We Calculate Wrong!

A holistic view of transportation systems is crucial to correctly assess their ecological footprint

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Executive Summary

In the past, the climate-relevant effects of various means of transportation were primarily discussed in connection with the burdens arising from the drive energy, here primarily CO_2. The fact that infrastructure is always necessary to provide any kind of transport service has so far largely been ignored. This study evaluates transport systems and their CO_2 footprint holistically, including the respective necessary infrastructure of routes (e.g., roads, rails), nodes (e.g., train stations, airports, parking), control infrastructure (e.g., signal boxes, switches, signaling systems, air traffic control systems, traffic lights, traffic signs) and it is also taking into account the construction of the respective means of transport. Furthermore, the physical relationships are considered, as they have a significant impact on the efficiency of the various transportation systems due to their inherent motion sequences.

Since the holistic approach used in this study has not yet been widely used in the discussion, not nearly all necessary figures, data and facts are available to make a fully comprehensive and complete comparison of carbon dioxide emissions from transport systems. However, the available data already allow conclusions to be drawn about the true CO_2 loads per passenger kilometer (PKM), which deviate considerably from currently widespread perceptions. The main results can be summarized as follows:

- Just focusing on propulsion energy when assessing the climate impact of transportation systems is insufficient and scientifically inappropriate; in particular, the required route infrastructure sometimes causes CO_2 emissions during construction and maintenance, that significantly exceed the emissions resulting from propulsion. Node infrastructure can also be a significant CO_2 emitter, largely impacting the overall balance of a system.

- For a complete assessment of the environmental impact of a transportation system, a holistic view including all necessary infrastructure components is mandatory. In addition, the total transport capacity of a transport system in terms of passenger kilometers (PKM) or ton kilometers (TKM) plays an essential role in this assessment as well.

- The railway transportation system is proving to be significantly less environmentally friendly than is generally assumed due to the immense CO_2 burdens for route- and node infrastructure. This is due to the immense quantities of steel, concrete (cement) and copper required for its infrastructure. Another factor is, that the railway transportation system has by far the least favorable properties in terms of mechanical efficiency of movement and, in this context, also has only a relatively small potential for optimization.

- The main cause of the high CO_2 pollution of the transport sector as a whole is not so much society's increasing demand for mobility, but rather the inefficiency of the use of transportation systems, their incompatibility and lack of inter-modality, and the ignoring of physical facts.

- The greatest lever for reducing CO_2 in connection with mobility is to be found in a more efficient use of the infrastructure that already exists today. For "motorized individual transportation" (MIT) for instance, which currently has a utilization rate of only 1.25%, the key to more intelligent use in the future lies in "Mobility as a Service" concepts, for which the technologies required are already largely available today.

- Subsidizing electric automotive mobility in its current form has a much smaller effect on CO_2 emissions than is commonly assumed. The same largely applies to the expansion/new construction of railway infrastructure. By contrast, a much more significant reduction in CO_2 could be achieved through significant structural changes in mobility and transport.

- Politically intended financial incentives to reduce CO_2 emissions in the transport sector will only have the intended effect, if they include all relevant CO_2 emissions on the one hand and are internationally and globally oriented on the other. CO_2 molecules produced in the manufacture of steel in India or China or in cement production in Indonesia have exactly the same effect on the global climate, as CO_2 molecules produced in the combustion of gasoline and kerosene or in the generation of electricity elsewhere.

- In the transportation sector, tens of millions of tons of CO_2 could be saved each year in Germany alone, without having to result in restrictions on mobility. To achieve this however, political decisions on transport policy must be less ideological and biased and more consistently geared toward the intended demand for mobility and transport, as well as to the scientific facts, and to what is technically feasible in engineering terms.

N.B. All figures used in the study regarding transportation volume provided by transportation systems in PKM and average utilization figures are for the pre-Corona pandemic period, 2019 and earlier. Comparable and reliably collected figures that are not influenced by the pandemic and the significantly changed mobility behavior during the pandemic will not be available for the year 2023 until the course of 2024 at the earliest.

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Preface

The work presented here is a continuation and complement of studies and other publications produced over the past three years. The basis is the translation of a study that I conducted on behalf of the Friedrich Naumann Foundation for Freedom, a German foundation committed to political education. The original version of this study was in German; it was released in April 2021, has been assigned the ISBN 978-3-948950-14-9 and is licensed as Creative Commons (CC BY-NC-ND 4.0). Due to its German origin, a few of the sources cited in the bibliography and reference list are in German.

New findings from the continuation of my work, results of further studies, the consideration of more current numbers, data and facts have been incorporated into the summary presented here.

Since the text still contains several abbreviations which may not be generally known in the English-speaking world, and also metric measurements are used throughout, a list of abbreviations, units and a metric conversion table can be found in the appendix.

1 Introduction and methodology

Few other topics are currently being discussed as intensively and emotionally as the "ecological footprint" of various transportation systems, usually reduced to more or less correct figures on CO_2 and NO_x emissions. Such discussions often result in highly simplified statements such as "taking the train is environmentally friendly", "driving a car is harmful to the environment" and "flying is even more harmful".

The fact that an appropriate evaluation is much more complex and that it is not sufficient to measure only the *exhaust gases at the tailpipe* in order to take the environmental aspect adequately into account will be illustrated in this study. Previous approaches to assessing and comparing greenhouse gases (GHG) emissions in a broader context have primarily aimed to include not only short-term emissions but also their long-term climate impact (1), (2). The approach taken in this study aims to evaluate transport sector emissions holistically, including ALL necessary infrastructure components. Emissions that so far have been attributed to "industry" or "the construction sector" are now attributed to the specific transportation system and assigned to the respective transportation service provided, as long as they are directly related to the provision of that service. This method is applied to the industrial production of cars, trains and airplanes as well as to the construction of roads, rails and railroad tracks, airports, train stations and all other infrastructure components. For example, large amounts of steel and aluminum are needed in the construction of trains, cars or airplanes, concrete and steel in the construction of roads, bridges, tunnels, runways. If the cause-effect relationship of each transportation system is appropriately taken into account, the energy consumption and pollutants produced by concrete and steel for highway bridges must be allocated to the energy and pollutant balance of the road transport mode; if the structures are railroad bridges or tunnels, they must be allocated accordingly to railway transportation, and the concrete for airport runways must be added to the balance of the aviation transport system. This approach is very complex, but even a few examples prove that it is not sufficient at all to measure only the direct *exhaust gases at the tailpipe in order* to take adequate account of the environmental aspect.

This study is based on the principles of “Holistic Excellence”, as applied in various models for the continuous improvement of organizations, companies, processes, etc. Holistic Excellence has many facets, the detailed description of which would go way beyond the scope and objectives of this paper. The most relevant points in this context are:

- The complexity of issues must be fully understood; existing cause-and-effect mechanisms must be systematically analyzed and fully taken into account,
- Decisions must be made on the basis of figures, data and facts; the latter must be obtained methodically, measured or empirically verifiable without prejudice or ideology.

Cause-effect relationships can go far beyond what is obvious. Regarding the topic of mobility, the entire public and political discussion revolves almost exclusively around the exhaust gases of the vehicles, without sufficiently taking into account the full complexities of such systems.

The following section first describes the methodology used to carry out such a holistic assessment from an excellence perspective. It is then followed by an exemplary presentation of the climate impact of the various components required to provide a respective transport service. Finally, some basic physical aspects relevant to transportation systems are addressed. This study focuses on the greenhouse gases associated with the use of different transportation systems, focusing on the aspect of CO_2 emissions; the study thus mirrors the current social and political discussion, knowing full well that there are other GHGs, some of which have a more intensive impact that would need to be included in the overall balances.

1.1 *Methodology*

For the four major transport systems - road, railway, air and water – Table 1 shows which components the respective systems require to provide a transport service. Each of these systems requires an actual means of transport, i.e., cars, trains, aircraft and ships. Likewise, all systems require their own specific infrastructure, which can be divided into a "node" infrastructure (train stations, airports, ports, parking lots, etc.), a "route" infrastructure (road network, railway network, waterways, etc.) and a "control" infrastructure (signal boxes, signal systems, traffic lights, traffic signs, air traffic control systems, lighthouses, buoys, etc.). Furthermore, the table lists the energy sources for the propulsion of the respective means of transport.

Necessary system components	**Railway**	**Road**	**Aviation**	**Shipping**
Vehicle	Train	Car	Airplane	Ship
Node Infrastructure	Stations	Parking space	Airports	Ports
Route Infrastructure	Railway network, infrastructure for electrification, if applicable	Road network, gas station infrastructure, power supply infrastructure, if applicable	Air	Oceans, fairways near the coast in deep-sea shipping, inland rivers and canals
Control Infrastructure	Signal boxes, signaling systems, switches, etc.	Traffic lights, traffic signs, etc.	Air traffic control incl. facilities (radar, radio beacon, etc.)	Lighthouses, radio beacons, etc., pilots in certain waters
Operating Energy for the vehicle	Electricity, Diesel	Gasoline, Diesel, sporadically electricity and gas	Kerosene, aviation fuel	Heavy oil, Marine diesel, occasionally LNG [1]

Table 1: The four basic transport systems and their respective necessary components

In order to achieve a correct ecological assessment of the different transportation systems, all components necessary for the respective system must be fully considered. Applying holistic cause-and-effect mechanisms to road traffic therefore means that all climate-relevant emissions from vehicle production, road construction and the maintenance and care of the road infrastructure, the production of all traffic signs and traffic lights, including installation and operation (electricity, maintenance, etc.) must be determined and included in the overall balance. Similarly, in railway transport, not only the electricity used to power the trains must be considered, but also the construction and maintenance of the trains and the railway network, the construction, operation and maintenance of the stations, as well as the construction and operation of all signal boxes, signaling systems, switches, etc., which are necessary to enable regulated and safe railway transport. In aviation, the construction and maintenance of aircraft as well as airports and their operation must find their way into the balance sheet accordingly, as well as everything that has to do with air traffic control.

To be clear from the outset: Not all the figures that would be necessary to correctly determine - for example - the CO_2 footprint of the entire railway or highway network that has already incurred in the construction of the respective infrastructure are available or even known. This would require exact figures on the materials used as well as the factual execution of the construction projects; in the past, people simply did not think about this. Until a few decades ago, CO_2 was considered a naturally occurring, non-toxic, invisible and odorless gas to which no real relevance was attached. It was only about 25 years ago that awareness of the greenhouse gas effect of CO_2 was first raised. However, this

[1] LNG: Liquified Natural Gas

important and correct change in perception and assessment now even more needs to be adequately considered in current and future decisions on mobility and transportation systems.

To approximate the relevance of infrastructure in the context of an appropriate holistic ecological consideration of transportation systems, this study therefore uses certain well documented real-life examples, for which figures, data and facts could be researched from generally accessible sources. These are, for example, the high-speed railway line between Cologne and Frankfurt, the Gotthard Base Tunnel in Switzerland, or the "Stuttgart21" project, the relocation of Stuttgart's main train station underground. For road traffic, we examined the A3 highway between Cologne and Frankfurt, which has at least six lanes throughout this stretch.

Another important point concerning the efficiency of the different transportation systems is the way in which the movement process takes place from a physical point of view. The movement processes as well as the physical quantities influencing the necessary energy amounts play an essential role and are examined and evaluated in a separate chapter in this study, for which we apply our calculations to a trip from Hamburg to Munich as an example.

1.2 *Materials and their carbon footprint*

In the industrial field, the largest energy consumers and CO_2 emitters include the steel industry, aluminum and copper production, and the cement and concrete industries. (3), (4).

To produce one ton (1,000 kg) of steel in a blast furnace, around twenty gigajoules (GJ) of energy are required, equivalent to around 5,600 MWh (megawatt hours). Since the energy for steel production comes primarily from (fossil) coke (coal), the production of one ton of crude steel generates more than 2 tons of CO_2 (3), (5), (6). This is only the energy and pollutant balance from the blast furnace and coke plant process; everything else that occurs in the rolling mill or during further refinement of the raw material steel must still be added in each case. The carbon footprint for aluminum or copper are even more negative than for steel; depending on the primary energy used, between eight and 12 metric tons of CO_2 are emitted to produce one ton of pure aluminum (7), for copper it's more than six tons on average, with a rather large span depending on the production method.

To understand why the production of metals such as iron (steel), copper or aluminum cause such large amounts of CO_2 during manufacturing, it is helpful to take a look at some basic chemical processes. Most of the metals we use in our industrialized world do not occur in nature directly as metals (in native form), but in the form of ores[2]. Ores are naturally occurring raw materials in which the metal atoms are bonded together with atoms of other elements. In the case of iron, this other element is often oxygen; iron ore consists mainly of iron oxide (Fe_3O_2, Fe_2O_3). In a rather complex chemical process, a great deal of energy must be expended to separate the oxygen from the iron, and in addition to the energy, it requires a material with which the oxygen can be bound. In iron production (steel production), carbon (C) is classically used in the form of coke. On the one hand, it provides the necessary energy in the blast furnace, and on the other hand, it binds the oxygen that is to be extracted from the starting material, iron ore, and this is precisely what leads to the large quantities of carbon dioxide (CO_2)[3]. Copper, today, exists in the earth's crust in the form of different ores, e.g., copper sulfides, copper carbonates, and copper oxides. Unfortunately, the ores only contain very little copper, between 0,5% and 2%. The lower the copper concentration is, the more intense

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[2] Regarding copper, native copper has been found in the past, but today's copper is mostly produced from copper ores.

[3] The use of hydrogen (H_2) for the production of "green steel" is already widely discussed today. However, it is often ignored that a considerable retooling of the steel plants would first be necessary, and, in addition, it would have to be ensured that very large quantities of hydrogen would actually be available that had been produced in a CO_2-neutral manner. From today's perspective, this is not likely to happen in the foreseeable future, because the energy balance of the hydrolysis process for hydrogen production is very poor. Around 60% of the primary energy used is lost in the chemical process of producing hydrogen from water.

processing is required, which increases the carbon intensity. Aluminum is not found in the earth's crust in native form at all; it always had to be produced in a complex and very energy-intensive process. A well-known aluminum ore is Bauxite ($Al(OH)_3$), another one the clay mineral Kaolinite ($Al_2Si_2O_5(OH)_4$) . Aluminum production requires large amounts of electricity to separate the aluminum atoms from the other elements in the ore, one ton of aluminum needs 15.7 MWh (megawatt hours) electricity on average (8). The CO_2 footprint of aluminum is thus highly correlated with the carbon footprint of electricity generation.

Concrete is also an ecologically problematic material, not least because of the use of cement, which already generates around one ton of CO_2 per ton of cement during production. Here, too, understanding the chemistry behind the process is helpful. The main raw material for cement is calcium oxide (CaO), which is obtained from limestone (calcium carbonate, $CaCO_3$). Using a lot of energy (temperatures of 1,700 degrees C), the calcium carbonate is broken down; in the process, one molecule of calcium oxide and one molecule of carbon dioxide are formed from each molecule of calcium carbonate ($CaCO_3 \rightarrow CaO + CO_2$). In cement production, only a small part of the CO_2 comes from the energy required for this process; by far the greater part comes directly from the chemical reaction.

Despite progress in energy efficiency, it must still be assumed that at least 300 kg of CO_2 are released per m^3 of concrete, long before the concrete in the structure can begin to harden; depending on the cement content, it can easily be more than 400 kg. It should be noted that, depending on the source, global cement and concrete production accounts for between six and eight percent of total annual CO_2 emissions, which is three to four times the CO_2 emissions of the entire global aviation industry (9), (10), (11), (12). Although intensive research is being carried out to reduce emissions from cement and concrete production, a major breakthrough is still to be seen (13).

From a climate point of view, it is irrelevant whether CO_2 and other emissions are produced in steel or cement production in China, India, Indonesia or Germany. Those emissions are part of the global climate balance sheet right from the start; atmospheric physicists today are in broad agreement that the warming effect of CO_2 in the atmosphere occurs after about 10 years, and the climate effect of CO_2 molecules is about 100 years due to the time they remain in the atmosphere (14). Regional or even local differences regarding the climatic effect of CO_2 dependent on the location of CO_2 emitters can thus be excluded.

Generally, it is important to have a fundamental understanding of the essential chemical and physical processes underlying the production of materials. Claims that simply replacing fossil energy with ecologically generated energy (wind power, solar power) leads to CO_2-free products are false in many cases and merely testify to a lack of understanding of the often very complex issues involved.

Table 2 shows the CO_2 emissions resulting from the production of one metric ton (1,000 kg) of the respective material.

Material (1 ton)	CO_2(tons)	Comments
Steel	2.18	Crude steel, only blast furnace and coke plant process (from ore to steel), any further processing, e.g., rolling mill, etc. needs to be added.
Aluminum	10.6	Aluminum production is very electricity intensive, CO_2 footprint highly dependents on electricity generation and can vary from 8 – 12 tons.
Copper	6.6	Processing from ore to metal only, any further processing, e.g. producing wires, etc. needs to be added.
Bronze	7.03	Bronze is a copper-tin alloy and thus is comprised of the CO_2 footprints of copper and tin.
Cement	1	Roughly 80% of the CO_2 results from the chemical process ($CaCO_3 \rightarrow CaO + CO_2$) and is independent of the energy used in the furnace. CO_2 of **concrete** per m³ is highly dependent on the amount of cement it contains; on average 0.3 tons CO_2 per m³ of concrete are a good assumption.
Gravel, Sand, Ballast	0.00485	

Table 2: CO_2 footprint of selected materials (material production only, no further processing included)

The CO_2 emissions shown in Table 2 were taken from (15), an official publication from the German "Federal Office for Economic Affairs and Export Control". Based on this information, we will make assumptions to determine the average CO_2 emissions for the construction of infrastructure.

Once the relevant figures for the CO_2 emissions of the necessary components of a transport system or part of it (e.g., a specific route) have been determined, those must be put into relation to the "traffic volume" provided, i.e., transportation performance in passenger kilometers (PKM), for freight ton kilometers (TKM). The following figures are available (16), (17), (18):

Transportation system	Traffic volume in billions of PKM
Road, motorized individual transport (MIT)	**965.5**
Rail ➢ thereof long-distance traffic ➢ thereof regional traffic	**95.8** 39.4 56.5 *) *) around 41 billion PKM from DB Regio, around 15 billion PKM from other companies
Aviation (departing and arriving from/at all German airports) ➢ thereof within Germany ➢ thereof outgoing to foreign countries ➢ thereof arriving from abroad	486.2 **10.3** 237.6 238.3

Table 3: Annual traffic performance of road, railway and air transport systems 2018

In our further considerations, we will focus on the specifics of passenger transportation within the railway, road and aviation transport systems; commercial shipping (apart from cruises and ferry connections) only provides freight transport services. In addition, we primarily focus on long-distance transportation as there is no local transport in the classical sense in aviation. In the case of road and railway systems, most of the aspects examined have fundamental validity, regardless of whether regional/local or long-distance transport is considered. However, some aspects differ more fundamentally, so that it would be methodologically questionable to transfer all the results from the considerations of long-distance transport to regional and local transport. For example, long-distance roads are built predominantly or, in the case of highways, even exclusively for motor vehicles, whereas in the case of local roads, it must be taken into account that pedestrians, cyclists and motor vehicles share the same use. These roads are therefore likely to be assigned only in part to MIT in their pollutant balance. In case where considerations in this paper are also valid for regional traffic, this is explicitly stated.

2 CO_2 emissions from infrastructure

2.1 *Route infrastructure*

2.1.1 *Route infrastructure for trains*

All trains run on rails made of high-performance steel, with one rail weighing 60 kg per meter (19). For one kilometer of rail, that is 60 t of steel; for one track (consisting of two rails), that is 120 t and thus more than 240 t of CO_2 per kilometer which is generated in steel production alone. As an example, the double-track high-speed line from Cologne to Frankfurt (around 700 km of rails) stands for more than 91,000 t of CO_2 from the production of rail steel alone.

Turning the rails into a high-speed line requires a track that must first be cleared and graded, and which, in the case of the Cologne-Frankfurt line, passes through quite a few tunnels and over many bridges. Whereas in the past, tracks were fixed on concrete “sleepers” (each weighing 265-560 kg) at intervals of 65 cm which lay in thousands of tons of compacted gravel, in tunnels and on newer, especially high-speed lines, a "slab track" is often used today, in which the rails lie on a multi-layer continuous concrete bed (20). Such slab tracks require significantly more concrete compared to sleepers in a ballast bed. For the above-mentioned example track, around 550,000 m³ of concrete have been used just for the slab track. For the respective tunnels, millions of cubic meters of rock were drilled or blasted out of the mountain during years of work, then had to be removed, recycled elsewhere, or landfilled, and during tunnel driving a reinforced concrete tube had to be built to prevent the collapse of the mountain above. In the 2,069 m long Idstein tunnel alone, 75,000 m³ of concrete and 9,500 t of steel were used; a total of 600,000 m³ of excavated soil and 55,000 m^3 of tunnel spoil were produced (21). The production of the concrete and steel for this one tunnel structure alone therefore produced at least 37,750 t of CO_2. If these figures are extrapolated to all the tunnels between Cologne and Frankfurt (around 47 km in 30 tunnels), the CO_2 emissions for the steel and concrete production of the tunnel structures amount to more than 850,000 tons. Bridge structures as well as the tracks at ground level or even the previously mentioned "slab track" are not yet included here. According to another source, around three million cubic meters of concrete were used in the tunnel structures of this line, and 7.5 million cubic meters of additional excavated tunnel material had been produced (22). For the total earthwork, this source indicates the movement of 30 million m^3 of material plus eleven million m^3 of tunnel excavation.

The greenhouse gas emissions generated during tunnel construction for railways have been studied in even more detail for the Stuttgart 21 project (23). There, analyzing the exact structural, geological and topographical conditions, more than 27,000 t of CO_2 need to be calculated for each kilometer of tunnel tube, assuming single-track tunnel tubes in accordance with the planning. Based on these figures, at least 1.3 million t of CO_2 would have to be estimated for the tunnels of our above-mentioned example railway line.

Regardless of which sources exactly are used as a basis, it can easily be assumed that far more than one million tons of CO_2 were produced just for the steel and concrete production of this 170 km long stretch. As mentioned before, these are only the CO_2 emissions accrued to produce the materials mentioned; energy-intensive and therefore pollutant-intensive is of course also the transport of the materials to the construction site, which can extend over hundreds or even thousands of kilometers, depending on the production and usage site. In addition, all the materials still have to be installed. The usual energy supply on construction sites is, for lack of an alternative, diesel fuel for construction vehicles, machines and power generators; in view of the aforementioned quantities of material to be moved and against the background that over a construction period of seven years up to 15,000 people were simultaneously involved in building the track, using hundreds if not thousands of large construction machines, we are talking here about hundreds of thousands of machine days and accordingly tens of millions of liters of diesel fuel. In addition, the neighboring A3 highway had to be temporarily relocated in several places over a total of 15 km for the construction of the railway line, and permanent realignment was necessary over more than 8 km (24). The construction measures required for this, and the associated environmental pollution were also caused by the construction of the railway line and must therefore be added to the environmental balance sheet of this railroad track.

In total, for the completion of this reference track several million tons of CO_2 have been emitted as its climate-impacting footprint between 1995 and 2002, before the first train had ever run. Even though this is one of the busiest railway lines in Germany, with around 220 million passengers traveling on it in the first 15 years of operation, the CO_2 emissions per person and trip are still in the double-digit kg range, having been generated years or decades earlier during the construction of the line. Even if 500 million passengers were to travel on the line in 35 years, the CO_2 impact "per capita and trip" would then at best be in the higher single-digit kilogram range, especially because maintenance work on the line (rail grinding, tunnel rehabilitation work, etc.) with ever new impacts will also have to be added.

The rails will probably have to be completely replaced after about 30 years, which means that another 91,000 tons of CO_2 will have to be added to the bill. The durability of ballast and sleeper track beds is currently assumed to be 30 to 40 years, but so far there is no real empirical data on the durability of "slab track" available; expectations range from 10-20 years longer to 10 years shorter, compared with the "classic ballast bed". In any case, the expenses including the ecological and pollutant balances resulting from material production and construction are repeated over time. The ICE (Intercity Express) lines, on which the first ICE trains were in service in Germany at the end of the 1980s and early 1990s, are currently being factually entirely rebuilt after 30 years (rail, track bed, catenary masts, electrification and control technology) (25), (26).

Apart from the aforementioned example, a far more general analysis of the required materials on average to build railroad infrastructure is given in (27). 14,896 metric tons of gravel and sand (in the so-called subgrade layer) are always required for each kilometer of double-track high-speed line. Table 4 summarizes all the required materials and distinguishes between slab track and concrete sleepers with ballast.

	Material	Quantity / km	CO_2 / material	CO_2 (t/km)
Concrete sleepers with ballast	Gravel, sand, ballast	21,955 t	0.00485 t/t	106.48
	Concrete	380 m³	0.3 t/m³	114.0
	Steel / Iron parts	39 t	2.18 t/t	85.02
	Plastic	4 t	unknown	
	Sub-Total			**305.5**
Slab track	Gravel, sand	14,896 t	0.00485 t/t	72.2
	Concrete	2,264 m³	0.3 t/m³	679.2
	Reinforcing steel	133 t	2.18 t/t	289.9
	Sub-Total			**1,041.3**
Rails	Steel	241.4 t	2.18 t/t	**526.25**
Overall Total	**Concrete Sleepers: 832 t /km**		**Slab track: 1,568 t /km**	

Table 4: CO_2 footprint for one kilometer of double-track railroad (materials only, construction not included)

Adding the numbers, we end up roughly anywhere between 832 and 1,568 tons of CO_2 just for the materials for one kilometer of double-track railroad line; electrification, tunnels, bridges and the construction itself not yet considered.

Let us now have a look at bridges and tunnels. In (27), 15 different bridges for the new lines Hanover-Würzburg, Cologne-Frankfurt, Mannheim-Stuttgart and Nuremberg-Erfurt were examined. The following quantities of materials and excavated soil per meter of rail bridge were determined. The wide range of material quantities for different bridges is due to the fact that, in the case of bridges, the height has a major influence on the material quantities of the bridge piers to be built, and the respective subsoil also has a significant influence on the required foundation structures. For one kilometer of double-track railroad bridge we simply multiply the mean values by 1,000. For the excavated earth we only take into account that it needs to be put somewhere, hopefully to be reused again at a construction site not too far from where it has been excavated, so an optimistic guess is that it is transported only 10 km. However, even with today's large construction vehicles a 10 km ride is good for 1.45 kg CO_2 per m³ soil.

Material	Quantity per length		CO_2 /material	CO_2 (t/km)
	Range / m	Mean / km		
Steel	2.67 – 7.24 t	4,220 t	2.18 t/t	9,200
Concrete	17.5 – 48.3 m³	31.600 m³	0.3 t/m³	9,480
Excavated Earth	10.34 – 58.88 m³	27.750 m³	0.00145 t/m³	40
Avg. total emissions for 1 km double-track railroad bridge				**18,720**

Table 5: CO_2 footprint for one kilometer of double-track railroad bridge (materials only, no construction)

Adding it all up, we end up with close to 19,000 t CO_2 for one kilometer of railroad bridge structure.

The material consumption of railroad tunnels was also investigated. The following material consumption per meter of double-track rail tunnel was analyzed for the fifteen tunnels considered on newly built tracks in recent years. Once again, the wide range of materials for different tunnels is due to the fact that each tunnel is unique, the tunnel shell is highly dependent on the geological formation it cuts through.

Material	Quantity per length		CO_2 /material	CO_2 (t/km)
	Range / m	Mean / km		
Steel	up to 6.9 t	2,100 t	2.18 t/t	4,578
Concrete	11 – 79.6 m³	40,200 m³	0.3 t/m³	12,060
Excavated Earth	47.5 – 222.4 m³	127,400 m³	0.00145 t/m³	185
Avg. total emissions for 1 km double-track railroad tunnel				**16,823**

Table 6: CO_2 footprint for one kilometer of double-track railroad tunnel (materials only, no construction)

On average, we have more than 16,820 t CO_2 for one kilometer of railroad tunnel, and this is for tunnels holding two tracks. For security reasons, nowadays many tunnels only hold one track, so for a double-track line, two separate tunnels have to be built. For very long tunnel, even a third evacuation tunnel" is required in the middle of the other two. In single track tunnels, the tunnel diameter can be a bit smaller, so a little less material is required, but on average, if two tunnels for a double-track line are the solution of choice, more than 30,000 tons are on the CO_2 bill for each kilometer.

These numbers only reflect the CO_2 footprint of the materials used but many other aspects need to be considered. For example, there is the immense effort for the construction work. Tunnel drilling machines are among the hugest machines for civil engineering, up to 150 m long with a power consumption of 4,200 kW. For large tunnels, several of these machines are needed for years, drilling up to 18 hours each day. Depending on the primary energy they are operated with, such machines easily stand for two tons of CO_2 per hour of operation (28).

An instructive example of railroad tunnel infrastructure is the **Gotthard Base Tunnel**. According to the construction company AlpTransit, a total of 152 km of tunnel tubes were built for the approximately 57 km long section, and 4 million m³ of concrete with 1.4 million t of cement were used in the tunnel shell, as were 125,000 t of steel arches, 16,000 t of reinforcing steel and 3 million m² of steel nets (28) , (29), (30).

To put these numbers into perspective, we use the two following comparisons. The well-known **Eiffel Tower** in Paris is the first one; it is made of 10,100 tons of steel. **The overall amount of steel used for the Gotthard Base Tunnel is so enormous that more than 21 Eiffel Towers could have been built.** For our second, volume-based comparison we use the world's third largest pyramid, the **Pyramid of the Sun**, in Teotihuacán near Mexico City, built by the Aztecs almost two thousand years ago. This pyramid has a base area of almost 50,000 square meters, is 65 meters high, and has an overall volume of very close to 1,000,000 m³ (which is why it is good for a comparison). **From the overall amount of concrete used in the Gotthard Base Tunnel one could build more than four of these huge pyramids in solid concrete**. **The excavated material, pressed together so that there are absolutely no more gaps or spaces, would suffice to build more than 28 solid pyramids of this size**. These comparisons show imposingly the enormous amounts of material necessary to build route infrastructure.

Four tunnel drilling machines, each weighing thousands of tons have been in operation for 320 days a year, 18 hours a day, for 6 years. Such tunnel boring machines are true giants. The machines are up to 150 m long, have a drill head diameter of more than 9 meters (for an internal tunnel diameter of 8.20 m) and require a drive power between 3.500 kW and 4,200 kW. For a complete CO_2 assessment, for example, we also have to consider the CO_2 emissions from the manufacturing of the tunnel drilling machines and their transport/removal to and from the construction site. And the power to operate such machines and the related emissions need to be included as well. If this power is made available from the electricity grid, this results in more than 2 tons of CO_2 for every hour of operation of such machines just from the electricity production. In the case that electricity cannot be provided to the construction site, the energy supply would be Diesel fuel for power generators, as this is also needed for construction vehicles on site. It also has to be considered that in case of the Gotthard

Base Tunnel, the construction site had to be airconditioned during the entire construction work. Otherwise, none of the workers would have been able to work there, since the natural temperatures inside a mountain the size of the Gotthard, reach at least 45° Celsius (113° Fahrenheit). Air-conditioning during construction had to ensure that the workplace temperature did not exceed 28° C (83° F), (31), (32). CO_2 emissions for air-conditioning are enormous, for lack of sufficiently detailed data, they are not included in our calculations, but must not be ignored as they are unavoidable.

In the Gotthard Base Tunnel, 290 km of rails and 30 switches are laid on 131,000 m³ of concrete for the slab track and an additional 380,000 concrete sleepers on a ballast track. Here, too, it is immediately obvious that, already due to the materials used, a total of several million tons of CO_2 were emitted before the first train could pass through the tunnel. The plausibility of this statement can be checked again with the figures calculated in detail for Stuttgart21; at 27,000 t CO_2 per tunnel kilometer, this would result in more than 4 million t CO_2 for the Gotthard structure, well knowing that there is much more to come, but no detailed figures are available.

Electrification of a railroad track is also very material- and thus CO_2-intensive. The copper contact wire alone (120 mm² cross-section), which is commonly used on rail lines, weighs more than one ton per kilometer. As we have seen in Table 3 the copper production process generates almost 7 t of CO_2 per ton, not including the further processing of the pure metal into wires. The actual contact wire and the various holding and tensioning ropes, which are made of copper, bronze (copper-tin alloy) and steel, catenary poles including foundation require large amounts of concrete and steel. For industrial bronze, a CO_2 value of more than 7 t per ton of metal alloy is given in (15). In (27), the following material quantities are given for the electrification of a double-track high-speed line, whereby a distinction must be made between tunnels and outside of tunnels. In tunnels, no poles are required for electrification; the catenary wire can be attached directly to the tunnel lining by means of so-called suspension columns.

Double-track high-speed rail	**Material**	**Quantity /km**	**CO_2 (/ material)**	**CO_2 (t/km)**
Tunnel line	Copper	2.1 t	6,6 t/t	13.9
	Bronze	2.5 t	7.03 t/t	17.6
	Steel	6.6 t	2.18 t/t	14.4
	Aluminum	4.3 t	10.6 t/t	45.6
	Concrete	0,1 m³	0.3 t/m³	0.03
Total				**91.4**
Line outside tunnel with metal poles (steel) and concrete foundation	Copper	2.1 t	6,6 t/t	13.9
	Bronze	2.5 t	7.03 t/t	17.6
	Steel	51 t	2.18 t/t	111.2
	Aluminum	4.3 t	10.6 t/t	45.6
	Concrete	38,2 m³	0.3 t/m³	11.5
Total				**199.7**

Table 7: CO_2 footprint 1 km double-track railroad electrification (materials only, no construction)

The overall material-only CO_2 footprint for 1 km of double-track electrification for high-speed trains ranges from 90 tons inside tunnels to almost 200 tons outside tunnels. Tracks not designed for high-speed, are somewhat less demanding with regard to the required materials but are still good for 70 tons in tunnels and 174 tons of CO_2 otherwise.

To get an idea of the total material quantities required for the electrification of a high-speed line, some figures are presented here for the approximately 170 km **track between Cologne and Frankfurt**, which was built in the 1990s. 4,000 catenary poles, weighing between 1.5 and 2 tons each (33), were installed outside the tunnels, and 1,600 suspension columns in the tunnels. In total, around 3,300 km of wires, ropes and cables were required for electrification along the 170 km line (34).

Furthermore, it must be taken into account that a power supply network needs to be operated in the background to provide the electricity for the electrified rail lines. This high-voltage network usually has its own overhead pylons and hundreds of its own converter stations, rectifiers and transformers to transform the traction current to the specific voltage and cycles required for railroad operation, which are different from country to country (Germany 15kV and 16 2/3 Hz)[4]. All of this has to be built and maintained. In Germany, this power grid spans over more than 7,900 km (35), thousands of pylons built of steel with foundations of concrete, millions of tons of steel, enormous amounts of concrete and tens of thousands of tons of copper were needed to set this up. Although it is impossible to determine the exact amounts of CO_2 which were emitted over the years for this background electricity network, we have to note that the fact of not having any CO_2 coming out of the exhaust pipes where the train is operated, is not free of charge, but causes very large amounts of CO_2 in connection with the electrification infrastructure required instead.

Thus, it has to be analyzed very carefully, whether the electrification of already existing railroad tracks really has a positive effect on the overall and holistic CO_2 balance sheet. At the end of 2017, just under 54% of railway lines in Germany were electrified, about 21,000 km out of an approximately 38,000 km[5] (36). In connection with the required infrastructure, electrification leads to thousands of tons of CO_2 emissions during construction, maintenance and occasional renewal (25). It takes substantial train traffic over a very long time to justify the CO_2 emissions occurring during construction, which of course need to be broken down on PKM and TKM, respectively.

The complete CO_2 emissions of the entire track infrastructure for railway systems cannot really be determined in retrospect without exact knowledge of the materials used in construction. However, based on the analysis of several representative lines, it can be assumed that CO_2 emissions of several hundred tons (non-electrified lines without bridges and tunnel structures) to tens of thousands of tons (high-speed lines on bridges and in tunnel structures) occur for each line kilometer. Even on lines with a very high utilization, CO_2 emissions in the mid to upper double-digit gram range are the result for each PKM (assumption: 3-4 million t CO_2 for the Cologne-Frankfurt construction project corresponds to around 80-106 g/PKM for 220 million passengers and 35-47 g/PKM for 500 million passengers). Necessary maintenance work and repairs as well as complete refurbishment after appropriate use are not yet taken into account here.

2.1.2 *Route infrastructure for cars*

For the assessment of road infrastructures, similar results as for railway are to be expected, whereby the already mentioned distinction between highways and municipal roads needs to be made.

The road infrastructure between Cologne and Frankfurt includes 174 km of the A3 autobahn, which has at least six lanes throughout this stretch. This corresponds to a paved area of 29 meters in cross-section (37) over the entire length, i.e., a good five million m^2. Assuming a concrete surface layer of 30 cm, which is not uncommon for heavily trafficked highways (38), more than 1.5 million m^3 of concrete are required for this surface layer alone, for which more than 375,000 t of CO_2 have been released during production. The construction of the route, the roadbed, on- and off-ramps, parking and rest areas, and all the bridges (made of reinforced concrete) still must be considered additionally, and of course, as with the railroad tracks, all the years of construction work. Impressive figures are also obtained for such “add-ons” as the crash barriers (guard rails) commonly used on highways in Germany: 4 meters of guard rail, including posts, are on the bill with 55 to 60 kg of steel, depending

[4] Worldwide, dozens of different railway electrification systems have been developed over the years (106). Even in Europe, four major electrification systems, ranging from 1.5 kV DC and 3 kV DC to 15 kV AC 16 2/3 Hz and 25 kV AC 50 Hz, require additional effort on electric engines providing cross-border services (107).
[5] This number represents the overall length of all railway tracks in Germany. It differs from the length of the operated railway network.

on the profile (39). For one kilometer, that is between 14 and 15 metric tons per guard rail, and for a complete freeway up to 60 metric tons per kilometer since each direction of travel is often secured on both sides. For the 174 km of the A3, this adds up to around 10,000 t of steel just for the crash barriers, for which 20,000 t of CO_2 are likely to have been emitted from the blast furnace and coke plant process alone.

In the event that roads are routed through tunnels, very similar CO_2 emission values apply to road tunnel construction as for railway tunnels, since the materials (steel and concrete) are the same. Ultimately, the decisive factors are the overall quantities, which are mainly determined by geological and topographical parameters, as well as the effort involved in drilling the tunnel tubes. When comparing railway and road, it must be understood that trains can only cope with significantly lower gradients, i.e., terrain inclination, compared to motor vehicles. In very hilly or even mountainous topography, railway lines therefore require much more and longer tunnels than highways. The A3 on the Cologne-Frankfurt route for example, has no tunnels at all, while the parallel railway line has around 47 kilometers of tunnels, which is more than 27% of the overall lines. For the same reason, valley-spanning bridges for railway lines are usually considerably longer than the viaducts of parallel highways. A comparison of the Zurich-Milan route makes this clear: In addition to the Gotthard Base Tunnel, trains travel through two further tunnels of around 15.5 km (Ceneri) and a good 7 km (Olimpino) in length, plus many smaller and medium-sized tunnels, so that a total tunnel section of more than 90 km in length is traversed. For the road infrastructure, the total length of the tunnels is less than 50 km, with the total length of the bridges on the road exceeding those on the railroad line by almost 8 km.

The total GHG emissions of the entire route infrastructure for roads, similar to rail, can only be roughly estimated in retrospect. Due to the materials used (concrete, asphalt, steel, etc.) and depending on the number of lanes, each kilometer of roadway generates CO_2 emissions ranging from several hundred tons to tens of thousands of tons (large viaducts and in tunnel structures). Depending on the exact routing, the level of expansion of the road and the capacity utilization, CO_2 emissions will also be in the double-digit gram range per PKM. Necessary maintenance work and repairs as well as complete refurbishment after appropriate use also need to be added over time, just as in railway transport. In view of the fact that the total traffic volume of road transport is 10 times higher than that of railway transport, the relatively smaller number of tunnels and the lack of electrification (see sec. 4.4), it can be assumed that the CO_2 pollution caused by the infrastructure of the highways per PKM is lower on average than for the comparable railway system.

In connection with the current intensive discussion on electromobility, it is also imperative to consider the amount of CO_2 that is emitted to set up a sufficient network of charging stations when looking at the envisioned road infrastructure. While the production of these charging stations and their installation must be fully taken into account, it is equally important to factor in the effort to provide the power supply for them. In populated areas for instance, it can be assumed that the nearest power line is not far from the location of the charging station, so that it is only necessary to check whether the additionally required quantities of electricity can be made available by means of the already existing electricity infrastructure. Even with fundamentally good conditions in cities, the example of Tübingen shows that the necessary charging infrastructure for electromobility is not always easy to provide (40). As especially long-distance highways are often located in rural areas, such infrastructure will have to be completely built from scratch in many cases. Existing rest areas on highways and trunk roads, even if there is light for basic facilities, do not necessarily have the sufficient electric infrastructure to charge two or three electric cars simultaneously.

2.1.3 *Route infrastructure for aircraft*

For the aviation transport system, considerations of route infrastructure are easily concluded: it is simply not needed; as the air “is simply there” no route infrastructure needs to be built, nor does it need any maintenance. This is a system-inherent advantage of aviation that plays an important role in a holistic view.

2.1.4 *Allocating CO_2 emissions from route infrastructure to traffic performance in PKM*

Now that we have seen the enormous amounts of CO_2 generated by the construction of route infrastructure, we need to find a way to allocate this to transportation performance in PKM. This is easy for aviation: zero CO_2 remains zero, regardless of how many PKM are traveled in the air.

Emissions from the path infrastructure only apply to travel by train and car. An exact allocation would require specific information on the exact amount of CO_2 emitted for a particular road or train track, its lifetime, the emissions generated by maintenance work and of course the exact traffic performance in PKM. None of this information is available.

For railroad traffic, we do have information for CO_2 emissions from building the trains' route infrastructure as described in section 2.1.1. Some assumptions have now to be made when trying to break down these numbers to come to a reasonable estimate for the CO_2 footprint per PKM that results from providing the railroad infrastructure. Since the infrastructure-based CO_2 footprint per PKM is highly impacted by the usage time of the infrastructure and the number of passengers over the years, and since such numbers are not available in required detail anywhere, we once again have to use educated approximations derived from available material. We have already stated that high-speed lines including their electrification have to be replaced after 30 years. Thus, we assume 30 years as a realistic time frame to appraise the CO_2 derived from building the track.

However, for structures like bridges and tunnels, 70 years seem to be a realistic time frame, as they last longer than 30 years. With this being stated, we now have to look at the overall traffic performance per year. Unfortunately, railroad companies do not provide such numbers, so another approach is required. What is known are the figures from Table 3, that roughly 96bn PKM are the overall annual railroad transportation performance (in Germany). This traffic is managed on a rail network of roughly 33.000 km. A simple calculation results in 2,9 million PKM per kilometer railway infrastructure; for ease of use we simply assume that 3 million PKM are performed on each kilometer. We should note that this assumption implies that all railroads are used equally, which is definitely not the case. However, due to the lack of data we consider it as our best reasonable alternative for calculations.

We also assume that almost 1,800 t of CO_2 were emitted per kilometer when the track including electrification was built. Utilization of approximately 30 years results in roughly 60 t CO_2 per year of usage, with 3 million PKM served each year, we have 20 grams CO_2 per PKM just for the railroad infrastructure. This number seems somewhat reasonable and leaves a positive first impression, but we have not considered tunnels and bridges yet.

For one kilometer of a single-track tunnel (which is standard for high-speed trains today to comply with safety regulations) almost 32,000 tons of CO_2 are emitted during the construction phase. Using the tunnel over a period of 70 years we have roughly 457 tons of CO_2 attributed to each year; with 3,000,000 PKM per year we need to add 152 grams of CO_2 for each PKM to our balance sheet, in addition to the 20 grams we already have for the track and electrification.

Railroad bridges have a similar footprint. 22,166 tons of CO_2 per kilometer during construction distributed over a utilization time of 70 years results in 317 tons per year. Breaking it down to 3,000,000 PKM results in 106 grams of CO_2 per PKM; once again, the 20 grams for track and electrification still come on top.

As a result, we are looking at CO_2 emissions resulting from the infrastructure construction of 20 grams per PKM in the very best case for simple tracks in the field, 126 grams per PKM on bridges, and 172 grams of CO_2 per PKM in tunnels.

It should be noted that these calculations change drastically, when we alter our assumptions about usage, e.g., the annual traffic performance. However, we started with an average value, derived from the overall transportation volume divided by the size of the overall network. If we increase the traffic on one track, this must result in a decrease of traffic on another track.

Next, we would also have to know exactly how many kilometers of a specific trip go through tunnels and across bridges. The German rail network of 33,000 km includes a total of more than 25,000 bridges, most of which are rather short, just spanning roads, streams and small rivers, but the longest extends to more than 8.6 km; and the tallest bridge spans the Wupper valley more than 100 m above the river. On average, we have a bridge structure after 1.3 km of railroad track. For tunnels, the situation in Germany is the following: There are about 760 tunnel structures with an overall length of more than 750 kilometers, 2.3% of the overall rail network.

However, neither bridges nor tunnels are evenly distributed; high-speed lines have far more of both. For example, the high-speed track between Cologne and Frankfurt is 180 km long, 46 kilometers are in tunnels, 25% of the overall track. Six kilometers are on large valley-spanning bridges, 3.3% of the track. For the remaining 130 km we have to assume that there are approximately another 100 small bridges.

We can see that bridge- and tunnel-intensive high-speed lines in particular can have an extreme CO_2 impact per PKM. Unfortunately, there is a lack of more precise data to make more concrete statements in this regard. In order not to slip too far into speculation and thus dilute the value of the previous work, we will leave it at this point with the general considerations outlined. For the future, it seems urgently necessary to determine concrete figures in order to be able to specify route-specific CO2 emissions.

As one example, a few years ago we carried out specific comparative calculations for the Zurich - Milan route. For the two land-based transport systems, rail and road, the CO_2 emissions generated during the construction of the road infrastructure were estimated and converted to the traffic volume in PKM, assuming decades of use. The results were very surprising, and the publication caused quite a stir (41). In a holistic view of CO_2 emissions, the airplane was the most efficient means of transport, although the emissions resulting from the drive energy were significantly higher than for cars or trains. However, the immense emissions from the construction of the extremely tunnel- and bridge-intensive route infrastructure meant that land-based transportation systems performed worse overall.

2.1.5 *Interim conclusion for route infrastructure*

The route infrastructure for road and railway transport causes CO_2 emissions far too large to ignore. Not taking into account the amounts of CO_2 caused by the construction and maintenance of this infrastructure leads to a distorted picture in the ecological assessment. The CO_2 footprint is higher for the more demanding tracks for high-speed trains and for tracks which require many bridges and tunnels because they lead through topographically challenging terrain.

It should be noted that infrastructure which has already been built, should be used as much and as efficiently as possible, the better the utilization the lower the CO_2 value per PKM. However, what we currently see happening in many countries is an extreme effort to build new railroad tracks, especially for high-speed trains. This is justified by the supposedly low CO_2 emissions of rail transport, which, however, ignores the immense emissions from the construction of the route infrastructure.

2.2 *Node infrastructure*

In order to get a fully comprehensive assessment for the respective infrastructure components, all (energy and pollution) costs associated with the construction, maintenance, and operation (heating, air conditioning, lighting, cleaning, etc.) of the facilities where travelers begin and end their trip or transfer to another transportation system must be considered.

For the 966 billion passenger kilometers (PKM) per year in motorized individual transport (MIT) mentioned earlier, around 48.5 million cars and vans are on the road in Germany. Assuming an average parking space of 12.5 m^2 per vehicle, the total parking space required in Germany would be well over 600 km^2 if all vehicles were parked at the same time. To put this into perspective: Cologne's entire urban area covers just over 400 km^2, Frankfurt's only just under 250 km^2 (42). Even though a considerable part of this required parking space is on private property, parking space in metropolitan areas is a scarce commodity these days.

Multi-story parking garages are nowadays often built as steel skeleton structures, while older parking garages and especially underground garages are usually made of reinforced concrete. Due to the CO_2 emissions already described, which had been produced during the manufacturing of these materials, we are dealing here with CO_2 quantities in the single-digit ton range per parking space.

The overall ecological consideration of the node infrastructure for road traffic must also include the additional pollution, which occurs when drivers are looking for a place to park their vehicles. It is increasingly reported from large cities that residents, in particular those without their own permanent parking space, spend minutes on the road, traveling significant distances to find a parking space. Since the search for a parking space is a stretch that is not part of the intended route from the starting point to the destination, it is useful to keep in mind that even such a "parking space search journey" of 1km in length is producing 118 g of CO_2 (33 g from vehicle production, 85 g from drive energy, as shown in sec. 4.4). A publication by DEKRA from 2016 states that the average parking space search takes 10 minutes and that an average of 4.5 km is driven during this time (43). The topic of "parking" has already been covered in more detail by Prognos on behalf of the VDA (German Association of the Automotive Industry) and FAT (Forschungsvereinigung Automobiltechnik e.V.) (44).

In railway transport, the node infrastructure in Germany includes approximately 5,700 train stations (45) and in aviation, correspondingly, all airports. In each case, both the construction and the energy consumption during operation must be taken into account. What quantities of CO_2 were produced during the construction of the station buildings, the thousands of concrete and stone platforms (more than 400 meters long for ICE stations), the underpasses beneath the tracks, the escalators and elevators, etc.? There are no generally valid answers to these questions in retrospect for the many stations built before and from the 1950s onward, which is why this study focusses on examples from the present.

For the project to put Stuttgart's main station 30 m underground, CO_2 emissions resulting only from concrete and steel production are estimated to be around 1.9 million metric tons (46). Other sources calculate the total CO_2 emissions for this project even significantly higher. Regardless of whether we are talking about around 2 or 3.5 million tons of CO_2, these are CO_2 quantities that have a significant impact on the overall eco-balance of railway as a mode of transport, regardless of how many people will use this station as the starting point, transfer point or end point of their railway journey in the coming decades. Of course, the 1.9 million t CO_2 for concrete and steel at Stuttgart 21 cannot be generalized, as the complete relocation of a large train station underground is not an everyday measure. However, it clearly shows the order of magnitude of CO_2 emissions to be considered in individual cases, which have simply been ignored in the ecological discussion to date. If the station continues to be used regularly by 225,000 passengers a day in the future, after more than 20 years there will still be 1 kg of CO_2 per station user on the eco-balance from the construction phase only (without looking at any repair or maintenance measures etc.) and, of course, without any specific transport volume having been provided yet.

The following is some further relevant information for general consideration. Platforms for the ICE high-speed train are around 400 meters long and, according to current specifications, they should be designed to be barrier-free so that passengers can board the train without steps. To achieve this, the platforms must be 76 cm above the top of rail. The platforms are usually made of reinforced concrete blocks on which concrete interlocking paving is laid. If you calculate a platform width of 5 meters, the information given above already results in more than 1,500 m³ of concrete for a single ICE platform. Platform foundations and special constructions, if the platforms of a station are connected via underground tunnels, require further CO_2-intensive construction measures. Escalators and elevators, which are common on modern train stations, add further amounts of CO_2. Even without specific information it becomes apparent that thousands of tons of CO_2 will be emitted on the material production side for train stations.

However, train station infrastructure needs to be operated year-round and at least a few numbers are available here. The annual electricity demand for stations of Deutsche Bahn for 2019 is estimated at 331 GWh (36), which results in about 189,000 t CO_2. Converted to the PKM performed in one year, this results in about 2.3 grams CO_2 for each PKM travelled.

For airports, there are also no comprehensive figures and data on this subject available, that would allow fully dependable calculations. It is for instance obvious that especially the construction (and even reconstruction before completion) of the new Berlin-Brandenburg airport, which was delayed for almost 10 years, will have caused enormous amounts of CO_2 before it went into operation. Regarding runways at airports, the following considerations and estimates apply: Corresponding to the size of the aircraft serving an airport, longer runways are usually 45m or 60m wide; if there are several runways, there are sometimes shorter runways with a width of 30m. The length is usually between 3,000 m and 4,000 m. A single, 4,000 m long and 60 m wide runway has a surface area of 240,000 m²; assuming a concrete pavement of 0.5 m, this results in 120,000 m³ of concrete, which will have caused about 42,000 t of CO_2 during production. The huge apron areas of airports can be roughly estimated in the same way. In (27) the overall sealed area of Frankfurt Rhein-Main Airport is specified as 8.91 million m². Assuming that a concrete layer of 0.5 m is laid out over this complete area, we would have almost 4.5 million m³ of concrete, and thus way over 1.3 million tons of CO_2 just for the concrete production over the years the airport was built and expanded.

The energy required to operate airports is also considerable. Since there is no single operator for airports in Germany, unlike for train stations, there are no practical figures available on the total energy consumption and the resulting emissions of all German airports. For Germany's largest airport, Frankfurt, the operator Fraport reports the total CO_2 emissions for 2018 adding up to 188,600 t (47)[6]. It needs to be noted that this number includes CO_2 emissions attributable to the electricity consumption, heating and air conditioning of many administrative buildings and offices located at the airport as well. Fraport's CO_2 emissions for the airport are offset by around 220 billion PKM counted cumulatively (arriving and departing) at Frankfurt in 2018. Since each flight requires two airports as hub infrastructure, the emissions are to be set in relation to half of the total PKM; roughly, this results in 1.7 g CO_2/PKM from the operation of the hub infrastructure at Frankfurt Airport.

In the case of large train stations and airports, proper care must be taken to separate the infrastructure required to provide the transportation from the "shopping mall and conference infrastructure" that is often also located there. It would be methodologically inaccurate to include the emissions resulting from the construction and operation of hundreds of stores, restaurants and, in some cases,

[6] Fraport reports these and other figures based on the internationally recognized *Scope 3 standard of* the *Greenhouse Gas Protocol (GHG Scope 3)* (103), *which* was developed by the *World Resources Institute (WRI)* and the *World Business Council for Sustainable Development (WBCSD)* (104), (105).

large conference centers in the emissions directly attributable to the transport, even if they are there for specific logistically understandable reasons of practicality.

For both railroad stations and airports, it must of course also be taken into account that regular maintenance and repairs are required permanently. Additional CO_2 emissions result from such activities, which have to be broken down according to the traffic volume in order to get a CO_2 value per PKM.

2.2.1 *Interim conclusion for node infrastructure*

Considerations and calculations regarding CO_2 emissions for the construction and operation of (any) node infrastructure have – as far as we can see - not been common or regularly carried out so far. They are however clearly necessary for a holistic view on environmental cost, because the construction and creation of node infrastructure regularly results in very large amounts of emissions. Further research on this topic will help to better understand it in the future. However, the CO_2 emissions from the operation of node infrastructure are quite impressive in total, but they only account for a small part of the CO_2 footprint for mobility when apportioned to PKM.

2.3 *Control infrastructure*

Very few numbers are also available for the CO_2 emissions caused by the control infrastructure of transportation systems.

In railway transport, this relates to the construction and operation of switching boxes (interlocking systems) as well as all systems required to control switches and signals on the railroad track. The German railroad company's (Deutsche Bahn) energy requirements for interlockings, switch control, and signaling systems amount to 196 GWh in 2019, another 131.5 GWh need to be added for weather-dependent switch heating in the same year (48). If the resulting 170,000 t of CO_2 are applied to the PKM performed in long-distance and regional railway transport (adapted to the specific energy distribution of these business segments), the result is 1.1 g/PKM in long-distance and 2.0 g/PKM in regional transport.

In the field of aviation, all systems used to coordinate and control flight operations on the ground at airports and in the air need to be considered: RADAR and radio equipment, ILS (instrument landing systems) and all other systems used by pilots and air traffic controllers for this purpose. German Air Traffic Control (DFS) provides the following figures on its annual energy consumption (49): 23 GWh of electricity are generated in a gas-fired combined heat and power plant (CHP), and an additional 47 GWh of electricity is purchased externally. Assuming the German electricity mix for the purchased electricity (0.518 kg CO_2/kWh in 2019) as well as the CO_2 value for energy generation in combined heat and power plants (0.202 kg CO_2/kWh), a CO_2 quantity of approximately 29,000 tons per year can be calculated for the total electricity required at DFS. This figure also includes the electricity for all DFS buildings, four control centers, the control towers at the airports and all radar, navigation and communication systems. As the DFS-owned CHP plant is a combined heat, power and cooling plant, it also generates hot and cold water for air conditioning, heating and long-district heating from 22 GWh of natural gas (4,444 t CO_2), which together then amounts to the annual CO_2 footprint of DFS to be estimated at around 33,500 tons. Such large number of pollutants in absolute terms needs to be contrasted with the 10.3 billion PKM of domestic air traffic, and also with the approximately 475 billion PKM of international arriving and departing traffic at and from German airports. DFS also controls some of the international air traffic in German (and in some cases European) airspace without directly touching German airports. Due to a lack of data, it is not possible to reliably determine the share of this traffic that can be attributed to the control activities of DFS. However, if we assume that, in addition to domestic German traffic, around 10% of the international traffic arriving and departing from German airports could be allocated to DFS for control purposes, this will add to around 47.5 billion PKM. If we further assume that the same traffic volume is controlled for international overflights, the annual 33,500 t CO_2 footprint from the energy consumption of DFS would be equivalent to around 105 billion PKM. This then corresponds to around 0.3 g CO_2/PKM, which would be attributable to the control infrastructure in the aviation transport system. Even if the CO_2 value of the electricity mix in Germany (518 g/kWh in 2019) is assumed for the total electricity consumed at DFS over the course of a year and the total CO_2 emissions caused by DFS thus increase to just under 41,000 t, the CO_2 emissions remain below 0.4 g/PKM.

In road traffic, traffic control is primarily based on traffic signs and traffic lights. In Germany, more than 2 million traffic signs and around 300,000 additional information signs are installed along the roads; the number of “traffic lights systems” is in the tens of thousands, with an even incomparably larger number of singular traffic lights.

Traffic signs are usually aluminum plates coated with various foils. New signs are erected daily, existing signs are constantly replaced or exchanged, both permanently or for short-term measures such as temporary detours or construction sites. In the simplest case, a pole made of aluminum or galvanized steel anchored in a concrete foundation is required for posting. On a larger scale, e.g., German highways, oftentimes much larger constructions have to be used, such as overarching sign gantries that need to stand on appropriately sized concrete foundations. A single round traffic sign with a plate thickness of 2mm and a diameter of 60cm (e.g., no stopping or parking, no through traffic, bicycle or pedestrian path, etc.) consists of slightly more than 1.5 kg of aluminum. The production of the primary aluminum alone generates 12 to 15 kg of CO_2. (7). This does not yet account for the further processing to produce the corresponding sheet metal or the actual production of the sign with foil and reflective surfaces.

Traffic signal systems and controls must be built, set up, programmed, and regularly maintained and operated. Figures indicating the total electricity consumption of all traffic lights in Germany could not be researched. For the city of Hamburg, the electricity consumption of the traffic lights installed in the city was reported to be more than 8.5 GWh in 2015, with a decreasing trend compared to previous years as existing traffic lights were successively replaced with more energy-efficient models (50). Assuming the electricity mix and the resulting CO_2 emissions of 0.57 kg / kWh from 2016, the electricity consumption of Hamburg's traffic lights alone resulted in a CO_2 impact of more than 4.8 tons in 2015.

2.3.1 *Interim conclusion for control infrastructure*

In comparison with the other infrastructure components, the analyses carried out for the control infrastructure suggest that the resulting CO_2 emissions per PKM are rather low. However, it must be noted that all numbers presented so far regarding the electricity consumption of the control infrastructure are only about its mere operation; of course, such systems and equipment must first be built and installed, which also involves substantial GHG emissions. For a holistic assessment, it will be necessary to consistently determine these emissions in the future and appropriately allocate them to the respective transport system.

3 CO_2 emissions during production of means of transport

Which resources and what energy are needed to build a train, a car or an airplane? What ecological impact does this have exactly? Once the means of transport is ready for use, another criterion is what transport volume it will provide during its entire (product) life. Since all technical systems also must undergo (sometimes even significant or constant) maintenance during their life span, these “costs” must also be taken into account, including the costs of repairs, spare parts, etc.

The manufacturers of a product can usually give at least an estimated indication of the percentage of their products' share that is made of steel, aluminum, CRP[7] components, plastics and other materials; often times there even exists at least a rough assessment of the life cycle of the respective materials and their ecological footprint. If we then distribute the energy used in the production itself over the output, we get an approximate overview of the overall energy costs and environmentally harmful factors of the respective means of transport.

The following example illustrates how complex these issues sometimes can be: A German car manufacturer produces a vehicle, in which the body is no longer primarily made of steel and aluminum but of CRP. The starting fiber for this comes from Japan and is transported from there to the American West Coast, where a first refining step is carried out. From there it goes to a specialized plant in Wackersdorf, Germany, where the fibers are fitted into corresponding mats, which are then impregnated with synthetic resin at the manufacturing plant in Saxony and finally pressed into the respective molds. According to the company, meticulous care is taken throughout this production process to ensure that it is as energy efficient as possible; wherever renewable energy can be used, it is. However, in order to be able to consistently determine the complete CO_2 emissions for the production of the CRP components ultimately used in the vehicle, the relevant figures and data from all four globally spread production sites for these CRP components, including all transport related emissions between the sites, would have to be taken into account. At present, realistic figures for such complex processes and operations are simply not available.

Despite the complexity described above, there are a few initial and approximative studies for these topics. One was carried out by the Institute for Energy and Environmental Research in Heidelberg (IFEU) together with the German Automobile Club (ADAC); for an upper mid-range car, it was calculated that a total of about 8 t of CO_2 is produced during <u>production and proper recycling</u> (51). Another survey differentiates between Diesel and gasoline engines and puts a „price tag" of 8.54 tons for Diesel and 7.81 tons of CO_2 otherwise on the vehicle production (52).

For the increasing numbers of electric vehicles, the life cycle assessment of battery production will also have to be included in such a calculation. In recent years, this has led to considerable debate among proponents and skeptics of electro mobility. In 2017, the Swedish environmental research institute IVL published an initial study on the CO_2 impact of the production of batteries for electric vehicles. It concluded on a value of 150 to 200 kg of CO_2 per kWh of battery power. According to this, a battery with a capacity of 50 kWh had a CO_2 impact of 7.5 to 10 tons; for larger batteries with 100 kWh, which are used in large electric SUVs or in vehicles of the American market leader for e-mobility, the battery production alone already accounted for 15 to 20 tons of CO_2. In 2019, a n updated version of this study has been published by IVL (53), in which a value of between 61 and 106 kg CO_2/kWh of battery capacity was given for most new battery types[8]. Those improvements are due on the one hand to innovations in manufacturing, and on the other hand to the fact that the electricity for battery production at some locations was generated almost 100% without fossil fuels, which however then does not promise any further improvements in this respect for the future. In addition, the recent version of the study already also factors in positive assumptions regarding the recycling or further use of the batteries when they are no longer suitable for use in the electric car. However, the total CO_2 emitted in the production of a car is currently higher for an e-car than for a car of comparable size with an internal combustion engine due to the high CO_2 emissions in battery production.

For the following considerations, we will stick to a value of 8 t CO_2. Statistically, in Germany such vehicle drives approx. 160,000 km during its lifetime, so that the CO_2 costs incurred in production amount to an additional 50 g for each vehicle kilometer driven. Since cars in Germany (and most European countries) are only occupied by 1.5 people on average (18), this results in a comparatively

[7] Carbon fiber Reinforced Plastic
[8] The highly emotional discussion that followed the publication of the first study has not helped to objectify the ideologically driven dispute between different groups in any way.

low transport volume of 240,000 PKM; we therefore have **33 grams of CO_2 just from the vehicle production for one single passenger kilometer driven,** which must be considered in the overall balance of motorized individual transport (MIT).

Corresponding analyses and calculations will also have to be carried out for the CO2 emissions from the production of trains and aircraft. Despite intensive research, no reliable figures could be compiled for those, which is why we will have to make do with an estimate. Plausibility considerations lead to the conclusion that the total quantity of materials required for the train or aircraft is a very significant parameter and thus the empty weight of the means of transport provides an initial indication of its CO_2 footprint from manufacturing.

In any case, the amounts of CO_2 involved in building a train or an airplane will be disproportionately larger than for a passenger car, and they will definitely be in the three-, four-, possibly five-digit ton range. On the other side, we are talking about transport volumes of hundreds of millions or billions of PKM. An Inter-City-Express train (ICE, high speed train in Germany) is designed for a service life of 25 years and covers around 500,000 km per year, which then leads to a total mileage of 12.5 million km (54). If you take into account the number of seats and the average capacity utilization (55), (56), this results in slightly more than 3.1 billion PKM, to which the CO_2 quantities from production, maintenance and proper disposal must be allocated appropriately. The ICE 3 has a dead weight of 408 tons and thus weighs about as much as 270 mid-size cars, three modern long-haul jets or eight medium-haul aircraft. The almost 13,000 times higher traffic performance of the ICE compared to a single passenger car contrast with the merely 270 times higher mass that is supposed to serve as a plausible order of magnitude for GHG emissions. Based on such preliminary figures, it can therefore be concluded that the CO_2 share from the production of an ICE per PKM must be significantly lower than the 33 g/PKM for a passenger car.

A passenger aircraft can travel up to 375,000 km over a month (57). Considering the number of seats and average load factor, this results in more than 111 million PKM per month. Assuming that the aircraft can fly for about 11 months a year (one month is estimated for maintenance work) and further assuming a service life of 25 years, this would add up to tens of billions of PKM, or even more than 30 billion PKM in a specific case (57). And even a plane mainly used for shorter, domestic or European flights, such as aircraft in the A320 family, will easily have an overall transportation performance of 4-6 billion PKM during their life, sometimes even more. Again, there are unfortunately no figures available from the aircraft manufacturing industry for the quantities of CO_2 generated during production. A typical medium-haul aircraft, such as the Airbus A321, has an empty weight of 47.5 tons (58), (59), (60), which is roughly equivalent to the weight of 32 average passenger cars. However, over the course of the aircraft's life, traffic volume is in the range of many billions of PKM, so that the CO_2 emissions from the construction of the aircraft to be credited to each PKM will be significantly lower than in road or railway transport.

3.1.1 *Interim conclusion for the production of means of transport*

In summary, it can be stated that it is obviously advantageous for the efficiency of any transport system if the specific transport volume provided by a single means of transport is as high as possible over its period of use, as the energy and pollutant costs from the production and maintenance of the means of transport can be distributed over as many passenger kilometers as possible. All the transport systems considered here have in common that the means of transport need to be serviced regularly during their lifetime. The effort required for this, which also causes CO_2 emissions, has so far not been considered at all. Nevertheless, this will not change the earlier conclusion that cars have the largest CO_2 footprint due to their comparatively low transport volume in comparison with trains and, above all, aircraft; on the contrary, the value of 33 g/PKM will become even larger.

4 Mechanical motion efficiency and energy supply

All calculations including the underlying physical formulas described in this section are further detailed in the appendix. At this point, only the basic facts, overall context and some results are presented.

For further consideration, it is helpful to recall some basics (from the high-school physics class): The key parameters for the drive energy required in any transport processes are the **speed** at which the vehicle moves, the **total mass to be moved,** the **acceleration processes** that occur in the course of the transport, and the **lifting work,** i.e., the work to be performed in the transport process to overcome gravity.

The first step is to calculate the total masses to be moved, which play a decisive role for all further considerations. More precisely: What is the total mass that must be moved to transport one person?

The average automobile registered in Germany currently has an approximate weight of 1.5 tons per vehicle. As the vehicles are only occupied by 1.5 persons on average, a vehicle weight of around 1,000 kg/person can be assumed.

In the case of trains, again the ICE 3 shall serve as an example, which has an empty mass of 408 tons and, depending on the series, 425-460 seats; hence, assuming average load factors of 55% (2017) and 56% (2019), almost 1.7 tons of train weight per passenger must be moved (56), (61). Even at full capacity of the trains, there are 935 kg of train weight for each passenger to be moved.

In Switzerland, whose railway system is considered one of the very best in international comparison, the analysis provides very surprising numbers. For example, the SBB RABe 502 (aka FV-Dosto, TWINDEXX Express) from Bombardier, which has been in service since 2018, represents an empty mass of 453 tons, a length of 200 m, and 606 seats in double-decker cars (62). If the train is fully occupied, around 750 kg of train weight per passenger will be moved, which would be better than a German ICE 3. However, if we consider the SBB's average seat occupancy rate of 2019 of just 28.9% (63), the train weight has to be distributed among only 175 passengers, so that almost 2.6 tons of train weight had to be moved for each passenger. The punctuality of Swiss trains is certainly exemplary, but the mechanical movement efficiency, which is decisive for energy consumption, is - based on these figures - definitely not.

The ratio between payload and total mass to be moved is no better in Germany's regional and commuter railway sector. Trains frequently used there have empty masses of between 120 t and 168 t (64). Based on the figures given by Deutsche Bahn for train kilometers, passenger kilometers and seats in the trains, the average load factor for the RE8 (RB27) between Koblenz and Mönchengladbach, for example, is 44% - 53%, attributed to the part of the route that belongs to the Rhineland Regional Transport System in North Rhine-Westphalia (65). (No figures are available for capacity utilization on this line for the section in Rhineland-Palatinate; it must be assumed to be lower, as this is a much less densely populated area). Hence, even with the aforementioned average load factor, train weights of significantly more than 1 t per passenger are realistic to assume (64). Since, especially in regional and local traffic, train utilization depends very much on the time of day, there are higher load factors for four to five hours a day, but for around 10 hours a day, often only 20 or 30 passengers are transported in trains with unloaded weights well in excess of 100 t.

What about the weight regarding aircraft? The Airbus A321 mentioned earlier has an empty weight of 47.5 t; distributed over the two hundred seats and the average load factor of around 82% (66), here "only" 290 kg of aircraft weight fly along for each passenger.

Yet another complication: In the case of airplanes and cars, it must also be considered that the operating energy in the form of fuel must also completely be carried within the respective means of transport. Since aircraft in domestic traffic are not refueled after every short flight, we assume that the tanks are filled to half capacity on average, which, with a tank volume of the A321 of 23,700 liters (l) and a kerosene weight of 0.785 kg/l (59) adds up to a weight of about 57 kg of kerosene per passenger. For a car, we make the same assumptions: 60 liters tank, half filled, gives a value of 17 kg fuel carried per person on average. If we further assume that a person, including luggage, carries a "payload" of 100 kg, irrespective of the means of transport, we have the following average total masses to move: motor vehicle: 1,117 kg/person; ICE 3: 1,800 kg/person; Airbus A321: 447 kg/person.

These figures already show the significant differences in the movement efficiency of the different transport systems, where the **total mass to be moved is one of the decisive variables** in the further calculations.

4.1 *Acceleration*

The energy required for acceleration is determined by the mass and the final velocity (in m/sec) of the vessel, with the energy requirement increasing quadratically with the velocity to be achieved.

Above, we have already determined the total mass to be accelerated per person, so that we can directly derive the necessary acceleration energy per single person from this.

Car:	1,117 kg accelerate to 36.1 m/ sec (130 km/h) →	728 kJ (kilojoules)
Train:	1,800 kg accelerate to 69.4 m/sec (250 km/h) →	4,340 kJ
Aircraft:	447 kg accelerate to 246 m/sec (0.8 Mach) →	13,525 kJ

Thus, if we consider a single acceleration process, it is for the airplane about three times as energy-intensive as for a train and 18 times as energy-intensive as for a passenger car due to the high final speed despite the significantly lower mass. However, our considerations on acceleration cannot yet stop at this point!

An airplane usually accelerates once during takeoff until it reaches its cruising speed at cruising altitude; from thereof, only air drag must be overcome until landing. Both cars and trains, on the other hand, must perform many acceleration processes in the course of their transport operation, as they have to reduce and raise speed again and again in between; at stops at traffic lights or train stations even down to a speed of 0 km/h.

If a person travels by ICE from Hamburg to Munich, the fastest connection has eight intermediate stops, so at least nine accelerations from complete standstill are necessary. Between the first two stops in Hamburg, the train will not accelerate to over 200 km/h and for the rest of the distance, the train, unlike an airplane, does not travel at the constant maximum speed of 250 km/h between two stops. Rather, there are always track sections where the train must travel more slowly, resulting in more acceleration phases. Since the final speed determines the energy requirement during acceleration quadratically, acceleration from 120 km/h to 200 km/h with a mass of 1,800 kg (1,777 kJ) or from 200 km/h to 270 km/h (2,285 kJ) is much more energy-intensive than acceleration from 0 to 120 km/h (1,000 kJ). If we assume that the train accelerates once to 120 km/h up to the first stop, then once to 250 km/h between each stop, and twice from 200 to 250 km/h between two stops, the amount of energy required per passenger for these acceleration processes adds up to 60,728 kJ. Even with this highly simplified calculation, which only does approximate justice to the complex movement profile of a train ride, this is already 4.5 times the acceleration energy required for a passenger in flight, because there a much smaller mass only is accelerated once.

In regional railway traffic, the energy consumption of acceleration processes reveals this fundamental deficit of railway transportation even more, as this kind of railway travel is characterized by frequent stops and the subsequent need to accelerate again and again. On the previously mentioned, only just under 150 km long route of the RE8 (RB27), the regional trains stop between 30 and 33 times; very energy-intensive accelerations from 0 to 140 km/h are therefore constantly necessary every 4.5 to 5 km. If we assume a train weight of only 1 t per passenger, so that the total mass is 1,100 kg, 30 acceleration processes from 0 to 140 km/h require a total energy of almost 25,000 kJ, almost twice as much as the acceleration energy required for a passenger in an A321 from takeoff to reaching the cruising speed of 875 km/h. If the train runs at off-peak times, so that the train mass to be moved is 3 t for each passenger, this value increases to more than 70,000 kJ.

It should not go unmentioned, that for a final energy evaluation of the entire train ride it must also be considered that modern electric train engines (and similar to electrically powered and hybrid passenger cars) can feed (recuperate) energy back into the power grid (or battery) during braking. In relation to the total energy required, however, this is only a fraction of what is needed for the large number of acceleration processes. For the numbers presented in this study, for which the detailed calculations are given in the appendix, the amounts of net energy consumed published by the German railway company have been used, so that the energy recovered by recuperation is already taken into account.

For the road transport system, a multitude of major and minor acceleration processes with subsequent deceleration (braking) will take place during our example travel from Hamburg to Munich; the exact energy requirement for this trip could only be determined with continuous measurement during the entire journey. To enable some kind of useful comparison, the following simplified assumptions are made: There are ten acceleration processes from 0 to 50 km/h, plus 3 accelerations from 0 to 130 km/h (after pauses) and a total of 50 accelerations from 90 to 130 km/h. In total, this results in an energy requirement of 22,214 kJ per person for the assumed total weight of 1,117 kg.

As a conclusion, it can be stated that a specific transport process is the more energy-efficient, the more uniform the movement of the vessel is. Ideally, there is only one acceleration process and then a constant speed until the deceleration process at the destination.

4.2 *Speed and air drag*

Now to the aspect of speed. At constant speed, energy is only necessary to overcome air drag (in the case of airplanes, cars and trains) and driving resistance (rolling and frictional resistance in the case of cars and trains on the road or rails, resistance when cornering on rails, etc.).

The force required to overcome air drag is determined by the air density, the "drag coefficient c_d", the "frontal area (front face)" and the speed . The air density (in kg/m^3) depends on temperature and relative humidity; the "c_d value" is between 0.25 and 0.4 for modern passenger cars, and sometimes significantly higher for SUVs and off-road vehicles. Modern aircraft generally have a c_d value of 0.08. In the case of a train, this value depends on the overall length; a reasonable approximation is 0.2-0.25 for the first car of an ICE train or the locomotive and for the last car, and 0.1 for each car in between.

Here, too, the speed causes the drag and with it the energy required to overcome drag to increase quadratically, while the air density decreases approximately logarithmically with increasing altitude. In addition, at speeds of more than 80 km/h, air drag is the decisive factor compared to driving resistance, which is why driving resistance will – for the sake of practicability - be ignored for the time being. In the case of trains, it should also be noted, that the passage through tunnels leads to considerably higher drag, since the air cannot escape to the sides as it does on the open track, but rather needs be pushed in front of the train like an increasingly heavy piston. Air drag can become twice as high when traveling fast through long and narrow tunnels compared to traveling at the same speed on an open track.

Below are three approximative and simplified calculations of the energy required to overcome drag for a transport performance of one PKM:

For railway transportation, it is assumed that an ICE 3 is traveling with an overall c_d value of 1.1, a speed of 250 km/h (69.4 m/s) and in an air density of 1.225 kg/m^3. To overcome the drag force of around 35 kN (kilo Newton) calculated from these figures over a distance of 1,000 m, an energy of 35 Megajoules (MJ) is required. If, as is the case with the average capacity utilization of the train, around 55% of the 400 plus seats in this train are taken, this results in around 156 kJ per PKM for each single passenger just to overcome the air drag.

For the car ride, a speed of 130 km/h (36.1 m/sec), a c_d value of 0.3 and a frontal area of 3 m² is assumed. The air density is the same as for train travel, so that 703 kJ of energy are required to overcome the drag for one kilometer. On a statistical average, 1.5 people travel in a car, resulting in a value of 469 kJ/PKM. If the same vehicle is traveling at 180 km/h, the value is 919 kJ/PKM; the 38% increase in speed requires 96% more energy to overcome the air drag.

For the journey in the airplane (A 321), we assume a speed of 0.8 Mach, which is about 243 m/s at a cruising altitude of 9 km. According to the "international standard atmosphere", the air density at this altitude is 0.466 kg/m³ (67), (68). The wing area, which is the relevant parameter for an aircraft instead of the frontal area, is 122 m² (59), (60), the respective c_d value is 0.08. For the entire aircraft, this results in a drag force of 134.3 kN, calculated at 1,000 m and with the average passenger load amounts to a value of 819 kJ/PKM.

4.3 *Lifting work*

In addition to the energy required to accelerate a mass and overcome air drag and driving resistance during the course of motion, the amount of energy required to perform the "lifting work" to overcome gravity also needs to be included into the equation as a further decisive variable for movement efficiency. The lifting work to be performed depends on the weight force of the mass and the altitude; the weight force is the mass in kg multiplied by the gravitational constant (9.81 m/s²).

If for instance a mass of 1 kg is lifted up 1 meter, an energy of 9.81 kJ is required for this. If we again assume a total transport mass of 447 kg per passenger in the airplane and assume that the flight is performed at a cruising altitude of 9,000 m, the energy required for the respective lifting work is accounts for 39,466 kJ per passenger. (For the sake simplicity, we have ignored the fact that the gravitational constant decreases slightly with increasing altitude).

For an aircraft taking off from the ground, the need to perform lifting work is obvious to everyone. As this is much less obvious for road and railway transport, this important parameter so far unfortunately has been oftentimes simply ignored in many discussions. In reality, lifting work is required on every single slope that the vehicle has to climb. Unfortunately, it is of little help if after a climbing segment there is downhill slope where, due to gravity, less energy has to be expended to drive downhill. If there is another incline afterwards, lifting work is yet needed again. What is really relevant regarding energy consumption is the sum of all gradients on an entire route, regardless of whether there is an overall difference in altitude between the start and the destination and, if so, how big that difference is. The only difference between a land-based means of transport and an airplane in terms of lifting work is that in the case of an airplane, the entire lifting work occurs during the climb at the beginning of the flight, whereas in the case of a train or car, many small pieces need to be summed up. Accordingly, the descent before landing at the end of a flight is the coherent part in which the airplane benefits from gravity from an energetic point of view; in the case of cars and trains, these are all the downhill sections.

In order to be able to calculate the lifting work for a specific land route, an exact elevation profile of the route is required, similar to the profiles known from bicycle races or hiking trails. We used *Google Earth,* which serves well to provide the elevation profile for any route for which navigation is available. Fig. 2 in the appendix (sec. 9.1.2) shows the shortest route from Hamburg to Munich including the respective elevation profile; a total elevation difference of 5,769 meters is shown. Since the presence of viaducts and valley-spanning bridges reduces the lifting work (as the valleys do not have to be crossed), we reduce the difference in altitude to be covered by a flat 20% to 4,615m. With the assumed average total weight of 1,117 kg per car passenger, this results in an amount of energy of 50,570 kJ per person to cope with the lifting work on the entire automotive route.

Unfortunately, there is no similar, generally available source with the exact elevation profiles for railroad tracks. In principle, however, they have lower gradients than roads, which is why a larger number of tunnels and viaducts are necessary. Against this background, it is assumed that the railway line has only half the summed-up height difference of the road route, which means that the energy for the lifting work to be performed can be calculated to 40,746 kJ per passenger, based on the 1,800 kg total weight. Once more, it becomes apparent that the very high total weight of passenger cars and especially trains to be moved in relation to their payload results in the maybe counter-intuitive fact that the energy required to overcome gravity is greater than for airplanes even if the land-based means of transport never get off the ground.

On a side note, the topic of lifting work also plays a non-negligible role for underground train stations. For example, once Stuttgart 21 is in operation, it must be considered that regarding the energy required for each passenger, whether arriving or departing, an additional "lifting work" for a height difference of around 30 m will have to be coped with, even for the passengers only passing through. Arriving passengers will have to be transported "up" by elevators or escalators, departing passengers will have to be transported in the same way "down" to the platform and then, together with the train weight, "up" again. With more than 200,000 passengers a day, this is a considerable amount of additional energy that is only necessary because of the station's underground location.

Aircraft, motor vehicles (with combustion engines) and trains pulled by diesel engines have another specific characteristic concerning the total mass to be moved, which at first sight seems to be a serious disadvantage. They have to carry the very energy that drives them forward within their closed system. That is why we have taken this into appropriate account earlier, when considering the total weight to be moved of those transportation means.

4.4 *CO_2 pollution attributed to the drive energy*

Of course, at this point it is also necessary to factor in the “well-known culprit”, i.e., how much CO_2 is produced during the actual combustion of the on-board fuel or in the less immediate generation of the electricity for moving the respective means of transport. Here it is important that kg and liters (l) should not be mixed up in the case of fuels, a mistake which can unfortunately be observed again and again in the public discussion. Since hydrocarbons are lighter than water, 1 l of gasoline is equivalent to about 0.75 kg, for kerosene it is about 0.785 kg and for diesel fuel about 0.83 kg. Each 1 kg of these hydrocarbons burns to produce 3.1 - 3.2 kg of CO_2; in the following, a value of 3.15 kg of CO_2 is used as a basis for each 1 kg of fuel burned (69). E.g., a car that consumes 8 l gasoline (6 kg)/100km produces 189 g CO_2 per km; a car that uses 5 l diesel/100km produces 131 g/km. The BUND (Bund für Umwelt und Naturschutz, a German NGO) claims an average CO_2 emission of German passenger cars for 2017 to be around 128 g per km; with the average load of 1.5 persons, this results in 85 g CO_2/PKM (70). Similar values are found, if the fuel consumption of modern mid-range cars is put in relation to the transport volume provided as discussed earlier. The often significantly lower values in automobile brochures are due to lower consumption figures, which are achieved almost exclusively in standardized driving cycles that do not necessarily correspond to daily reality.

It must also be considered that fuels must first be refined from crude oil, transported from the refineries to large tank farms and from there to the filling stations. This requires additional energy and associated pollutant emissions must be considered in any realistic overall assessment. For the automotive sector, an additional 10% of emissions is often estimated for this purpose, which however for the time being is not considered in the calculations in this paper.

In air travel, the consumption of all German airlines in 2018 was 3.55 l/100 PKM on average (71), which corresponds to 90 g CO_2/PKM[9].

In the discussions about GHG emissions from aviation, we have to keep in mind that there are several other, non-CO2-related climates-influencing effects. Besides CO_2, there are at least 11 other physical and chemical effects, nitrogen oxide (NO_x) emissions influence ozone, methane and stratospheric water vapor in the atmosphere, soot and sulfur emissions influence aerosols, which have an interacting effect with clouds, and contrails influence cirrus clouds in high-humidity regions. Some of these interactions result in a warming effect, others lead to a cooling. For several years, the so-called RFI (Radiative Forcing Index) has often been included in the public debate (72), (73). It should be noted that one of the "spiritual fathers" of the RFI, an internationally respected atmospheric physicist, completely distances himself from the widespread "application of the RFI" and simply calls it "nonsensical" and "misused" (74).

More recently, atmospheric scientists have developed a more appropriate parameter, the ERF (Effective Radiative Forcing), which describes the effects of aviation on global warming in accordance with the current state of research (75). All relevant climate factors of aviation, but CO_2, have in common, that they are currently not sufficiently understood to determine their overall influence on the climate. Currently, contrails are considered to be an important warming factor, but much more research is still necessary to quantify the climate effects and even to understand better, under what conditions contrails are created. Nevertheless, current research puts a lot of emphasis on reducing contrails in aviation, either by using different aviation fuel, (76), (77), or simply by small altitude changes of planes, (78), (79).

As for the electricity, taking into account the electricity mix commonly used in Germany and for domestic consumption, CO_2 emissions in 2016 were 0.572 kg/kWh, in 2017 they were 0.534 kg/kWh and then in 2018, according to preliminary calculations, 0.518 kg/kWh. These figures, officially published by the German Federal Environmental Agency (Umweltbundesamt, UBA), are used in this study as the basis for all CO_2 calculations for electricity consumption (80), (81). Here, we cannot help to clarify, that it is simply scientifically inadmissible to claim, that German trains run on their entire long-distance services exclusively on green electricity and are therefore more or less emission-free (82), (83). Even when there is no wind and/or sun at all, electrically powered trains travel through the countryside at speeds of up to 300 km/h, whereby the real-time electricity can then come neither from wind turbines nor from solar plants[10]. Likewise, electric vehicles are also charged at night when solar power is not available, certainly not from own roof-mounted solar panels on the car owner's house. For a fair comparison of electricity driven vehicles, the pollution balance of the total electricity mix in a respective country must be considered, as electricity is neither green nor blue nor black; electricity is electrons flowing through a conductor without "awareness" by which primary energy they were originally induced.

It should also be noted at this point that, contrary to a widespread opinion to the contrary, our current electricity - be it from wind and solar or nuclear power plants - is never CO_2-free and will not be for the foreseeable future. Power plants as well as solar cells and wind turbines must first be

[9] When discussing the overall aviation emissions, one always has to keep in mind, that numbers about the annual worldwide kerosene production never distinguish between civil and military aviation. This would be roughly the same as including in a country's road traffic emissions those caused by its land forces. Modern military fighter aircraft easily burn between 3 and 5 tons of kerosene per hour, thus emitting anywhere between 9 and 15 tons of CO_2 during one hour of operation.
[10] The railway company's claim that it runs its long-distance trains 100% on "green electricity" and thus CO_2-free is justified with the assertion that the company buys as much regeneratively generated electricity as it consumes in long-distance transport. This claim simply ignores the fact that even this electricity cannot be generated completely without CO_2 emissions and, above all, is not always available in the required quantities. An ICE train traveling from Frankfurt to Paris is also powered by electricity from nuclear energy during its journey, at the latest after it crosses the French border, because electricity from nuclear power plants is definitely fed into the grid in France.

industrially manufactured, transported, built, commissioned and then operated, and the same applies to the entire infrastructure for distributing the electricity to the consumer. Furthermore, electricity can never be transported, transformed or converted (from direct current to alternating current or vice versa) without losses. In line with the idea of a holistic view of cause and effect of energy issues, all of this must be included in the calculation, just as, for example, the refinery and distribution costs to produce combustion fuels mentioned earlier. For instance, even a rough assessment of the materials used in a wind turbine and the reinforced concrete foundation required for its installation (84) quickly proves that it is simply wrong to consider wind or solar energy as "zero-emission" energy as it is now often claimed in advertising electric cars.

The previously mentioned amounts of CO_2 produced during electricity generation must therefore be equally considered for electrically powered trains as well as electric cars. An ICE 3 has a continuous power of 8,000 kW; this will not always be fully required during operation, but if the train runs at a power of 60%-65% over a period of one hour (approximately the travel time between Cologne and Frankfurt), at least 5,000 kWh will be added to the bill, corresponding to 2.6 t CO_2. The CO_2 impact per PKM for railway trips in Germany can be determined more specifically from the following data: Deutsche Bahn states the total traction energy (energy to drive the trains) for 2017 as 10,190 GWh plus 436 million liters of diesel fuel (56); for 2019, it was 9,552 GWh plus 410.6 million liters of diesel (61). Long-distance transport accounted for 32.8% of the electricity and 2.5% of the diesel. For regional traffic, it was 43.2% of electricity and 76.1% of diesel, and the rest of electricity and diesel was for freight transport (48). For long-distance transport, these figures make for a CO_2 impact of 45 g/PKM in 2017, for 2019 it was 37 g/PKM, for regional transport it was 77 g/PKM in 2017 and 71 g/PKM in 2019. All figures provided by the railroad company in this regard refer to net electricity volumes, and do not take into account the previously mentioned line and conversion losses or the emissions generated during the construction and maintenance of the electrical infrastructure. All detailed calculations for the figures listed here can be found in the appendix.

At this point, it will be fair to say that the comparison of pollutant emissions from different transport systems is very difficult, especially when some means of transport are powered by internal combustion engines and others by electricity. For years now, there have been very ideology-driven discussions, in which the supporters of the different camps accuse each other of making the respective favored means of transport look better and the other means of transport look worse than they are. “Impressive” examples of this can be found in (85) (flying vs. taking the train) and (81), (86) (diesel car vs. electric car). Especially the last referenced study has triggered a flood of position statements, counterstatements, rejoinders of the counterstatements, meta-reports about this study and resulting comments and counter-reports etc., which have not necessarily been helpful to a fact-based discussion. A fair and holistic comparison deserves to be exclusively made on the basis of concrete, reliable figures, data and facts, and the argumentation should be plausibly derived from those findings in as unbiased a manner as possible.

4.5 *As the crow flies or land distance*

Another factor to be considered when comparing the movement efficiency of different transport systems is the actual travelling distance between the starting and the destination location. In some cases, land-based modes of transport such as railway and road must cover considerably longer distances than air travel. For three typical routes in Germany, Frankfurt-Munich, Munich-Hamburg or Berlin-Munich, for example, railway and car journeys involve between 35% and 43% more kilometers than the air distance between the respective locations. It should be noted at this point that even in air traffic, the shortest distance between two airports may not always be used. Prescribed arrival and departure routes as well as the need to stagger air traffic and weather-related re-routing can result in detours of up to 20% of the shortest possible route to be flown. Even then, however, it can still be assumed that the actual distance to be covered is shorter than that of a land-based mode of transportation. Since the pollutant comparisons in this study are wherever possible based on PKM, 600 km "as the crow flies", for example, is preferable to 800 km of land-based travel, even if the total CO_2 impact per PKM is 30% higher for the aircraft.

It should be noted, that for road traffic we have assumed that primarily the highway network in Germany is used; if secondary roads are to be used or if the trip on the Munich - Berlin route is made through the Czech Republic, the travel distances may be shorter, but it would not reduce the calculated trip duration, an important aspect for many travelers.

5 Tabular overview

Table summarizes the considerations made so far. The color coding in the table is only of qualitative and not quantitative nature and provides an evaluation (based on the criterion specified in the first column) of how the transport system is to be classified relative to the other systems. By means of the respective transport volume of the transport system (see Table 3), individual statements can be made in relation to PKM.

	Rail	***Road***	**Aviation**
Means of transport	Train	CAR	Airplane
CO_2 from drive energy	**37 - 71 g/PKM**	**85 g/PKM**	**90 g/PKM**
Utilization of the means of transport (average values)	**55.5%**	**30%**	**81.4%**
CO_2 from construction & maintenance	**Less than for passenger car, more than for aircraft**	**33 g/PKM**	**Less than for train and car**
Route infrastructure			
CO_2 from construction & maintenance	**Route-dependent (1)**	**Route-dependent (2)**	**0 Not necessary**
Node infrastructure			
CO_2 from construction, maintenance and operation	**No generally admitted statement possible due to lack of more comprehensive data. (3)**		
Control infrastructure	**No generally admitted statement possible due to lack of more comprehensive data. (4)**		
Other aspects	**(5)**		
Transport efficiency: Mass of the vehicle to be moved per person	1.7 t (ICE 3, average load factor)	1 t (average passenger car with 1.5-person load)	0.3 – 0.5t (depending on aircraft type, average load factor)
Mechanical Movement efficiency	Many acceleration operations due to stations on the way	Variety of traffic-dependent acceleration processes	Acceleration at start, then largely uniform
Distance to be covered	Railroad line-oriented	Highway-oriented	Flightpath-oriented (as the crow flies)

Table 8: Qualitative statements on the ecological assessment of the components of different transport systems

Please note, that the final judgement on the respective carbon footprint of a transportation system cannot be determined by just counting the above green, yellow or red boxes. It is rather imperative to factor in the numbered, detailed explanations below:

(1) The complete GHG emissions of the entire track infrastructure for railways cannot properly be estimated in retrospect. Due to the high-impact materials (steel, concrete, copper, etc.) used here, CO_2 emissions of several hundred tons (non-electrified lines without bridges or tunnel structures) to tens of thousands of tons (high-speed lines on bridges and in tunnel structures) are

incurred here for each single line kilometer. Even on busy routes, this results in CO_2 loads in the mid to upper double-digit gram range per PKM. More precise estimates can be made for specific route sections when detailed facts and figures about CO_2 emissions and traffic performance over the track's life span are available. E.g., 3-4 million t CO_2 for the Cologne-Frankfurt construction project corresponds to around 80-106 g/PKM for 220 million passengers and 35-47 g/PKM for 500 million passengers. 4 million t CO_2 for the construction of the Gotthard Base Tunnel extrapolated to the current approximately 4 million annual users over 50 years burdens each user with 20 kg CO_2 per trip, which means more than 350 g/PKM. This does not take into account necessary maintenance work and repairs or complete refurbishment after appropriate use.
In section 2.1.4 we had calculated "average" path infrastructure emissions of 20 grams per PKM in the very best case for simple tracks in the field, 126 grams per PKM on bridges, and 172 grams of CO2 per PKM in tunnels.

(2) For the road infrastructure of the automotive transportation system, no general and generally valid statements regarding the impact of construction and operation can be made since the necessary data and facts cannot be reliably estimated in retrospect. The so far available figures and data support the conclusion, that due to the 10-fold traffic load compared to railway traffic and due to the significantly lower number of tunnel constructions in mountainous terrain, the CO_2 pollution per PKM tends to be significantly lower in this regard.

(3) A serious, generally admitted statement is not possible at present. However, the examples calculated show that individual construction measures (e.g., Stuttgart 21) result in very high CO_2 emissions that have a lasting negative impact on the overall balance of the transport system over decades.

(4) A serious, generally admitted statement is not possible at present. However, the calculated examples show that the CO_2 impacts from the control infrastructure are rather negligible in relation to the other infrastructure components.

(5) The ratio between payload and total mass to be moved is particularly inefficient in trains and in passenger cars. The movement efficiency of the actual transport process is also suboptimal due to the frequent, sometimes extreme acceleration processes. As far as the distance to be covered between two locations is concerned, the railway and road transport systems depend on the respective route infrastructure. Since the road network as a whole is more finely meshed than the railway network, the necessary "detours" in road transport are generally smaller than in railway transport. In aviation, aircraft only fly within narrowly defined corridors on departure and arrival; in between they orient themselves to "airways" and the current weather situation in the area flown over, so that they come much closer to the most efficient possible connection than is the case with land-based means of transport.

6 Other ecological aspects of transportation systems

So far, our considerations have focused almost exclusively on climate-relevant emissions and, for the sake of simplicity, specifically on CO_2. Of course, many other ecological aspects such as noise or land consumption also deserve to be considered. These aspects are important "secondary parameters" for a fully comprehensive, holistic consideration of the matter and they also deserve a closer look. Some of them have already partly been examined by the author of this paper, but they still need to be presented in written form.

There is however one other very important aspect in connection with CO_2 emissions that needs to be explained at this point and which is directly related to innovation and technical progress. For example, in aviation, the average consumption of kerosene per 100 PKM has been reduced from 6.3 l in

1990 to 3.55 l in 2018 (71); this corresponds to a 44% saving, which is transferred 1:1 to CO_2 emissions, a decline from 159 g/PKM to 90 g/PKM.

Similar efficiency improvements have been achieved in internal combustion engines for passenger cars, but at the same time there has been a significant trend towards larger and more powerful engines in vehicles, so that the potential positive environmental effects resulting from the innovation were cancelled out. In 1995, the average engine power of new cars registered in Germany was 70 kW (95 hp); by 2013, it was as high as 101 kW (137 hp). Then, for a few years, it seemed like the end of the increase had been reached (87), but in 2019, after another ten years with engine outputs increasing year by year, the average had risen to 116 kW (158 hp), (88), (89). The 66% increase in average engine output compared with 1995 is therefore unfortunately only matched by a 19% reduction in fuel consumption and the resulting CO_2 emissions.

The situation is quite different for CO_2 emissions generated during infrastructure construction. CO_2 emissions generated during infrastructure construction will never decrease during the lifespan of the infrastructure, breaking them down on PKM they remain the same at all times, no matter what innovations occur at some later time. Proponents of route infrastructure often advocate the high-impact constructional measure itself with the very long service life of the structure, over which the ecological expenditure is supposed to be amortized. In the case of high-speed railway lines, as we now know, this is at least 30 years. For the CO_2 pollution attributable to such transport system, however, this means that innovation and progress cannot have any significantly improving effect for decades. In concrete terms, the CO_2 emissions generated in the 1990s during the construction of the high-speed line between Cologne and Frankfurt, which still must be attributed to travelers today, continue to be effective to the same extent as was the state of the art at the time of construction. It even has to be considered that these CO_2 emissions have been relevant for the climate and have had a warming effect for years and sometimes decades, long before the actual transportation is performed.

This is a very fundamental disadvantage with long-lived infrastructure; the larger the share of infrastructure in the total emissions profile of the respective transport system is, the more difficult it is to contribute to the reduction of CO_2 emissions by means of innovation and technological progress.

In addition, emissions from transportation systems are often viewed through an unwarranted "local lens." Definitely, electric vehicles improve the immediately surrounding air where they travel; however, the issue here is not CO_2, but nitrogen oxide (NOx) and, in summer, ozone (O_3) pollution. An electric train e.g., does not produce any exhaust gases where it travels. For the climate, in the case of CO_2, however, it does not matter at all where the greenhouse gas is produced. CO_2 molecules cause a warming effect in the atmosphere for an average of one hundred years; they are distributed evenly in the atmosphere, regardless of where they originate. If the steel used comes from China or India, a CO_2 molecule produced there in the blast furnace process will have the same GHG effect on the climate for 100 years as a CO_2 molecule coming out of a tailpipe in Germany. Such holistic approach illustrates once again, that climate protection can only work on a global scale; it does not help at all to pursue local or regional "solution approaches" when this only shifts CO_2 emissions "out of one's own field of vision".

7 Assessment of the Status Quo, potentials and political regulation

Based on the analyses and results so far, the question must now be asked as to what concrete contributions to climate protection the different transportation systems are capable of making. The focus here should not be on bans or demands to fully do without, but rather on considering which technologies and systems that already exist or are currently being developed can be used to meet mobility requirements today and in the future in the most appropriate and efficient way.

7.1 *Evaluation/potential of the railway transportation system*

The railway transportation system is generally considered to be the "most environmentally friendly" of the three systems under consideration. The analysis so far shows very clearly that this is only true if the view is reduced to the pure drive energy. However, contrary to widespread opinion, propulsion is not CO_2-free for either long-distance or local trains and will not be for the foreseeable future. When the CO_2 balance is taken in the appropriate full-scale approach, the environmental friendliness of the railroads is put into perspective even further: The construction and maintenance of the infrastructure lead to hundreds of millions of tons of CO_2, which always had and will continue to have a negative impact on the overall balance for decades to come. Additional burdens are the worst ratio of payload to total mass to be moved, as well as system-inherent inefficiencies, such as that trains can only travel on the comparatively coarse-meshed railway network. In addition, large masses must be brought to a complete standstill at each station and accelerated back to cruising speed after a short stop. From a physical point of view, this is very inefficient for a transport operation.

Given that for the foreseeable future railway lines will continue to be built primarily of steel for rails, steel and concrete for the slab track, tunnels and bridges, as well as copper, steel and concrete for electrification, this results in GHG emissions that can significantly exceed drive-related emissions. Node infrastructure also contributes significantly to CO_2 emissions, although individual exemplary examples such as Stuttgart 21 should not be generalized. The frequently mentioned goal of doubling railway transport performance in Germany within 10 years would result in approx. 80 billion instead of 40 billion PKM being performed by long-distance railway transport in Germany, but this would only reduce MIT in its current form by less than 5%. To achieve this political goal, an additional €86 billion is to be invested in the railway infrastructure in Germany over the next ten years (90). It remains to be seen how much traffic can actually be shifted to rail over the course of the years, because it is already foreseeable that the additional capacities will not be created precisely where the greatest demand is expected (91). It seems advisable to ask the question, to what extent infrastructure investments of billions of euros in the railway system really make sense, and to what extent these investments will even be able to be part of an efficient solution for future mobility requirements in the long term. After all, the many inherent disadvantages of the railway system are not sustainably addressed by such infrastructure measures.

7.2 *Evaluation/potential of the road transport system*

The road transport system as operated today is the least efficient of all compared systems in terms of the resources used. A high number of vehicles, each with comparatively low transport performance, as well as very low utilization of the individual vehicle lead to overall CO_2 emissions per PKM, which in total are considerably higher than the exhaust gas values that are often discussed politically and publicly. As a land-based transport system, it requires a GHG-intensive infrastructure, just like the railway system, although the CO_2 impacts resulting from the construction and maintenance of the road system are to some extent put in a slightly less negative perspective by the very high overall transport performance.[11]

On the other hand, the road transport system is currently on the verge of collapse in many places; despite its critical GHG footprint and proven resource inefficiency, using an individual vehicle is

[11] Coaches/overland buses as a means of long-distance transport have not been considered separately so far due to their currently minor importance; it should be pointed out here, that long-distance coaches stand out with very good efficiency values even at average capacity utilization. Even if only 30 people are transported in a large bus, this corresponds to a traffic performance of 20 averagely occupied passenger cars; however, the GHG emissions from propulsion only reach 3 to 4 times that of a single passenger car, the space requirement on the road at a travel speed of 100 km/h corresponds to that of only a maximum of 2 passenger cars, and the CO_2 emissions generated during production are also significantly lower over the years than for motor vehicles due to the comparatively high transport volume of a single bus, as soon as they are apportioned to PKM.

convenient for most people and it is by far the largest contributor to meeting today's mobility needs. However, it is precisely the huge transportation volume and the currently inefficient use of the system, which provides by far the greatest leverage for sustainable improvements. Around 48 million passenger cars (and vans) are on the road in Germany these days to cover the 966 billion passenger kilometers in motorized individual transport (MIT) each year; the annual number of new registrations is around 3.4 million vehicles. Statistically, each of these vehicles is driven for less than one hour per day and requires public or private parking space for the remaining 23 hours. At no time, even while the longest traffic jams are forming, even half of the vehicles are on the road at the same time (92). The low daily usage time of each single vehicle together with the also very low utilization rate of 1.5 people on average (30% assuming five seats) results in a daily overall usage rate of only 1.25%.

These figures allow for the following thought experiment: The entire motorized individual traffic (MIT) could also be managed with less than half of the cars, without anyone having to abstain from any individual trip at any time. That way, one could permanently do without half of the number of first-time registered new vehicles and would thus gradually have halved the total number of cars after about 13-15 years, which would, among other things, free up a great deal of currently used parking space. If one also assumes the calculated 8 t CO_2 from the production of an average automobile, this approach will lead to **annual savings of more than 13 million t CO_2**, which would be saved by just not producing cars that are no longer necessary. If, in addition, it would be possible to increase the average "occupancy" of a motor vehicle from the current 1.5 persons per trip to 2 or even 2.5, additional vehicles and also about 25% (with 2 persons) or 40% (with 2.5 persons) of the trips currently made could be entirely saved. This would result in significant savings in the fuels needed (or electricity for future electric vehicles). The reduction of today's trips by 25%, which arithmetically results immediately at an average vehicle utilization of 2 persons, would **reduce today's CO_2 emissions of the MIV by 31.5 million tons per year**, simply because 25% less gasoline is needed. Fewer vehicles and less traffic will require fewer roads, less new road construction and repair, which would also result in further reductions in CO_2 emissions for the road infrastructure.

The figures for transportation volume presented above easily spur yet another thought experiment: A mere 10% increase in the average number of people traveling in a car (from 1.5 to 1.65) would mathematically substitute for all current passenger railway transportation in Germany. This would also apply to the very CO_2-expensive construction of the railway infrastructure, which causes millions of tons of CO_2. Of course, from today's perspective, this is a purely theoretical calculation; however, against the background that the route infrastructure for both systems often runs largely in parallel, this could be a scenario worth considering. Again: **Less than half of the passenger cars registered today could handle the entire traffic demand on road and railway together with just a slight increase in the average vehicle utilization. Millions of tons of CO_2 could be saved year after year without having to restrict personal and individual mobility, if smart(er) concepts for practical usage could be designed.**

What would be needed to incentivize such more efficient car use in the future? On the one hand, an "intelligent platform" is required, in order to ensure that a car is always available when it is needed. Ultimately, this would be nothing more than a further developed car-sharing system, the beginnings of which are already available in many places today. Probably a key to any practical solution would be to create a widely accepted incentive to travel in a car with "strangers" who need to travel the same stretch at the same time; this again is nothing else than what car-sharing agencies have been successfully starting to offer for years and what is the totally common practice in public transport, trains and planes. Sharing a vehicle at the same time can be incentivized by the price to be paid; those who want to travel by themselves should still be able to do so if they are willing to pay a little more. It is also helpful to understand, that the shared vehicles for MIT of the future will have little to do with cars as we know them today. "Private compartments" for one or two people in autonomous driving vehicles will be the standard, as will be vehicles, in which the drive unit and chassis are separate from the "payload body," so that the lower parts of the vehicles can carry freight at night and people during the day (93). Thus, no one would have to sit in a car in blazing midsummer heat body to body with sweating, unknown fellow travelers on a filthy back seat. Digital technologies, needed to implement such "Mobility as a Service" platforms, are already available today and are advancing fast to sustainable stages of development. It will not be long, before an autonomous vehicle could be waiting for its passengers on their doorstep just a few minutes after being requested. The most important prerequisite for this scenario, however, is that such a **paradigm shift is** attractive to society: **Away from owning a car and toward using a car whenever it is needed.**

In short: Systems that combine and make good use of the infrastructure already in place, as well as future innovative possibilities offered by digitization, must quickly and diligently be further developed; within the next one to two decades, digitization and automation will make solutions available in the context of mobility, that many of us cannot even imagine today. Here, politics and the public are called upon to create the necessary framework conditions for the development of travel solutions that support the needs of individual transportation in a smart and goal-oriented way.

7.3 *Evaluation/potential of the aviation transport system*

For the aviation transport system, the energy required for propulsion is currently obtained almost exclusively from fossil raw materials. The fact that the current social and political discussion on GHG emissions from the transport sector primarily revolves around propulsion energy has led to a very negative public image of air transportation in recent years.

It is therefore interesting to note that from a physical standpoint the aviation system performs best of all three transportation systems studied regarding all other relevant aspects; in particular, the lack of need for any route infrastructure represents a significant and lasting systemic advantage over road and railway transportation. For air transport, there can be only one goal for the future: the fuel required for propulsion must become climate neutral. Synthetic kerosene, which is produced from the CO_2 in the air and hydrogen using electricity from renewable sources, is currently in the laboratory and testing phase. Experiments are also being conducted with kerosene from biomass; at individual airports, airlines can already refuel with (significantly more expensive) kerosene that is not of fossil origin (94), (95), (96). It will however take several years before significant amounts of such climate-neutral fuels are available, and only time will tell whether the processes known today will ever be able to cover the entire demand for the globally increasing air traffic. According to the IATA (International Air Transport Association), a total of around 200 million liters of SAF were available in 2022; 450 billion liters per year will be needed to decarbonize air transport by 2050 (97). Furthermore, the first electrically powered air cabs, which also require no road infrastructure at all, have left the laboratories and are currently in the testing phase.

Short term, more thought should be given to optimizing routes and flight altitudes in day-to-day air traffic according to criteria of ecological efficiency (74). Nevertheless, the lack of need for any route infrastructure, the advantage of the shortest route between locations and the already highest efficiency in the ratio of payload to total mass moved are inherent significant advantages of aviation that will remain valid for the foreseeable future.

7.4 *Political control and regulation: emissions trading and other measures*

Political considerations to influence transport-related CO_2 emissions by means of trading emission certificates, taxes or other levies have led to various measures in recent years. Based on the diverse and complex interrelationships presented in this study, it can be stated that such activities will only be successful if, on the one hand, they include ALL emissions, including those from transportation infrastructure and vehicle manufacturing, and, on the other hand, they are correctly applied internationally and globally. The climate will not be helped if for example rail steel and cement for tunnel construction in Germany comes from countries without CO_2 pricing, and the emissions to transport such materials to Germany are also not priced in either. CO_2 emissions that are generated somewhere in the world without being included in a corresponding local pricing and offsetting system represent an unwarranted incentive to relocate the production of CO_2-intensive materials elsewhere.

For instance, the EU Emissions Trading System (EU ETS), introduced at the beginning of this century, allocates tradable emission allowances to companies (98). This creates an appropriate incentive for companies to reduce CO_2 emissions, while retaining entrepreneurial decision-making leeway. Where exactly emissions are (actually) reduced and how respective costs are allocated within the corporate structure remains within the responsibility of corporate decision-makers.

The findings of this study will not affect any transportation infrastructure that is already in place or largely completed; however, transport policy considerations should focus much more strongly on a fully comprehensive, holistic view of the challenge in the future. Sticking convulsively to what seems to be known and proven today, will not result in the desired significant global CO_2 reduction in the long term, but rather threatens to lead to a widespread frustration, since ever higher taxes , charges and liabilities will be levied just to keep comparatively inefficient and largely improvable transportation systems going.

8 Conclusion

The focus of this study is, on a comprehensive ecological comparison of different transportation systems, with a particular emphasis on CO_2 emissions. When taking a fully holistic view however, quite a few more aspects do also play an important role in decisions for and against certain transport systems. These aspects, which are important, but have not yet been considered here, include at minimum the following:

- Additional ecological aspects such as noise, vibrations, land consumption, etc.,
- Availability of the traffic systems today and in the future,
- Flexibility of the traffic systems regarding changing requirements and needs,
- System resilience and fault tolerance in the event of unforeseen events,
- Economic aspects, in particular financial aspects.

All of these and even more criteria must be analyzed and evaluated as well for a real holistic assessment, taking into account the entire system; at least all of the system components listed in the previously presented table must be examined in depth in order to be able to make an educated statement for the complete transportation domain in terms of economy, reliability, flexibility, resilience/redundancy, etc.

Consequently, for each of the previously mentioned aspects, separate extensive analyses and calculations are desirable. The methodology presented and applied here could be analogically applied to other ecological aspects as well as to non-ecological criteria.

In summary, it is imperative that future ecological assessments of transport systems are not only based on drive energy, but that the entire transportation system, including all infrastructure components, be considered. It is also mandatory that the course of movement of a transportation process, which is based on laws of physics, be included in such assessment. As shown above, the total mass to be moved in the respective transport process plays a decisive role.

Using exemplary examples, this study hopes to have pinpointed the fact, that in particular the specific route infrastructure and node infrastructure of a transportation system do have considerable influence on its ecological footprint. The exhaust gases from the propulsion system of the means of transport only account for a part of the total emissions; depending on the transport system and the specific route, the exhaust gases may even be the smaller part.

Matter-of-factly, it seems neither justified nor helpful to demonize certain transport systems in principle and hail others as the solution to all our future climate problems. We urgently need to think holistically across the entire process chain, keep an eye on all the necessary infrastructure components, and systematically analyze and consider cause-and-effect relationships. Building new high-speed train lines or expanding rail-based public transportation as quickly as possible and building new lines or subways for this purpose may sound particularly environmentally friendly, but in the long run they could actually have a counterproductive effect on the overall ecological balance. Instead of subsidizing the sale of electric cars with billions of taxpayers' money without addressing the issues of traffic performance and utilization of the individual vehicles in parallel, it might be much more sustainable to think about incentives to improve the use of vehicles in private transport.

Some developments that are already prominently emerging today will strongly influence the way in which the mobility requirements are to be met in the future. An ideology-free open-mindedness towards new insights, processes, methods and technologies in this field is imperative in order not to continue to walk the "beaten pathways" in the future. **Public and political discussion must be consistently objectified across all parties and even more oriented toward scientific and technical laws. Physics, chemistry and mathematics are free of ideology and truly non-partisan; they apply worldwide to all people and all political camps.** Scientific and mathematical laws can neither be changed by majority decisions in democratic societies, nor by decree in dictatorships; the fact that there are factual, natural limits to what can be done must not be ignored.

The future of transport systems should be determined significantly stronger by inter-modality. In the future, the systems should complement each other in a much more meaningful way; competition for improvement is to be generally welcomed and can be achieved and, if necessary, steered by sensible regulation. Ignoring CO_2 emissions resulting from the construction and maintenance of the necessary transport infrastructure is not helpful to anyone, and certainly not to the climate. Spending tens of billions of taxpayers' money every year on the construction of a railway infrastructure, which in the end is not or only in small parts borne by the users of the railway system, does not support competition for the most economically and ecologically sensible means of transport (99). With mobility being regarded as a basic need, it must still be recognized that physical transport is an ecologically and economically costly good. Recent considerations about entirely free public transport are consciously or unconsciously setting the wrong accents here.

Future political decisions should be geared to take the overall increase in mobility requirements worldwide into appropriate account. Much greater differentiation considering unchangeable conditions into appropriate account is unavoidable in this context. In the densely populated Netherlands for instance, where tunnels are hardly necessary due to the lack of mountains, and bridges must only be built over canals and irrigation channels, the ecological balance for a railroad track looks much different than in Germany’s mountain regions, such as the “Westerwald”, the “Thuringian Forest” or even more so the Alps. It is also essential to assess the CO_2 emissions generated by future infrastructure expansion. Again, in this context it is important to remember that transport systems that do not require any route infrastructure have fundamental and lasting advantages over other transport systems.

Finally, the fact, that decisions for new roads and bridges, railway lines, stations or airports have very long-term effects, and the wished-for benefits can often only be expected after years or decades, must also be taken into proper account. The probability of occurrence of the assumptions that are made at the time of planning and construction about the systems’ working life and traffic performance over the coming decades is significantly dependent on what fundamental innovations are to be developed during their intended operating life. History teaches us that even in the context of transportation systems, "disruptive innovations" have brought unexpected and profound changes, illustrated with an anecdote that happened about 120 years ago:

At the time of the penultimate turn of the century, a survey was made among young men of the nobility (who at that time had the privilege of traveling). The question was: "What needs to be done so that you can travel faster and more comfortably in the future?" Almost all respondents answered, "We just need faster horses."

<u>Proper foresight looks different!</u>

9 Appendix

9.1 *Physical calculations*

9.1.1 *Acceleration energy per passenger*

Energy for acceleration per passenger

$F_{accel} = m/2 * v^2$

	mass (kg)	v_s (km/h)	v_t(km/h)	v_s (m/s)	v_t (m/s)	**kJ**
ICE 3 train	1.800	0	60	0	16,67	**250**
		60	120	16,67	33,33	**750**
		120	180	33,33	50,00	**1.250**
		180	220	50,00	61,11	**1.111**
		220	270	61,11	75,00	**1.701**
		270	290	75	80,56	**778**
		0	120	0	33,33	**1.000**
		0	270	0	75,00	**5.063**
		0	290	0	80,56	**5.840**

car	1.117	0	130	0	36,11	**728**
		80	100	22,22	27,78	**155**
		80	130	22,22	36,11	**452**
		100	130	27,78	36,11	**297**
		0	150	0	41,67	**970**

A 321	447	0	0,8 Mach	0	243,00	**13.197**

9.1.2 *Energy for lifting work per passenger*

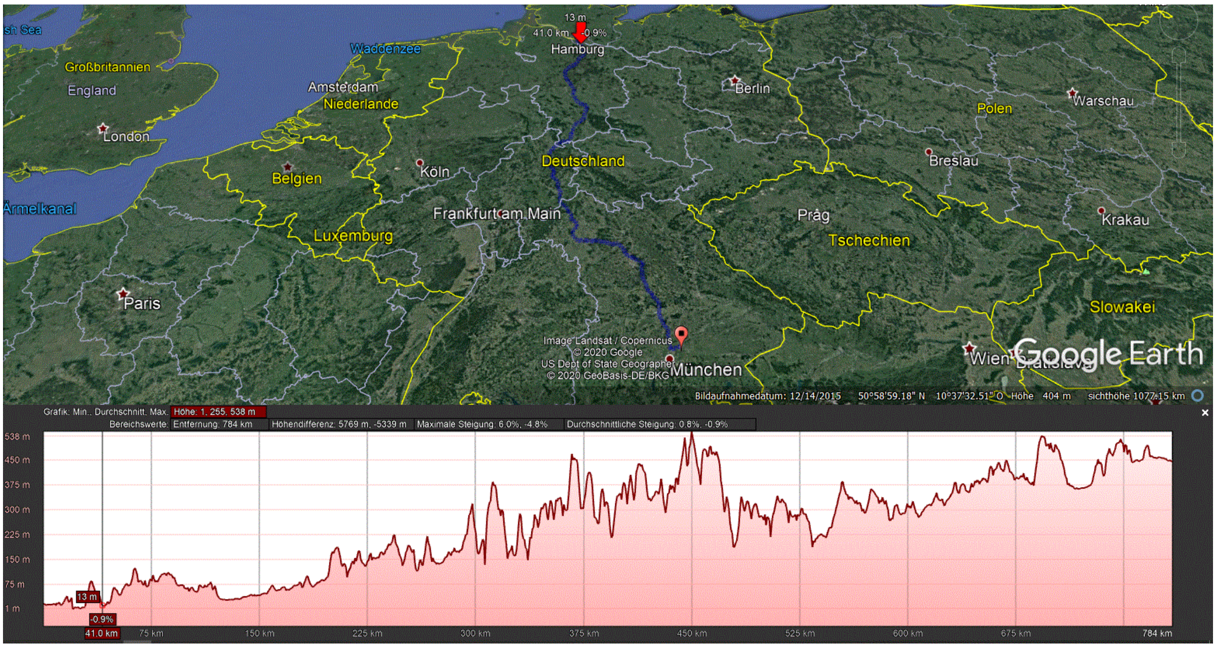

Fig.2: Fastest connection from Hamburg to Munich incl. elevation profile
(Source: Google Earth)

Energy for lifting work per passenger

$F_{lift} = F_G * h = m * 9{,}81 * h$

	Mass (kg)	Altitude (m)	kJ
ICE 3 train	1.800	2.308	**40.746**
	1.800	100	**1.766**
car	1.117	4.615	**50.570**
	1.117	100	**1.096**
A 321	447	9.000	**39.466**
	447	100	**439**

9.1.3 *Energy to overcome air drag per PKM*

Energy to overcome drag in km $F_{drag} = \rho/2 * c_d * A * v^2$							# pass-engers	kJ per PKM
	ρ (kg/m³)	c_d	A (m²)	v (km/h)	v (m/s)	**kJ**		
ICE 3 train	1,225	1,1	11	80	22,22	**3.660**	231	16
				100	27,78	**5.719**		25
				150	41,67	**12.867**		56
				180	50,00	**18.528**		80
				200	55,56	**22.874**		99
				230	63,89	**30.251**		131
				250	69,44	**35.741**		155
				270	75,00	**41.688**		180
				290	80,56	**48.093**		208
car	1,225	0,3	3	50	13,89	**106**	1,5	71
				80	22,22	**272**		181
				130	36,11	**719**		479
				150	41,67	**957**		638
				180	50,00	**1.378**		919
A 321	0,466	0,08	122	0,8 Mach	243,00	**134.282**	164	819

9.2 *Energy calculations and CO_2 emissions for railway travel by Deutsche Bahn*

Energy consumption and CO_2 emissions Deutsche Bahn 2017:

Traction energy (drive energy) for German rail traffic						
		kWh	CO_2 in kg			
Electricity (drive energy) 2017	100,00%	10.190.000.000	5.441.460.000			
Long Distance traffic	32,80%	3.342.320.000	1.784.798.880			
Regional traffic	43,20%	4.402.080.000	2.350.710.720			
Freight / cargo traffic	24,00%	2.445.600.000	1.305.950.400			
		liter	CO_2 in kg	CO_2 in kg (electricity and Diesel)	Traffic volume (PKM/TKM)	CO_2
Diesel (drive energy) 2017	100,00%	436.000.000	1.139.922.000	6.581.382.000		
Long Distance traffic	2,50%	10.900.000	28.498.050	1.813.296.930	40.548.000.000	**44,72 g/PKM**
Regional traffic	76,10%	331.796.000	867.480.642	3.218.191.362	41.876.000.000	**76,85 g/PKM**
Freight / cargo traffic	21,50%	93.740.000	245.083.230	1.551.033.630	92.651.000.000	**16,74 g/TKM**

Assumtions: All kWh figures are net electricity quantities; line and conversion losses must also be taken into account. Electricity consumption of other rail traffic and construction site traffic is not taken into account.
Amount of CO_2 in kg / kWh: 0,534 Source: Umweltbundesamt (Federal Environmental Agency, Germany)

Energy consumption and CO_2 emissions Deutsche Bahn 2019:

Traction energy (drive energy) for German rail traffic						
		kWh	CO_2 in kg			
Electricity (drive energy) 2019	100,00%	9.552.000.000	5.100.768.000			
Long Distance traffic	32,80%	3.133.056.000	1.673.051.904			
Regional traffic	43,20%	4.126.464.000	2.203.531.776			
Freight / cargo traffic	24,00%	2.292.480.000	1.224.184.320			
		liter	CO_2 in kg	CO_2 in kg (electricity and Diesel)	Traffic volume (PKM/TKM)	CO_2
Diesel (drive energy) 2019	100,00%	410.600.000	1.073.513.700	6.174.281.700		
Long Distance traffic	2,50%	10.265.000	26.837.843	1.699.889.747	44.151.000.000	**38,50 g/PKM**
Regional traffic	76,10%	312.466.600	816.943.926	3.020.475.702	41.634.000.000	**72,55 g/PKM**
Freight / cargo traffic	21,50%	88.279.000	230.805.446	1.454.989.766	88.237.000.000	**16,49 g/TKM**

Control infrastructure					
Electricity for control infrastructure 2019	kWh				
Switch control / signals	196.000.000	104.664.000			
Switch heating	131.500.000	70.221.000			
			CO_2 control infrastructure.		
			174.885.000		
Long Distance traffic		27,53%	48.148.956	44.151.000.000	**1,09 g/PKM**
Regional traffic		48,92%	85.554.226	41.634.000.000	**2,05 g/PKM**
Freight / cargo traffic		23,57%	41.212.225	88.237.000.000	**0,47 g/TKM**

Node infrastruktur					
Electricity for train station operations	kWh	CO_2 in kg	**CO_2 in kg**		
	331.500.000	177.021.000	**177.021.000**	85.785.000.000	**2,06 g/PKM**

Assumtions: All kWh figures are net electricity quantities; line and conversion losses must also be taken into account. Electricity consumption of other rail traffic and construction site traffic is not taken into account.
Amount of CO_2 in kg / kWh: 0,534 Source: Umweltbundesamt (Federal Environmental Agency, Germany)

9.3 *Abbreviations, units and metric conversions*

9.3.1 *Some abbreviations used in the text*

CHP: Combined Heat- & power Plant

CRP: Carbon fiber Reinforced Plastic

DFS: Deutsche Flugsicherung (German ATC)

EU-ETS: European Emission Trade System

GHG: Greenhouse Gas(es)

LNG: Liquified Natural Gas

MIT: Motorized Individual Transportation

NGO: Non-Governmental Organization

9.3.2 *Units and metric conversions*

Abbreviation	**Unit**		**(Metric) Conversion**
g	Gram	weight unit	1,000 g = 1 kg *28.35 g = 1 oz.*
kg	Kilogram	weight unit	1 kg = 1,000 g *1 kg = 2.205 lbs. = 35.27 oz.*
t	(metric) ton	weight unit	1 t = 1,000 kg *1 t = 2,204.6 lbs.*
mm	millimeter	distance unit	1,000 mm = 1 m *25,4 mm = 1 in*
m	meter	distance unit	1 m = 1,000 mm *1 m = 3.28 ft = 1.09 yds.*
km	Kilometer	distance unit	1 km = 1,000 m *1 km = 0.622 mi; 1 mi = 1,609 m*
ml	milliliter	volume unit	1,000 ml = 1 l *29.574 ml = 1 fl. oz. (US)*
l	liter	volume unit	1 l = 1,000 ml *1 l = 1.057 US liq. qt.*
J	Joule	energy unit	1 J = 1 Ws = 1 Nm
kJ	Kilo joule	energy unit	1 kJ = 1,000 J
MJ	Mega joule	energy unit	1 MJ = 1,000 kJ
Ws	watt second	energy unit (electrical work)	1 Ws = 1 J 3,600,000 Ws = 1 kWh
kWh	kilowatt hour	energy unit (electrical work)	1,000 kWh = 1 MWh
MWh	Megawatt hour	energy unit (electrical work)	1 MWh = 1,000 kWh
GWh	gigawatt hour	energy unit (electrical work)	1,000 MWh = 1 GWh
Nm	Newton meter	energy unit (mechanical work)	1 Nm = 1 J
PKM	person kilometer	transport volume unit	1 person transported over a distance of 1 km
TKM	ton kilometer	transport volume unit	1 (metric) ton transported over a distance of 1 km

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