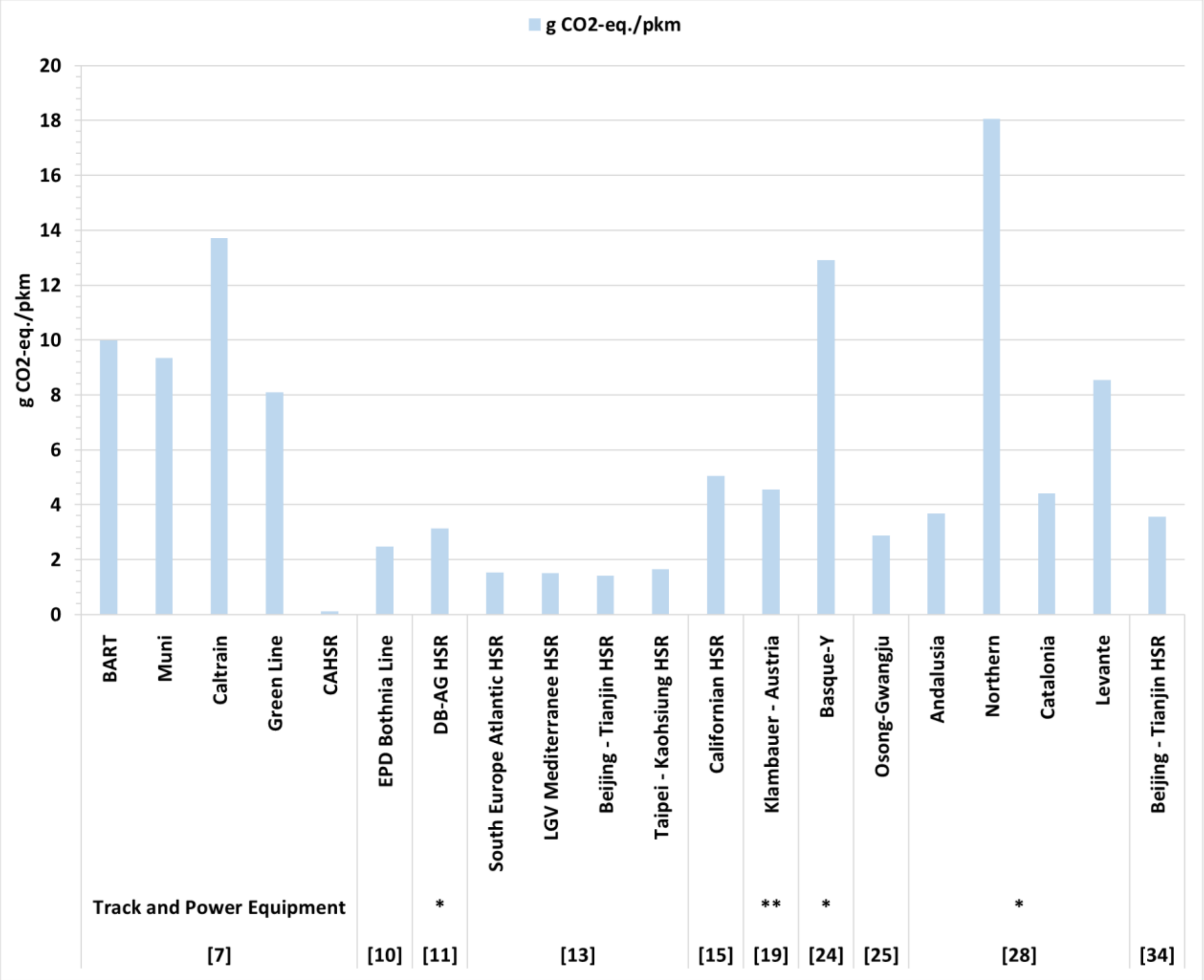


Figure 17: CO_2-eq. emissions of track per passenger-kilometre

Due to the strong variation of the results, which depends on the number of passengers, an averaging of all routes is not performed here.

3 Analysis of Roadway Life Cycle Emissions

In this chapter, the contents of literature comparisons already carried out for the road mode of transport are depicted. Subsequently, their results, advantages and disadvantages as well as their findings will be discussed. Based on these conclusions, a separate literature analysis is employed which aims at comparing the emission values determined in the studies. Finally, this results in recommendations for a better comparability in future studies.

3.1 Existing Literature Reviews

- E., Hoxha et al: Life cycle assessment of roads: *Exploring research trends and harmonization challenges*, Science of the Total Environment, 2021 [36]

In this extensive literature research concerning the transparency of the determination of environmental impacts of roads, the authors question which structure a life cycle assessment has to have and which contents have to be defined in order to enable comparability between studies. An important aspect concerns the presentation cross-sectional dimensions.
„The limited cross-sectional dimensions available constitute a significant weakness for the reproducibility and comparison of road case studies. […] the cross-sectional dimensions of the road and the materials specification must be detailed in the scope of the study. A lack of this information limits the comparability of the LCA results across studies, and therefore, their practical utility is questioned.” [36]

- Vasiliki, Dimoula, et al.: A Holistic Approach for Estimating Carbon Emissions of Road and Rail Transport Systems, Aerosol and Air Quality Research 16, 2016 [38]

This study investigates the environmental impacts caused by the construction and operation of the road and rail modes of transport. A comparison of different studies shows that the construction of a dual motorway emits an average of 18 tons CO_2-eq. per kilometre and year. The construction of the rail infrastructure emits 35 tons CO_2-eq. per kilometre and year.
“It must be noticed that the results of each of the previous studies are very heterogeneous, since their scope, their data sources, their system boundaries and their assumptions are different.” [38]
Based on the analysis of previous studies, the following aspects, among others, are identified:

- Emissions from material production account for 60-90 % of absolute CO_2 emissions

- Construction activities account for 5-7 % of absolute CO_2 emissions
- The transport of materials related to the construction of roads contributes 10 % of absolute CO_2 emissions. [38]

3.2 Analysis of Considered Literature

The literature considered in the following section of this work is primarily based on the scientific online databases of *ScienceDirect* [1] and *Mendeley* [2]. Concerning road infrastructure, three studies are selected for further processing. Some of the found studies deal with the basic problems in the preparation of LCAs of the road mode. In the further course of this thesis, a comparison between the pavements of the transport modes shall be established. For this reason, studies are consulted that deal with the emissions of the pavement of roads.

Due to the fact that road superstructures can be constructed in diverse ways, a direct comparison of construction methods is difficult. For each country, there are clearly defined specifications for the superstructure. Additionally, there is some leeway in the selection of the superstructure for certain given loads.

Furthermore, the boundary conditions of the LCAs considered in the studies differ. For example, the lower base layers are either considered or not.

The first study was conducted by *Gschösser* [39] and deals, among other things, with the new construction of a highway section. This section has four lanes and a width of 20.5 metres. According to Swiss regulatory, the traffic load class corresponds to class T6 and the subgrade wearing capacity to class S3. The pavement of this highway over a length of ten kilometres is taken as the functional unit. Components of the analysis are material production, transport and paving on the construction site. Emissions are reported for three different types of pavement. These superstructure types are an asphalt, a concrete and a composite superstructure. The concrete superstructure is not reinforced in this case. Figure 18 shows the individual types of superstructures.

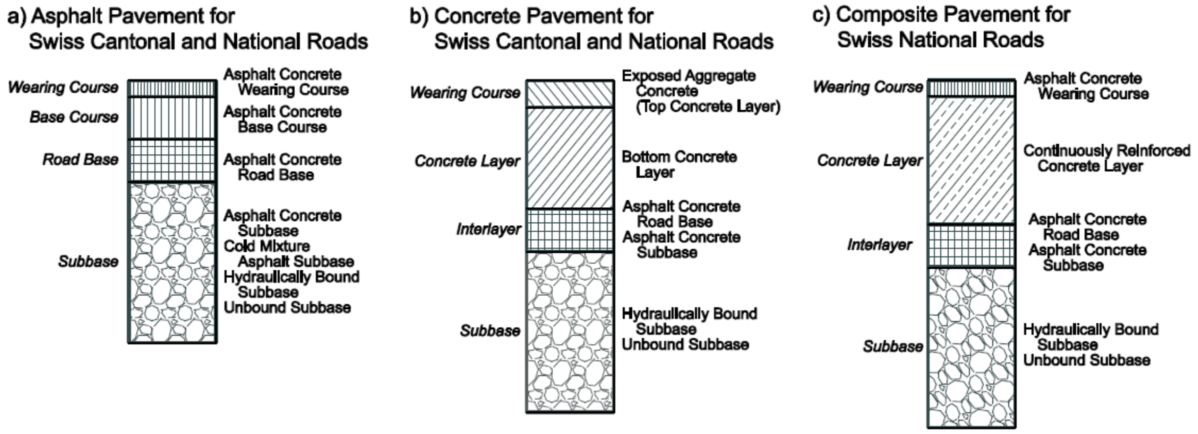


Figure 18: Layer composition of road pavement in *Gschösser* [39]

According to the national guidelines, different types of layers and thicknesses of the individual layers can be used. In his study, *Gschösser* [39] shows the emissions of the three types of superstructure, each for a specific layer composition.

The second considered study on road pavement emissions was conducted by *Jullien et al*. [40]. In this study, the emissions from the construction of the road superstructure are analysed. A defined service is used as the functional unit. Similarly, to the traffic load class in the aforementioned study, this study also quantifies by the means of a transport volume. The functional unit is defined as level of service for a traffic of 25*10^6 trucks/year/lane for a 1-km long, 2-lane road. Of these, 20 % are heavy vehicles and 80 % are passenger cars. There are two construction types: the asphalt method and the concrete method. In this study, reinforced concrete is used. The superstructures do not include a subbase and are illustrated in Figure 19.

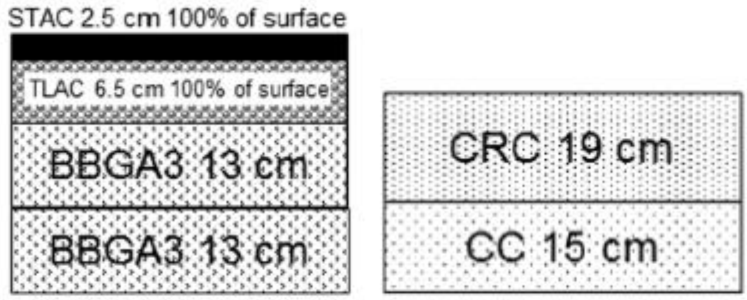


Figure 19: Layer composition of road pavement in *Jullien et al.* [40]

The third study that provides usable data on road construction emissions was carried out by *Wei and Chen.* [41]. It describes the emissions from various urban transportation infrastructure systems. However, the data is not superstructure-specific; it also includes tunnels, bridges and other structures. For this reason, this study is described solely as a supplement.

The functional unit of this study is one kilometre of project length. Emissions are shown separately for material production, construction, maintenance and disposal.

Regarding the characteristics and dimensions of the road infrastructure, no information is provided. There is only a distinction between road classes with different widths. The emissions of a 2nd-class road with a width of 21 meters are used, which is similar to the study conducted by *Gschösser* [39].

3.3 Emissions per Kilometre of Lane

In order to contextualise the results of the three aforementioned studies, the primary aim is the alignment of the various functional units. For this purpose, the emissions are related to one lane and a service life of 30 years. Subsequently, an attempt is made to use the layer thicknesses to conclude on correlations between the emissions determined in the studies. It must be noticed again that the study of *Wei and Chen* [41] does not differentiate between types of superstructure. Furthermore, the emissions of tunnels, bridges and other structures are included and a representation of possible cross-sections is not available.

Table 8 shows a list of the used literature and their reported emissions per FU and per kilometre of lane for one year.

	Short Title	Country	Details	Contents	FU	Emissions	
						t CO2-eq./lane-km*year	**t CO2-eq/FU**
[39]	Gschösser Construction	Switzerland	Asphalt Pavement	Materials+ Transport+ Construction	Traffic load class T6 S3, 4 lanes (20,5m) length of 10 km	5,52	6629
	Gschösser Construction	Switzerland	Concrete Pavement unreinforced	Materials+ Transport+ Construction	Traffic load class T6 S3, 4 lanes (20,5m) length of 10 km	12,98	15576
	Gschösser Construction	Switzerland	Composite Pavement	Materials+ Transport+ Construction	Traffic load class T6 S3, 4 lanes (20,5m) length of 10 km	13,59	16312
[40]	Jullien, et al. Construction	France	Concrete Pavement reinforced		Service for 25*10^6 Trucks/year/lane for a 1 km, 2-lane	12,50	initial constr. 750
	Jullien, et al. Construction	France	Bitumious Pavement		Service for 25*10^6 Trucks/year/lane for a 1 km, 2-lane	3,50	initial constr. 210
[41]	Wei, Chen Construction	China	2. Class (4-)6 lanes 21 m width	Materials+ Transport+ Construction	1 km length of project no cross-section also T+B area	29,17	175

Table 8: Reported CO_2-eq. emissions of road pavements

Figure 20 shows the emission values per kilometre of roadway and year for a service life of 30 years. It should be noted that the described road structures differ, which was mentioned in chapter 3.2.

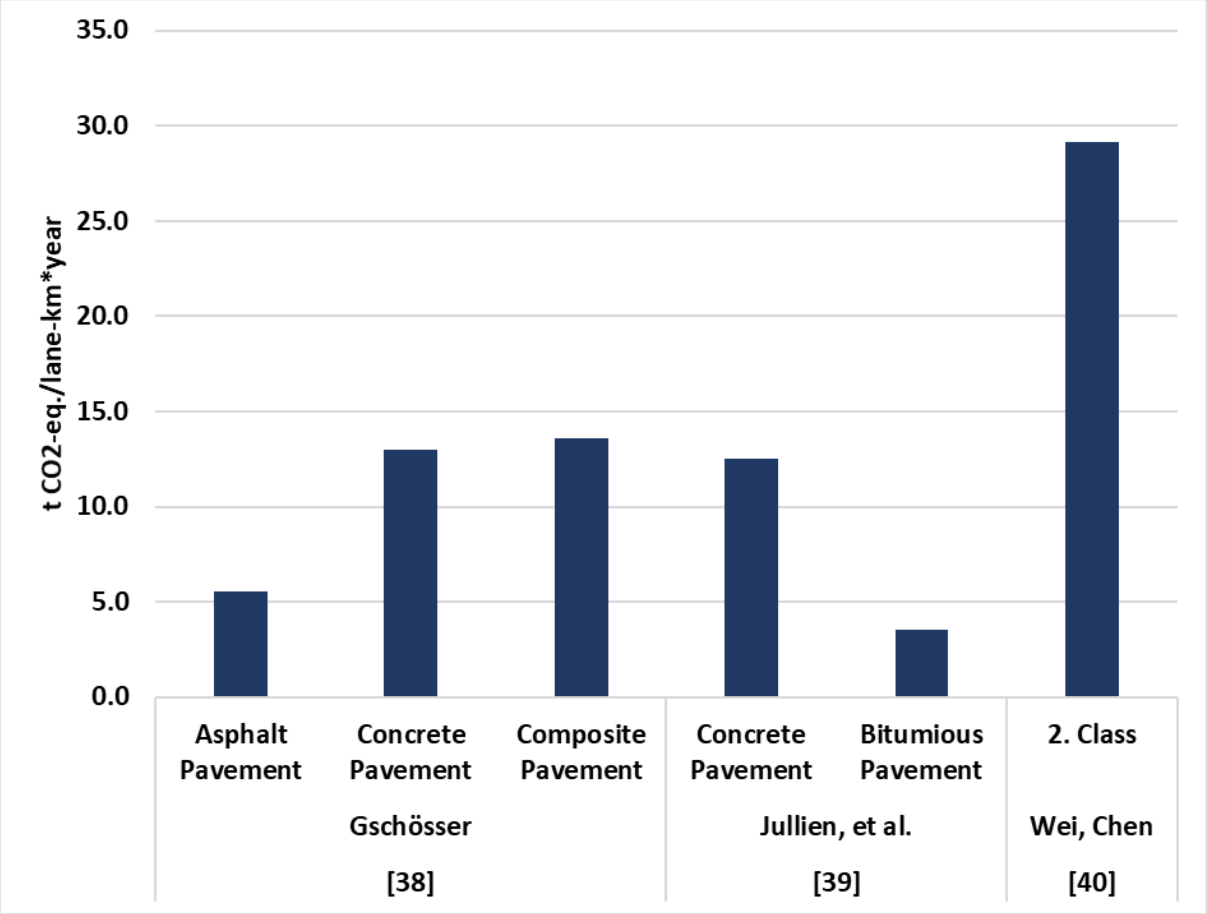


Figure 20: Reported CO_2-eq. emissions of road pavements

Figure 20 illustrates that the concrete construction method has a significantly higher emission output than the asphalt construction method. The study by *Wei and Chen* [41] also considers the emissions from tunnels and bridges as well as intersection areas. For this reason, the values of this study are significantly higher than those of the other two studies and will not be used in the following sections of this work.

By using the broken down data of *Gschösser* [39], the superstructure types of *Jullien et al.* [40] are recalculated, to find a possible relationship. The results of this recalculation can be seen in Appendix 4.

It can be said that the emission values calculated with the data of *Gschösser* [39] deviate by up to 90 percent from those in the original study by *Jullien et al*. [40]. This is probably due to the fact that it is not possible to compare exactly the same materials, solely those that were considered in *Gschösser's* study [39]. In addition, this deviation might also be influenced by the assumed emissions of the production phase. In *Gschösser's* study [39], material production accounts for about 90 percent of the total emissions of the construction

phase. Nevertheless, the emissions of the production phase are difficult to determine uniformly, as *Park et al*. [42] point out:
"However, basic materials for LCA of construction materials are still insufficient because a life cycle environmental load emission estimation methodology for the construction area has not been established and an environmental impact database with representative features by material has not been conducted. […] there are no detailed procedures and standards for estimating the environmental impacts of the production stage of construction materials." [42]

3.4 Findings Concerning the Roadway Sector

Usually, the boundary conditions and system restrictions for life cycle assessments regarding road traffic differ to a significant extent. Hence, a direct comparison of the results is also not meaningful. For this reason, an attempt is made to compare the results at the component level. Unfortunately, the reviewed studies do not differentiate between components in their results. Therefore, it is not possible to elaborate a list of emissions, as it was done for the rail mode of transport in chapter 2.2.
At this point, reference is made to the literature review by *Hoxha et al*. [36], in which a classification of the road cross-section into different subgroups is suggested. In addition to these elements, an LCA should also take into account the components of tunnels, bridges, and other structures such as service stations, as it is the case with railways.

4 Comparison Rail - Road

In general, a component-specific analysis should be carried out in the LCAs, since such an investigation ensures comparability with other LCAs of the same mode of transport. The compared functional units of the LCAs must be defined in the same way to allow a comparison. In addition, the system boundaries must also be determined in the same way, or at least highly similarly.

In this work, the two transport modes road and rail are compared in terms of the component track. The reason why this comparison is chosen is that in this segment these modes of transport differ most clearly. With respect to tunnels and bridges, similar requirements apply to the two modes of transport (e.g. in terms of construction, materials used and the like), and there is no particular difference between these structures in terms of life cycle assessments. Both, the CO_2-eq. emissions and the respective land consumption of the components are considered. The data of the respective routes originates from the literature analysis carried out in the previous part of this work.

4.1 Determination of Transport Performance

The Western Railway Line and the West Motorway A1 between Vienna and Salzburg (Austria) will be compared in this chapter.

Based on the maximum number of people respectively net tons carried on a track, the aim is to figure out how many lanes of the highway are needed to ensure the same transport service as one track of the railway. This is done, in order to compare emissions for infrastructure provision on a similar basis of the two modes of transport.

On the basis of this comparison, the ratio of the number of tracks to the number of lanes is obtained. This ratio is determined in three ways: (i) for real conditions with a distinction between passenger and freight traffic, (ii) for a theoretical utilization of the tracks via passenger traffic, and (iii) on the basis of a statement by the *Austrian federal railways OeBB* [43].

According to the Oe*BB* [43], a double-track electrified high-capacity railway line has the same capacity as a highway with three lanes in each direction.

The month of January 2020 is the reference period for this analysis.

The Institute of Railway Engineering and Transport Economy of Graz University of Technology provides data for this work on the monthly volume of vehicles on sections of the Western Railway Line. A thorough examination of this data results in the discovery of one of the most heavily used sections. This section will further be taken into consideration. It is located west of Linz main station in the area between Wels and Hörsching. The Western Railway Line is double-tracked in this area.

The considered measurement cross-section of the West Motorway A1 is located between node Passau and Traun at kilometre 174.3.

The records of the traffic volume on the Austrian motorways are available on the homepage of the *Asfinag* [44]. According to this data, one of the most heavily trafficked measurement cross-sections is located very close to the previously selected section of the Western Railway Line. This allows for a comparison of the two modes of transport within the same geographical region.

4.1.1 Observed Traffic Data

First of all, data from the Institute of Railway Engineering and Transport Economy of Graz University of Technology is used to determine how many passenger and freight vehicles are operated on the section in one month. By subdividing the passenger vehicles into different categories, and considering the number of seats and an assumed seat occupancy rate of 80 %, it is possible to obtain the number of passengers transported. The determined number of passengers is highly dependent on the occupancy rate of the vehicles. With respect to freight traffic, the Institute's data shows a breakdown into various wagon and weight classes. Observed traffic performances of the Western Railway Line can be seen in Table 9. The calculation of this results can be found in Appendix 5.
For passenger traffic on the highway, the number of passenger cars (≤3.5 tons) is determined with a theoretical occupancy rate of 1.36 people per car. This occupancy rate represents the average over one week. Underlaying data for this can be found in the final report on *Österreich unterwegs* [45].
To determine the net tons transported on the highway, the number of motor vehicles >3.5 tons was multiplied by an average load. Due to the fact that it is not possible to draw conclusions about individual vehicle classes on the basis of the *Asfinag data* [44], a distribution among different truck types is assumed. Based on the maximum permissible load minus the utilization of this load and an assumption about the number of empty runs, the average load can be determined. Data on the distributions of load utilization and empty runs are depicted from *Facanha and Horvath* [46]. Taking these assumptions into account, the average load is 6.75 tons. Appendix 6 shows the breakdown for the determination of the average load.

In order to compare the same transport services (i.e. number of passengers, number of net tons) with each other, the transport services are calculated for one lane. The calculations of the number of passengers and net tons transported in freight traffic of the road mode of transport can be seen in Appendix 7. The following table shows the resulting transport services per track and lane.

Transport Service	Western Railway Line	West Motorway A1
Passengers/lane*month	1,115,304	445,771
Net tons/lane*month	932,559	344,858

Table 9: Transport service of the Western Railway Line and the West Motorway A1

For passenger traffic, the ratio of the number of tracks of the Western Railway Line to the number of lanes of the West Motorway is 1:2.5.
For freight traffic, this ratio corresponds to 1:2.7.

These two ratios are now weighted averaged over the number of vehicles. The weighted average of passenger and freight traffic results in a ratio of 1:2.6. The calculation of the ratios can be seen in Appendix 8.

4.1.2 Theoretical Capacity

Subsequent to the transport service, a theoretical comparison of the transport performance of the modes is being carried out. This comparison is made on the basis of the number of passengers transported on the cross-section in one hour. In the railway sector, among other things, the train speed deviation and the headway limit the number of trains that can operate. For the Western Railway Line, it is therefore defined that only trains of the *Railjet* category travel with headways of two minutes. This value is based on comparable lines operated by the *Swiss federal railways* equipped with ECTS Level 2 and velocities greater than 160 km/h [56]. This means that 30 *Railjets* with 404 seats can pass the cross-section in one hour. With an occupancy rate of 80 %, this results in a maximum transportable number of 9696 passengers per hour.
The maximum number of vehicles that can be transported on a motorway is determined by using information provided by the Institute of Roads and Transportation of Graz University of Technology [50]. For the local conditions of a route with a gradient of less than 2 %, a heavy traffic share of 0 % and a route control system, the maximum possible traffic volume of a three-lane section is 5800 vehicles per direction per hour. This value corresponds to 8000 vehicles for a four-lane section per direction per hour. Taking into account the occupancy rate of 1.36 persons per vehicle, the transport capacities of the sections are 7888 and 10880 passengers per hour. Table 10 lists the theoretical capacity.

	Western Railway Line	**West Motorway A1**	
# RailwayTracks or # Motorway Lanes	1	3	4
Passengers/hour	9,696	7,888	10,880

Table 10: Theoretical capacity

To provide the same level of theoretical capacity on the section of highway as on one track of a high-performance line, it requires 3.6 lanes.

4.1.3 Ratios of Transport Performances

The following table summarises the calculated relations of the number of tracks to the number of lanes.

Ratio	Observed Traffic Data	Theoretical Capacity	OeBB [45]
# Railway Tracks / # Motorway Lanes	1 : 2.6	1 : 3.6	1 : 3.0

Table 11: Relationship tracks to lanes

The ratio of the observed conditions is within the range of the ratio stated by *OeBB* [43]. The assumptions of the occupancy rate and the loading of the lorries therefore seem to be plausible. Based on these three ratios, a comparison between the modes of transport will be carried out in chapter 4.2.

4.2 Comparisons of Environmental Impacts

For the three previously determined ratios, an evaluation of the emissions of the respective tracks is carried out in the following. The average emissions determined in this study are used for this purpose. In addition, the respective land consumption of the transport modes is considered. This will be done on the basis of the width of the standard cross-sections.

The considered components of the rail track are the ballast superstructure with sleepers (or slab track) and the rails. Figure 21 shows the standard cross-section.

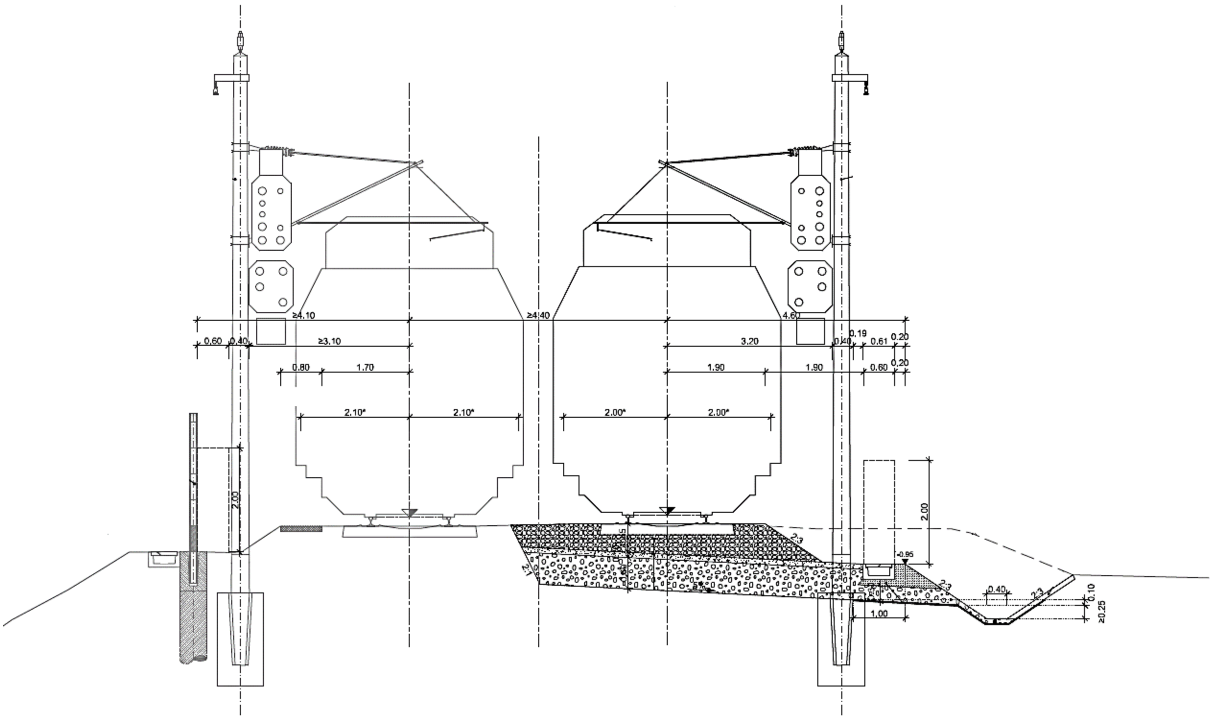


Figure 21: Cross-section of the considered HSR line [47]

The considered components of the roadway range from the lower base course over any intermediate layers to the upper base course and subsequent surface course. A distinction is made between asphalt and concrete pavements. The respective layer structures follow the *RVS 03.08.63* [49] and can be taken from Figure 23 and Figure 24.
The calculation of the Austrian road network is based on the study of *Gschösser* [39]. Although it is said in chapter 3.3 that there is a difference compared to the calculated emissions from the study of *Jullien et al*. [40], the study conducted by *Gschösser* provides a detailed breakdown of the individual components and their emissions. The emissions of the individual layers are interpolated linearly over the layer thickness. The emission values in *Gschösser* [39] are determined for Switzerland and, therefore, differ in the energy mix. Nevertheless, these values provide a good reference point for a comparison of the transport modes in the Austrian network.

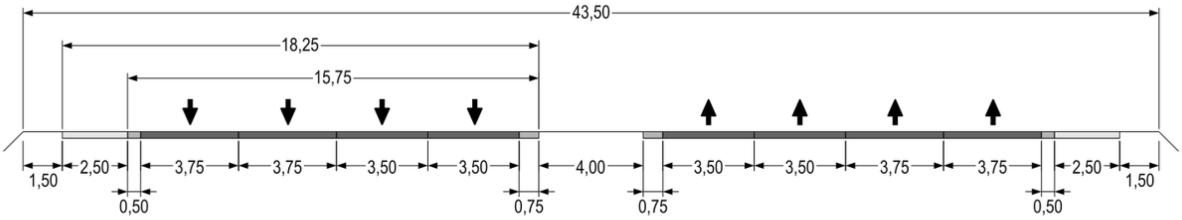


Figure 22: Cross-section of the considered motorway section [48]

The emissions of the construction of the superstructure determined in chapter 2.4.1 are 27.84 tons CO_2-eq. per kilometre of HSR line. By allocating these emissions of a double-track line to one track, it is possible to obtain the emissions of 13.92 tons CO_2-eq. per kilometre and year.

The emissions for the highway section are calculated by using the study of *Gschösser* [39]. For this purpose, the emissions of the individual layers are converted to the layer structure of an Austrian highway.
The determination of the layer thicknesses for the considered freeway section from the node Passau to Traun is calculated according to *RVS 03.08.63* [49].
Taking into account the distribution of heavy traffic, the load class follows LK 82 and thus results in the following layer structure of a bituminous construction method:

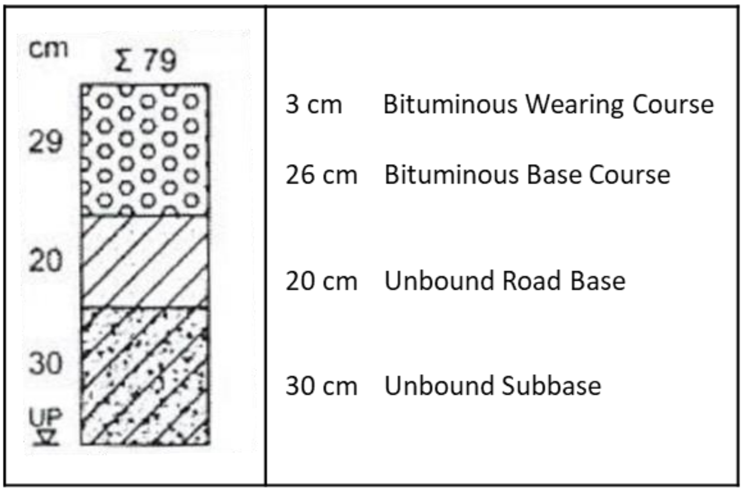


Figure 23: Asphalt pavement according to RVS 03.08.63 [49]

Table 12 shows the CO_2-eq. emissions of the individual layers, which are listed below. These are determined on the basis of the calculations in *Gschösser's* study [39]. The service life corresponds to 30 years and the processes of material production, material transport and installation are considered.

Layer	Material	Thickness	t CO_2-eq. per lane-km*year
Bit. Wearing Course	**AC MR 8 ASTRA**	**30 mm**	**0.92**
Bit. Base Course	**AC B 22 H**	**260 mm**	**5.83**
Unbound Road Base	**Crushed Gravel**	**200 mm**	**0.69**
Unbound Subbase	**Crushed Gravel**	**300 mm**	**1.03**
Sum			**8.47**

Table 12: CO2-eq. emissions of asphalt pavement

In addition to the asphalt construction method, the concrete construction method is also used. Figure 24 illustrates the layer thicknesses.

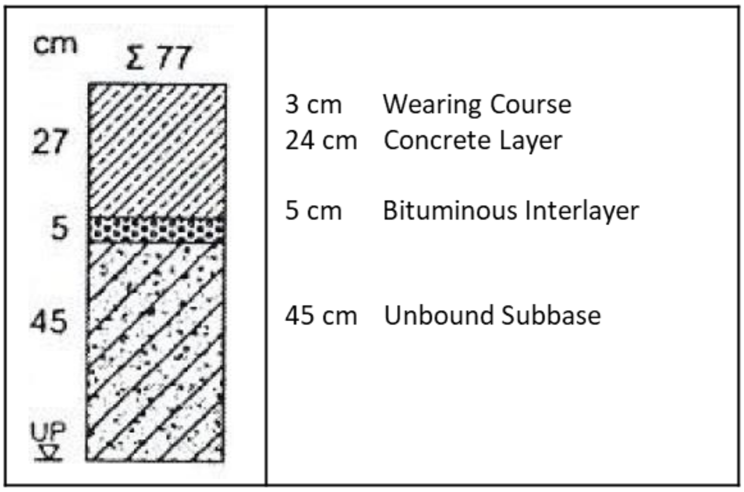


Figure 24: Concrete pavement according to RVS 03.08.63 [49]

Table 13 lists the corresponding CO_2-eq. emissions for each layer. These are again calculated by using the data from *Gschösser* [39].

Layer	Material	Thickness	t CO_2-eq. per lane-km*year
Wearing Course	**EA Concrete**	**30 mm**	**1.54**
Concrete Layer	**Bottom Concrete**	**240 mm**	**10.84**
Interlayer	**AC T 22 H**	**50 mm**	**0.89**
Unbound Subbase	**Crushed Gravel**	**450 mm**	**1.55**
Sum			**14.82**

Table 13: CO2-eq. emissions of concrete pavement

Due to the high emission potential of cement production, the emissions of concrete construction are significantly higher than those of asphalt construction.

4.2.1 Comparison of CO_2-eq. Emissions

If the CO_2-eq. emissions of the transport modes are now compared and the previously determined ratios are considered, the situation for asphalt construction is as follows:

Comparisons	**Observed Traffic Data**	**Theoretical Capacity**	**OeBB [45]**
# Railway Tracks/ # Motorway Lanes	1 : 2.6	1 : 3.6	1 : 3.0
t CO_2-eq. of Railway	13.92	13.92	13.92
t CO_2-eq. of Roadway	22.28	30.49	25.41
Ratio Rail-/Roadway	63 %	46 %	55 %

Table 14: Ratio between railway and roadway CO_2-eq. emissions

With the same transport performance, the rail mode has lower CO_2-eq. emissions than the road mode of transport with asphalt construction. In the observed case, the emissions of the rail account for only about 60 % of the emissions of the road. When considering the concrete construction method, the emission potential of rail is only about 30 % of the emissions of road. Figure 25 illustrates the calculated CO_2-eq. emissions of the modes of transport.

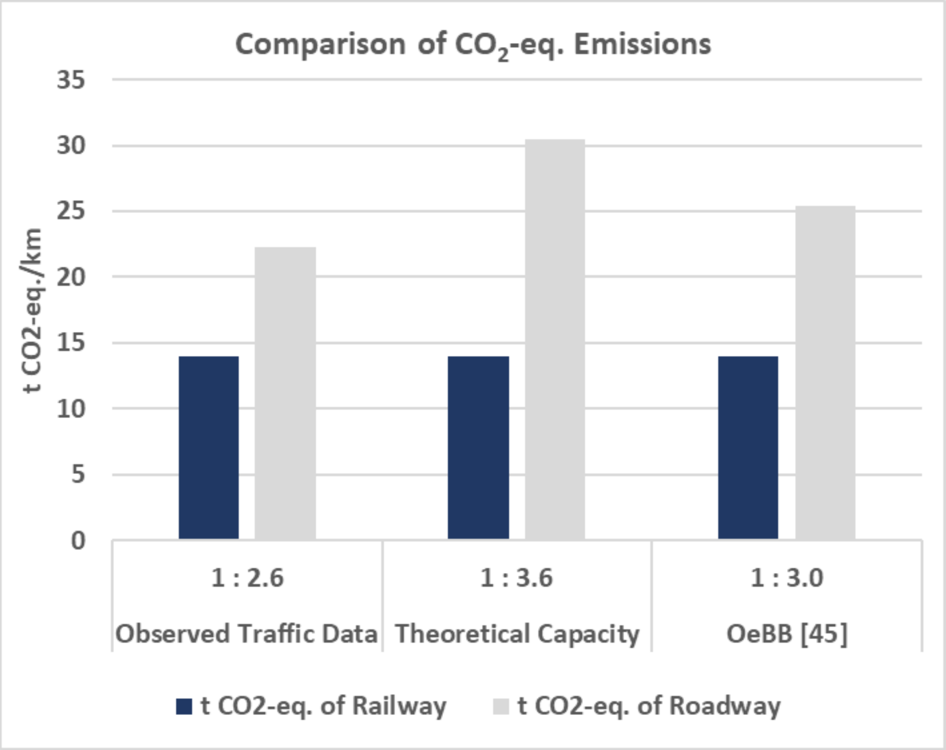


Figure 25: Calculated CO_2-eq. emissions of the modes of transport

However, due to the large number of influencing factors, the ratio between the modes of transport can fluctuate to a great extent. Such influencing factors include the occupancy or loading level of the vehicles and also the used construction materials.

4.2.2 Comparison of Land Occupancy

By using the standard cross-sections of the line sections, it is also possible to determine the land consumption via the ratios. However, this is theoretical, since it does not take into account the additional land consumption in the peripheral areas of the lines. Nonetheless, the comparison provides a good indication.

According to the standard cross-section, the maximum width of the double-track high-performance section under consideration is 14 metres. The standard cross-section of the 8-lane highway section has a width of 43.5 metres. However, the modes of transport are compared on the basis of performance, which is why a 6-lane highway is compared with a double-track section on the basis of a ratio of 1:3. The latter has a width of 37 metres. Therefore, the highway occupies 2.64 times more area than the high-performance line with the same capacity under the abovementioned boundary conditions. Figure 26 illustrates the comparison of the widths of the cross-sections.

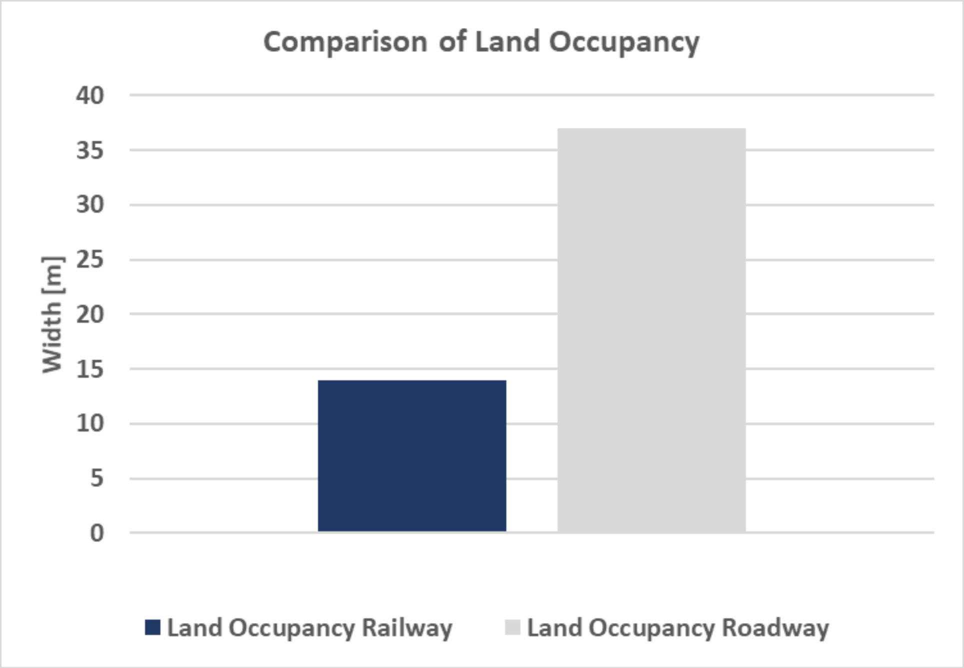


Figure 26: Comparison of land occupancy

5 Recommendations for Easier Comparisons

Findings of the literature research show that life cycle assessments of the infrastructure of different modes of transport have been carried out, but that it is difficult to compare them with each other. Different assumptions, calculation methods and other boundary conditions lead to incomparability. Furthermore, it can be said that more life cycle assessments have been carried out for the rail mode than for the road mode of transport. Most of the publications consider specific line sections in their analyses and do not provide statements on larger interconnected networks. In the rail sector, most analyses deal with high-speed lines. For studies that look at both, rail infrastructure and road infrastructure, it should be mentioned that analyses have been conducted for both modes, however, they have not been put into context with each other and no comparisons between them have been drawn. The majority of the considered publications deals solely with CO_2 emissions and do not include other impact indicators in the analysis.
Despite the fact that a large number of studies has already been carried out regarding life cycle emissions of railway lines, the results of the studies considered in this paper are difficult to reproduce and have not been produced yet in a particularly transparent manner. This circumstance complicates drawing conclusions about the emissions of infrastructure components from this data. Only if detailed information on the characteristics of the line, the applied traffic performance, the calculation method and other assumptions are available, a proper comparison between the studies can be conducted.
A comparison of the data is even more difficult if there is no information on the track type. The determination of the used superstructure type is not possible in some studies. Additionally, it is not clearly defined in every study, whether tunnels are analysed as single or double-track tunnels. In order to enable a comparison of emission data at the component level in future, some points need to be clearly defined in an LCA. These are explained in the following chapters and recommendations about their contents are given.

In theory, studies of the environmental impacts of infrastructure projects can be made more reproducible by a trivial task. This is a listing of all assumptions, circumstances and knowledge that the authors of the study have made and often take for granted.

5.1 Goal of the Study

Due to the fact that all further steps of a life cycle assessment are based on the objective, a clear definition of it is of utmost importance. The comparability of the results with outcomes of other studies depends to a significant extent on it. The definition of the objective is also strongly reflected in the choice of the functional unit of a study. A comparison between different studies can ultimately only be made between studies with the same or very similar functions. A conversion of the functional unit via transport services, as carried out in this work, requires their exact knowledge.

An important issue for the subsequent traceability of the made calculations is a description of the system considered in the study in question. This can simply be a short list with the basic data such as lengths, cross-sections and service life of the respective components. Cross-sections of the considered components should be attached for illustration. Such a description facilitates the apprehension of the analysis. Furthermore, basic characteristics of the system, such as the type of superstructure or the design and number of tracks of bridges and tunnels, should be included. In some of the studies considered in this thesis, it is not even clearly described how many tracks are taken into account.

The following statement by *Hoxha et al.* [36] also applies for the rail mode of transport.

"To guide the road infrastructure sector towards more sustainable choices, it is essential to increase the transparency and, thus, the reproducibility of the results. The ability to compare the results of different technological and material choices will enable road owners to reduce emissions throughout the lifetime of the road by providing accurate and usable information." [36]

This aspect also includes local conditions, such as the prevailing electricity mix. This in fact has a significant influence on the level of emissions. *"Energy and electrical mixes are probably the most influencing factor for the absolute value of CO2 and GHG levels of emissions, but also for their relative contributions of the processes."* [3]

Accurate knowledge of the transport service on a route is also crucial here, otherwise the results can be immensely distorted. For planned construction projects, the transport performance is an estimate and depends on the planned demand in the project area. Therefore, robust data is required for the most accurate calculation.

In some of the studies considered in this thesis, traffic performance has to be researched. For a good reproducibility of the study results, at least the sources of this data should be provided in the studies.

5.2 System Boundaries

Different LCAs concerning different modes of transport, but also those within one mode, can only be compared in a meaningful way if the system boundaries of the studies are defined in the same or at least in a similar way.

"Consistent system boundaries across all technologies or transport modes are crucial for a fair comparison between the alternatives." [33]

5.3 Life Cycle Phases

In order to achieve better comparability and better knowledge of the occurrence of emissions during the life cycle, a distinction should be made between different life cycle phases. Even if the end-of-life and planning phases are not taken into account due to a lack of data, at least the construction, operation and maintenance phases should be distinguished. A combination of life cycle phases, which can often be found in the considered studies, is not recommended. Combining these phases limits comparability.

A general division of the life cycle of a product into different life cycle phases is illustrated in Figure 27.

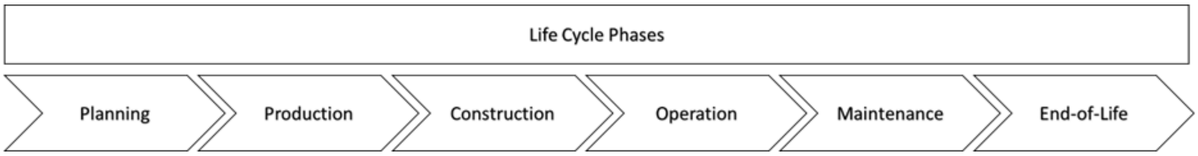


Figure 27: Life cycle phases

5.4 Considered Activities

A wide variety of processes can, of course, be taken into account in the individual life cycle phases. To ensure a high degree of transparency and reproducibility, the considered processes should be described. Figure 28 shows a simple example of such a list of the processes which are taken into consideration. Basically, such a trivial description is sufficient to depict the significant processes.

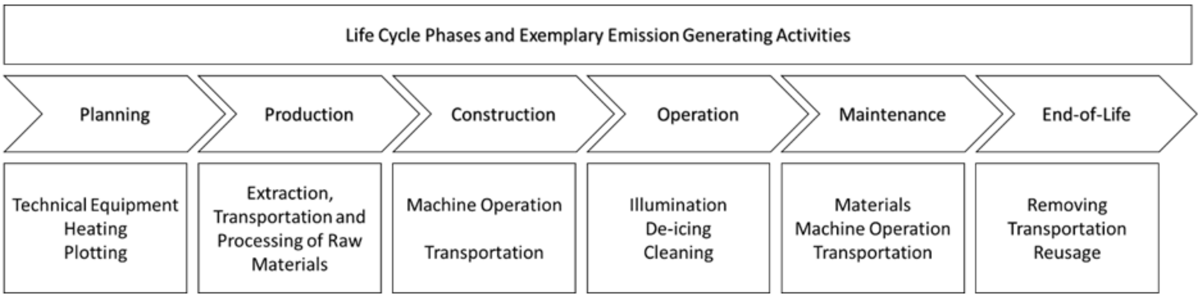


Figure 28: Life cycle phases and included processes

5.5 Service Life

Due to various circumstances, the lifetimes of components differ from case to case. This depends on the purpose of the study and leads to differentiated maintenance activities. However, the description of the components considered in the study should also include a list of the applied service lives. This is necessary to be able to argue in a comparison with other studies, or to be able to convert the data. A reasonable service life based on apparent boundary conditions has to be considered and transparently documented.

5.6 Component-based Consideration

The findings of the literature comparison clearly show that it is highly advisable to consider the various components of an infrastructure system separately and to determine their emissions separately as well. This will facilitate subsequent comparability. The best approach is a separate consideration of the individual components. If this is done in another way, it should at least be specified which elements are considered together.

Figure 29 shows the breakdown of an overall system to the processes of the individual components.

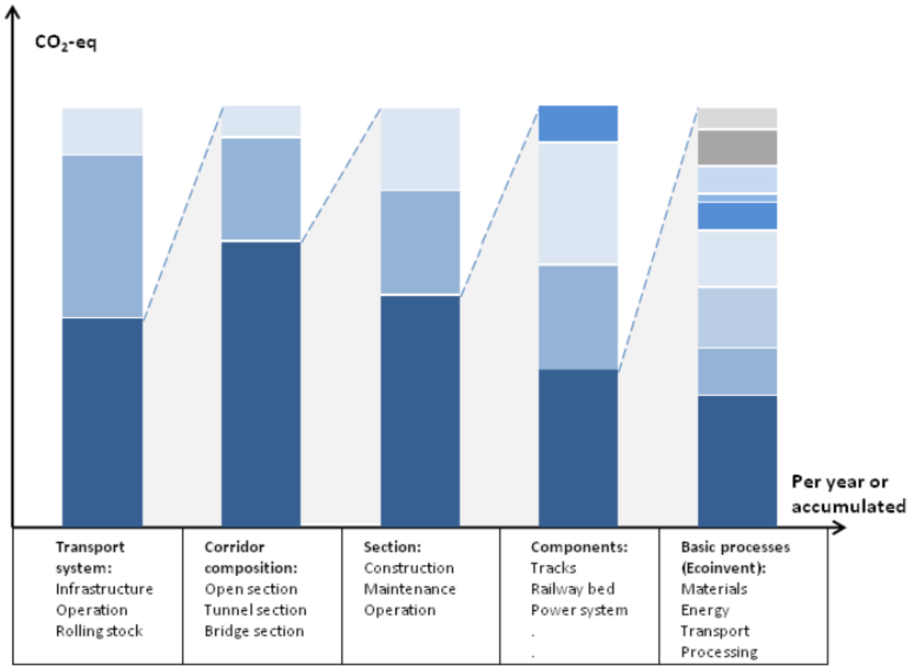


Figure 29: Component-based breakdown of transportation system [33]

5.7 Environmental Indicators

In order to better be able to weigh the environmental impacts of infrastructure systems against each other, it is reasonable to focus not only on one environmental indicator, but also to include others in the assessment. Only in this way it is possible to capture the characteristics of the system holistically. Therefore, future comparisons should also deal with other indicators, like the ones mentioned in chapter 2.2.5.

6 Summary

Life cycle assessments are used to evaluate the environmental impact of a wide range of products and systems. In the field of transport, life cycle assessments are often limited to the emissions of vehicle operation. However, in order to present a holistic picture of the emissions of a mode of transport, all other emissions arising in the life cycle must also be taken into account. This thesis deals mainly with emissions from the construction of the infrastructure.

The aim of this work is to examine existing life cycle analyses of the emissions of the infrastructure of the modes of transport, rail and road, with regard to their reproducibility and to perform a comparison of the two modes of transport on the basis of the obtained data.

An analysis of a broad variety of studies dealing with the emissions of the infrastructure of the modes of transport is carried out. In addition to insights into their characteristics and contents, data for a comparison of the modes of transport are obtained from these studies. The existing studies are prepared heterogeneously to a high extent. This makes a direct comparison of their results difficult. Furthermore, data generation from the studies is limited due to poorly communicated contents in many cases. To ensure a better comparability and reproducibility of the study results in future works, it is recommended to list all assumptions, construction methods, local conditions and background data used for the preparation of the studies. Furthermore, the different life cycle phases and components of a line should be considered separately. This is the only way to ensure that the calculated results are fully comprehensible for later comparisons.

With regard to the rail infrastructure, various lines and line networks as well as infrastructure components are compared. It can be stated that there are partly large differences between similar lines, which can be explained by the local conditions and also by the used emission data as calculation basis. Studies concerning the road infrastructure are even more diverse due to many possible construction methods, although just a few studies deal with the life cycle emissions of road pavement.

To ensure a fair comparison of the infrastructure of the road and rail modes, a transport performance-dependent comparison is carried out. For this purpose, the number of passengers and goods transported on a track or lane are first determined. Based on this data, a transport performance-dependent ratio of the number of tracks in relation to the number of lanes is determined. This ratio and the previously obtained emission data allow a comparison of the emissions of the infrastructure of the modes of transport. The superstructure of the modes of transport is compared. This comparison shows that for the same transport performance on a given section, the superstructure of the rail mode has about 40 to 55 percent lower CO_2-eq. emissions than the superstructure of the road mode of transport. The comparison of the land occupancy shows, that the highway occupies 2.64 times more land than the high-performance railway line with comparable capacity.

This work represents a further step towards a holistic comparison of the environmental impacts of the two investigated modes of transport. However, future comparisons should also include the emissions of additional life cycle phases such as end-of-life and consider different environmental indicators in order to enable a holistic comparison.

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Appendix 6: Average Net Load of a Lorry

Appendix 7: Traffic Performance of the Road Mode of Transport

Appendix 8: Determination of the Weighted Ratio of the Observed Data

Appendix 1: Content and Characteristics of the Considered Literature [12]

Analysis of Conducted Literature

No.	5	6	7	8	9	10	11	12	13	14	16	17	18	19	20	21	22	23	24	25	26	31
Literature	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[18]	[19]	[20]	[21]	[22]	[23]	[24]	[25]	[26]	[27]	[28]	[34]
Short Title	Chester, Horvath 2007	Chester, Horvath 2009	Chester, Horvath 2010	EPD - Bothnia Line 2014	Schmied, Mottschall 2010	Tuchschmid 2011	UIC (Baron) 2011	UIC 2016	Chang, Kendall 2011	Mottschall, Bergmann 2013	NTNU, Grossrieder 2011	Klambauer, 2017	Fridell et al. 2019	Yue et al. 2015	Pons et al. 2020	Westin, Kågeson 2012	Bueno et al. 2017	Lee et al. 2020	Chester, Cano 2016	Åkerman 2011	Kortazar et al. 2021	Cheng et al. 2020
Vehicle Fleet																						
- Locomotives	C,O,M	C,O,M	C,O,M	C,O,M	C,O,M	C,O,M	C,O							C,O,M					C,O,M	C,O,M	C,O,M	
- Wagons	C,O,M	C,O,M	C,O,M	C,O,M	C,O,M	C,O,M	C,O							C,O,M					C,O,M	C,M	C,O,M	
- Railcars	C,O,M	C,O,M	C,O,M	C,O,M	C,O,M	C,O,M	C,O							C,O,M					C,O,M	C,O,M		
Track System																						
- Normal Track	C,O,M	C,O,M	C,O,M	C,O,M	C,O,M	C,O,M	C,O	C,O,M	C	C, O, M	C,M	C,M,D	C,O,M	C	C,O,M, D	C,O,M	C,O,M	C	C,O,M	C,O,M	C,O,M	C
- Tunnels				C,O,M	C,O,M	C,O,M	C,O	C,O,M	C	C, O, M	C,M		C,O,M	C		C,O,M	C,O,M	C		C,O,M	C,O,M	C
- Bridges				C,O,M	C,O,M	C,O,M	C,O	C,O,M	C	C, O, M	C,M		C,O,M	C			C,O,M	C		C,O,M	C,O,M	C
- Embankments/ Cuttings				C,O,M	C,O,M	C,O,M	C,O			C, O, M			C,O,M		?C,O,M?		C,O,M	C		C,O,M	?	C
- Catenary Equipment	C,O,M	C,O,M	C,O,M	C,O,M	C,O,M	C,O,M	C,O	C,O,M	C	C, O, M	C,M		C,O,M				C,O,M	C	C,O,M	C,O,M	?	C
- Signals and Communication				C,O,M	C,O,M	C,O,M		C,O,M	C	C, O, M	C,M		C,O,M				C,O,M	C		C,O,M	?	C
- Substations	C,O,M	C,O,M	C,O,M	C,O,M	C,O,M	C,O,M	C,O	?	?	C, O, M							C,O,M	?		?C,O,M?	?	C
Other buildings																						
- Railway Stations	C,O,M			C,O,M	C,O,M	C,O,M	C,O	C,O,M		C,O,M						C,O,M	C,O,M	C	C,O,M		?	C
- Maintenance Stations				C,O,M	C,O,M	C,O,M	C,O	C,O,M		C,O,M												
- Terminals				C,O,M		C,O,M																
- Administration Buildings				C,O,M		C,O,M																
- Parkings	C,O,M	C,O,M	C,O,M	C,O,M		C,O,M													C,O,M			
Additional Information																						
- Type of Rail	HSR, HR, LR	HSR, Commuter, LR	HSR, HRT	HSR	Passenger Fright		HSR	HSR, Fright, Intercity	HSR	network of DB			Fright	HSR	HSR	HSR	HSR	HSR	Light Rail	HSR	HSR	HSR
- Impact Category	many	many	many	many	CO_2 (-eq.)	many	CO_2	CO_2	CO_2-eq.	CO_2-eq.	many	many	many		many	CO_2	CO_2	CO_2-eq.	many	CO_2-eq.	many	CF,WF,LF,MF
- Functional Unit	pmt	pmt	pmt	1 km line per year	1 km/a, pkm, tkm		1 km line per year	1 line, 1 km per year, pkt, tkm	1 km railway	pkt, tkm	1 m per year	1 km single track per year	vkt, tkm	skt, pkm	10 km of straight twin-track	pkt	pkt	1 km railway	pmt	1 km of double track	pkm, 1 km per year	1 km track, 1 ha/km
- Is the FU convertable?	No	No	No	No	Yes			No		No	No	No	Yes				Yes	No	No	Yes	Yes	No
- Are the Components seperated?	Yes	No	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes 3	Track	Rarely		No			Yes	No	Yes	No	Yes
Legend: C... Construction O... Operation M... Maintenance D... Disposal				Power, Signalling and Telecommunication addressed together	Life cycle phases Construction and Maintenance only reported together	Life cycle phases Construction and Maintenance only reported together ; Maintenance is covered by an additional share of construction materials	Service life of tunnels and bridges is equal to 100 years	Recalculation of three lines with data form other studies	No service life introduced	Life cycle phases Construction and Maintenance only reported together	Differentiation into open track, tunnels and bridges	Life cycle phases only reported together	Life Cycle Phases only reported together; Assumed emissions, primilary dealing with allocation of emissions	Different assumptions (number of tunnels, electricity mix)	End-of-Life also considered. Comparison of ballast and ballastless rail tracks. Service life is equal to 75 years.	Theoretical shift of emissions	Planned project. Only assumptions considering number of passengers and the like.	No time-horizon introduced	Time-dependent and time-independent	Modified emissions of the Bothnia Line. C+M only reported together.	Describes four lines. C+M only reported together. Addresses emissions of Tuchschmid et al.	

Appendix 2: CO$_2$-eq. Emissions of all Components of a Line

Service Life	60	factor f1: CO2-> CO2-eq:	1.04	calculated	Wikipedia [54]
		Mile -> km	1.604	UIC Statistics [53]	different service life

									Line			Track			Transport Performance				Share of ...			
No.	Short Title	Country	Details	Year	Contents	Description	Passenger	Freight	Average		Length of Line	Average		Length of Track	Passengers	Freight	Transport Pass.	Transport Freight	Tunnels	Bridges	Single/Double	T+B
	g CO$_2$-eq./pkt_tkm						**g CO2-eq./pkm**	**g CO2-eq./tkm**	**t CO2-eq./km.a**	**t CO2/km.a**	**km**	**t CO2-eq./km.a**	**t CO2/km.a**	**km**	**million pkm**	**million tkm**	**million Gtkm**	**million Gtkm**	**%**	**%**	**%**	**%**
[7]	Chester, Horvath 2007	USA	BART												2015							
	Construction					Station+Track+Power only	23.07		17.40		167				126							
	Maintenance					Track+Station	8.96		6.76													
	Chester, Horvath 2007	USA	Muni																			
	Construction					Station+Track+Power only	10.04		5.42		115				62.05							
	Maintenance					Track+Station	3.08		1.66													
	Chester, Horvath 2007	USA	Caltrain																			
	Construction					Station+Track+Power only	15.40		1.48		124.6				12							
	Maintenance					Track+Station	1.81		0.17													
	Chester, Horvath 2007	USA	Green Line																			
	Construction					Station+Track+Power only	23.07		53.66		36.4				84.68							
	Maintenance					Track+Station	16.52		38.43													
	Chester, Horvath 2007	USA	CAHSR																			
	Construction					Station+Track+Power only	0.11		0.89		1100				8728.18							
	Maintenance					Track+Station	0.001		0.01													
[10]	EPD - Bothnia Line 2014	Sweden	Nyland - Umea																			
	Construction + Maintenence + Operation					Single Track (Freight-) Line	5.6	8.2	22.67 5,55* *		190			190	343.8	506.4			13	6		19
[11]	Schmied, Mottschall 2010	Germany	DB-AG	2008	Earthworks, Track, Bridges, Tunnels, Equipment for Signals, Telecommunication and Electricity transport, Stations, Maintenance Stations	Durchschnitt D-weit																
	Construction + Maintenance						8.40	8.30	46.95		33862.3	24.80		64112.5	76929	113633.4	169137.5	246964.8				
	Schmied, Mottschall 2010	Germany	DB-AG HSR	2008		HSR																
	Construction + Maintenance						7.50		71.80		2438.2	35.90		4876.4	23332.7							
	Schmied, Mottschall 2010	Germany	PNV	2008		Average																
	Construction + Maintenance						14.8															
	Schmied, Mottschall 2010	Germany	PFV	2008		Average																
	Construction + Maintenance						8.7															
	Schmied, Mottschall 2010	Germany	GV	2008		Average																
	Construction + Maintenance						5.5															
[12]	Tuchschmid 2011	Germany		2008	Earthworks, Track, Bridges, Tunnels, Equipment for Signals, Telecommunication and Electricity transport, Stations, Maintenance Stations, Junctions																	
	Construction + Maintenance					60 Years Service Life	8.94	7.07	41.60	40.00	33855	21.94	21.1	64105	66634	114569	169137.5	246964.8	1.3	1.8	47/53	3.1
	Operation of Trains						66.46	21.84														
	Tuchschmid 2011	Switzerland		2008																		
	Construction + Maintenance					60 Years Service Life	8.84	6.97	71.76	69.00	3051	29.64	28.50	7377	16182	4181	41800	27600	5.4	1.9	44/56	7.3
	Operation of Trains						0.42	4.68														
	Tuchschmid 2011	France		2009!!																		
	Construction + Maintenance					60 Years Service Life	11.44	15.60	46.70	44.9	29901	29.22	28.1	47842	85697	26482	154484	64832	5.4	1.9	43/57	7.3
	Operation of Trains						11.65	11.44														
	Tuchschmid 2011	Italy		2008																		
	Construction + Maintenance					60 Years Service Life	12.58	16.95	53.77	51.7	16529	37.34	35.9	23835	45767	22116	?	?	8.5	3.3	56/44	11.8
	Operation of Trains						56.68	23.61														
	Tuchschmid 2011	Spain		2008																		
	Construction + Maintenance					60 Years Service Life	12.38	24.44	44.62	42.9	11801	29.33	28.2	17960	22073	10174	41546	24739	4.2	1.1	73/27	5.3
	Operation of Trains						32.55	21.74														
	Tuchschmid 2011	Norway		2008																		
	Construction + Maintenance					60 Years Service Life	21.53	18.51	32.55	31.3	4114	30.58	29.4	4374	3080	3666	?	?	6.8	1.5	94/6	8.3
	Operation of Trains						0.42	4.06														
	Tuchschmid 2011	Belgium		2008																		
	Construction + Maintenance					60 Years Service Life	6.66	5.72	38.58	37.1	3513	21.63	20.8	6283	10404	7882	26737	19408	1.3	2.2	12./88	3.5
	Operation of Trains						32.66	20.70														
	Tuchschmid 2011	Japan		2008																		
	Construction + Maintenance					60 Years Service Life	2.39	/	74.67	71.8	7527	50.23	48.3	11195	253555	22100	226488	59503	5.5	14.2	0/32	19.7
	Operation of Trains						11.96	/														
	Tuchschmid 2011	India		2008																		
	Construction + Maintenance					60 Years Service Life	1.10	2.90	37.96	36.5	63810	21.74	20.9	111599	769956	521371	524939	962769	1.3	1.8	71/29	3.1
	Operation of Trains						7.80	10.70														
[13]	UIC (Baron) 2011	France	South Europe Atlantic HSR		Conception, Earthworks, Track, Bridges, Tunnels, Equipment for Signals, Telecommunication and Electricity transport, Stations, Maintenance Stations																	
	Construction					100 Years Service Life	3.85		60.33	58.01	302	30.16	29.00	604	4674				/	6.4		6.4
	Construction					60 Years =	5.30		82.09													
	UIC (Baron) 2011	France	LGV Mediterranee HSR																			
	Construction					100 Years Service Life	4.13		70.95	68.22	250	35.48	34.11	500	3939				5.1	14.5		19.6
	Construction					60 Years =	6.34		99.96													
	UIC (Baron) 2011	China	Beijing - Tianjin HSR 1																			
	Construction					100 Years Service Life	6.2		144.56	139.00	117	72.28	69.50	234	2696				/	85		85
	Construction					60 Years =	9.4		215.68													
	UIC (Baron) 2011	Taiwan	Taipei - Kaohsiung HSR																			
	Construction					100 Years Service Life	9.26		183.58	176.52	345	91.79	88.26	690	6863				13.6	73		86.6
	Construction					60 Years =	14.14		281.36													

[15]	Chang, Kendall 2011	USA	Californian HSR		Track bed, Tunnel, Aerial Structures, Electrification, Cut fill	planned																
	Construction					60 Years Service Life	9.50		75.41		725				5752.7				6.8	8.4		15.2
						30 Years for Track bed																
						Pkm like Chester																
[18]	NTNU, Grossrieder 2011	Norway	Oslo - Trondheim HSR	2010																		
	Construction						104.74				486								14.8	2.3		17.1
[19]	Klambauer, 2017	Austria	1 km Track																			
	Construction + Maintenance + End-of-life		Concrete Sleepers without Signals, Catenary,..			C,M and EoL																
[24]	Bueno et al. 2017	Spain	Basque-Y		Conception, Earthworks, track, Viaducts, Tunnels, Equipment, Secondary Stations, Stations	planned																
	Construction + Maintenance					60 Years Service Life	102.60		251.00		180				440.6	360,9			60	10		70
[25]	Lee et al. 2020	Japan	Osong-Gwangju		Earthworks, Tunnels, Bridges, Crossings, Track, Energy/ Telecom																	
	Construction					100 Years Service Life	8.42		152.10		185.4				3349.95				24.7	40	40	64.7
						Allocation pkm like km of line																
	Construction					60 Years Service Life	12.99		234.80													
[28]	Kortazar (in Press)	Spain	Andalusia	2016	like Tuchschmid																	
	Construction + Maintenance					60 Years Service Life for all	12.59		67.440	64.846	647				3467				7.2	7.2	7.2	14.4
	Kortazar (in Press)	Spain	Northern	2016	like Tuchschmid																	
	Construction + Maintenance					60 Years Service Life for all	61.74		80.886	77.775	445				583				10.5	4.7	4.7	15.2
	Kortazar (in Press)	Spain	Catalonia	2016	like Tuchschmid																	
	Construction + Maintenance					60 Years Service Life for all	15.10		86.937	83.593	883				5083				10.8	7.5	7.5	18.3
	Kortazar (in Press)	Spain	Levante	2016	like Tuchschmid																	
	Construction + Maintenance					60 Years Service Life for all	29.21		79.260	76.212	608				1650				9.7	6.1	6.1	15.8
[34]	Cheng et al. 2020	China	Beijing - Tianjin HSR	2007	Rails, Electrics, Bridges, Subgrades, Tunnels										Baron et al.:							
	Construction					100 Years Service Life	13.36		300.18	288.63	120				2696				0.0	84		84
						No Stations - Area not described																
	Construction					60 Years Service Life	19.66		441.60	424.62												

Appendix 3: CO_2-eq. Emissions of the Tracks

Service Life of Rails, Ballast and Slee 30

factor f1= 1.04
Mile -> km 1.604
Faktor Track Land 0.5

🟦 calculated
🟥 UIC Statistics [53]
🟨 from Wikipedia [54]

0.3 assumed share of emissions of the whole system

									Line			Transport Performance				Share of ...			
	Short Title	Location	Details	Year	Contents	Description	Passenger	Freight	Average		Length of line	Passengers	Freight	Transport Pass.	Transport Freight	Tunnels	Bridges	Single/Double	T+B
	g CO_2-eq./pkt_tkm						**g CO2-eq./pkm**	**g CO2-eq./tkm**	**t CO2-eq./km.a**	**t CO2/km.a**	**km**	**million pkm**	**million tkm**	**million Gtkm**	**million Gtkm**	**%**	**%**	**%**	**%**
[7]	Chester, Horvath 2007	USA	BART		Track+Power Construction							2015							
	Construction	BART				Track 25 Years Concrete 50 Years Ballast 25 Years	9.98		7.53		167	126							
	Chester, Horvath 2007	USA	Muni																
	Construction	Muni				Track 25 Years Concrete 50 Years Ballast 25 Years	9.35		5.05		115	62.05							
	Chester, Horvath 2007	USA	Caltrain																
	Construction	Caltrain				Track 25 Years Concrete 50 Years Ballast 25 Years	13.72		1.32		124.6	12							
	Chester, Horvath 2007	USA	Green Line																
	Construction	Green Line				Track 25 Years Concrete 50 Years Ballast 25 Years	8.10		18.85		36.4	84.68							
	Chester, Horvath 2007	USA	CAHSR	2005															
	Construction Maintenance	CAHSR				Track 25 Years Concrete 50 Years Ballast 25 Years	0.11		0.89		1100	8728.18							
[10]	EPD - Bothnia Line 2014	Sweden	Nyland - Umea		Track														
	Construction	Nyland - Umea				Single Track (Freight-) Line 30 Years Service Life Concrete Sleepers	2.49	2.88	12.18		190	343.8	506.4	653.22	1114.08	13	6		19
[11]	Schmied, Mottschall 2010	Germany	DB-AG HSR	2008	Track	HGS													
	Construction + Maintenance	DB-AG HSR				Rails 30 Years Sleepers 30-35 Years Ballast 15 Years	3.13		30.00		2438.2	23332.7							
[13]	UIC (Baron) 2011	France	South Europe Atlantic HSR		Rail	30 Years Service Life													
	Construction	South Europe Atlantic HSR				Concrete Sleepers 30 ballast 25	1.532		23.71	22.80	302	4674				/	6.4		6.4
	UIC (Baron) 2011	France	LGV Mediterranee HSR			30 Years Service Life													
	Construction	LGV Mediterranee HSR				Concrete Sleepers	1.505		23.71	22.80	250	3939				5.1	14.5		19.6
	UIC (Baron) 2011	China	Beijing - Tianjin HSR			30 Years Service Life													
	Construction	Beijing - Tianjin HSR				Balastless	1.426		32.86	31.60	117	2696				/	85		85
	UIC (Baron) 2011	Taiwan	Taipei - Kaohsiung HSR			30 Years Service Life													
	Construction	Taipei - Kaohsiung HSR				Balastless	1.652		32.86	31.60	345	6863				13.6	73		86.6

Service Life of Rails, Ballast and Slee 30

factor f1= 1.04
Mile -> km 1.604
Faktor Track Land 0.5

🟦 calculated
🟧 UIC Statistics [53]
🟨 from Wikipedia [54]

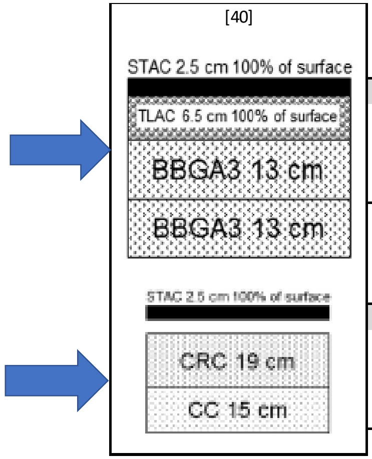
0.3 assumed share of emissions of the whole system

	Short Title	Location	Details	Year	Contents	Description	Passenger	Freight	Line			Transport Performance				Share of ...			
									Average		Length of line	Passengers	Freight	Transport Pass.	Transport Freight	Tunnels	Bridges	Single/Double	T+B
	g CO_2-eq./pkt_tkm						**g CO2-eq./pkm**	**g CO2-eq./tkm**	**t CO2-eq./km.a**	**t CO2/km.a**	**km**	**million pkm**	**million tkm**	**million Gtkm**	**million Gtkm**	**%**	**%**	**%**	**%**
[15]	Chang, Kendall 2011 Construction	USA Californian HSR	Californian HSR		Track bed	planned Rheda 2000	5.04		39.96		725	like Chester 5752.7				6.8	8.4		15.2
[19]	Klambauer, 2017 Construction + Maintanence + End-of Life	Austria 1 km Track	1 km Track Concrete Sleepers without Signals, Catenary,..			Concrete	4.57	1.95	2017 20.81		2019 4827	2019 11606	24286	32295.5	28915.5				
[24]	Bueno et al. 2017 Construction + Maintenance	Spain Basque-Y	Basque-Y		Track	planned 60 Years Service Life Ballastless Replacement after 30 years	12.91		31.60		180	440.6	360,9			60	10		70
[25]	Lee et al. 2020 Honam Line Construction	Japan Osong-Gwangju	Osong-Gwangju		Tracks	30 Years Service Life Allocation pkm like km of line Ballastless	2.89		52.17		185.4	3349.95				24.7	40	40	64.7
[27]	Åkerman 2011 Construction + Maintenance	Sweden Europabanan	Europabanan		Track without foundation	planned 60 Years Service Life undefined kind of sleepers Replacement after 30 years			30.00	28.85	730								
[28]	Kortazar (in Press) Construction + Maintenance	Spain Andalusia	Andalusia	2016	Rail	planned 60 Years Service Life Assumption 30% undefined kind of sleepers	3.68		19.73	19.45	647	3467				7.2	7.2	7.2	14.4
	Kortazar (in Press) Construction + Maintenance	Spain Northern	Northern	2016		planned 60 Years Service Life undefined kind of sleepers	18.06		23.66	23.33	445	583				10.5	4.7	4.7	15.2
	Kortazar (in Press) Construction + Maintenance	Spain Catalonia	Catalonia	2016		planned 60 Years Service Life undefined kind of sleepers	4.42		25.43	25.08	883	5083				10.8	7.5	7.5	18.3
	Kortazar (in Press) Construction + Maintenance	Spain Levante	Levante	2016		planned 60 Years Service Life undefined kind of sleepers	8.54		23.18	22.86	608	1650				9.7	6.1	6.1	15.8
[34]	Cheng et al. 2020 Construction	China Beijing - Tianjin HSR	Beijing - Tianjin HSR	2007 2014	Rails	60 Years Service Life Replacement after 30 years Ballastless	3.57		80.094	77.01	120	Baron et al.: 2696				0.0	84		84

Appendix 4: Recalculation of Jullien’s [40] Layer Composition with Gschösser’s [39] Data

Gschösser [39]	Material	Thickness [cm]	GWP/p	GWP/lane*km*year	GWP/cm*lane*km*year
Wearing Course	AC MR 8 ASTRA	3.0	1103	0.92	3.06
Base Course	AC B 22 H	7.0	1879	1.57	2.2369
Road Base	AC T 22 H	8.0	1703	1.42	1.77
Subbase					

Gschösser [39]	Material	Thickness [cm]	GWP/p	GWP/lane*km*year	GWP/cm.lane.km.a
Wearing Course	AC MR 8 ASTRA	3.0	1103	0.92	3.06
Base Course	EA Concrete	5.0	3077	2.56	5.13
Road Base	Bottom Concrete	190	10301	8.58	0.45



	Material	Thickness	GWP/lane*km*yea	**Jullien et al. [40]**
Wearing Course	STAC	2.5	0.77	
Base Course	TLAC	6.5	1.45	
Road Base	BBGA3	26	4.61	
		Sum	6.83	3.50

	Material	Thickness	GWP/lane*km*yea	**Jullien et al. [40]**
Wearing Course	STAC	2.5	0.77	
Base Course	CRC	19	9.74	
Road Base	CC	15	0.68	
		Sum	11.19	12.50

Appendix 5: Traffic Performance of the Rail Mode of Transport

Linz Hbf - Wels at Hörsching	**#Tracks**
BA51019111	2

Passenger

SysFzg		# seats	Occupancy	# SysFzg	# Passengers
F9	4010	523	80%	1027	429697
F10	4110	323	80%	14	3618
F11	4011_ICE_T	369	80%	224	66125
F12	4020	184	80%	0	0
F13	4024_Talent, 4124, 1425	199	80%	929	147897
F14	4746_CityJet, 4744	244	80%	928	181146
F15	5022_Desiro	117	80%	130	12168
F16	5047	124	80%	193	19146
F17	RailJet_Wagen	60	80%	20209	970032
F18	RIC_Wagen	80	80%	6001	384064
F25	NahverkehrsDOSTO	110	80%	87	7656
F26	4023_Talent	151	80%	71	8577
F27	4758_Talent3	151	80%	4	483

Passenger/month	2230607
Passenger/track*month	**1115304**

Freight

SysFzg		# axles	weight [t]	weight_wagon [t]	# SysFzg	net weight [t]
F19	2achs_GW_AL8.11t	2	8.11	16.0	1580	348
F20	2achs_GW_AL13.71t	2	13.71	16.0	397	4534
F21	2achs_GW_AL20.32t	2	20.32	16.0	733	18061
F22	4achs_GW_Y25_AL6.4t	4	6.4	16.0	16033	153917
F23	4achs_GW_Y25_AL14.16t	4	14.16	16.0	5822	236606
F24	4achs_GW_Y25_AL20.32t	4	20.32	16.0	15644	1021240
	unknown				11852	430412

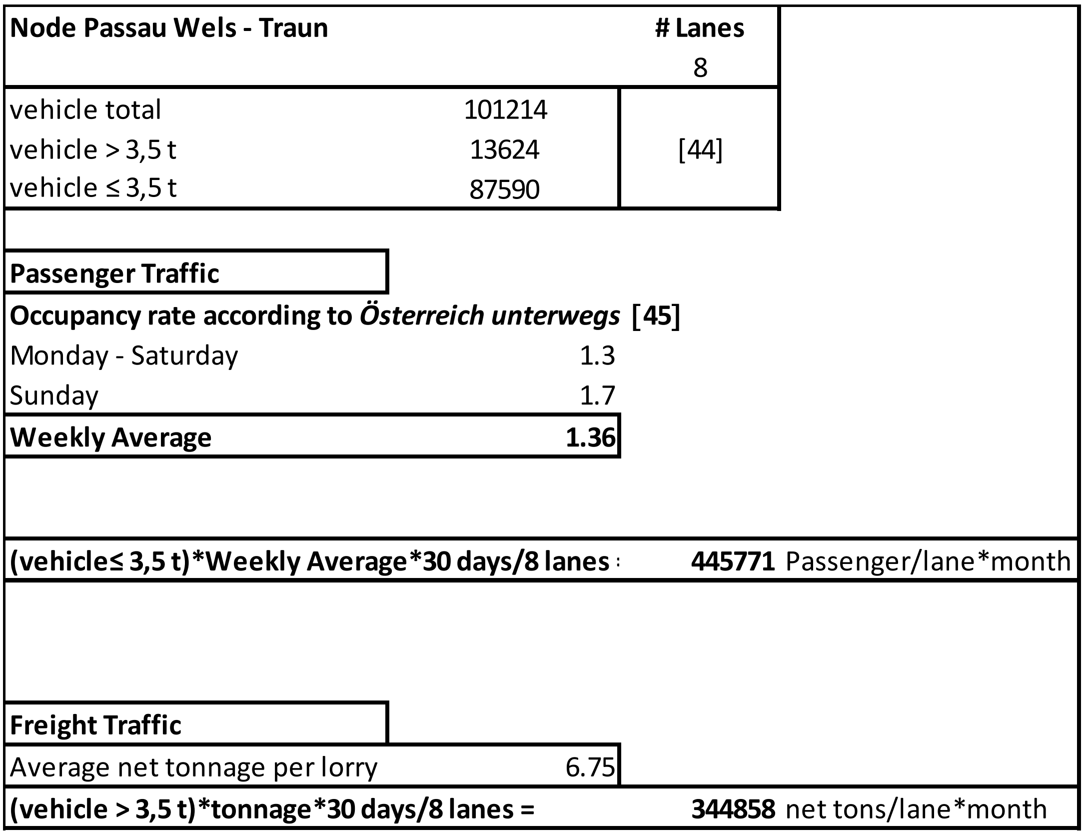
net tons/month	1865117
net tons/track*month	932559

Appendix 6: Average Net Load of a Lorry

Vehicles > 3.5 t	Max. Weight	Load Capacity	Capacity utilisation	Average Load	Weighting
Truck + Trailer	40	27	20.25	15.19	20%
Standard Truck	25	12	9	6.75	50%
Small Truck	7.5	2	1.5	1.13	30%
			Weighted Sum	6.75	net tons

Utilisation	75%	[46]
Empty Runs	25%	

Appendix 7: Traffic Performance of the Road Mode of Transport



Node Passau Wels - Traun			**# Lanes**	
			8	
vehicle total	101214		[44]	
vehicle > 3,5 t	13624			
vehicle ≤ 3,5 t	87590			
Passenger Traffic				
Occupancy rate according to *Österreich unterwegs*			**[45]**	
Monday - Saturday		1.3		
Sunday		1.7		
Weekly Average		**1.36**		
(vehicle≤ 3,5 t)*Weekly Average*30 days/8 lanes			**445771**	Passenger/lane*month
Freight Traffic				
Average net tonnage per lorry		6.75		
(vehicle > 3,5 t)*tonnage*30 days/8 lanes =			**344858**	net tons/lane*month

Appendix 8: Determination of the Weighted Ratio of the Observed Data

Calculation of Ratios

Passenger Traffic		
Rail	**1115304**	Passenger/track*month
Road	**445771**	Passenger/lane*month
Ratio_P = $\frac{Passenger/track * month}{Passenger/lane * month} =$		2.50
Ratio_P =	**1:2.5**	**(#tracks : #lanes)**

Freight Traffic		
Rail	**932559**	net tons/track*month
Road	**344858**	net tons/lane*month
Ratio_F = $\frac{net\ tons/track * month}{net\ tons/lane * month} =$		2.70
Ratio_F =	**1:2.7**	**(#tracks : #lanes)**

Weighted Ratio = $\frac{Ratio\_P * \#Vehicle_{Passenger} + Ratio\_F * \#VehicleFreight}{\#Vehicle_{Passenger} + \#Vehicle_{\ Freight}}$

Weighted Ratio = 2.6

Weighted Ratio =	**1:2.6**	**(#tracks : #lanes)**

WISSEN ▪ TECHNIK ▪ LEIDENSCHAFT

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