

Holistic ecological assessment of transportation systems

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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 CO₂. 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 CO₂ footprint holistically for the first time, 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 is new and has not yet been widely used in the scientific 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 CO₂ 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 CO₂ emissions during construction and maintenance, that significantly exceed the emissions resulting from propulsion. Node infrastructure can also be a significant CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ could be achieved through significant structural changes in mobility and transport.

- Politically intended financial incentives to reduce CO₂ emissions in the transport sector will only have the intended effect, if they include all relevant CO₂ emissions on the one hand and are internationally and globally oriented on the other. CO₂ 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 CO₂ 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 CO₂ 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.

Preface for this English version

This text presented here in English is a translation of a study which was commissioned by 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.

Due to various requests to make the full study also available in English, this version has been prepared and was released in June 2021. Since the text 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 were added to the appendix.

Many thanks to my friends Wolfgang Jakubek, Thomas A. Dalton and A. Bradley Shingleton for the careful review of the English text and their helpful comments which improved the readability considerably. Many thanks as well to the smart guys behind the automatic translation program “DeepL” (<https://www.deepl.com>), which was used for the first translation, which was subsequently further edited and adapted by the author of the study.

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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 CO₂ 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 for the first time 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 CO₂ 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 - the following table 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
Path 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 respective systems, all components necessary for the respective transportation 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 CO₂ 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, CO₂ was considered a naturally occurring, non-toxic, invisible and odorless gas to which no real relevance was attached. It was only

¹ LNG: Liquid Natural Gas

about 20 years ago that awareness of the greenhouse gas effect of CO₂ was first raised. However, this 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 CO₂ emitters include the steel industry, aluminum production, and the cement and concrete industries. (3), (4).

To produce one ton (1,000 kg) of steel in a blast furnace, around 20 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 1 ton of crude steel generates around 2 tons of CO₂ (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 is even more negative than for steel; depending on the primary energy used, between eight and 12 metric tons of CO₂ are emitted to produce one ton of pure aluminum (7). Concrete production is also an ecologically problematic material, not least because of the use of cement, which already generates around one ton of CO₂ per ton of cement during production. Despite progress in energy efficiency, it must still be assumed that at least 300 kg of CO₂ are released per m³ 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 CO₂ emissions, which is three to four times the CO₂ emissions of the entire global aviation industry (8), (9), (10), (11). Although intensive research is being carried out to reduce emissions from cement and concrete production, a major breakthrough is still to be seen (12). From a climate point of view, it is irrelevant whether CO₂ 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 CO₂ in the atmosphere occurs after about 10 years, and the climate effect of CO₂ molecules is about 100 years due to the time they remain in the atmosphere (13). Regional or even local differences regarding the climatic effect of CO₂ dependent on the location of CO₂ emitters can thus be excluded.

Once the relevant figures for the CO₂ 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 "transportation volume" provided, i.e. transportation performance in passenger kilometers (PKM), for freight ton kilometers (TKM). The following figures are available (14), (15), (16):

Transportation system	Traffic volume in billions of PKM
Road , motorized individual transport (MIT)	965.5
Rail <ul style="list-style-type: none"> ➤ thereof long-distance traffic ➤ thereof regional traffic 	95.8 39.4 56.5 *)
Aviation (departing and arriving from/at all German airports) <ul style="list-style-type: none"> ➤ thereof within Germany ➤ thereof outgoing to foreign countries ➤ thereof arriving from abroad 	486.2 10.3 237.6 238.3

Table 2: 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 MPT in their pollutant balance. In case where considerations in this paper are also valid for regional traffic, this is explicitly stated.

2 CO₂ emissions during production (and proper disposal) 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, CRP² 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.

² Carbon fiber Reinforced Plastic

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 CO₂ 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 CO₂ is produced during production and proper recycling (17).

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 CO₂ impact of the production of batteries for electric vehicles. It concluded on a value of 150 to 200 kg of CO₂ per kWh of battery power. According to this, a battery with a capacity of 50 kWh had a CO₂ 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 CO₂. In 2019, an updated version of this study has been published by IVL (18), in which a value of between 61 and 106 kg CO₂/kWh of battery capacity was given for most new battery types³. 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 CO₂ 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 CO₂ emissions in battery production.

For the following considerations, we will stick to a value of 8 t CO₂ determined by ADAC and IFEU as an example for an average automobile. Statistically, in Germany such vehicle drives approx. 160,000 km during its lifetime, so that the CO₂ costs incurred in production amount to an additional 50 g for each vehicle kilometer driven. Since cars in Germany are only occupied by 1.5 people on average (16), this results in a comparatively low transport volume of 240,000 PKM; we therefore have **33 grams of CO₂ 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 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 CO₂ footprint from manufacturing.

³ 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.

In any case, the amounts of CO₂ 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 flip 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 (19). If you take into account the number of seats and the average capacity utilization (20), (21), this results in slightly more than 3.1 billion PKM, to which the CO₂ quantities from production, maintenance and proper disposal must be allocated appropriately. The ICE3, which will henceforth be used as a “model train”, has a dead weight of 408 t 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 contrasts 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 CO₂ 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 (22). 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 (22). Again, there are unfortunately no figures available from the aircraft manufacturing industry for the quantities of CO₂ generated during production. A typical medium-haul aircraft, such as the Airbus A321, has an empty weight of 47.5 tons (23), (24), (25), 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 CO₂ emissions from the construction of the aircraft to be credited to each PKM will be significantly lower than in road or railway transport.

Interim conclusion: 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 CO₂ emissions, has so far not been considered at all. Nevertheless, this will not change the earlier conclusion that cars have the largest CO₂ 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.

3 CO₂ emissions from infrastructure

3.1 Route infrastructure

All trains run on rails made of high-performance steel, with one rail weighing 60 kg per meter (26). For one kilometer of rail, that is 60 t of steel; for one track (consisting of two rails), that is 120 t and thus 240 t of CO₂ 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 84,000 t of CO₂ 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 used today, in which the rails lie on a multi-layer continu-

ous concrete bed (27). 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 earth and 55,000 m³ of tunnel spoil were produced (28). The production of the concrete and steel for this one tunnel structure alone therefore produced at least 37,750 t of CO₂. If these figures are extrapolated to all the tunnels between Cologne and Frankfurt (around 47 km in 30 tunnels), the CO₂ 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 3 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 (29). For the total earthwork, this source indicates the movement of 30 million m³ of material plus eleven million m³ 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 (30). There, analyzing the exact structural, geological and topographical conditions, more than 27,000 t of CO₂ 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 CO₂ 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 CO₂ were produced just for the steel and concrete production of this 170 km long stretch. As mentioned before, these are only the CO₂ 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 (31). 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 CO₂ have been produced 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 CO₂ 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 CO₂ 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 84,000 tons of CO₂ will 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, are currently being factually entirely rebuilt after less than 30 years (rail, track bed, catenary masts, electrification and control technology) (32), (33).

The complete CO₂ 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, on the basis of research for several representative lines, it can be assumed that CO₂ 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, CO₂ emissions in the mid- to upper double-digit gram range are calculated for each PKM (assumption: 3-4 million t CO₂ 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.

Another instructive example of railroad 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 are 125,000 t of steel arches, 16,000 t of reinforcing steel and 3 million m² of steel nets (34). Four tunnel drilling machines, each weighing several thousand tons and with an output of 3,500 kW have been in operation for 320 days a year, 18 hours a day, for 6 years. In the 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 ballast track. Here, too, it is immediately obvious that, already due to the materials used, a total of several million tons of CO₂ were emitted before the first train could pass through the Gotthard Tunnel. The plausibility of this statement can be checked again with the figures calculated in detail for Stuttgart21; at 27,000 t CO₂ per tunnel kilometer, this results in 4.1 million t CO₂ for the Gotthard structure. A complete analysis, which, for example, would also have to consider the CO₂ emissions from the manufacturing of the tunnel drilling machines and their transport/removal, the arrival and departure of thousands of workers to the construction site, and much more, shows that 4 million t CO₂ is rather a lower limit.

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 6 lanes throughout this stretch. This corresponds to a paved area of 29 meters in cross-section (35) over the entire length, i.e., a good 5 million m². Assuming a concrete surface layer of 30 cm, which is not uncommon for heavily trafficked highways (36), more than 1.5 million m³ of concrete are required for this surface layer alone, for which more than 375,000 t of CO₂ 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 on the profile (37). 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 CO₂ 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 CO₂ 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. 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 CO₂ 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, CO₂ 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 CO₂ pollution caused by the infrastructure of the highways per PKM is lower on average than for the comparable railway system.

To be able to robustly compare the GHG emissions for the construction and maintenance of the route infrastructure between road and railway, calculations need to be made on a route-specific basis. This is the only way to prevent, for example, the inclusion of railway lines that are reserved exclusively for freight transport, or the inclusion of trunk (long distance) roads into the calculation, for which comparable railway lines do not even exist.

In connection with the current intensive discussion on electromobility, it is also imperative to consider the amount of CO₂ 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 in Germany 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 (38). 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.

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.

Interim conclusion: The infrastructure of the road and railway transport systems causes CO₂ emissions that are far too large to ignore. Not taking into account the amounts of CO₂ caused by the construction and maintenance of this infrastructure leads to a distorted picture in the ecological assessment.

3.2 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 47 million cars and vans are on the road in Germany. Assuming an average parking space of 12.5 m² per vehicle, the total parking space required in Germany would be well over 500 km² if all vehicles were parked at the same time. To put this into perspective: Cologne's entire urban area covers just over 400 km², Frankfurt's only just under 250 km² (39). 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 CO₂ emissions already described, which had been produced during the manufacturing of these materials, we are dealing here with CO₂ 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, that 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 CO₂ (33 g from vehicle production, 85 g from drive energy, as shown in sec. 4.5). 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 (40). 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.) (41).

In railway transport, the hub infrastructure in Germany includes approximately 5,600 train stations (42) 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 CO₂ 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, CO₂ emissions resulting only from concrete and steel production are estimated to be around 1.9 million metric tons (43). Other sources calculate the total CO₂ emissions for this project even significantly higher. Regardless of whether we are talking about around 2 or 3.5 million tons of CO₂, these are CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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.

Regarding the operation of the train stations, the annual electricity demand of Deutsche Bahn for 2019 is estimated at 331 GWh (44), which results in about 189,000 t CO₂. Converted to the PKM performed in one year, this results in about 2.3 grams CO₂ for each PKM. Doing the math, for each railway journey of 500 km in length, 1.15 kg of CO₂ therefore needs to be added to the total bill, resulting only from the power supply for the operation of the stations.

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 CO₂ before it went into operation. Regarding runways at all 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 CO₂ during production. The huge apron areas of airports can be roughly estimated in the same way.

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 Rhein-Main, the operator Fraport reports the total CO₂ emissions for 2018 adding up to 188,600 t (45)⁴. It needs to be noted that this number includes CO₂ emissions attributable to the electricity consumption, heating and air conditioning of many administrative buildings and offices located at the airport as well. Fraport's CO₂ 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 CO₂/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, large conference centers in the emissions directly attributable to the transport, even if they are there for specific logistically understandable reasons of practicality.

Interim conclusion: Considerations and calculations regarding CO₂ 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. The CO₂ emissions from the operation of node infrastructure are quite considerable in

⁴ Fraport reports these and other figures based on the internationally recognized *Scope 3 standard of the Greenhouse Gas Protocol (GHG Scope 3)* (85), which was developed by the *World Resources Institute (WRI)* and the *World Business Council for Sustainable Development (WBCSD)* (86), (87).

total, but they only account for a small part of the CO₂ footprint for mobility when apportioned to PKM.

3.3 Control infrastructure

Very few numbers are also available for the CO₂ 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 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 (46). If the resulting 170,000 t of CO₂ 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 (47): 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 CO₂/kWh in 2019) as well as the CO₂ value for energy generation in combined heat and power plants (0.202 kg CO₂/kWh), a CO₂ 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 CO₂), which together then amounts to the annual CO₂ 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 public 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 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 CO₂ footprint from the energy consumption of DFS would be equivalent to around 105 billion PKM. This then corresponds to around 0.3 g CO₂/PKM, which would be attributable to the control infrastructure in the aviation transport system. Even if the CO₂ 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 CO₂ emissions caused by DFS thus increase to just under 41,000 t, the CO₂ 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 galva-

nized 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 CO₂ (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 (48). Assuming the electricity mix and the resulting CO₂ emissions of 0.57 kg / kWh from 2016, the electricity consumption of Hamburg's traffic lights alone resulted in a CO₂ impact of more than 4.8 tons in 2015.

Interim conclusion: In comparison with the other infrastructure components, the analyses carried out for the control infrastructure suggest that the resulting CO₂ 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.

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 (21), (49). 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, TWIN-DEXX 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 (50). 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% (51), 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 (52). 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 (53). (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 (52). 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 200 seats and the average load factor of around 82% (54), 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 (24) 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; ICE3: 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 8 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 10 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 to 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 m^2 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/m^3 (55). The wing area, which is the relevant parameter for an aircraft instead of the frontal area, is 122 m^2 (24), (25), 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/s^2).

If for instance a mass of 1 kg is lifted by 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.

4.4 Fuel and electrification

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 seri-

ous 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.

In comparison, electric engines, already widely used on the railroad network in Germany, do not need to carry their "fuel"; they are powered by an overhead line (catenary wire). 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 (44). But of course, such power supply for a railway track must first be built as well. In sec. 3.1., this aspect was already briefly mentioned; it will now be considered in a little more detail: The copper contact wire alone (120 mm² cross-section), which is common on railway lines in Germany, weighs about one ton per kilometer (56). The copper production process generates around 3 t of CO₂ per ton, not including the further processing of the pure metal into wires. The actual contact wire and the various holding and tensioning wires, which are made of copper, bronze (copper-tin alloy) and steel, as well as the associated masts, must be manufactured and built, with the respective resources needed for this. For the necessary copper and other metals used, it needs to be noted that there are no significant natural deposits of those in Germany, with the ecological footprint starting with the ore mines in the countries of origin, followed by the processing into crude metal, to the manufacturing of the wires or ropes. In the case of tin, the element that is needed to produce bronze along with copper, around 16 t of CO₂ are emitted to obtain one ton of the pure metal (57). In addition to the more than one ton of copper for the contact wire, several more tons of metal per kilometer of railroad track are required for the tethers, plus several tons of concrete and steel for the catenary poles and their foundations. On the Cologne-Frankfurt line alone, 4,000 catenary poles were installed outside the tunnels, plus 1,600 "suspension columns" in the tunnels. In total, around 3,300 km of wires, ropes and cables were required for the electrification on the 170 km long track (29). Depending on length and material, catenary poles weigh between 1.5 and 2 tons each (58). If one adds up the figures and data given in the sources mentioned, the electrification of a railroad track already results in at least 20 t of CO₂ emissions per kilometer just for the copper required as raw material for the catenary, as well as concrete and steel for the masts. The steel for the tensioning wires, the anchors and the so-called "chain weights" on the masts are not included in this rough calculation, nor are the emissions caused by the construction work. Furthermore, it must be mentioned that in Germany a separate power grid of over 7,900 km is operated in the background for the electrified railway lines (59). This railway-owned high-voltage network (110 kV) has its own overhead line pylons and hundreds of own converter stations, rectifiers and transformers to transform the traction current to the 15 kV and 16 2/3 Hz required for railroad operation. In summary, the fact that the energy for an electrically powered train does not need to be carried in a tank and that this mass can be saved in transport is by no means "to be had for free". In connection with the electrification infrastructure required, it instead leads to thousands of tons of CO₂ emission during construction, maintenance and occasional renewal (32).

4.5 CO₂ 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 CO₂ 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 CO₂; in the following, a value of 3.15 kg of CO₂ is used as a basis for each 1 kg of fuel burned (60). E.g., a car that consumes 8 l gasoline (6 kg)/100km produces 189 g CO₂ 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 CO₂ 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 CO₂/PKM (61). 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 (62), which corresponds to 90 g CO₂/PKM⁵.

As for the electricity, taking into account the electricity mix commonly used in Germany and for domestic consumption, CO₂ 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 CO₂ calculations for electricity consumption (63), (64). 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 (65), (66). 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 plants⁶. 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 CO₂-free and will not be for the foreseeable future. Power plants as well as solar cells and wind turbines must first be 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 (67) quick-

⁵ In the discussions about GHG emissions from aviation, the so-called RFI (Radiative Forcing Index) is often included in the public debate (83), (84). 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" (80). Moreover, calculations of the RFI included all aviation emissions without separating 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. In the meantime, leading atmospheric physicists and climate experts have developed the ERF (Effective Radiative Forcing), a parameter that describes the effects of aviation on global warming in accordance with the current state of research (88).

⁶ The railway company's claim that it runs its long-distance trains 100% on "green electricity" and thus CO₂-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 CO₂ 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.

ly 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 CO₂ 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 CO₂. The CO₂ 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 (21); for 2019, it was 9,552 GWh plus 410.6 million liters of diesel (49). 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 (46). For long-distance transport, these figures make for a CO₂ 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 (68) (flying vs. taking the train) and (64), (69) (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.

4.6 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 CO₂ 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 3 summarizes the considerations made so far. The color coding in the table is only qualitative and not quantitative 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 2), individual statements can be made in relation to PKM.

	Rail	Road	Aviation
Means of transport	Train	CAR	Airplane
CO ₂ from drive	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	Airline-oriented

Table 3: 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, CO₂ 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 CO₂ loads in the mid to upper double-digit gram range per PKM. More precise estimates can be made for specific route sections, such as: 3-4 million t CO₂ 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 CO₂ for the construction of the Gotthard Base Tunnel extrapolated to the current approximately 4 million users over 50 years burdens each user with 20 kg CO₂ 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. Electrification of a railway line must al-

so be estimated around at least 20 t CO₂ for each kilometer, which especially on little-used branch lines drives up total emissions per PKM.

- (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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂. Of course, many other ecological aspects such as noise or land requirements also deserve to be considered. These aspects are important "secondary parameters" for a fully comprehensive, real holistic consideration of the matter and have already partly been examined by the author of this paper, but they have not been included in this study as required by the client.

There is however one other very important aspect in connection with CO₂ 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 (62); this corresponds to a 44% saving, which is transferred 1:1 to CO₂ 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 (70), but in 2019, after another ten years with engine outputs increasing year by year, the average had risen to 116 kW (158 hp), (71), (72). 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 CO₂ emissions.

The situation is quite different for CO₂ emissions generated during infrastructure construction. These occur exclusively at the time of construction. Therefore, proponents 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 CO₂ 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 CO₂ 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. All the improvements achieved in steel and concrete production over the past 20 years and all the innovations in diesel engines for construction vehicles (catalytic converters, particulate filters, reduced fuel consumption, etc.) have no effect on the example route between Cologne and Frankfurt built between 1995 and 2002, as the millions of tons of CO₂ already emitted into the environment will not be recaptured just because better technologies are available today.

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 CO₂ 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 CO₂, but nitrogen oxide (NO_x) and, in summer, ozone (O₃) pollution. An electric train e.g., does not produce any exhaust gases where it travels. For the climate, in the case of CO₂, however, it does not matter at all where the greenhouse gas is produced. CO₂ molecules cause a warming effect in the atmosphere for an average of 100 years; they are distributed evenly in the atmosphere, regardless of where they originate. If the steel used comes from China or India, a CO₂ molecule produced there in the blast furnace process will have the same GHG effect on the climate for 100 years as a CO₂ 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 CO₂ 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 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. Contrary to widespread opinion, propulsion is not CO₂-free for either long-distance or local trains and will not be for the foreseeable future. When the CO₂ 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 CO₂, which had and will 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 CO₂ 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 (73). 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 (74). 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 CO₂ 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 CO₂ 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.⁷

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 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, that provides by far the greatest leverage for sustainable improvements. Around 47 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 (75). 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%.

⁷ 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 CO₂ 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.

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 CO₂ from the production of an average automobile, this approach will lead to **annual savings of more than 13 million t CO₂**, 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 CO₂ emissions of the MIV by 31.5 million tons per year**. Fewer vehicles and less traffic will require fewer roads, less new road construction and repair, which would also result in further reductions in CO₂ 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 CO₂-expensive construction of the railway infrastructure, which causes millions of tons of CO₂.* 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 CO₂ 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 (76). 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 components to be considered; 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 CO₂ 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 (77), (78), (79). 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. Thinking even further: 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 (80). 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 CO₂ 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 CO₂ pricing, and the emissions to transport such materials to Germany are also not priced in either. CO₂ 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 CO₂-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 (81). This creates an appropriate incentive for companies to reduce CO₂ 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 CO₂ 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, as commissioned, on a comprehensive ecological comparison of different transportation systems, with a particular emphasis on CO₂ 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 con-**

sistently 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 world-wide 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 CO₂ 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 (82). 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 railway line 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 CO₂ 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."

Proper foresight looks different!

9 Appendix

9.1 Physical calculations

9.1.1 Acceleration energy per passenger

Energy for acceleration per passenger						
$F_{\text{accel}} = m/2 * v^2$						
	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

$$F_{\text{lift}} = F_G \cdot h = m \cdot 9,81 \cdot h$$

	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							# pass- engers	kJ per PKM
$F_{\text{drag}} = \text{Rho}/2 * c_d * A * v^2$								
	Rho (kg/m ³)	c _d	A (m ²)	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 CO₂ emissions for railway travel by Deutsche Bahn

Energy consumption and CO₂ 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

Assumptions: 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 CO₂ in kg / kWh: 0,534

Source: Umweltbundesamt (Federal Environmental Agency, Germany)

Energy consumption and CO₂ 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

Assumptions: 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 CO₂ 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: Liquid 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

10 Literature and references

1. Jens Borken-Kleefeld, Terje Berntsen, Jan Fuglestvedt. Specific Climate Impact of Passenger and Freight Transport. *Environmental Science Technology*. 2010, Vol. 44, pp. 5700-5706.
2. Jens Borken-Kleefeld, Jan Fuglestvedt, Terje Berntsen. Supporting Information for: Mode, load, and specific climate impact from passenger trips. *Environmental Science & Technology*. 2013, Vols. 47, 14, pp. 7608-7614.
3. Brandenburg, Landesamt für Umwelt. [Online] 2019. [Cited: 12 15, 19.] <https://lfu.brandenburg.de/cms/detail.php/bb1.c.523833.de>.
4. FIZ, Karlsruhe. EnEff:Industrie. [Online] 2018. [Cited: 12 15, 2019.] <https://eneff-industrie.info/quickinfos/energieintensive-branchen/daten-zu-besonders-energiehungrigen-produktionsbereichen/>.
5. UBA. Emissionsfaktoren zur Eisen- und Stahlindustrie für die Emissionsberichterstattung. [Online] 2010. <http://www.uba.de/uba-info-medien/4362.html>.
6. Energiewirtschaft, Forschungsgesellschaft für. CO2 Verminderung in der Metallerzeugung, S.4. [Online] 2018. [Cited: 12 15, 2019.]
7. Umweltagentur, NÖ Energie- und Aluminium. [Online] 2019. [Cited: 12 15, 2019.] <https://www.wir-leben-nachhaltig.at/aktuell/detailansicht/aluminium/>.
8. Wikipedia. Zement, Umweltschutzaspekte. [Online] 2019. [Cited: 12 15, 2019.] <https://de.wikipedia.org/wiki/Zement#Umweltschutzaspekte>.
9. Klimabilanz Zementindustrie. [Online] 2019. [Cited: 12 15, 2019.] <https://www.chemietechnik.de/klimabilanz-der-zementindustrie/>.
10. Welt. Klimakiller Beton. [Online] 2011. [Cited: 12 15, 2019.] https://www.welt.de/print/die_welt/debatte/article13499011/Klimakiller-Beton.html.
11. ZDF. Zement - Der heimliche Klimakiller. [Online] 2018. [Cited: 12 15, 2019.] <https://www.zdf.de/dokumentation/planet-e/planet-e-zement---der-heimliche-klimakiller-100.html>.
12. Deutschlandfunk. Klimasünder Beton - Ein Baustoff sucht seinen Nachfolger. [Online] 12 20, 2020. [Cited: 12 24, 20.] https://www.deutschlandfunk.de/klimasuender-beton-ein-baustoff-sucht-nachfolger.740.de.html?dram:article_id=488355.
13. Ricke., Katherine L. and Caldeira, Ken. Maximum warming occurs about one decade after a corbondioxide emission. [Online] 2014. [Cited: 01 06, 21.] <https://iopscience.iop.org/article/10.1088/1748-9326/9/12/124002/pdf>.
14. Statistisches_Bundesamt. Luftverkehr auf allen Flugplätzen - Fachserie 8 Reihe 6.2 - 2018. [Online] 2019. [Cited: 12 15, 2019.] https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Transport-Verkehr/Personenverkehr/Publikationen/Downloads-Luftverkehr/luftverkehr-alle-flugplaetze-2080620187004.pdf;jsessionid=9FB84A3F57BD035C3F8E8C7471B9C9A0.internet742?__blob=publicationFile.
15. BMVI. Verkehr in Zahlen 2017/2018. [Online] 2019. [Cited: 12 15, 2019.] <https://www.bmvi.de/SharedDocs/DE/Publikationen/G/verkehr-in-zahlen-pdf-2017-2018.html>.
16. UBA. Daten zum Verkehr. [Online] 2018. [Cited: 12 15, 2019.] <https://www.umweltbundesamt.de/daten/verkehr>.

17. IFEU-ADAC. [Online] 2019. [Cited: 12 15, 2019.] <https://www.adac.de/verkehr/tanken-kraftstoff-antrieb/alternative-antriebe/studie-oekobilanz-pkw-antriebe-2018/>.
18. Emilsson, E. and Dahllöf, L. Report C444 - Lithium-Ion Vehicle Battery Production - Status on Energy Use, CO₂, ... [Online] 2019. [Cited: 12 04, 20.] <https://www.ivl.se/english/ivl/publications/publication.html?id=5808>.
19. Handelsblatt. Welche Strecke legt ein Zug insgesamt zurück? [Online] 2013. [Cited: 12 15, 2019.] <https://www.handelsblatt.com/technik/das-technologie-update/weisheit-der-woche/schienenverkehr-welche-strecke-legt-ein-zug-insgesamt-zurueck/8896436.html?ticket=ST-51043305-2RyidOktPLdICL01yqgb-ap5>.
20. Wikipedia. ICE3. [Online] 2019. [Cited: 12 15, 2019.] https://de.wikipedia.org/wiki/ICE_3.
21. DB. *Daten & Fakten 2017*. 2018.
22. Planefinder. *Planefinder App: Analyse der Flugbewegungen des Flugzeugs mit der Registrierung D-ABYZ für September 2019*. 2019.
23. Flugzeuginfo.net. Flugzeuginfo.net: Airbus A321. [Online] 2019. http://www.flugzeuginfo.net/acdata_php/acdata_a321_dt.php.
24. Airbus. AIRCRAFT CHARACTERISTICS Airbus 321. [Online] 04 01, 2020. [Cited: 05 23, 2020.] <https://www.airbus.com/aircraft/support-services/airport-operations-and-technical-data/aircraft-characteristics.html>.
25. Wikipedia. Airbus-A320-Familie. [Online] 2020. [Cited: 05 23, 2020.] https://de.wikipedia.org/wiki/Airbus-A320-Familie#A321_2.
26. —. Schiene_(Schienenverkehr). [Online] 2019. [Cited: 12 15, 2019.] [https://de.wikipedia.org/wiki/Schiene_\(Schienenverkehr\)](https://de.wikipedia.org/wiki/Schiene_(Schienenverkehr)).
27. Gleisbau-Welt. Feste Fahrbahn. *Gleisbau-Welt.de*. [Online] 2019. [Cited: 12 15, 2019.] <https://www.gleisbau-welt.de/lexikon/infrastruktur/oberbau/feste-fahrbahn/>.
28. Wikipedia. Idsteintunnel. [Online] 2019. [Cited: 12 15, 2019.] <https://de.wikipedia.org/wiki/Idsteintunnel>.
29. —. Schnellfahrstrecke Köln-Rhein_Main. [Online] 2019. [Cited: 12 15, 2019.] https://de.wikipedia.org/wiki/Schnellfahrstrecke_K%C3%B6ln%E2%80%93Rhein/Main.
30. Rößler. Quantifizierung der THG-Emissionen des Projekts Stuttgart 21. [Online] 2017. [Cited: 12 15, 2019.] https://www.umstieg-21.de/assets/files/thg-endbericht_s21_251017.pdf.
31. NBS, ARGE. Web Archive: ARGE NBS Los A. [Online] 2019. <https://web.archive.org/web/20060208054606/http://www.arge-nbs.de/deutsch/strassenbau/index.php>.
32. Tagesschau. Tagesschau. *Bahn sperrt Hauptstrecken monatelang*. [Online] 2018. [Cited: 12 15, 2019.] <https://www.tagesschau.de/wirtschaft/deutschebahn-sanierung-101.html>.
33. Spiegel_Online. Bahnpassagiere müssen längere Fahrzeit einplanen. [Online] 2019. [Cited: 10 05, 20.] <https://www.spiegel.de/reise/aktuell/ice-strecke-hannover-goettingen-30-minuten-laengere-fahrzeit-ab-11-juni-a-1268770.html>.
34. AlpTransit. *Projektkennzahlen Rohbau Gotthard-Basistunnel*.
35. Wikipedia. Richtlinie Anlage von Autobahnen. [Online] 2019. [Cited: 12 15, 2019.] https://de.wikipedia.org/wiki/Richtlinien_f%C3%BCr_die_Anlage_von_Autobahnen.

36. —. Deckschicht_Straßenbau. [Online] 2019. [Cited: 12 15, 2019.] [https://de.wikipedia.org/wiki/Decke_\(Straßenbau\)](https://de.wikipedia.org/wiki/Decke_(Straßenbau)).
37. Leitplanken. [Online] 2019. [Cited: 12 15, 2019.] <https://leitplanken-kaufen.de/>.
38. Welt. "Ich grabe nicht ganz Tübingen um,...". [Online] 2019. [Cited: 12 15, 2019.] <https://www.welt.de/wirtschaft/article200285740/Boris-Palmer-Ich-grabe-nicht-ganz-Tuebingen-um-damit-Sie-Ihre-Ladesaeulen-kriegen.html>.
39. Wikipedia. Liste der 100 flächengrößten Gemeinden Deutschlands. [Online] 2019. [Cited: 12 15, 2019.] https://de.wikipedia.org/wiki/Liste_der_100_fl%C3%A4chengr%C3%B6%C3%9Ften_Gemeinden_Deutschlands.
40. DEKRA. Fakten zum Parken. [Online] 2016. [Cited: 12 04, 20.] <https://www.dekra-infoportal.de/statistik/fakten-zum-parken/>.
41. Prognos AG. *Auskunft über verfügbare Parkplätze in Städten*. 2015.
42. Statista. Anzahl Bahnhöfe. [Online] 2019. <https://de.statista.com/statistik/daten/studie/13357/umfrage/anzahl-der-bahnhoefe-im-besitz-der-db-ag/>.
43. KONTEXT:Wochenzeitung. CO2-Schleuder S-21. [Online] 2019. [Cited: 12 15, 2019.] <https://www.kontextwochenzeitung.de/politik/345/co2-schleuder-s-21-4704.html>.
44. Deutscher_Bundestag. Elektrifizierungsgrad der Schieneninfrastruktur. [Online] 2019. [Cited: 12 15, 2019.] <https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=2ahUKewjk4e6BtoXmAHVjw8QBHQDGBkYQFjAAegQIBRAC&url=https%3A%2F%2Fwww.bundestag.de%2Fblob%2F549342%2F...%2Fwd-5-027-18-pdf-data.pdf&usg=AOvVaw1YSdqOyFxDVLxuoTGzxfL>.
45. Fraport. Umwelterklärung 2019. [Online] [Cited: 01 21, 21.] https://www.fraport.com/content/dam/fraport-company/umwelt/klimaschutz/bin%C3%A4rdokumente/verkuerzte-umwelterkla-rung_2019.pdf/_jcr_content/renditions/original.media_file.download_attachment.file/verkuerzte-umwelterkla-rung_2019.pdf.
46. Bundestag, Deutscher. *Antwort der Bundesregierung auf die Kleine Anfrage der FDP Fraktion betreffend "Energieverbrauch der Deutschen Bahn AG"*. 2020.
47. DFS. E-Mail Antwort der DFS auf Anfrage zum jährlichen Energieverbrauch. 2020.
48. Hamburg, Bürgerschaft der Stadt. Kleine Anfrage vom 16.06.2016. [Online] 06 16, 2016. [Cited: 12 15, 2019.] <https://kleineanfragen.de/hamburg/21/4741-umruestung-von-ampeln-in-hamburg-auf-neueste-led-technik.txt>.
49. DB. *Daten & Fakten 2019*. 2020.
50. Wikipedia. *SBB RABe 502*. [Online] [Cited: 07 10, 20.] https://de.wikipedia.org/wiki/SBB_RABe_502.
51. Statistikportal, SBB. SBB Verkehrsleistungen. [Online] [Cited: 07 10, 20.] <https://reporting.sbb.ch/verkehr?years=0,1,4,5,6,7&scroll=0&highlighted=70291c3c32fba876bef5ed8198c49e1f>.
52. Alstom Corodia Continental. [Online] [Cited: 12 17, 20.] https://de.wikipedia.org/wiki/Alstom_Corodia_Continental.

53. RE 8 - Rhein-Erft-Express und RB 27 - Rhein-Erft-Bahn. [Online] 2020. [Cited: 12 17, 20.] <https://www.nvr.de/streckennetz-und-angebot/linienuebersicht/re-8-rhein-erft-express-und-rb-27-rhein-erft-bahn>.
54. Lufthansa. LH-Group Auslastung 2018. [Online] 2019. [Cited: 12 15, 2019.] <https://newsroom.lufthansagroup.com/german/newsroom/mit-142-millionen-passagieren-im-jahr-2018-ist-die-lufthansa-group-die-nummer-eins-in-europa/s/41337be6-ca07-4298-bf9b-cee7e91c69e3>.
55. DWD. ICAO-Standardatmosphäre. [Online] 2020. [Cited: 05 23, 2020.] https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwif_sPT_cnpAhXB0aQKHSGMBj4QFjABegQIARAB&url=https%3A%2F%2Fwww.dwd.de%2FDE%2Fservice%2Fflexikon%2Fbegriffe%2FS%2Fstandardatmosphaere_pdf.pdf%3F__blob%3DpublicationFile%26v%3D3&usg=A0vV.
56. Wikipedia. Oberleitung. [Online] 2019. [Cited: 12 15, 2019.] <https://de.wikipedia.org/wiki/Oberleitung>.
57. Giegrich, Liebich, Fehrenbach. UBA, Ableitung von Kriterien zur Beurteilung einer hochwertigen Verwertung gefährlicher Abfälle. [Online] 2007. [Cited: 12 15, 2019.] <https://www.umweltbundesamt.de/publikationen/ableitung-von-kriterien-zur-beurteilung-einer>.
58. Bahn. Erster Oberleitungsmast gestellt. [Online] 2018. [Cited: 12 15, 2019.] http://www.bahnprojekt-stuttgart-ulm.de/no_cache/projekt/aktuell/archiv-suche/news-archiv-detail/news/1432-erster-oberleitungsmast-gestellt/newsParameter/detail/News/.
59. DB_Energie. DB Energie - Über uns. [Online] 2019. [Cited: 12 15, 2019.] <https://www.dbenergie.de/dbenergie-de/db-energie-unternehmen/unternehmen-1345392>.
60. Klimaschutz-Portal. Klimawirkung Luftverkehr. [Online] 2019. [Cited: 12 15, 2019.] <https://www.klimaschutz-portal.aero/klimakiller-nr-1/klimawirkung-des-luftverkehrs/>.
61. BUND. CO2-Emissionen des Verkehrs. [Online] 2019. <https://www.bund.net/themen/mobilitaet/autos/co2-emissionen/?wc=24308>.
62. Klimaschutz-Portal. Verbrauch senken. [Online] 2019. [Cited: 12 15, 2019.] <https://www.klimaschutz-portal.aero/verbrauch-senken/>.
63. UBA. *Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990-2018*. 2019.
64. Eisenkopf, A. Böse Studie: Elektroautos lassen nur woanders verbrennen. [Online] 2019. [Cited: 12 09, 20.] https://www.achgut.com/artikel/boese_studie_elektroautos_lassen_nur_woanders_verbrennen/P15#comment_entries.
65. Deutsche_Welle. Wie grün ist die Deutsche Bahn wirklich? [Online] 2018. [Cited: 12 15, 2019.] <https://www.dw.com/de/wie-gr%C3%BCn-ist-die-deutsche-bahn-wirklich/a-41894678>.
66. Frankfurter_Rundschau. Die grüne Mär der Bahn. [Online] 2018. [Cited: 12 15, 2019.] <https://www.fr.de/wirtschaft/gruene-bahn-10991713.html>.
67. Windpark Geisberg - Technik. [Online] [Cited: 12 09, 20.] <https://www.windpark-geisberg.de>.
68. Kuhne, Manfred. Energieverbrauch von Bahn und Flugzeug. [Online] 2015. [Cited: 12 15, 2019.] <https://www.airliners.de/energieverbrauch-bahn-flugzeug-apropos/36592>.

69. C. Buchal, H.-D. Karl, H.-W. Sinn 2019. Kohlemotoren, Windmotoren und Dieselmotoren: Was zeigt die CO₂-Bilanz? *ifo Schnelldienst*. 08 2019.
70. Stockburger, C. Spiegel Mobilität: Die Mär vom Mehr. [Online] 2013. [Cited: 12 11, 20.] <https://www.spiegel.de/auto/aktuell/durchschnittliche-ps-zahl-der-neuwagen-in-deutschland-gesunken-a-931262.html>.
71. Spiegel Mobilität: Deutsche Autofahrer stellen PS-Rekord bei Neuzulassungen auf. [Online] 2020. [Cited: 12 10, 20.] <https://www.spiegel.de/auto/deutsche-autofahrer-stellen-ps-rekord-bei-neuzulassungen-auf-a-742a5bf1-30c5-4eca-8a96-9918b23ccf57>.
72. Statista: urchschnittliche Motorleistung von neu zugelassenen Personenkraftwagen in Deutschland in den Jahren 2004 bis 2018. [Online] [Cited: 12 10, 20.] <https://de.statista.com/statistik/daten/studie/12937/umfrage/entwicklung-der-motorleistung-von-neuwagen/>.
73. Tagesspiegel. Wofür die Deutsche Bahn 86 Milliarden Euro braucht. [Online] 2019. [Cited: 10 15, 20.] <https://www.tagesspiegel.de/wirtschaft/marode-infrastruktur-wofuer-die-deutsche-bahn-86-milliarden-euro-braucht/24844350.html>.
74. —. Scheitern mit Ansage: Interne Analyse stellt Bahn alarmierendes Zeugnis aus. [Online] 2019. [Cited: 10 15, 20.] <https://www.tagesspiegel.de/wirtschaft/scheitern-mit-ansage-interne-analyse-stellt-bahn-alarmierendes-zeugnis-aus/24313964.html>.
75. infas. Mobilität in Deutschland. [Online] 2018. [Cited: 12 15, 2019.] https://www.bmvi.de/SharedDocs/DE/Anlage/G/mid-ergebnisbericht.pdf?__blob=publicationFile.
76. Herrmann, Andreas and Brenner, Walter. *Die autonome Revolution: Wie selbstfahrende Autos unsere Welt erobern*. s.l. : Frankfurter Allgemeine Buch, 2018.
77. NZZ. Synthetisches Flugbenzin. [Online] 2019. [Cited: 12 15, 2019.] <https://www.nzz.ch/mobilitaet/luftfahrt/synthetisches-flugbenzin-abheben-mit-kerosin-aus-windstrom-ld.1520098>.
78. Tagesspiegel. Forscher entwickeln klimaschonendes Kerosin. [Online] 2019. [Cited: 12 15, 2019.] <https://www.tagesspiegel.de/wissen/treibstoff-aus-luft-wasser-und-licht-forscher-entwickeln-klimaschonendes-kerosin/24976042.html>.
79. Golem.de. [Online] 2019. [Cited: 12 15, 2019.] <https://www.golem.de/news/sun-to-liquid-wie-mit-sonnenlicht-sauberes-kerosin-erzeugt-wird-1806-134969.html>.
80. Wirtschaftswoche. Tempolimit am Himmel. [Online] 2019. [Cited: 12 15, 2019.] <https://www.wiwo.de/politik/deutschland/inlandsfluege-ein-tempolimit-am-himmel-koennte-dem-klima-helfen/25308762.html>.
81. Union, Europäische. Emissionsobergrenzen und -zertifikate. [Online] [Cited: 01 08, 21.] https://ec.europa.eu/clima/Policies/ets/cap_de.
82. Wikipedia. Leistungs und Finanzierungsvereinbarung. [Online] 2019. [Cited: 12 15, 2019.] https://de.wikipedia.org/wiki/Leistungs-_und_Finanzierungsvereinbarung.
83. UBA. Klimawirksamkeit des Flugverkehrs. [Online] 2012. [Cited: 12 15, 2019.] https://www.umweltbundesamt.de/sites/default/files/medien/377/dokumente/klimawirksamkeit_des_flugverkehrs.pdf.
84. Atmosfair. Fliegen und Klima. [Online] 2019. [Cited: 12 15, 2019.] https://www.atmosfair.de/de/fliegen_und_klima/flugverkehr_und_klima/klimawirkung_flugverkehr/.

85. Greenhouse Gas Protocol. [Online] [Cited: 01 21, 21.] <https://ghgprotocol.org/standards/scope-3-standard>.
86. World Resources Institute. [Online] [Cited: 01 21, 21.] <https://www.wri.org/>.
87. World Business Council for Sustainable Development. [Online] [Cited: 01 21, 21.] <https://www.wbcsd.org/>.
88. D.S. Lee, et.al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*. 2021, Vol. 244.