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Katharina Weber, Muhammad Usman Zahid and Maximilian Zangl were students in the Master of Arts program of the Department of Public Policy at Central European University during the 2020-2021 Academic Year. Mario Holzner is Executive Director at The Vienna Institute for International Economic Studies (wiiw).

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# Executive summary

In a study published in 2018 the Vienna Institute for International Economic Studies (wiiw) proposed the construction of a 'European Silk Road' encompassing a high-speed railway (HSR) network for Europe. To compliment the economic feasibility analysis by wiiw, this report aims to determine the environmental impact of the suggested northern core route – from Lyon to Moscow – by focussing on the net greenhouse-gas emissions, in $CO_2$-eq.. The study uses a life cycle assessment (LCA) for the analysis of construction, maintenance, operation, and disposal of the HSR, to provide an estimate of how many tons of $CO_2$-eq. can be saved over the span of 60 years. In generating a modal shift from road and air transport, the construction of an HSR line provides the potential for saving up to 10% of net $CO_2$-eq. emissions in the EU27 for one year. Thus, the proposed high-speed line contributes to the current targets and goals of the European Union to reduce emissions and present smart, sustainable and inclusive economic solutions.

Keywords: Infrastructure, Transport, High Speed Rail, Environmental Effects

JEL classification: H54, R42, L92, Q51

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# 1. Introduction

The EU aims to be climate neutral by 2050, which includes the goal of a 90% reduction in greenhouse gas emissions from transport (EC, 2019). The transport sector alone accounts for around 24% of global carbon ($CO_2$) emissions and consumes more than half of the global demand for fossil fuels (IEA, 2019). The UN's Agenda 2030 specifically states that "more freight should be transported by rail" (EC, 2019). In a study published in 2018 proposing the construction of a European Silk Road, the Vienna Institute for International Economic Studies (wiiw) provided a possible solution for this envisioned shift to rail, suggesting inter alia a high-speed rail network along the envisaged routes. It would extend around 11,000 kilometres on a northern route from Lisbon to Uralsk on the Russian-Kazakh border, and on a southern route from Milan to Volgograd and Baku, also including other modes of transport and a string of logistic centres and ports. A central part is the route from Lyon to Moscow (Figure 1).

**Figure 1 / European Silk Road Routes including the proposed trainline from Lyon to Moscow**


The report by the wiiw focusses on the economic effects and advantages of a European Silk Road. In Europe, connecting the West with the East will generate growth and employment in the short and long-term. Conservative estimates foresee a potential of 3.5% economic growth on average as well as an increase in employment of around two million over an investment period of 10 years, due to the construction efforts in the countries concerned (Holzner et al., 2018). Under favourable circumstances and at continued low interest rates, over 7 million jobs can be expected to be created in greater Europe. Furthermore, such large-scale investment in infrastructure projects can reduce economic disparities in various regions and create long term gains in productivity and trade. Not only can this type of investment remove economic divergence but it can also create a move towards political integration, offering a new narrative for Europe. This is specifically important in the context of the persisting inequalities between west and east European countries, as well as the European disintegration process, that has culminated for the time being with Brexit.

In a separate note, wiiw suggested a specific, extra-budgetary financing model for the European Silk Road, which was estimated to cost in total about one trillion euros, or roughly 7% of the EU's GDP (Holzner, 2019). In order to conduct and finance the project, wiiw suggested establishing a European Silk Road Trust owned by the euro area countries, other EU countries and third countries that wish to join in the construction of the European Silk Road. The trust could rely on a public guarantee when it comes to issuing long-term bonds (at currently zero or even negative real interest rates). It would formally be part of the private sector, especially as it would have sufficient income of its own from private customers (tolls). As a strong core guarantor of the Trust, the gradual development of a European Sovereign Wealth Fund by euro area member states was suggested, following the structure of the Norwegian oil fund, sourced e.g. from part of the profits of the ECB. Other options which would make use of existing institutions would include for instance a substantial increase in the European Fund for Strategic Investment and/or a larger capital injection in the European Investment Bank (EIB) in order to finance the European Silk Road.

Recently, the proposal by the wiiw has gained significance as the idea of a European high-speed railway (HSR) network is also being considered as a mechanism for economic recovery after the Covid-19 pandemic. The Macroeconomic Policy Institute (IMK) in Düsseldorf, the Observatoire Français des Conjonctures Économiques (OFCE) in Paris and the wiiw have jointly proposed dedicating a part of the EU's Recovery Fund *inter alia* to the development of a pan-European HSR network – an Ultra-Rapid-Train connecting EU capitals (Creel et al., 2020). Apart from the economic recovery, an HSR network could also be an important step towards achieving the announced goal of reducing greenhouse-gas (GHG) emissions of the Paris agreements and the Agenda 2030. Furthermore, this infrastructure project could be a major milestone in the process of attaining the United Nation's Sustainable Development Goals. It targets sustainable communities, infrastructure, climate action and economic growth. While the economic analysis as well as the financing of the project have been studied comprehensively in wiiw reports, the environmental effects of constructing a European Silk Road, specifically the HSR network, have not been examined so far. This study closes that gap by conducting an environmental impact evaluation of the proposed European HSR network. The goal is to determine the net GHG emissions of constructing and operating an HSR network and to provide an estimate of how many tons of $CO_2$ could be saved as compared to road and air travel, over the life cycle of 60 years. The analysis will focus only on the proposed northern core HSR line from Lyon to Moscow, the cost of which was estimated at 200.4 billion euros.

# 2. Literature review

Many studies focus on the Life Cycle Assessment (LCA) of railways but are very specific to already existing train line infrastructure. While these studies give good insight into how to assess the $CO_2$ or $CO_2$ -eq. of already existing infrastructure, the study at hand has been conducted for a hypothetical line from Lyon to Moscow, rather than an existing project. The aim of the literature review was therefore to find reliable data as a baseline for building our model.

Generally, an LCA is defined as an analysis that evaluates the environmental impact of a product. In our case this is the entire lifecycle of an HSR line. Input factors are compared and quantified and contain construction, operation, maintenance, and waste disposal over a period of 60-100 years. The output is the total burden the line will impose on the environment, measured in $CO_2$ or rather $CO_2$-eq. (Asplan Viak, 2011).

LCAs are standardised under the International Organization of Standardization (ISO). The ISO requires adherence to certain norms to enable comparison and quantification of different studies. Specifically these are ISO 14040 and ISO 14044, which prescribe the following structure: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices as well as optional elements (ISO 1440:2006). LCIs are usually provided by the project conductors, in Germany for example Deutsche Bahn, or they are delivered by service platforms. The leading platform is Ecoinvent, which supplies data for any kind of material used as an input. Ecoinvent is widely used in LCAs and enables researchers to access data on anything from energy or water supply to building material and disposal management. However, the line for our study is in the conception phase and therefore no primary data points are available to feed into these tools. All the above-mentioned guidelines help quantify LCAs and make them comparable. Hence, results provided by current LCA studies on railway infrastructure allow accurate data on which to base our study.

Despite the comparability through the framework of the ISO standards, a review of the literature revealed significant differences in results. In the following, an overview is provided of the different methods used by the studies as well as the different circumstances. Regional differences turned out to be one of the key factors determining results. Therefore, the literature review is structured by region, starting with assessments conducted within Europe and moving on to studies in North America and Asia.

Von Rozycki et al. (2003) were one of the first to attempt an LCA for an HSR network in Germany. The study was conducted in cooperation with Deutsche Bahn (DB) and the Martin-Luther University Halle-Wittenberg. The method used is the main process elements (MPE) or process-based approach. MPE is performed by mapping all processes associated with all life cycle phases of the project. Inputs (e.g., electricity, steel) and outputs (e.g., air emissions, water discharges) associated with each process are included, enabling the total environmental load to be calculated (Jones et al., 2016). Most studies incorporate this form of analysis.

A different approach was demonstrated by Åkermann (2011), who uses a simplified method for the LCA combined with assumptions for energy mix and passenger occupancy, for the Europabanan line in Sweden. Data for the LCA itself is mostly used from the Bothnia Line. The comparison between the Europabanan and Bothnia line works because both lines are in Sweden and demonstrate similarities in production, construction, and terrain. Due to a better energy mix and construction practices, Sweden has one of the lowest $CO_2$-eq. for construction in the EU and acts as a good example for emission targets (UIC, 2017). While the author provides a robust and simplified framework, there are no passenger km measurements (pkm). Pkm is an immensely important measurement for comparability in LCA studies. Passenger kilometres are calculated as the total weighted travel distance in kilometres made by all persons within the reference population in a reference year (Eurostat, 2018).

Another LCA conducted in Scandinavia is a Norwegian study examining the line from Oslo to Trondheim. The author uses the software SimaPro, providing an accurate main process element approach that covers all the rules and regulations set by the ISO. Grossrieder (2011) however, does not focus on comparison with other means of transportation but on core output factors and development over 60 years for Norway. Due to the terrain in Norway, construction usually includes high numbers of tunnels which emit high amounts of emissions. A study by Asplan Viak (2011) sheds more light on this. The environmental engineering company conducted an LCA on the Follo line of which over 90% consists of tunnels. Their research showed that tunnels and bridges are the main sources of pollution in the construction phase. The Asplan Viak assessment is an extreme outlier and will not be considered for our case.

The next two studies taken into consideration contribute the most important and comparable data. Kortazar et al. (2021) and Jones et al. (2016), albeit using slightly different methodologies, provide the newest and most accurate assessments. Kortazar et al. acknowledge and incorporate previous studies but see a lack of focus on the environmental burden of the construction of the infrastructure. Their study was conducted in Spain, which has the second longest HSR network in the world. They established a baseline scenario which they test against different conditions. The calculation of it is very close to our testing model. The total environmental burden measured in kg $CO_2$-eq./pkm can be offset with a certain threshold of passengers. Kortazar et al. (2021) conclude that the main factor for lowering $CO_2$-eq emissions is the density of passenger and freight transport. Jones et al. (2016) on the other hand contribute with a case study for Portugal, combining a process based on an economic input output approach (EIO-LCA). The study gives an overview of average emissions from HSR in kg$CO_2$-eq./pkm for different countries and for Europe as a whole.

To continue, we review studies outside the European Union. Chester and Horvath (2012) examined the LCA of a potential HSR line in California. They used current railway data to integrate a process-based approach. Interestingly, the authors decided to implement a different passenger flow model. They concluded different scenarios for train occupancy instead of determining an average for the line, because they argue that relying on an average misleads the output. To prevent this, we have implemented different scenarios for passenger flows in a similar manner for the purpose of this research. The study also demonstrates that the energy mix used to run an HSR network is an important factor because a suboptimal energy mix could potentially negate $CO_2$ savings (Chester and Horvath, 2010). Barnes (2014) adds to Chester and Horvath (2010) by further analysing specific factors that increase GHG emissions during construction. The two main processes that lead to the increase are the concrete mix and elevating the level of the track in certain parts of the line.

Yue et al. (2015) examined the Beijing-Shanghai line. They provide the highest emission factors by far, although they excluded infrastructure maintenance, operation and disposal due to lack of data. High emissions mainly result from the usage of heavy-weight metals and the lack of reduction of fly ash in concrete, which is used as a hardener but is very harmful for the environment (Yue et al., 2015; Barnes, 2014). Additionally, China’s energy mix contributes to high emission factors. The authors call for a cleaner and more sustainable energy mix. They argue that shifting the energy mix to renewable energy could have the biggest environmental impact. Nonetheless, the authors were able to establish a baseline scenario and test it against different occupancy levels, infrastructure compositions and energy mixes. This makes their model flexible and provides a bandwidth of results for different situations.

In summary, the literature review shows that despite standardisation through regulations and tools available for producing LCAs, the outcomes of the examined studies differ. Decisive factors for the differences are mostly geographical location, including the share of bridges and tunnels, materials used for construction and different energy mixes among the different countries. To use reliable data for our calculations, we consider twelve studies to incorporate into our model. This will ensure a balanced approach and a realistic estimation of the range of possible outcomes.

# 3. Methodology

While HSR infrastructure already exists in some parts of the route and other networks would need updating, the analysis builds on the assumption that the entire Lyon-Moscow route of 3434 km would need to be constructed. This implies that our results for $CO_2$-eq. emission savings are per definition lower-bound estimates. It is not differentiated for the various greenhouse-gases, but rather all GHG emissions are expressed as $CO_2$-equivalent.

Drawing on the literature, our study has been developed based on an LCA methodology. We calculate the net $CO_2$-eq. emissions of the proposed HSR line from Lyon to Moscow considering the phases of construction, maintenance, operation, and disposal. While the construction of new HSR infrastructure will create new $CO_2$-eq. the environmental benefit lies in the modal shift of passengers from more polluting modes of transport such as air and road travel (Kortazar et al., 2021). Mathematically this can be represented as

$$NetCO_2eq. = \sum CO_2eq._{HSRConstruction} + \sum CO_2eq._{HSROperation} - \sum CO_2eq._{aToHSR} \quad [1]$$

where $a$ denotes the alternative passenger modes of transport to the HSR and the emissions are summed over 60 years.

Simplifying the second term of the equation provides:

$$NetCO_2eq. = \sum CO_2eq._{HSRConstruction} - \sum CO_2eq._{Avoided} \quad [2]$$

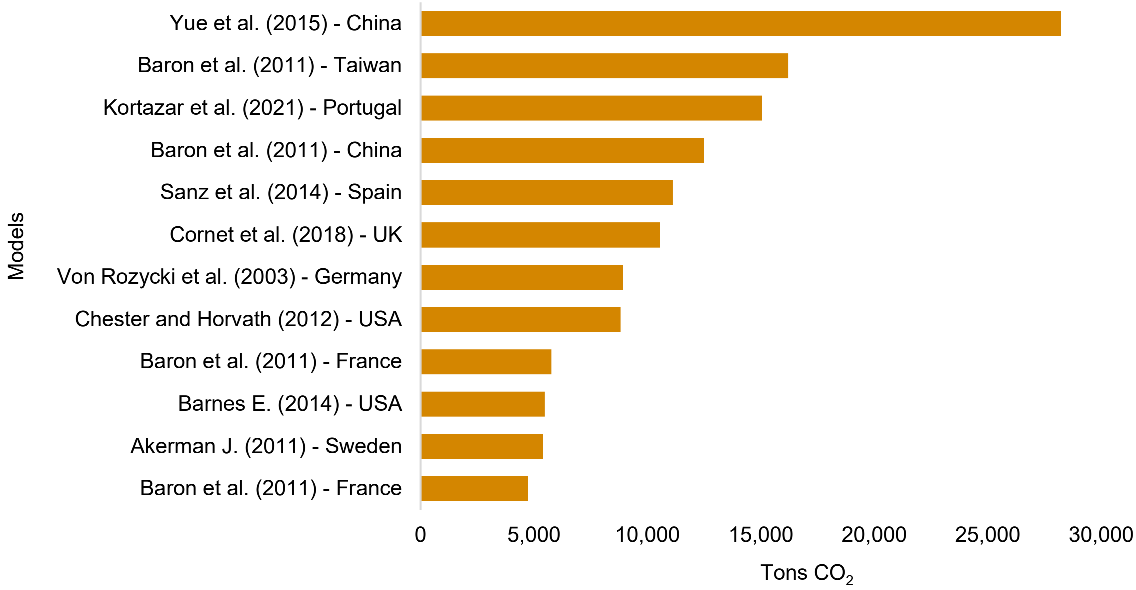
The following analysis takes a two-step approach according to the two parts of this equation. First, the life cycle emissions from HSR infrastructure are estimated. Second, avoided $CO_2$-eq. emissions compared to aviation and road transport are calculated. This provides an indication of how much $CO_2$-eq. could be saved if an HSR network were constructed.

## 3.1. EMISSIONS FROM CONSTRUCTION

The emissions for constructing 3434 km of line are estimated according to emission factors deduced from the existing life cycle assessment studies for railway infrastructure. Hence, the emission factor includes all inputs for the construction of rails, maintenance, operation and disposal of the infrastructure. Some studies also include vehicle manufacturing, maintenance, operation and disposal (Akerman, 2011; Chester and Horvath, 2010; Yue et al., 2015).

The $CO_2$-eq. emissions per kilometre of constructed railway vary widely among the different studies (Figure 2). This is for two reasons. First, as explained above, some LCA include more input factors than others. Second, the complexity of construction varies widely among different studies. Bridges and tunnels account for the highest emissions during construction (Asplan Viak, 2011). As the number of bridges and tunnels range from under 30% to over 80%, these differences lead to emission factors ranging from 4,735 $tCO_2$ /km (Baron et al., 2011) to 28,224.6 $tCO_2$ /km (Yue et al., 2015) (Figure 2). For the train line from Lyon to Moscow the number of bridges and tunnels required can hardly be estimated within the scope of this study. The analysis therefore covers three models: an optimistic, moderate and conservative model. The moderate approach uses the mean of the available data on railway construction emission factors. The optimistic and conservative approaches rely on values of one standard deviation from the mean, covering the upper and lower bounds of available data. Table 4 in Appendix 1.1 shows an overview of the different emission factors of construction in the examined studies.

**Figure 2 / Construction emission models, $tCO_2$/km**




Source: based on Bueno et al. 2017

## 3.2. AVOIDED GHG EMISSIONS

To estimate avoided $CO_2$-eq. emissions the modal shift from aviation to train as well as road to train are determined. This is calculated as:

$$CO_2eq._{Avoided} = \sum_{Aviation} CO_2eq._{AviationToHSR} + \sum_{Road} CO_2eq._{RoadToHSR} \quad [3]$$

The avoided $CO_2$-eq. depends on three factors: One, the difference between the emission factors for operation of the mode of transport expressed in tons per passenger kilometre (pkm); two, the number of passengers shifting to train as a mode of transport; and three, the average distance travelled by passengers. Multiplying those three aspects will provide the sum of avoided GHG due to modal shifts over 60 years. Mathematically expressed this means:

$$\sum_{Aviation} CO_2eq._{AviationToHSR} = \Delta CO_2eq._{Aviation/HSR} \times \; pax\ shifted \; \times \; \begin{matrix} distance \\ travelled \end{matrix} \quad [4]$$

### 3.2.1. Difference in emission factors

Emission factors for operating the different modes of transport are relatively consistent across studies and the literature. Trains have the lowest $CO_2$ emissions per passenger kilometre with a European average emission factor of 0.027 kg$CO_2$ /pkm (Jones et al. 2016). Travelling by plane produces 4.5 times the emissions per passenger kilometre, with an emission factor of 0.126 kg$CO_2$ /pkm (Fraunhofer ISI 2020). Passenger cars travelling on the highway emit 0.132 kg$CO_2$/pkm (Fraunhofer ISI 2020). Consequently, for every passenger shifting from aviation to train 0.099 kg$CO_2$ /pkm can be avoided and for every passenger shifting from road to train 0.105 kg$CO_2$ /pkm can be saved.

### 3.2.2. Passenger shift from road and air travel

The success of new HSR infrastructure will greatly depend on how many people will use it as a means of transport. Only if enough passengers substitute their current mode of transport with travelling by train, can the emissions from construction be offset. If the passenger number using the new train line is too low, construction emissions will not be offset. Therefore, estimating expected passenger flows is one of the most important aspects in determining the environmental impact of the proposed HSR network. Estimates are based on current passenger flows of which a certain share is expected to shift.

The chosen data is based on values from the year 2019, as the Covid-19 pandemic has significantly impacted passenger flows between countries and thus data from 2020 is not representative. The number of passengers by air could be determined by passengers travelling between airports and reporting countries along the proposed route from Lyon to Moscow. A detailed list of included airports and assumptions concerning passenger flows can be found in Appendix 1.2. In 2019, total passenger flows on this route amounted to 93.5 million.

The number of passengers by road is estimated according to the average traffic flow on the nine core network corridors of the Trans-European Road Network (CEDR, 2019). This amounted to 58,952 vehicles per day in 2019. Assuming an occupancy rate of 1.6 for cars (Fraunhofer ISI 2020) we can estimate 34.4 million passengers using the corridor from Lyon to Moscow within one year. Using these passenger flows as a baseline, an annual growth rate of 2% for aviation and a growth rate of 0.75% for road travel is assumed (Eurocontrol, 2018; Alonso Raposo et al., 2019).

To determine a substitution rate, there are several factors that need to be considered within the emissions calculations. The main factors determining the choice of travel are price, travel time, travel time reliability, frequency of connections and other factors such as convenience, comfort, and safety (EEA, 2020c). Several studies have shown that trains can substitute aviation transport for a travel time of up to four hours (ÖBB, 2021). With an average velocity of 250km/h for HSR (EIM, 2008) this means that the train would be a good substitute for routes of up to 1000 km. Substitution rates range from 10% up to 90% (Steer Davies Gleave, 2006) depending on the line length, and availability of other means of transport within origin and destinations, which makes it difficult to predict an accurate rate. The study therefore looks at three possible scenarios; these are based on the study on the California HSR by Chester and Horvath (2010). For air travel a shift of 25%, 50% and 75% of passengers to railway is assumed, and for road transport a shift of 2%, 2.25% and 2.5% of passengers is assumed. Taking the three models from construction together with these three models provides nine models which are explored (Table 1).

**Table 1 / Conceptual Depiction of Emissions Models**

| | Construction Models | | |
|---|---|---|---|
| **Passenger Shift Models** | Conservative (C) | Medium (M) | Optimistic (O) |
| Conservative (C) | C/C | C/M | C/O |
| Medium (M) | M/C | M/M | M/O |
| Optimistic (O) | O/C | O/M | O/O |

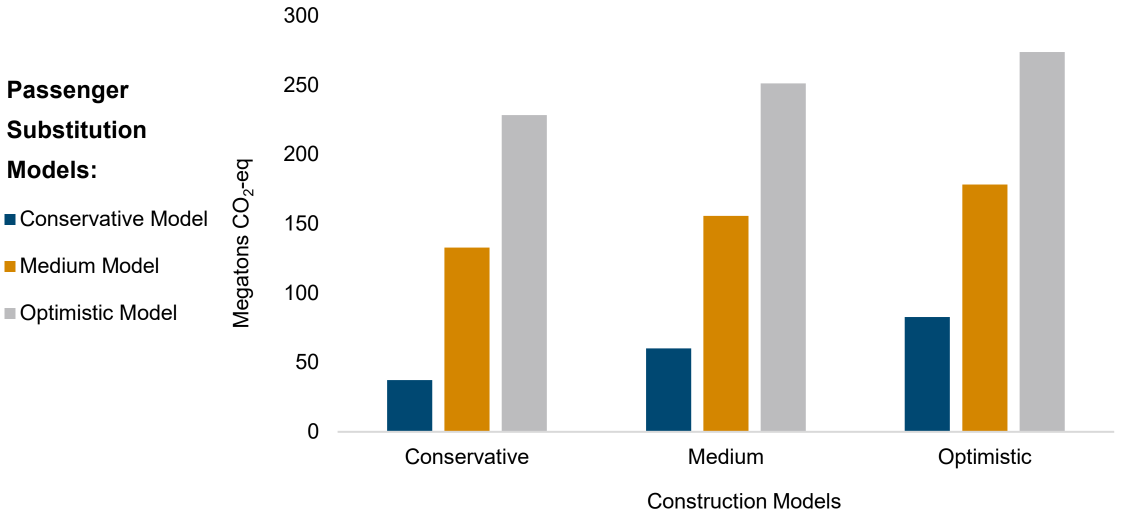
### 3.2.3. Average distance travelled

As the emission factors are expressed in passenger kilometres (pkm), the distance travelled also plays an important role in calculating total emissions. As discussed above HSR travel has a cutoff point of around 1000 km. This means it will be used as a mode of transport for medium-distance trips ranging from 300 – 1000 km (Eurostat 2018). Comparing flight distances regularly used on the route confirms this assumption. Only flights to Russia significantly surpass the 1000 km mark. The model is therefore built on the median of the medium-distance-range, which is 650 km. A more thorough approach would be to look at the individual expected passenger flows for the different passages of the route from Lyon to Moscow and use the weighted mean distance. Due to limitations in available data, we chose the simplified assumption, for both aviation and road travel.

# 4. Results and discussion

The results show that constructing an HSR network across Europe would be a step towards the goal set out by the EU for cutting emissions in the transport sector. All the explored models provide net negative $CO_2$-eq. emissions. This indicates that more $CO_2$-eq. emissions could be avoided by the modal shift of passengers compared to the emissions of construction and operation of the HSR line. While the most conservative model only predicts avoidance of 37.4 mil $tCO_2$-eq./km, the medium model calculates 155.7 mil $tCO_2$-eq./km of savings and the optimistic model demonstrates possible savings of 273.9 mil $tCO_2$-eq./km (Figure 3). Further, in the most optimistic model, emissions would already be offset after 3.2 years of operation. In the medium model the breakeven would be reached after 11.8 years of operation, while the most conservative model would be compensated after 37 years of operation (Table 3).

**Figure 3 / Model estimates of net negative emissions, in megatons $CO_2$-eq.**




Source: own assumptions and calculations

**Table 2 / Net negative emissions by model type**

| | Construction Models | | |
|---|---|---|---|
| **Passenger Substitution Models** | **Conservative Model** | **Medium Model** | **Optimistic Model** |
| **Conservative** | - 37,430,999.89 | - 133,003,527.39 | - 228,576,054.89 |
| **Medium** | - 60,118,629.40 | - 155,691,156.90 | - 251,263,684.40 |
| **Optimistic** | - 82,806,258.91 | - 178,378,786.41 | - 273,951,313.91 |

Source: own assumptions and calculations

**Table 3 / Years to offset construction emissions**

| | Construction Models | | |
|---|---|---|---|
| **Passenger Substitution Models** | **Conservative** | **Medium** | **Optimistic** |
| **Conservative** | 37.1 | 18.8 | 12.6 |
| **Medium** | 23.2 | 11.8 | 7.9 |
| **Optimistic** | 9.4 | 4.7 | 3.2 |

Source: own assumptions and calculations

To put the results into perspective, the most optimistic model is comparable to approximately the amount of 10% of net emissions within the EU27 in a year (EPA, 2020; EEA, 2020b). While this might not seem considerable, several aspects need to be taken into account. First, only passenger travel is included and avoided emissions from freight were not considered. An additional shift within the freight-transport sector would increase the environmental benefits of an HSR line. Second, the construction, maintenance and disposal of road and air infrastructure have not been considered, while all aspects for rail are included. This penalises rail compared to the other modes of transport. Third, the wiiw has shown the notable economic benefits of constructing a pan-European HSR network. The environmental benefits should thus not be evaluated independently but in addition to the economic advantages. Lastly, the examined passage of the line is only one part of the larger network which has the potential to save further $CO_2$-eq. emissions. Also, the costs of the Lyon-Moscow HSR of an estimated 200.4 billion euros have to be taken into consideration.

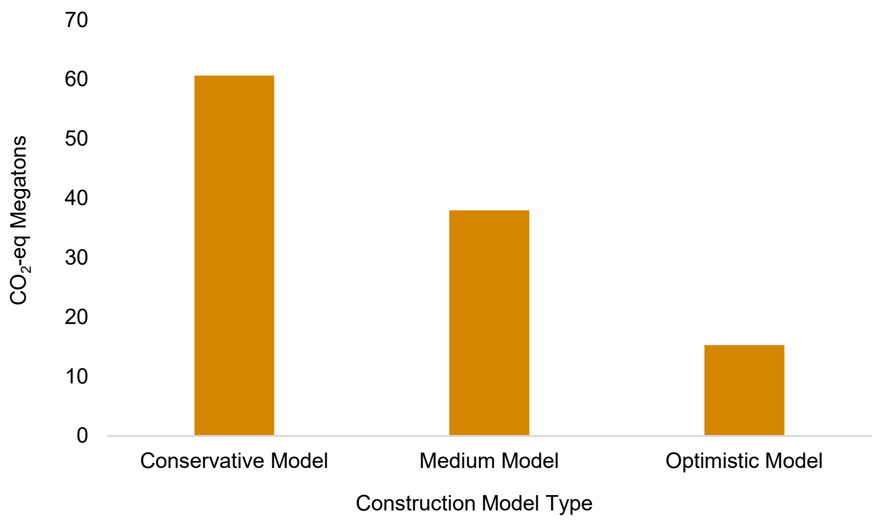
Looking at the bandwidth of results between the nine models there is a need to discuss which model would be the most accurate. Therefore, in the following sections, the different models are examined more closely to provide an indication of which scenarios should be used as an estimate and a basis for the impact evaluation.

## 4.1. CONSTRUCTION MODELS

The conservative model is based on the mean plus one standard deviation from the considered literature, with 17,668 $tCO_2$-eq./km resulting in a total of 60.7 mil $tCO_2$-eq. for construction (Figure 4). The higher emission factor is mostly due to differences in construction as seen in the case of Yue et al. (2015). Specifically, the lack of light-weight metals and the usage of fly ash in concrete as well as a country's energy mix lead to extremely high emission factors (Yue et al., 2015; Barnes, 2014). As in Europe construction practices and material used are more sustainable and have lower emissions, an emission factor as high as assumed in the conservative model is unlikely.

The optimistic model, which utilises the mean minus one standard deviation of emissions found in the literature is more representative. France alongside Sweden has the lowest amount of emissions during the life cycle of railways (UIC, 2017). This is due to a less carbon-based energy mix, relatively more sustainable construction materials used and a lower share of bridges and tunnels. With an emission factor of 4,455 $tCO_2$-eq./km the total carbon emissions for construction amounts to 15.3 mil $tCO_2$-eq (Figure 4). In comparison to the other two models this is only about 25% of the conservative model and 40% of the moderate model total emissions. Nonetheless, this could be achievable with a sustainable energy mix, sufficient numbers for passengers and freight, and sustainable construction practices, i.e. limiting or cutting out fly ash in concrete.

**Figure 4 / Construction emissions by model, $CO_2$-eq megatons**




Source: own assumptions and calculations

The medium model is based on the average of twelve studies of $tCO_2$-eq./km emitted during construction. The emissions factor in this model is 11,062 $tCO_2$-eq./km and total emissions emitted from construction in this model amount to 38 mil $tCO_2$-eq. (Figure 4). This correlates with other recent projects throughout Europe. For example, Spain has the second longest HSR network in the world and several LCAs have been conducted for different parts of the infrastructure (Kortazar et al., 2021). The quality of assessment is very reliable, because of the diversity of the sample studies used.

Additionally, the coherence found within the European studies shows that the medium model is the most realistic. Nevertheless, we see potential for outcomes according to the optimistic model, if sustainable construction practices are applied and cleaner energy mixes are used.

## 4.2. AVOIDED GHG EMISSIONS

For avoided $tCO_2$-eq. emissions, again a conservative, medium and optimistic scenario have been examined, based on different expected substitution rates for aviation and road. While substitution rates range as wide as 10% - 90% across the literature, several factors can indicate a more accurate expected substitution rate. As mentioned, the main factors determining the choice of travel are price, travel time, travel time reliability and frequency of connections (EEA, 2020c). Linked to those factors are density of population and competition from low-price airlines impacting the substitution rate (Steer Davies Gleave, 2006).

The route from Lyon to Moscow encompasses many corridors where, according to aforementioned factors, a high substitution rate can be expected. Looking at routes within the 4 hour / 1000 km distance, on the proposed lines this would for example include routes such as Lyon to Brussels (730 km), Paris to

Berlin (1,050 km), Berlin to Warsaw (575 km), Warsaw to Minsk (545 km) Minsk to Moscow (713 km). Duisburg to Warsaw would also only take about 4.5 hours. The data on passenger flows show that these routes are currently covered mainly by aviation. For example, in 2019 1.8 million passengers travelled from Brussels airport to Germany with an average flight distance of 383 km (Eurostat, 2021a). If a reliable and fast railway system were in place, due to convenience and time of travel for such routes a substitution rate of the optimistic model could be expected (75%).

One factor which will constrain the substitution rates is the strong competition of low-price airlines, covering most of the routes. From a cost perspective it may be hard for an HSR network to compete with those airlines. However, with the emission trading system adopted by the European Union and possible further policies pushing for the reduction of GHG emissions, an increase in prices of flights can also be expected, which would benefit the substitution rates. Overall, we believe the substitution rate to lie on the upper end of the range, or in other words either the medium or the optimistic model, with substitution rates of 50% or 75%.

On the other hand, shifts from the car are expected to be very low. All the factors such as price, reliability and convenience of the car hinder significant shifts to the train. Adding to this are electric cars which produce very low carbon emissions. This is an enticing alternative for the increasingly environmentally conscious European consumer market. Due to those reasons the substitution rate can be estimated reliably at around 2 – 3% (Chester and Horvath, 2010). The model does not depend on whether a 2%, 2.25% or 2.5% substitution rate for cars is used. Therefore, for road travel it does not matter whether the conservative, medium or optimistic model is chosen.

In conclusion the models medium-medium or medium-optimistic seem to be the most likely (Table 2). This would result in emissions savings equivalent to the net $tCO_2$-eq. of the Netherlands (M/M) or Poland (M/O) for a year (EEA, 2020b).

# 5. Limitations

Our study faces three major limitations. First, estimating outcomes over the next 60 years entails uncertainties which cannot be accounted for. Assumptions include a steady growth rate as well as a continuous substitution rate. Assuming the same substitution rate for 60 years may overestimate passenger flows. On the other hand, a relatively low growth rate was chosen to account for this aspect.

Second, we could not be consider the fact that the continuous improvement of other modes of transport will reduce emissions as technology advances. Electrical cars are expected to cut emissions from road travel significantly in the future. Current targets set by the EU and member states regarding private car emission requirements aim to eliminate combustion engines within the next 10 to 15 years (Wappelhorst, 2020). Similarly, airplane fuel efficiency has been increasing and is expected to reduce the emission factor for aviation (EESI, 2019). However, train emissions can also be expected to decrease as the energy mix within the different EU countries moves towards renewable energies. Nevertheless, the shift to electric cars barely changes the results of our model. Appendix 1.3 provides deeper insights into the effects of improved fuel efficiencies.

Third, GHG savings from freight transport are not explicitly included in this study as their quantification would need further research. Qualitatively, though, we see strong grounds to expect a positive impact on emissions if freight transport shifts to rail are incorporated. A recent study by the European Environment Agency (EEA 2021) found that transport of freight via rail emits 43-times less CO2 than transport via air. More specifically, a study by Bueno et al. (2017) on evaluating the environmental performance of a high speed rail project in the Basque Country in Spain demonstrated that net CO2 emissions improve by a factor of 1.3 – 2.1, depending on the model, when including freight into the calculations. Although the authors came to the conclusion that the Basque Y line they studied will not reach a net negative CO2-balance, emissions dropped from 1.92 MtCO2 net emissions if only passenger transport is considered to up to 0.9 MtCO2 net emissions when including both passenger and freight transport. For our study this is suggestive that the projected CO2 savings could potentially double, when including freight into the calculations.

# 6. Conclusion

In conclusion, we could show that the construction of an HSR network across Europe provides not only economic advantages, as examined by Holzner et al. (2018), but also presents the potential for a positive environmental impact. It could be determined that the most optimistic model projects an emissions avoidance equivalent to 10% net emissions of the EU-27 in one year just for passenger transport. The emissions from construction would be offset after 8-12 years of operation, relying on the medium-medium and medium-optimistic model. Even when relying on the most conservative model, the project breaks even after 37 years between emissions created by construction and emissions avoided due to a modal shift in transport. Considering that freight transport was not recognised within the calculations, the potential is in fact higher than portrayed by this study. Existing studies suggest that projected $CO_2$ savings could potentially double, when including freight into the calculations. We argue that the construction and operation of an HSR could significantly reduce passenger flows from aviation, contributing to the goal of the EU to reduce emissions from aviation by at least 10% (EC, 2019). While the idea, let alone the construction, of an HSR network seems radical it certainly can have an extensive impact not only on the further economic integration of Europe, but it can also contribute to a greener, more sustainable, more innovative and technologically advanced future. The estimated costs of the European Silk Road HSR line between Lyon and Moscow of more than 200 billion euros are substantial. However, as a share of 2020 EU GDP this makes only 1.5%. Considering that the investment would likely spread over at least a decade, the amount involved appears modest, from a European perspective.

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# Appendix 1

## 1.1 COMPARISON OF LCA STUDIES

**Table 4 / Comparison of LCA studies**

| Project | Country | Reference | km | Operations $kg\text{-}CO_2/pkm$ | Construction $tCO_2/km$ |
|---|---|---|---|---|---|
| Hannover-Wuerzburg | Germany | von Rozycki et al. (2003) | 325 | | 8,923.1 |
| Europabanan line | Sweden | Akerman J. (2011) | 740 | | 5,405.4 |
| Oslo-Trondheim | Norway | Grossrieder (2011) | 486 | | |
| LGV Med | France | Baron et al. (2011) | 251 | | 5,760.0 |
| South Europe Atlantic | France | Baron et al. (2011) | 302 | | 4,735.1 |
| Taipei-Kaohsiung | Taiwan | Baron et al. (2011) | 345 | | 16,202.9 |
| Bejing-Tianjin | China | Baron et al. (2011) | 117 | | 12,478.6 |
| California HSR (CASHR) | USA | Chester and Horvath (2012) | 1100 | 0.05883 | 8,818.2 |
| California HSR (CASHR) | USA | Barnes E. (2014) | 1100 | | 5,477.3 |
| Madrid-Barcelona | Spain | Sanz et al. (2014) | 621 | | 11,111.1 |
| Beijing-Shanghai | China | Yue et al. (2015) | 1318 | 0.0429 | 28,224.6 |
| Turkish HSR | Turkey | Banar and Özdemir (2015) | 888 | 0.0120 | |
| Lisbon and Porto | Portugal | Jones et al. (2016) | 297 | 0.0070 | |
| UK HS2 | UK | Cornet et al. (2018) | 530 | | 10,547.2 |
| Botniabanan/Bothnia Line | Sweden | EPD (2019) | 190 | 0.0130 | |
| Y Basque | Spain | Kortazar et al. (2021) | 180 | | 15,055.6 |
| | | | **mean** | **0.0267** | **11,061.6** |
| | | | **$\sigma$** | **0.0228** | **6,606.8** |
| | | | **$-1\sigma$** | **0.0039** | **4,454.8** |
| | | | **$+1\sigma$** | **0.0496** | **17,668.3** |

## 1.2 PASSENGER FLOW ASSUMPTIONS AND CALCULATIONS

Passenger flow assumptions are based on flight data retrieved from Eurostat from reporting airports to reporting countries (2021). Although taking data from airports to the reporting country will slightly overestimate passenger flows, this is the closest estimate available. Overestimation is accounted for by the fact that Belarus cannot be included in the estimation as no passenger data is publicly available. The included airports were chosen along the proposed route of the new train line as the passengers travelling from those airports will be the ones who can potentially shift to rail. Table 4 shows the passenger flows for 2019.

**Table 5 / Aviation passenger flows 2019**

| Airports/Member States | European Union - 28 countries | Belgium | Germany | France | Netherlands | Poland |
|---|---|---|---|---|---|---|
| Antwerp Airport | 212,056 | 4,752 | 1,324 | 12,547 | 1,813 | 12,884 |
| Brussels Airport | 17,516,725 | 1,313 | 1,818,943 | 1,530,737 | 284,967 | 383,252 |
| Brussels South Airport | 6,900,029 | 981 | 4,292 | 881,604 | 160 | 464,935 |
| Berlin Brandenburg Airport | 8,401,606 | 163,681 | 128,899 | 490,618 | 317,908 | 27,341 |
| Frankfurt Main Airport | 38,279,748 | 576,121 | 7,346,079 | 2,348,382 | 880,203 | 1,609,316 |
| Bonn Airport | 9,507,447 | 59 | 3,121,317 | 104,467 | 242 | 193,928 |
| Dusseldorf Airport | 17,530,047 | 72 | 4,237,555 | 690,808 | 255,966 | 326,241 |
| Berlin Tegel Airport | 19,751,181 | 347,183 | 8,143,918 | 1,312,998 | 683,726 | 289,573 |
| Frankfurt Hahn Airport | 1,102,269 | - | 1,004 | 612 | 172 | 185 |
| Lyon Saint-Exupery Airport | 9,109,364 | 259,965 | 779,337 | 3,811,655 | 322,779 | 85,343 |
| Paris Charles De Gaulle Airport | 36,843,706 | 193,190 | 4,528,537 | 6,868,846 | 1,235,131 | 742,459 |
| Paris Orly Airport | 24,632,558 | 150 | 310,042 | 13,871,504 | 147,753 | 1,297 |
| Maastricht Airport | 296,392 | 177 | 1,034 | 5,346 | 279 | 1,062 |
| Warsaw Modlin Airport | 2,772,058 | 174,100 | 113,103 | 107,937 | 62,812 | 185 |
| Warsaw Chopina Airport | 12,267,010 | 464,141 | 1,599,099 | 798,071 | 599,875 | 1,767,473 |
| Warsaw Strachowice Airport | 2,843,556 | 46,370 | 396,490 | 105,908 | 121,329 | 344,194 |
| Totals of EU Passengers in 2019 | **207,965,752** | **2,232,255** | **32,530,973** | **32,942,040** | **4,915,115** | **6,249,668** |

Source: Eurostat, 2021a

As Eurostat does not provide data for flights to Moscow, the number of passengers had to be estimated. It is based on the total number of passengers travelling to Russia from the EU, which was 52,191,000 in 2019 (IATA, 2019). Of all flights going to Russia, 63% arrive and depart from Moscow (Russian Federal Agency for Air transport and Aviation, 2021). No data for country-specific passenger flows to Russia is available. It was assumed that out of the total number of passengers travelling from the EU to Russia, the proportion coming from countries along the proposed line will be the same as the proportion these countries contribute to the total number of passengers traveling outside the EU (Table 6). For example, out of the 433 million passengers who travelled outside the EU in 2019 by plane, 75 million passengers came from or arrived in Germany, making up 18%. Consequently, the assumed passenger flow from Germany to Russia is 18% of all passengers travelling from the EU to Russia, which translates to 6 million passengers. The numbers for all countries along the route are added up and then multiplied by the 63% of these flows, which go to Moscow. Table 5 and 6 show the individual data points:

### Table 6 / Passenger flows (Moscow)

| Assumptions: | |
|---|---|
| Total PAX Russia: 2019 | 52,191,000 |
| Percentage of total PAX to Moscow | 63% |
| **Total PAX Moscow** | **32,880,330** |

Source: IATA, 2019; Russian Federal Agency for Air Transport and Aviation, 2021

### Table 7 / Passengers from EU to Russia in 2019

| Passenger Flows Extra-European Flights | PAX extra-European flights (absolute) | PAX extra-European flights (relative) | PAX to Moscow |
|---|---|---|---|
| European Union - 28 countries | 433,806,053 | | |
| Belgium | 10,315,507 | 0.0238 | 781,864 |
| Germany | 79,372,647 | 0.1830 | 6,016,050 |
| France | 60,812,342 | 0.1402 | 4,609,271 |
| Netherlands | 30,120,164 | 0.0694 | 2,282,958 |
| Poland | 12,719,860 | 0.0293 | 964,102 |
| **Total PAX to Russia** | | | **14,654,245** |

Source: Eurostat, 2021b

## 1.3 ROBUSTNESS CHECK

The model was tested for sensitivity of the different included elements. The variables of interest are passenger flows, expected growth rate of passenger flows, average distance travelled, substitution rates and emission factors. The model is most sensitive to the expected substitution rates for aviation. Any substitution rate below 15% *ceteris paribus* will not offset the emissions from construction within 60 years for the most conservative model. This aspect highlights again that passenger flows and occupancy rates will be key to the aspired GHG emissions avoidance. While a change in substitution rates for the car does not have a significant effect, it can act as a counterbalance or reinforcement of adjustments in the substitution rate for aviation. A decrease or increase in expected growth rates barely affects the model, given that the values realistically have only a range of approximately 5 percentage points. Even when assuming no growth rate, the time until emissions from construction are offset will only be prolonged by two years.

The emission factors of cars turned out to play a minor role. Although a 100% shift to electric cars as of today would cut emissions from road travel by 50%, when relying on an emission factor of 69 $gCO_2$/pkm (Fraunhofer ISI, 2020), the final results of the model barely change. This is mostly due to the fact that we expect a very low substitution rate for the shift from car to train. On the other hand, improvements in emissions from flying can potentially change the results significantly. So far, no reliable improvements in emission factors can be projected, but hypothetically a 10% decrease in emissions from aviation will lead to 30% less GHG savings, when using the most conservative model. Nevertheless, until an HSR construction and operation no longer produces net negative emissions, emissions from aviation would need to drop by more than 30% for the most conservative model and by more than 55% for any of the medium models.

# Appendix 2: Energy in the European Union (energy mix)

## 2.1 OVERVIEW

The European Union has implemented regulations to further secure energy supplies, sustainable energy consumption, lower fossil fuel dependence and improvements in energy efficiency. According to Regulation (EC) No 1099/2008 on energy statistics, the European Commission has formed a very useful tool to gather statistics for current energy usage within the European Union. This drives sound decision-making by providing goals and targets for industries. For 2020 the goals were to reach 20% energy from reusable sources and 20% better fuel efficiency (EC, 2017). The 2020 target of increasing to a 20% reusable energy mix was met, but issues with fuel efficiency remain. The current problem with both goals is that there are major differences in progress between countries. Due to the fact that some countries are struggling to meet current goals, the 2030 and 2050 outlook has been rather conservative. There is a call for further EU wide integration to reduce emissions (EEA, 2020a).

## 2.2 ENERGY MIX

The transport sector is the highest contributor to $CO_2$ emissions within the EU with around 28% (UIC, 2017). However, the rail sector is only responsible for about 2.9% of transport emissions. Furthermore, overall energy consumption per unit decreased and energy efficiency increased in the period 2005 to 2015. The share of renewable energy sources has tripled.

**Table 8 / Energy mix for railways**

| Energy Mix Railway Europe | |
|---|---|
| Oil | 31.8% |
| Coal | 2.5% |
| Biofuels | 0.4% |
| Electricity | 67.6% |
| of which Fossil | 29.2% |
| of which Nuclear | 18.1% |
| of which Renewable | 20.3% |

Source: UIC, 2017

The current energy mix shows a trend towards renewable energy which indicates that railways will emit less and less $CO_2$-eq. The energy mix in table 7 shows that electricity is mostly used for powering trains. With further technological advancements, the usage of fossil fuels can be minimised (UIC, 2017). Our study assumes the current energy mix. Further research has to be done to include future energy mix goals for the European Union and the railway sector.

# Appendix 3: Technical details of the railway

## 3.1 EUROPEAN RAILWAY TECHNICAL STRATEGY

The European Rail Infrastructure Managers (EIM), with the help of other related institutions, has designed a strategy to develop the current directives on technical specifications for interoperability. The goal of the strategy report was to further the competitiveness and increase the market share of rail by 2035, by assessing economic, social, and technical needs and requirements as well as efficiently solve problems associated with them. The report estimates that economic growth combined with emission saving opportunities will enable the sector to continuously gain market share. Therefore, preparation and cost-efficient solutions are needed. EIM supports uniformity and standardisation in cross border traffic and is proposing technical guidelines that should be taken into consideration for this project as well (EIM, 2008).

## 3.2 GAUGE SIZE

Uniform gauge sizes should be considered when planning and constructing new railway lines. Standardisation simplifies international transport of goods and passengers via rail. Gauge sizes in the European Union and Russia differ. Although there is uniformity within most of Europe (with the exception of Spain and Portugal), in our case Belarus and Russia use a wider gauge. The different rail widths are mainly a result of historical factors. Countries didn't want to be overrun by an invading enemy.

**Table 9 / Comparison of gauge Sizes**

| Country | Gauge Size |
|---|---|
| Belgium | 1435mm |
| France | 1435mm |
| Germany | 1435mm |
| Netherlands | 1435mm |
| Poland | 1435mm |
| Belarus | 1520mm |
| Russia | 1520mm |
| Spain | 1668mm and 1435mm |
| Portugal | 1668mm |

We assume the construction of a completely new line, because of these difficulties. Updating or using different parts of already existing tracks interferes with a lot of different rules and regulations for each country and is likely to run into bureaucratic obstacles. The line from Lyon to Moscow is assumed to have a gauge size of 1435mm, as European Union directives and regulations include technical specifications for the interoperability of the rail system (Regulation (EU) No 1299/2014).

Gauge changing bogies could be introduced between countries that differ in gauge size, but the technology has been proven to be insufficient at this point. Spain has tried to solve this matter but has failed to develop a viable solution. The current market leader is China, yet issues with the bogies have been prohibiting progress. There have been initiatives to proceed with further investigation for passenger trains, but these ultimately failed due to lack of feasibility. Freight trains pose yet another challenge. Due to the weight, the transport bogies would have to be manufactured better and require more maintenance. Specifics on loading gauge (the maximum height and width of the rolling stock) can be found in the directive by the UIC (Loading Guidelines, 2020). To conclude, passenger trains might be suited for gauge changing bogies in the future, but they will still not be feasible for freight trains (Shang-Su, 2020).

## 3.3 AXLE LOAD

The axle load in the European Union for conventional freight trains is 22.5 tons and for passenger trains going under 250 km/h it is 20 tons. Trains with a higher maximum speed naturally have a lower axle load. This should be taken into consideration when choosing the speed of the train (EIM, 2008).

Freight provides a better opportunity for raising axle loads. The current strategy is to gradually raise axle load by providing better and more advanced solutions for wagons. The EIM predicts a further axle load raise by 2035. This is only possible if tracks are built in accordance with the axle load requirements.

## 3.4 FREIGHT

The study of the Basque Y line gives a detailed overview of freight comparisons between different modes of transportation in Spain. The study uses reference data from 2010 that accurately depicts values that can be used for a rough estimate. Results show that the more freight transported via HSR the lower the emission factor will be. However, there is always a conflict between freight and passenger transport. Freight trains are scheduled around passenger trains and can only operate when the line is not used for passenger transport purposes (Bueno et al., 2017). This aspect needs to be addressed and further options should be explored to ensure the smooth operation of freight. One option could be to explore a four track HSR network.

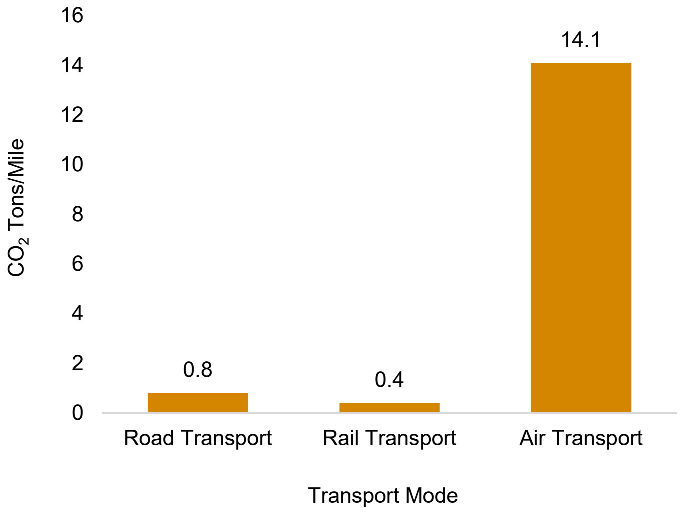
**Table 10 / $CO_2$ Emissions by Mode of Transport**

| Mode of Transport (Freight) | $CO_2$ emissions in kg/tkm |
|---|---|
| Road | 0,091 $kgCO_2$ /tkm |
| Rail (CR and HSR) | 0,019 $kgCO_2$ /tkm |
| Air | 0,54 $kgCO_2$ /tkm |
| Seaborne | 0,02 $kgCO_2$ /tkm |

Source: Bueno et al. 2017

Another study that conducted an LCA of freight transport is the American study by Horvath (2006). The conversion from $gCO_2$ /tmile to $kgCO_2$ /tkm shows that in the American model freight trains emit 0.025 kg $CO_2$ /tkm. This is 35 times less than air transportation emissions. In his example, rail outperforms road by one half.

**Figure 5 / $CO_2$ Pollutant in t/mile**




Source: Horvath, 2006

To put this in total numbers Miranda-Pinto (2017) introduced a road-rail model that could be used in different scenarios. The author considered different road sections in Brazil that can be converted into rail way lines. The consideration was to analyse the heaviest freight transport industries, in this case cellulose pulp production, and calculate distances between factories and the nearest ports. The study included 75% of all paper produced in Brazil and found remarkable results that call for further investigation into the model. The end result was a reduction in emissions of up to 77.4%.

Overall, the European Union has been seeking new green emissions strategies. The European Commission has set targets for a gradual move from road to rail freight transport for 2030 and 2050. However, the current strategies, i.e. fuel taxes, engine emission standards, etc., are not sufficient to hit the current emissions targets (Miranda-Pinto, 2017).

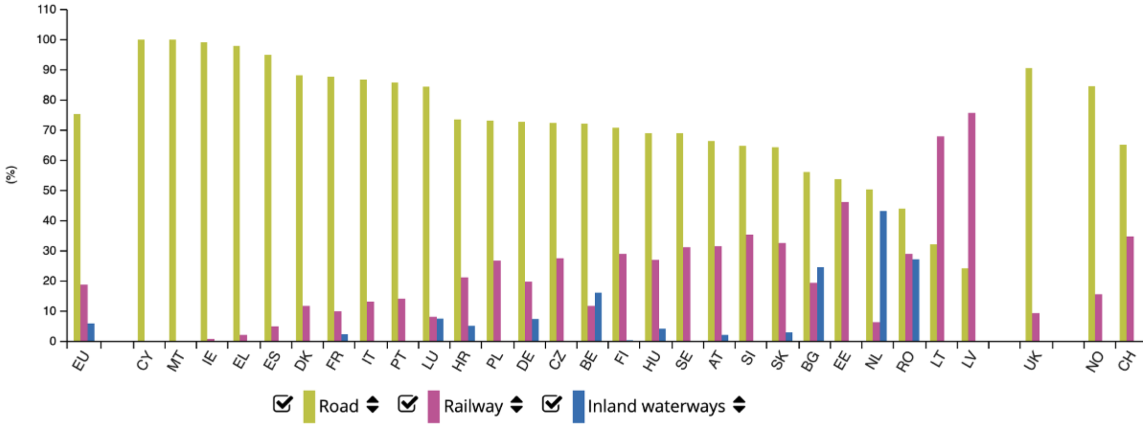
Countries have been testing and implementing the Global Green Freight Action Plan, which was issued with the Global Green Freight Action Statement at the 2014 UN Climate Summit in New York. This plan encourages and assists not only countries but logistical companies that want to create a greener option for their business (Global Green Freight, 2018). Rough estimates from the UN environment program calculate that around 100 MMT of emissions could be saved (UNEP, 2014). With a promising strategy of a road-rail combination this could certainly be achieved.

Other positive factors that have to be considered when using rail freight transportation would further reduce time and costs. Trains are less likely to be subject to delays due to traffic. This comes into play when we consider border crossings. Our HSR network would lead trains in and out of the EU and could provide smoother and more efficient transport. Furthermore, one train conductor replaces around 50 truck drivers. Due to the size of loading capacity, trains can transport more tons of freight with less staff and reduce road traffic at the same time. Also, there are certain regulations for truck drivers that limit working hours and therefore increase delivery times. Train conductors are stationed around Europe and can easily change at any given time to ensure continuation of transport (Rail Cargo Group, 2020).

## 3.5 MODAL SPLIT OF FREIGHT

Road freight transport is irreplaceable due to the inefficiency of trains, transporting freights over short distances. However, there are still opportunities for rail to take on more market share. The current situation within the European Union shows that the modal split has to shift towards rail, and this is also included in the goals and targets laid out by the EU. Figure 6 shows the modal split in European countries. East European countries have a higher percentage of freight on railways than central and west European countries.

**Figure 6 / Modal split of freight transport: 2018**




Note: Include estimates for EU27, Belgium, Finland and Switzerland.
Source: Eurostat, 2018

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