Mining global transport: Determining the material stocks (and flows) of global transport until 2050

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List of Abbreviations

- MFA : Material Flow Analysis
- IEA: International Energy Agency
- UNCTAD: United Nations Commission on Trade and Development
- UITP: International Association of Public Transport (Union Internationale des Transports Publics)
- UIC: International Union of Railways (Union intionationale des Chemins de fer)
- PBL: Planbureau voor de Leefomgeving
- LCV: Light Commercial Vehicle
- MFT: Medium Freight Truck
- HFT: Heavy Freight Truck
- IMAGE: Integrated Model to Assess the Global Environment
- TIMER: The IMage Energy Regional model
- IAM: Integrated Assessment Model
- SSP: Shared Socio-economic Pathways
- GVW: Gross Vehicle Weight
- tkm: tonne-kilometre
- pkm: passenger-kilometre
- Tera-kilometre: 10^{12} kilometre
- GT: Gross Tonnage, a volumetric measure to depict the size of a boat
- DWT: Deadweight Tonnage, a weight measure of the carrying capacity of a boat
- LDW: Light Deadweight, the empty weight of a boat thus without cargo or people
- SSP: Shared Socioeconomic Pathway

1. Executive summary

The research for this thesis relates to the assessment of the material needs for the vehicle fleet for global passenger and freight transport. The specific vehicles in these two categories that were assessed are: maritime vessels, inland shipping vessels, trucks, planes, buses and trains which will be divided into smaller categories of vehicles. First the global stock of the vehicles will be assessed, which is followed by a global dynamic stock and flow MFA (Material Flow Analysis) of these transport vehicles between 1970 and 2050. The MFA will base the stock and flows on the baseline and 2°C scenario of the SSP2 (Shared Socioeconomic Pathway). In these scenarios the extent to which the fleet is electrified is assessed as well as the material consequences thereof.

Firstly, when assessing the current stock of materials in vehicles, we found that the largest quantity of materials is in maritime vessels. This is followed by Heavy Freight Trucks and Light Commercial Vehicles come third, as can be seen in Figure 1. These values were calculated through a data analysis, using all reliable data that could be found regarding the number of vehicles. This was multiplied by an average weight of the vehicle, which in turn was multiplied by the material fraction within the various types of vehicles.

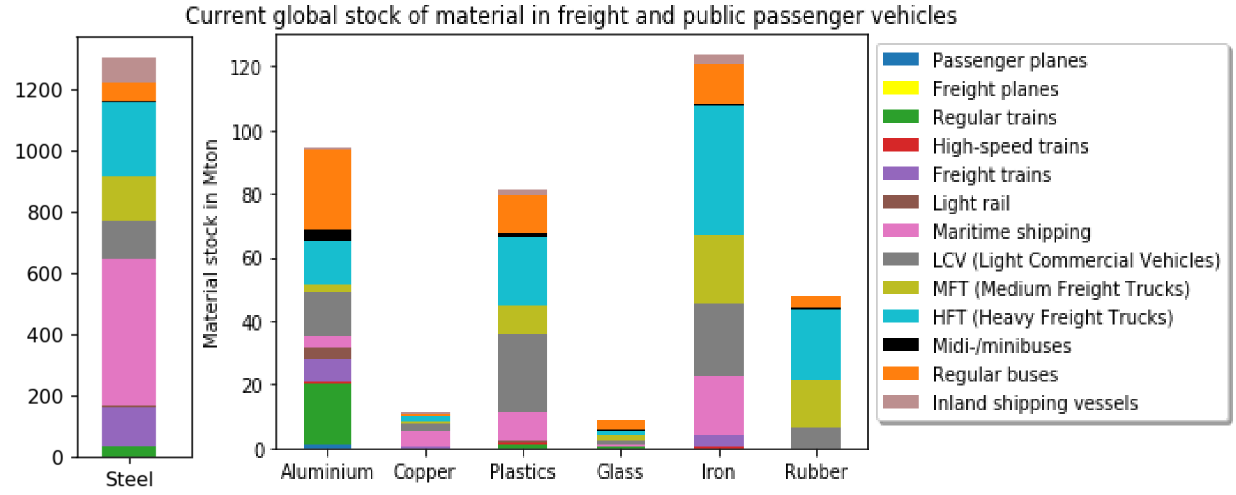

Figure 1 The current global stock of material in freight and public passenger vehicles

Secondly, when looking at material content and dividing it by the number of passenger- or tonne-kilometres per year for the various vehicle types, we calculated a value to denote the material efficiency of the vehicle is (Table 1 below).

Table 1 Compiled efficiency of vehicles

Freight vehicles (in g/tkm)		**Passenger vehicles (in g/pkm)**	
Freight planes	0.727	Passenger planes	0.172
Freight trains	14.039	Regular trains	4.549
Maritime freight vessels	4.976	High-speed trains	3.322
Inland freight vessels	18.781	Midi-/minibuses	14.61
LCV	200.571	Regular buses	11.96
MFT	30.521		
HFT	21.697		

Once the current stock is determined and the material efficiency is calculated, the dynamic MFA model can be built. The model is built based on the output in terms of tonne- and passenger-kilometres of the baseline and the 2°C scenario spanning over the period 1970 until 2050.

The dynamic model first calculates a stock of vehicles and then the stock of materials. On this basis, the inflow and outflow of vehicles is calculated. This is represented in figure 2 below, which outline an increase in demand (inflow) between 2020 and 2050. The IMAGE scenarios thus predict a significant increase in the use of materials in the coming decades.

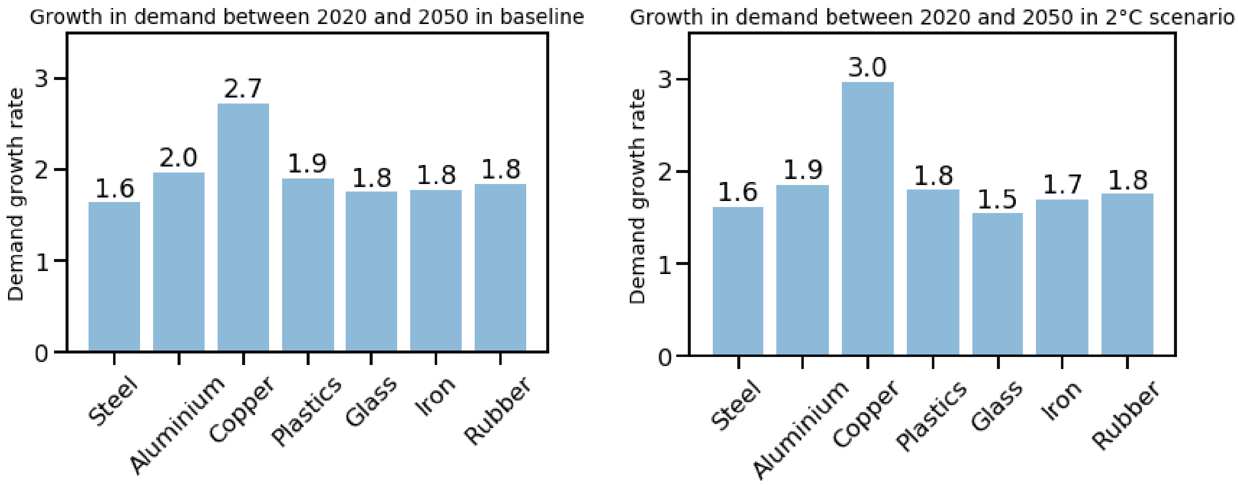

Figure 2 Demand growth rate increase between 2020 and 2050 in the baseline and the 2°C scenario

With regard to fleet electrification, the scenarios predicted little to no use of fully electric buses and trucks. However, use of hybrid and plug-in hybrid trucks will increase significantly in both scenarios towards 2050. This will lead to an increase in demand for metals such as cobalt, copper, manganese, zinc and lithium as can be seen in the following figure 3.

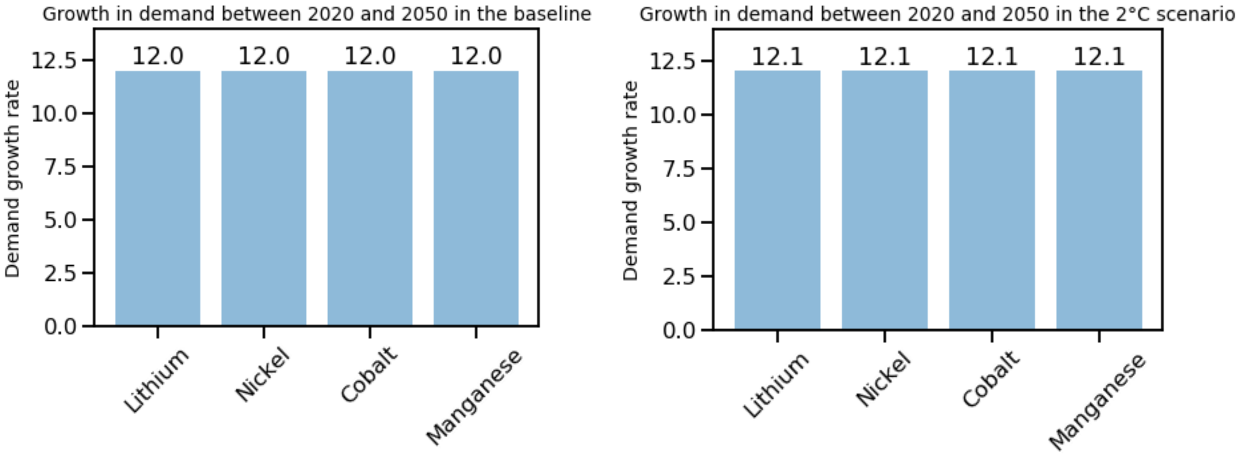

Figure 3 Demand growth of metals required to build batteries for vehicles as a result of fleet electrification between 2020 and 2050 in the baseline and the 2°C scenario

2. Introduction

The concept of planetary boundaries was first addressed in the Limits to Growth report by the club of Rome. The reports attempts to outline, with the use of a computer model, how mankind's impact on the world will lead to significant environmental decay and depletion of resources. The report predicted that unbridled growth would eventually lead to significant decline in industrial capacity and population (Meadows et al., 1972). The publication has been criticised later for the prediction that shortages would occur in various key resources, such as oil, and various metals such as gold and silver (Lomborg & Rubin, 2009). However, the publication inspired numerous later studies that examined how human expansion would be limited by earthly factors. A seminal work of such analyses is the study of the planetary boundaries (Rockström et al., 2009). In this study the human stresses upon the world are measured in terms of nine processes, which are either anthropogenic or exacerbated by humans. The processes outlined in the article are: climate change, ocean acidification, stratospheric ozone depletion, atmospheric aerosol loading, biogeochemical flows (interference with P and N cycles), global freshwater use, land-system change, rate of biodiversity loss and chemical pollution. The conclusion in this study was, that for the nitrogen cycle, climate change and biodiversity loss humanity exceeded the planetary boundaries already (Rockström et al., 2009). Thus, it is important to measure to what extent industrial and other human processes impact the world in various manners.

When studying human development, a central theme is the extent to which travel is possible, both in terms of goods and people; in other words, the capacity for transport in relation to the planetary boundaries. In the early days of human civilization, Roman roads, initially built for military purposes, soon became vital for the complex trade of the Roman Empire. The roads allowed for fully loaded carts moving at greater speeds and further distances (Berechman, 2003). Later, European maritime vessels would begin the process of globalisation in the 16th and 17th century, setting the stage for the current vastly interconnected global passenger and goods transport systems (Bernstein, 2009). The capacity for transport, which is based on the infrastructure and the vehicles, is therefore central to the magnitude and direction of human development. However, unlike earlier ages the world currently faces the challenge of planetary boundaries. The new challenge is how to shape global transport, which is so central to the functioning and development of society, in a manner that accounts for planetary boundaries.

One important source of stress on planetary boundaries resulting from the transport sector , is the significant emission of greenhouse gasses (GHG). The sector currently accounts for 23% of total energy related emissions (Sims et al., 2014). Furthermore, in the current trajectory of emissions by the RCP2.6, the transport sector will account for 34% of the total GHG emissions by 2100 (Girod et al., 2012). It should be noted, however, that this increased share is not entirely due to an increased demand, but also to the fact that transport emissions are relatively less easy to mitigate. In the coming decades, transport demand and the associated GHG emissions are expected to increase, especially in the emerging economies (Sims et al., 2014). Transport is thus a significant emitter of GHG, which is well documented (Cristea et al., 2013; Cuenot et al., 2012). In the area of global transport, one aspect is however underreported, which is the impact of material requirements for global passenger and freight transport now and in the future. Given the significance of transport and the projected rise in demand, it is apparent that greater understanding of the material use of this sector could have a positive impact on transport policy decisions. Deetman et al. (2018) made an analysis of the global material stock of cars and electronic appliances. In terms of material requirements for global transport this analysis did not consider left two other large categories ,other transport vehicles and infrastructure. Our research addresses the materials in the remaining transport vehicles used for freight and passenger transport. The framework used for this study is the Material Flow Analysis (MFA). To determine the number of vehicles in the future, the second shared socio-economic pathway of the IAM (Integrated Assessment Model) IMAGE (Integrated Model to Assess the Global Environment) is used. Below, a concise description of these two aspects of this thesis is given. Before this , we will address the importance of studying the material requirements of society.

2.1 Why study material use

The main goal of this research is to outline the number of freight and public passenger vehicles in the world and the material stock of global transport vehicles. The second step in this research is the assessment of the number of vehicles in the second SSP scenario of the IAM IMAGE. Such research is relevant, because the extraction, refining and moulding of material from the earth into the products we use, is one of the central elements of human impact on the planet. The extraction and refinement of metals impacts the environment in particular in terms of greenhouse gasses, land use and water use (Nuss & Eckelman, 2014; Tost et al., 2018). The environmental impact of other prevalent materials in vehicles is also thoroughly documented, for example for rubber and plastic. During the extraction and production of these materials a wide array of environmental damages can be found (Das et al., 2016; Harding et al., 2007). Any material used will have some impact on the environment and, given the planetary boundaries that we are already experiencing, a central challenge to humanity is, how to decrease the use of materials. It is therefore important to asses how much material will be needed in the future. Once the amounts are known, we can determine where there are possibilities to decrease the material requirements of society. Secondly, assessing the demand for materials accurately could expose possible shortages or indicate the growth in demand resulting from a significant scale up of current global production. An example of such an assessment is the study by Kleijn and van der Voet (2010), which shows that different pathways of energy transitions can have a significant effect on the material requirements of society (Kleijn & van der Voet, 2010). Another study related to this research shows that the metals lithium and cobalt would experience a significant increase in demand in various future pathways (Deetman et al., 2018). These materials can be described as critical materials, because, given the currently proven reserves, the supply is very limited and reserves could run out when demand increases significantly.. Moreover, there is the problem that these metals are often mined in very poor regions, where small local mines, called artisanal, result in even more significant environmental damage than regular large scale mines (Carvalho, 2017). Yet another study, on copper, states that if the whole world were to enjoy the lifestyle of the current developed world, proven reserves would not be sufficient (Gordon et al., 2006). These studies clearly outline the significance of researching the current and future material requirements of society. Lastly, outlining future material stocks allows us to identify possibilities for recycling.

2.2 Integrated assessment modelling and SSP

An integrated assessment model is a logical next step after the first computer generated climate models were developed during the 1960s. A model is called integrated when it combines the knowledge of a broad variety of disciplines (Weyant et al., 1996). The models thus seek the integration of various research communities (Parson & Fisher-vanden, 1997). The goal of Integrated Assessment Models is to couple climate models with economics and policy responses and test the impact of future scenarios, which is called an Integrated Analysis (IA). This idea stems from the Limits to Growth report by the Club of Rome. The report assessed possible future environmental impacts such as DDT and lead pollution and climate change (Edwards, 2011). Since the 1970s IAMs gradually improved as computers improved as well as understanding of the models in the various academic disciplines (Sarofim & Reilly, 2011). As the models evolved their use became more widespread. The assessments are used, for example, to identify areas where further research is needed, as well as to create consensus on issues (Sarofim & Reilly, 2011). The IAMs have most notably been used to create various scenarios of human development. Examples of currently often used scenarios developed through IAMs are the Representative Concentration Pathways (RCP) and the Shared Socioeconomic Pathways (SSP) (Riahi et al., 2017). These pathways are applied to assess a wide variety of global factors. For example, the SSPs have been used, for land-use (Doelman et al., 2018), the energy sector (Bauer et al., 2017) and air pollution (Rao et al., 2017). This paper uses the second SSP. There are in total five SSPs with each a different storyline. For example, the first SSP assumes a world of green growth, in which the world works together to improve, among other things, the environmental impact. The third SSP can be characterised by regional rivalry; cooperation between countries is low and countries revert to nationalism, which hinders cooperation and the achievement of sustainability goals (O'Neill et al., 2015). The SSPs differ in a wide variety of factors such as: politics, education, social inequality and energy use. Furthermore, the SSPs can elaborate several scenarios per pathway. These scenarios aim to show how within the storyline of a specific SSP certain policy objectives could be attained and how it would play out. The two scenarios used in our research are the baseline scenario and the 2°C scenario of the second SSP. This means the changes that would have to be made to the baseline in order to limit global warming to below 2°C above pre-industrial level. The second SSP can be characterised as a middle of the road scenario, in which, , changes happen at a moderate pace, based on historical patterns. The world remains somewhat unequal and divided, although some international cooperation persists and moderate successes are achieved in terms of sustainability and poverty reduction. This stands in opposition to the baseline of the second SSP, in which global warming is estimated to be approximately 3.8°C above pre-industrial levels in 2100 (Fricko et al., 2017).

One aspect of IAMs and the research done with the models is still underdeveloped, which is the integration of IAMs and the concepts and tools of Industrial Ecology (IE). Examples of insight from IE that are lacking in the IAMs, are life cycle perspectives of technology and physical links between capital stock and material flows (Pauliuk et al., 2017). Linking IAM and IE is not a completely untested concept, though. An example of this is a recent study which linked various SSP pathways of IMAGE with material use in order to make an assessment of future demand of various rare metals (Deetman et al., 2018).

2.3 Material Flow Analysis (MFA)

Our research aims to apply the framework of Material Flow Analysis to global transport vehicles. In the past MFA studies descriptions of assets in society were mostly done in terms of monetary value. One of the central changes that MFA studies brough forth, is that they allow us to study society not in terms of monetary value, but in terms of material (Graedel, 2019). . The MFA framework considers the world as an 'industrial metabolism', into which and from which materials flow. For the first time we can therefore trace where materials go, and where they come from. This is also the aim of our research:. how many vehicles exist in the world today, how many new vehicles will flow in and how many used vehicles will flow out?

There are, in general, two types of material flow analyses. The first is static, which means an analysis of the stocks, inflows and outflows at a specific point in time. The second is a dynamic analysis, which assesses the stocks, inflows and outflows over a time interval (Chen & Graedel, 2012). Furthermore, in general there are two approaches to conducting MFA studies, the top-down and bottom-up approach. The top-down approach uses the numbers of inflow and outflow to determine the stock. Bottom-up works the other way around and makes a determination of the inflow and outflow based on the stock (Gerst & Graedel, 2008). This paper aims to both determine a stock of global transport vehicles and create a dynamic MFA model assessing the materials in global transport vehicles in future scenarios. There are some other studies on materials in vehicles with the aid of a dynamic MFA. One is a study on aluminium in US cars. In this study a bottom-up MFA analysis was performed, which showed that material stocks of cars would increase by a factor of 1.8 between 2008 and 2035 (Cheah et al., 2009). Another dynamic MFA study on cars sought to assess the future waste generated by batteries for electric vehicles until 2040 (Richa et al., 2014). These studies prove that MFA is an effective and fruitful tool for this kind of research.

2.4 Outlining the research gap and research question

In terms of global MFA studies, various broad studies have been done to asses the state of specific materials in the world. Cullen et al. (2012) studied the global flow of steel. An interesting result from this study is, that during casting a quarter of all the liquid steel that is produced will be not turned into goods. Instead, it is discarded as scrap during forming, casting and fabrication (Cullen et al., 2012). Yoshimura and Matsuno (2018) made a dynamic MFA model of global copper and summed up all the previous global MFA studies on copper. MFA studies can be redone in order to implement new insights and apply recent trends which lead to new conclusions, such as the insight that the global in-use stock of copper was underestimated until now (Yoshimura & Matsuno, 2018). Then there is a global material flow analysis on a less prevalent metal, manganese (Sun et al., 2020). In yet another article the dynamics and results of MFA studies for 48 critical metals are laid out (Watari et al., 2020).

One of the applications of determining material stock in society is in the field of urban mining (Brunner & Rechberger, 2004). Urban mining refers to extracting material from secondary sources rather than natural deposits. Secondary sources in the context of urban mining means the use of any material originating from a human technological process. This is often also called the technosphere (Johansson et al., 2013). Previous studies, that sought to outline the possibilities for urban mining in the technosphere and determine the material stock, vary in terms of scope and object of study. Usually such studies use an MFA (Material Flow Analysis) framework. A recent study by Marinova et al. (2020) and a companion paper by Deetman et al. (2020) examine the global building stock in the technosphere (Deetman et al., 2020; Marinova et al., 2020). These studies, as well as the above-mentioned paper by Deetman et al. (2018) on cars, electrical appliance and renewable energy technologies, are novel in their methodology, in the sense that the couple material requirements to an IAM (Deetman et al., 2018). All three studies are based on IMAGE, as is our present study.

Various MFA studies have been done on cars, both regional and global, as we have shown above. Studies on public transport or freight vehicles are less abundant. One exception is an MFA study conducted on the Italian highway and railway transport system (Federici et al., 2008). The study included not only an MFA, but also looked at the thermodynamic and environmental flows. This Italian study shows some similarities to the subject of this paper, but has a much narrower scope. Our research is therefore unique in its attempt to outline the global number of vehicles and their material content, and to couple vehicles to an IAM. After the addition of materials in building, electrical appliances and renewable energy technologies, we hope to provide another piece to the IAM IMAGE.

The research gap that we try to fill is is the lack of a global assessment of materials in the current vehicle stock and the material demand to supply the transport needs of the future. Furthermore, IAMs have often not been coupled to models from the IE community in order to improve the models by including the material requirements of society. An important knowledge gap exists in the study of the global use of resources. The global scenarios that are developed with the IAMs are widely used to assist in the development of policy. Currently, IAMs do not integrate material flows in such a manner that policy makers understand the implications of various policy scenarios. It is therefore vital to constantly improve the models with the newest insights. This paper will, in an effort to remedy this shortcoming in IAMS, determine the number of vehicles on the basis of the output of two scenarios of the IAM IMAGE. The vehicles are divided into five categories: airplanes, trains, ships, trucks and buses. In the dynamic model we will study those materials that reoccur in more than one of the vehicle categories. Mostly these are bulk metals, thus: steel, aluminium, copper and iron. However, glass, rubber and plastics will also be addressed, in order to be able to compare the vehicles with regard to their material efficiency. Together, these materials constitute the majority of materials used in vehicles Particularly for battery electric vehicles, the rare metals in batteries will also be addressed.

In this thesis we will seek to determine the use of materials in the transport sector based on two scenarios of the IMAGE model. We will make scenarios based on current developments and past trends, such as increasing sizes of ships for international shipping (Panteia et al., 2015). The goal is to assess what materials are required to address future transport needs and investigate how different scenarios of development influence the quantity and quality of future material needs. The central question of this thesis is therefore: **What are the global material requirements until 2050 of public passenger vehicles and freight transport vehicles in the second Shared Socio-economic Pathway of IMAGE?**

Sub-questions are:

1. What is the current stock of materials in global freight and public transport vehicles?
2. How can information regarding vehicle stocks and vehicle use be linked to IMAGE/TIMER variables?
3. How will the stock of materials in the passenger and freight vehicles develop between 1970 and 2050 under the assumptions of the baseline and 2°C scenario of the second SSP storyline as modelled in IMAGE?
4. What are the inflows and outflows of the passenger and freight vehicles stocks?
5. What are the material consequences of an increasing share of electric and hybrid-electric vehicles in the global fleet?

3. Methods and Data

3.1 Type of material Flow Analysis

The approach of this thesis will be based on MFA (Material Flow Analysis) and two analyses will be done. The first is a static MFA of the current vehicle stock and the second is a dynamic bottom-up MFA. In this research the vehicles in use are considered the stock, newly built vehicles the inflow into the stock and vehicles at the end-of-life the outflow. We will determine the stock of materials in all global transport vehicles which, with the aid of the IMAGE/TIMER integrated assessment model, will be turned into a dynamic model spanning over the period 1970 until 2050. The data on the number of vehicles required to create the static MFA were taken from global, regional and in some cases national sources. If complete information is unavailable, the vehicles can be calculated using the mileage and load with sources regarding the current tonne- and passenger-kilometres (other than IMAGE) as described below. Furthermore, the static model requires an approximate composition of the fleet, in terms of different types of vehicles within a category. Lastly, we need to know the weight and the material fractions of the vehicles. Once the static model is created, we can make the dynamic model. To turn the static model into a dynamic model using the IMAGE data, the two essential data points are the mileage and the load. The mileage is the number of kilometres a vehicle travels per year and the load is the number of passengers or tonnes that a vehicle carries on average. The load is not always given as such and can be deduced by using the load capacity (the total number of people or tonnes of goods a vehicle can carry), and multiply it by the average load factor (the average percentage of used load capacity of a vehicle).

Once we have determined a dynamic stock, the inflow and outflow can be calculated. The data required for this part of the model is the average lifetime of vehicles, the standard deviation as a percentage of the mean and a first year wherein the vehicles started appearing in the world.

3.2 Data sources

Because of the novel nature and wide scope of this research, a wide array of sources is needed. Firstly, there are the sources regarding the vehicle fleets and their material composition. With regard to data on global fleets, a wide variety of organisations study the various transport modes and assess global developments. Many organisations write such reports in order to further a specific agenda. Such are, for example, organisations studying a specific transport type in order to convince policy makers to invest in this particular transport mode. One example is the International Union of Railways (UIC), which has published a variety or reports regarding rail transport, including one pertaining to global rail transport (UIC, 2018b). Sometimes such reports are written are simply to sell them as a type of market analysis. Lastly there are governmental, inter-governmental and non-governmental organisations that write reports on the state of transport vehicles. For the material composition of vehicles, reports are harder to find. Such reports are often academic and form part of a Life Cycle Analysis (LCA) or MFA study. For example an LCA of an Airbus airplane (Howe et al., 2013). Then there are reports made particularly from a sustainability perspective. Finally, data regarding fleets can sometimes be found in annual reports of national public transport companies, which make a statement of all the vehicles in the fleet. Such reports, however, are usually only available in more developed countries.

Secondly, there is the data that is required to determine the number of vehicles from the IMAGE output. International organisations that assess the state of one or several vehicle types do so, in general, in two forms: either they contain only the collected data, or they include forecasts of future scenarios. A lot of the data used in our research has been taken from the analyses of these organisations. The best-known among these organisations is the International Energy Agency (IEA). Apart from its yearly flagship report World Energy Outlook, the IEA writes a variety of reports relating to energy in specific sectors. These may focus on regions or energy sources, and also on specific transport modes. One example is a report published in 2017 on the future of road freight and trucks

(IEA, 2017). Another example is a report on rail travel published in 2019 (IEA, 2019a). For these reports, the IEA often makes use of organisations that promote a specific transport mode. Another organisation is the International Association of Public transport (UITP), which studies various public transport modes such as light rail (UITP, 2012)(UITP, 2019b)(UITP, 2018c) and buses (UITP, 2019a). Next to these, the European Union and the United Nations also commission and write reports regarding global transport. An example is the report about global maritime freight transport by UNCTAD (United Nations Commission on Trade and Development) (UNCTAD, 2019). A last category that produces relevant information on global transport is business analysis. However, such reports are usually only fully accessible on payment. Finally, it has to be noted, that more specific information often cannot be found in these reports. For example, information on the maximum capacity of a vehicle, which however can be found in data published by the manufacturers.

3.3 IMAGE/TIMER

The goal of an IAM is to depict the manners in which humans impact the natural environment. As the models progress, this is not limited to air pollution and climate change, but extends to other human impacts on the environment, such as water scarcity and quality or the depletion of unrenewable resources (E. Stehfest et al., 2014). The IMAGE model seeks to make a complete and integrated picture of human impact. This broad undertaking has been divided into a variety of categories and clusters. There are two broad clusters, the first being energy and climate and the second food, land, water and biodiversity. The models for these respective two clusters are IMAGE/TIMER (The IMage Energy Regional model) and IMAGE/Land&Climate. For this thesis the IMAGE/TIMER part of the IMAGE will be used. TIMER seeks to simulate the energy system. It divides the world into several regions and considers demand and supply for 12 energy carriers (van Vuuren, 2007). For the assessment of energy use in the world, a scenario needs to be made describing which economic sectors use energy and how much. This can be divided into various energy demand categories: Industry, Transport, Residential, Services, Electricity, Heat and Other (van Vuuren, 2007). The category transport has been used for this thesis. Since TIMER was built to determine energy requirements of the above-mentioned categories ,it is also necessary to determine developments in use. For this, TIMER assessed how much transport was used in the past and modelled scenarios for the future.

In order to determine the quantity of travel and freight transport in the respective regions and for the various transport modes, TIMER considered a variety of factors. To determine the share of an energy carrier or technology, including possible changes over time, multi-nomial logit equations are used. These equations compare technologies and fuel types on relative costs (van Vuuren, 2007). These same equations were used to create a TRAVEL model for the determination of the modal distribution and shifts in transport, dividing global transport into a variety of categories (Girod et al., 2012). The TRAVEL model can be seen as part of the TIMER model, allowing to analyse energy use to a greater extent and for the various modes of transport individually. This model differentiates between the use of various travel modes on the basis of assumptions on passenger transport. The passenger modes that are identified in the model are: bicycle, foot, bus, train, high-speed train and air (Girod et al., 2012). The two main assumptions are the TTB rule (travel-time-budget rule) and the TMB-rule (Travel-Money-Budget rule). As for TMB, empirical data suggest that people spend approximately 12% of their country’s GDP on travel. The TTB rule assumes that people generally spend approximately 1.2 hours travelling per day with an average annual increase of 0.25 minutes (Girod et al., 2012). Freight transport uses a less detailed analysis. Modal distribution and shifts for freight are based on demand sensitivity of the prices of the transport modes, i.e. the share of the energy price in total service costs (E. Stehfest et al., 2014). The modal split of the baseline SSP2 scenario of IMAGE/TIMER gives the following split for global passenger and freight transport in the year 2018 and 2050. The fractions are determined on the basis of the Tera-tonne-/passenger-kilometres given by IMAGE/TIMER.

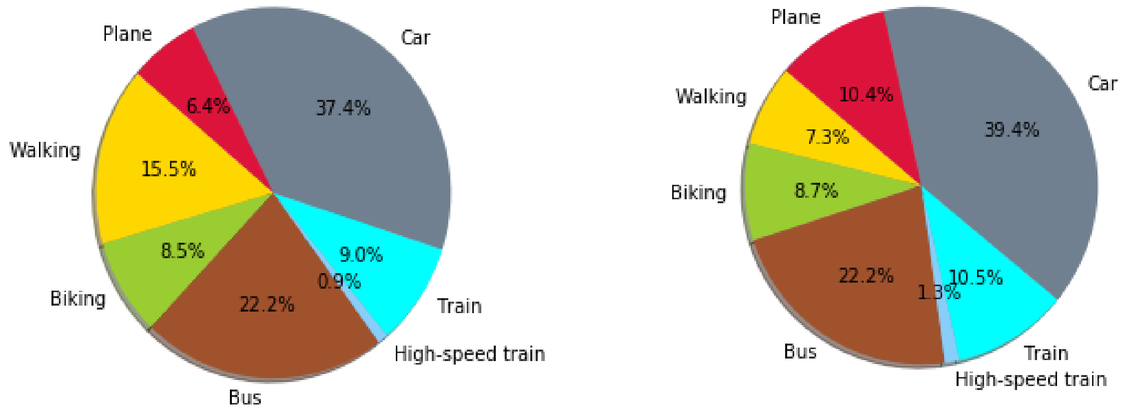

Figure 4 Modal split for passenger transport in 2018 (left) and 2050 (right) according to IMAGE/TIMER in terms of passenger-kilometre

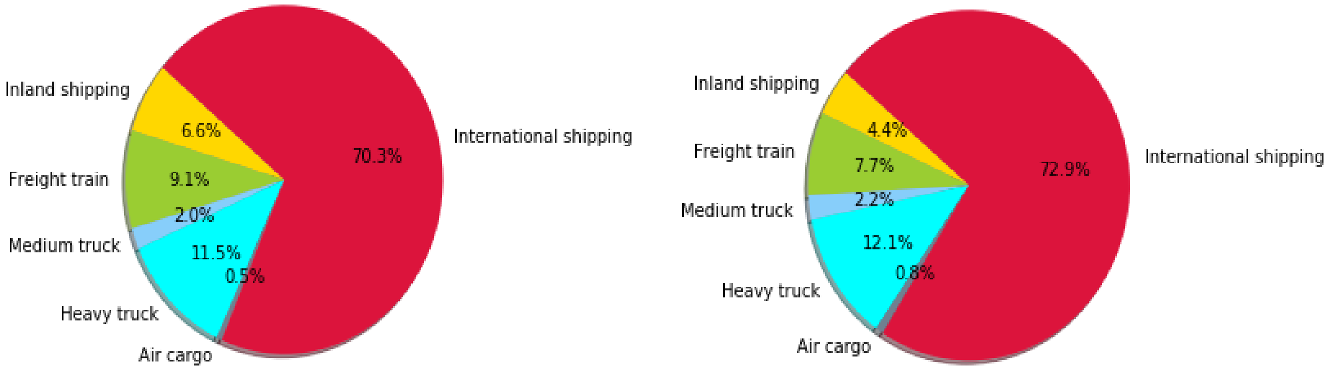

Figure 5 Modal split for freight transport in 2018 (left) and 2050 (right) according to IMAGE/TIMER in terms of tonne-kilometre

3.4 Determination of materials in the current fleet

The first objective of our research is the determination of the material stock in the current global fleet of freight and public passenger vehicles. For this, data has to be found on the amount of vehicles and the composition of the fleets for each vehicle type. In the second part of the thesis we will make projections based on the IMAGE model outputs. For this, the vehicle categories defined by IMAGE/TIMER will be used. For passenger these are planes, buses, trains, high-speed trains, bikes and walking. For freight distinction is made between inland shipping, international shipping, medium freight truck, heavy freight truck, train freight and air freight. This entails the determination of the percentages for the larger variant and the smaller variant within the total fleet for the respective vehicle categories.. Secondly, the weight of the vehicles must be found. The weight is averaged for each vehicle type within the vehicle categories. This means that, for example, the weight of a variety of minibuses is averaged to determine the weight for the vehicle type minibus within the vehicle category buses. Lastly, this is multiplied by the material fractions of each vehicle type to determine the material content. This is outlined in the following figure 6.

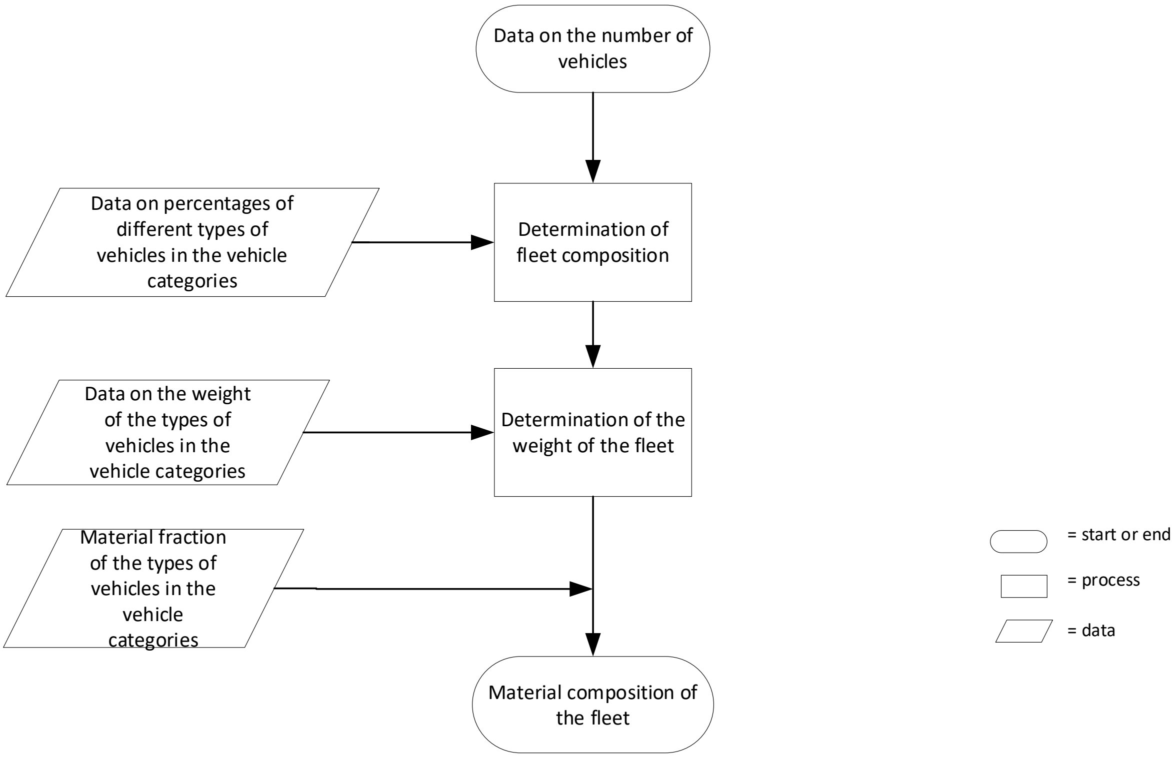

Figure 6 Visualisation of how the material composition of the current fleet is determined

3.5 Determination of the future fleet based on the IMAGE scenarios

The second objective of this thesis is to determine how the vehicle stock in the world will develop based on IMAGE scenarios. For this, an assessment needs to be made of the number of vehicles that currently account for the IMAGE scenario output of yearly global passenger- and tonne-kilometres. Going from passenger- and tonne-kilometre to vehicle numbers means that two values need to be found. The first is the mileage, which is the number of kilometres a vehicle drives, flies or sails per year. The second is the load, which stands for the weight a vehicle carries on average per trip, in other words the number of tons of goods or passengers.

$$Vehicle\ amount = \frac{tkm\ or\ pkm}{(load \cdot mileage)}$$

The load is not always a given fact and sometimes needs to be calculated. For this, we need another important variable, the load factor or occupancy rate. This is the percentage of the maximum load capacity of a vehicle that is actually used on average. Finding an accurate load and mileage for a transport mode on a global level is not easy. These values are not always included in national statistics and if such values are available, this is limited to developed countries. Therefore, there might exist a slight bias exists towards western data in some instances. All these values, the load, mileage and load factor, are also indicators of the efficiency of a transport mode. The values can change over time, they may increase or decrease, so the next step in improving the model is the creation of scenarios with varying efficiency improvements. In Figure 7 a visual representation of the model can be seen.

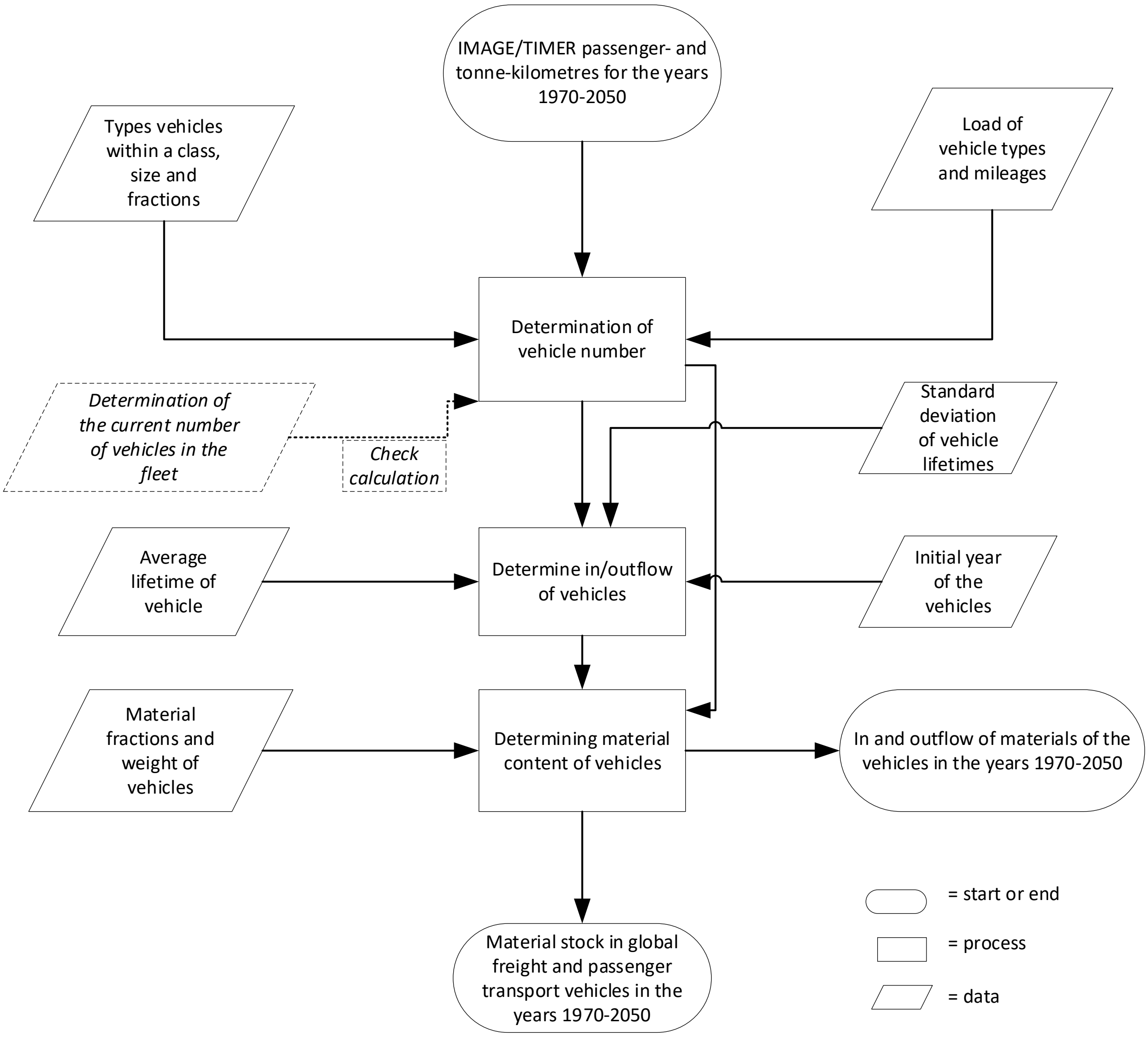

Figure 7 A visual representation of the second model determining the stock and flows based on the IMAGE output

As was mentioned above, IMAGE/TIMER makes a distinction between various vehicle categories. Such a category, however, can still contain a wide variety of vehicles. For example, passenger air transport can broadly be defined in wide and narrow body jets, which differ greatly in size (Doman et al., 2016). Another example can be found in international shipping, where ships carrying the same good, such as oil tankers, can vary greatly (Equasis, 2019). IMAGE/TIMER makes no further distinction, most likely because it concentrates on emissions from the burning of fuel in the vehicles. For this, a distinction between fuel types and varying sizes of the vehicles is of less significance. However, for the assessment of the material requirements, size does matter. It is therefore important to determine whether such differences exist and divide up the tonne- or passenger-kilometres between the loads of vehicles types within the classes. Afterwards a mileage can be added. Once the number of vehicles is determined, the material fractions of the various vehicle classes and the weight of the vehicle classes and types can be multiplied by the number of vehicles. The data acquired in the first part of the research is used to verify the calculation of the second part which can be seen in the validation of the calculation paragraphs of chapter 4. Because the validation of the calculation is not a part of the model to calculate vehicle amount based on tonne- and passenger-kilometres it is visualised with dotted lines in figure 7.

Lastly, the inflow and outflow of vehicles need to be determined. This is calculated with the open-source Python module developed for Material Flow Analysis called ODYM (Open Dynamic Material systems Model) (Pauliuk & Heeren, 2019). The input of the model to ODYM is the vehicle stock during the years 1970 until 2050. Main factors are the stock of vehicles over the years, an average lifetime, the standard deviation of the average lifetime and the year of conception of the vehicle. In Appendix A a more complete description of the calculation can be found.

4. Determining vehicle stocks

In this chapter the values that are needed to determine the vehicle stock and material content within vehicles will be found through data analysis. The subchapters are outlined as follows. Firstly, an assessment is made of what data is available to determine the current vehicle stock and passenger- and tonne-kilometres. Secondly, the mileage, the load capacity and load factors are determined to calculate the dynamic vehicle stock based on IMAGE/TIMER. Thirdly, we will do a check of this calculation using the available data. Fourthly, an average weight per vehicle type is determined. Lastly, the material fractions are determined and applied to the weight to determine the material content of the vehicle category.

4.1 Air transport

4.1.1 Assessment of the current situation

4.1.1.1 Number of airplanes

Various organisations have made estimates of the number of passenger and cargo airplanes that are currently flying across the globe. One estimate made by Airbus places the number of airplanes worldwide in use in 2019 at 24,494 (Airbus, 2019b). In this estimate Airbus determined that 1,812 of these are for freight. Another estimate, made by the website Statista, places the number of airplanes worldwide in 2018 at 25,830 (Mazareanu, 2019). Yet another estimate, made by the consulting firm Ascend, puts the global stock in 2017 at 23,600 airplanes in use and 2,500 stored (Morris, 2017). According to Boeing the world fleet lies at approximately 23,400 (Boeing, 2018). Lastly, the EIA (United States Energy Information administration) estimated the global stock of airplanes slightly above Boeing and Airbus at approximately 28000 in the year 2013 (Doman et al., 2016). Table 2 below compares the various estimates. Although there is clearly no consensus on the global stock all numbers are in the same order of magnitude. Unfortunately, the different sources estimated the stock during different years, which makes the average less useful.

Table 2 Various estimates by various sources of the current global plane stock

Source	year	Passenger aircrafts	Freight aircrafts
(Airbus, 2019b)	2019	22,682	1,812
(Mazareanu, 2019)	2018	23,841	1,989
(Morris, 2017)	2017	24,010	2,010
(Boeing, 2018)	2017	21,530	1,870
(Doman et al., 2016)	2013	25,844	2,156
average		23,581	1,967

4.1.1.2 Passenger- and tonne-kilometres

With regard to the global passenger kilometres per year the amount determined by the IMAGE/TIMER model is well below that of IATA (International Air Transport Association). For the year 2018 IATA determined that there were 8.3 tera passenger-kilometres (IATA, 2019b). IMAGE/TIMER determined the number of passenger-miles for this year at 4.23 tera passenger-kilometres. With regard to freight IATA report gives, 0.26 tera tonne-kilometres for the year 2018. IMAGE/TIMER overestimated the freight transport compared to the IATA as for the year 2018 it determined 0.57 tera tonne-kilometres of freight. These values are shown in Table 3.

Table 3 Passenger- and Tonne-kilometres according to IATA and IMAGE compared (in Tera-km : 10^{12} km)

Source	Tera Passenger-kilometres	Tera Tonne-kilometres	Year
(IATA, 2019b)	8.3	0.26	2018
IMAGE/TIMER	4.23	0.57	2018

4.1.2 Translating tonne- and passenger-kilometres to vehicle number

4.1.2.1 Load capacity

Airplanes vary significantly in terms of size. Even a specific model can have varying sizes, usually depending on the year of construction, since older models are usually smaller. The two largest airplane manufacturers, dominating the market, are Boeing and Airbus. In terms of most prevalent models, for Airbus the A220/320 is sold the most, followed by A330/340/350 and A300/310 (Airbus, 2020). For Boeing, the 737 is the best sold airplane, followed by the 777, the 787 and then the 747 (Boeing, 2020). The most common airplanes of these two largest aircraft manufacturers, holding 88% of the market, are laid out in Table 4 below (Trefis Team, 2019).

Table 4 The most popular passenger plane types of Airbus and Boeing

Airbus					**Sources**
Type	A220/A320	A330/A340/A350		A300/A310	
Number of planes[1]	16,180	3,053		816	(Airbus, 2020)
Seats[2]	100-220	220-300 or 70t (for freight)		210-250	(Airbus, 2019a)
Weight (Operating empty weight)[3]	42,200 kg	121,900 kg		90,100 kg	(Airliners.net, n.d.)
Boeing					
Type	737	777	747	787	
Number of planes[4]	11,837	1,695	1,572	1,459	(Boeing, 2020)
Seats	172-230	317-396	410	248-336	(Boeing, n.d.)
Weight (operating empty weight)	27,500 – 41,100 kg	139,000 - 160,100 kg	162,400 – 181,000 kg	110,000 kg	(Airliners.net, n.d.)

For freight aircrafts we have used the study by Casanova et al. (2017). For the determination of the load this study gives a useful intersection of the freight planes around the globe (Casanova et al., 2017). When applying a weighted average on these airplanes we found an average load of 61 tons. In Appendix B the dataset and the calculation can be found.

4.1.2.2 Load factor

Cargo by air is transported in two ways: through designated freight planes and by using extra space on passenger planes. According to Boeing about 50 percent of the cargo is delivered by cargo planes (Boeing, 2018). This is relevant when studying ton-kms to determine future transport vehicle needs. Another important factor to take into account is the occupancy and load factor of the airplanes. According to IATA in the year 2018 passenger aircrafts were filled for approximately 82 percent and cargo aircrafts for approximately 49 percent. The occupancy rate of passenger transport has been rising steadily in the last decades.. In 2000 occupancy was approximately 71 percent. The load factor of freight transport on the other hand behaves more erratic in terms of efficiency. In 2000 it was near 52 percent, in 2010 54 percent and then decreasing again to the current 49 percent (IATA, 2019a).

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[1] These numbers represent the total number of orders (including the ones already delivered) by Airbus per February 2020 (Airbus, 2020).

[2] These are averages from the various models of the various types of the models as seating varies per variety of the model group (Airbus, 2019a).

[3] The operating empty weight, thus the weight of the plane minus fuel and passengers is retrieved from Airliners.net (Airliners.net, n.d.).

[4] These numbers stem from the 2019 annual report by Boeing and represents the commercial jets that were delivered as well as the not yet delivered orders (Boeing, 2020).

4.1.2.3 Mileage

An important factor for the mileage of airplanes is the turn-time, the time between landing and take-off. Small changes in turn-time have significant effect on the number of trips a plane is capable of making per year. A 10 minute reduction in turn-time can increase the yearly trips of short distance flights by 8 percent (Mirza, 2008). On average, according to the article by Boeing, airplanes make 2304 trips per year of 500 nautical miles (Mirza, 2008). This would give a mileage of 2,133,504 vehicle kms per year. This mileage is used for both passenger and freight planes.

4.1.2.4 Graph of number of airplanes

Figure 8 shows the number of airplanes of the SSP2 baseline , calculated by dividing the IMAGE/TIMER data by the mileage, load capacity and load factor. This number is based on the assumption that these values remain constant.

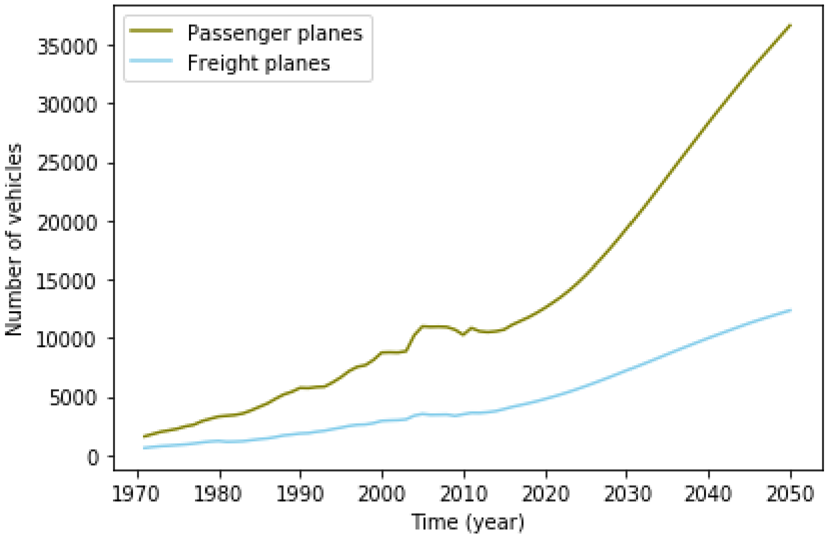

Figure 8 Number of airplanes calculated with the IMAGE/TIMER SSP2 baseline scenario data

4.1.3 Vehicle calculation validation

Below we will validate whether the mileage and load found in the paragraphs above are realistic numbers. We will do this by applying the calculation to the current passenger- and tonne-kms of IATA and check this with the current (average) stock of planes of the various sources seen in paragraph 4.1.1.1. With regard to passenger planes we find a seat average of 206 as a weighted average of the various planes. If we then use the 0.819 load factor of IATA, we get an average load of 169 passengers. The number of seat-kilometres is divided by the average number of trips multiplied by the average speed and the average seat amount. This gives 23,091 passenger planes, which is close to the average number of planes of 23,581.

With regard to freight the load factor IATA calculated is 0.493. Half of the freight load is carried by passenger aircrafts, so the number of tonne-miles needs to be halved as well. According to IATA global freight planes have moved 0,263 tera tonne-kms of a possible 0,532 tera million tonne kms (IATA, 2019b). Since half of the air freight is moved by passenger planes, it needs to be halved, the number of tonne-kms actually shipped by air freight planes is 0.1315 tera tonne-kms. Now the load is found and the mileage is assumed to be similar to that of passenger planes. Halving the tonne-miles and applying the load factor, we calculate the number of planes at 2,051, which is very close to the average number of freight planes of 1,967 planes.

4.1.4 Vehicle to kilograms

Using the numbers of the various plane types that are laid out in Table 4 and their respective weight, an average weight per passenger plane of 60,558 kg is calculated.

To determine the average weight of a freight aircraft the same overview of the global freight fleet is used that was used to determine the average load capacity (Casanova et al., 2017). Using the fleet analysis made in this study, three sizes can be distinguished. Boeing also differentiates freight planes in three categories (Boeing, 2018). These categories are standard, medium and large body planes. The standard holds less than 45 tonnes, the medium is in the range between 45 and 80 tonnes and the large category can hold more than 80 tonnes. The prevalence of the three respective categories is 38% for standard, 29% for medium and 33% for large size airplanes (Casanova et al., 2017). In each category the two most prevalent planes are chosen to determine an average weight for the category. The standard body will be made from an average of the Boeing 737 and the Boeing 757, the medium will be equated to the A300 Airbus and the Boeing 767 and for the large category we will take an average of the 747 and 777 Boeing. These models were chosen, because Boeing and Casanova et al. (2017) determined these planes to be in their respective category and because these are known to be prevalent airplanes in the world fleet (Boeing, 2018). This gives an average weight of freight planes of 95,843 kg.

4.1.5 Kilogram of vehicle to material

In an LCA of an Airbus aircraft the material content of an aircraft was determined as is laid out in Table 5 (Howe et al., 2013). The present research is based on the assumption that for the various models of the global fleet the material content will be relatively similar. One material component that is remarkable is CFRP (Carbon Fibre Reinforced Polymer). CFRP is a useful material as it is strong and light, therefore ideal for airplanes and thus increasingly used to manufacture airplanes. Although the material is useful during the use phase of airplanes, the material is difficult to recycle due to its complex nature and the combination of various materials in CFRP (Pimenta & Pinho, 2011). CFRP is composed of two broad materials, carbon fibre and epoxy resin. Since this paper looks at the category plastic and not at composites, the CFRP in airplanes is divided into plastics and carbon fibre. The fractions used will be 35% of CFRP counted as plastic and the other 65% as other materials (Timmis et al., 2015). Lastly, an assessment is made of the percentage of copper in an airplane. This is done by combining information about wiring in planes and the material content of wiring. All material fraction calculations and assumptions can be seen in Appendix B.

Table 5 Material fractions of planes (Howe et al., 2013), (Timmis et al., 2015), (Asmatulu et al., 2013) *and* (Bao et al., 2017)

Material	Percentage
Aluminium	68 %
Steel	9 %
Plastics	5.25 %
Copper	0.46 %
Titanium	6 %
Other	11.29 %

Using the average weight per plane calculated in paragraph 4.1.4, the material fractions as shown in Table 5 and the average vehicle number of Table 2, the material composition of the fleet is found. Table 6 will give the material content of the current fleet.

Table 6 Material composition of an approximation of the current fleet based on the findings of Table 2, 4 and 5 and paragraph 4.1.4

Material	**Materials in the passenger fleet (in ktons)**	**Materials in the freight fleet (in ktons)**
Aluminium	971.53	128.20
Steel	128.59	16.97
Plastics	75.01	9.90
Copper	6.62	0.87
Titanium	85.72	11.31
other	161.26	21.28

Below the dynamic stock, based on the IMAGE/TIMER model, is shown in two stacked graphs. It should be noted that the underlying assumption is that the material composition, as well as material efficiency remains constant. This is not fully realistic., However, applying changes for each vehicle category is beyond the scope of this research and should be addressed in future studies.

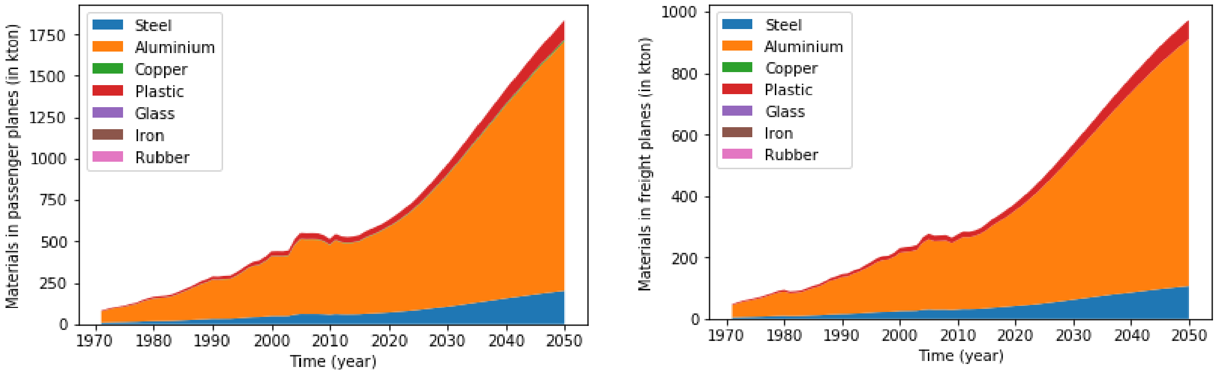

Figure 9 Material content of passenger and freight planes using IMAGE/TIMER data

4.2 Rail transport

4.2.1 Assessment of the current situation

4.2.1.1 Global number of trains

When estimating the global number of trains, first we must establish what is considered to be a train. In most literature rail transport is considered as a group and the vehicles in it referred to as rolling stock. The types of vehicles that are included in rolling stock are: high-speed trains, locomotives, multiple units (with a differentiation between diesel and electric), coaches, freight wagons, metro vehicles and light-rail vehicles (Ecorys, 2012).

There is no source available which studied the global number of trains. Therefore, this paragraph will combine all the available local data. This is compiled in the table below. The one statistic that is globally recorded for rolling stock is the amount of high-speed trains, which is currently 4959 (including, however, trains that are still being built) (UIC, 2020).

Table 7 Compiled local data about rolling stock

Source(s)	**Country / region**	**year**	**Regular passenger trains** (coaches)	**Freight Trains**		**HST** (trains)
(IEA, 2019a)	India	2016	55,500	11,500	locomotives	none
				278,000	Wagons	
(Railway Association of Canada, 2018)	Canada	2017	512	2,842	Locomotives	none
				55,357	wagons	
(National Bureau of Statistics of China, n.d.) (Lawrence et al., 2019)	China	2018	52,399[5]	21,482	Locomotives	2600
				839,213	wagons	
(Bureau of Transportation Statistics, n.d.-a) (National Transit Database, 2019)	United States	2018	18,314	29,031	Locomotives	20
				1,690,396	wagons	
(Rail Freight Forward, n.d.) (Eurostat, 2020) (Deutsche Bahn, 2019)(NS, 2019)(Trenitalia, 2018)(Department for Transport, 2018)	Europe	2018 & 2015	88,790	40,000	Locomotives	N.A.
				880,000	Wagons	
(JR East, 2017)(UIC, 2018b) (IEA, 2019a)	Japan	2017	31,319[6]	N.A.		N.A.
(Murray, 2014)(EBRD, 2016)	Russia	2014	N.A.	20,300	Locomotives	N.A.
				1,229,200	Wagons	

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[5] In Chinese national statistics the total number of coaches is stated, including, however, high-speed coaches. The World Bank states that Chinese HST usually have 8 coaches per train; therefore, 2600*8 = 20800 is subtracted from the stated 73199 (Lawrence et al., 2019) (National Bureau of Statistics of China, n.d.).

[6] This is an own estimation based on several sources which can be found in appendix C.

Secondly, an important part of global passenger rail transport is not included in the IMAGE/TIMER model, which is light rail. This paper will utilize the UITP definition of light rail: a public transport mode that is operating on at least one rail in an urban, suburban or regional environment (UITP, 2012). This includes metro, tram and the various transport modes that lie in between. In the EU the modal split for passenger transport showed that off all the passenger-kilometres that were travelled in 2015 1.8% went to tram & metro and 7.6% to regular rail (Diemer & Dittrich, 2018). Europe, however, is not indicative of the global light rail distribution. This can be seen in the global number of light-rail vehicles, excluding metro's, of which 55.7% are located in Europe (UITP, 2019b). This is different from metros, which are more prevalent in the Asia-Pacific region, which accounts for 47.1% of the vehicles, followed by Europe with 22.6% (UITP, 2018b).

Table 8 Compiled global data about light rail expressed in number of vehicles (UITP, 2018b) *and* (UITP, 2019b)

	North America	**Latin America**	**Europe**	**MENA** (Middle East and North Africa)	**Eurasia**	**Asia-Pacific**
Metro vehicles	14,200	9,000	25,800	3,300	8,100	53,700
Other light-rail vehicles	2,919	131	20,754	10,471	10,430	2,396

4.2.1.2 Passenger- and tonne-kilometres

In the year 2017 the tonne-kilometres and passenger-kilometres as determined by IMAGE are 9.2 Tera tonne-km for freight and 5.7 Tera passenger-km for regular trains, next to 0.6 Tera tonne-km for high-speed trains (HST). According to a report by the UIC (International Union of Railways, an international organisation for the standardisation of train transport), the global numbers for 2017 were 2,78 Tera passenger-km, 8,99 Tera tonne-km and 0.83 Tera passenger-km for HST (UIC, 2018b). The IEA has also made estimations: :approximately 3.1 Tera passenger-km for normal trains, 0.9 tera passenger-km for HST and 10.5 tera tonne-km for freight (IEA, 2019a). Regarding freight activity the data from IMAGE, the UIC and IEA are remarkably similar. Regarding the passenger kilometres, however, IMAGE appears to be making an overestimation. The passenger- and tonne-kilometres are shown in Table 9. The 2018 global travel by light rail is approximately 0.57 Tera passenger-km (APTA, 2019)(UITP, 2019b). The calculation that was done to arrive at this number can be found in appendix C.

Table 9 The passenger- and tonne-kilometres of the various sources for the year 2017 (in Tera-km : 10^{12} km)

Data source	**Tera passenger-km for regular trains**	**Tera passenger-km for high-speed trains**	**Tera tonne-kilometres for freight trains**
IMAGE/TIMER	5.7	0.6	9.2
(UIC, 2018b)	2.78	0.83	8.99
(IEA, 2019a)	3.1	0.9	10.5

4.2.2 Translating tonne- and passenger-kilometres to vehicles

4.2.2.1 Load capacity

In this subchapter, rail transport, three categories of rail transport are in fact examined: regular and high-speed passenger rail and freight rail. Therefore, three average load capacities need to be found. Firstly, with regard to the two passenger rail types it is important to discuss the difference between regular and high-speed rail.

The factor that makes high-speed rail different from regular rail is to a large extent the speed, but other criteria also are relevant for the definition. The EU directive 96/48/EC states that firstly trains travelling 250 km/h and above are considered high-speed. Trains travelling 200 km/h and above can also be considered high-speed if factors such as track equipment, signalling systems and geographic and temporal systems comply with the directive (UIC, 2018a). In the following Table 10 the average of a variety of high-speed and regular trains can be found. The full tables from which the average is taken can be found in appendix C.

Table 10 Average number of seats and weight of regular and high-speed trains (UNECE, 2017)(Connor, 2011)(Railfaneurope.net, n.d.)(NS, n.d.) (Lawrence et al., 2019)

Train type	**Seats**	**Carriages per train**	**Weight of train (in tons)**
Average high-speed train	472	N.A.	424
Average regular train	376	4.5	252

Determining the load capacity of freight trains is more difficult, because the conditions vary significantly across the regions of the world. This is most apparent when comparing the US and the EU, as the US employs much longer freight trains than the EU on top of double stacking freight containers (Furtado, 2013). The analysis and calculations of how the various values outlined in Table 11 were found, can be seen in appendix C.

Table 11 Freight in Europe and the US (Furtado, 2013) (Dick et al., 2019), (IRG-rail, 2013) *and* (Bureau of Transportation Statistics, 2017)

Data per freight train	**US**	**EU**	**average**
Average number of railcars per train (number)	81.5	37.5	59.5
Average capacity per railcar[7] (in tons)	70	70	70
Average load per railcar (in tons)	31	17	31
Average load per train (in tons)	3,100	626	1,863
Weight of railcar (in tons)	26	26	26
Capacity (in tons)[8]	5,705	2,625	4,165
Average train weight of railcar + 1.5 locomotive of 145 tons (in tons)	2,264	1,120	1,765

4.2.2.2 Load factor

In Table 11 above the load factor for freight trains is determined on the basis of the average loads of freight trains in the US and the EU. When the load of the freight trains is divided by the load capacity, the global average load factor is approximately 44.73%.

The main areas for high-speed rail are China, Japan, Europe and Korea. China represents almost half of the global high-speed rail passenger kilometres and therefore needs to be taken into account when calculating high-speed rail train stock as well. IMAGE/TIMER does underestimate the contribution of China to high-speed rail as in the model's estimate China accounts for only 0.003% of global high-speed rail travel. The occupancy rate of Chinese high-speed rail is approximately 72.5% (Lawrence et al., 2019). The load factor for China is averaged with the average for Europe, 65% (Prussi & Lonza, 2018). Combining these two gives a load factor of 68.75%.

The load factor and thereby the load of regular trains can, as was the case with freight trains, vary significantly across regions, as can be seen in Table 12.

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[7] The calculation of the average capacity of a railcar is created from a weighted average of the different types of railcars and the prevalence, this can be found in appendix C.

[8] The capacity is calculated using the average load capacity of a container of 90 tons and multiplying that with the number of containers. The problem with this methodology is, that it does not account for the fact that in the US on a large segment of the track double stacking is possible. This is what accounts for the high tonnage per train in the US (Furtado, 2013).

Table 12 Load, load factor and mileage for regular trains from various sources for various regions(SBB is the national railway company of Switzerland)

Source	**Load factor** (percentage of seats filled)		**Load** (average number of passengers per train)		**Mileage** (km per vehicle per year)	
SBB for the year 2014 and country data based on UIC analysis (Messmer & Frischknecht, 2016a)	23%	regional	67	Regional SBB	166,023	Regional
	26%	metropolitan	99	Metropolitan SBB		
			107	Austria		
			125	Germany		
			208	France	152,935	Metropolitan
			166	Italy		
Ecoinvent 2.0 SBB data 2002	17%	regional	NA		NA	
(IEA, 2019a)	NA		1,500	India	117,500	
			900	China		
			400	Global average		
Values used for the model:	100%		400		138489.5	

According to the IEA in 2016 approximately 66% of global passenger rail travel was done in India and China (IEA, 2019a). IMAGE/TIMER has a slightly lower but relatively similar value for the China and India fraction of global passenger rail of 57%. Applying the European load only would therefore constitute an incorrect representation of global passenger train stock. Therefore, the load of 400 passengers as determined by the IEA will be applied.

4.2.2.3 Mileage

For freight trains, the mileage will be determined on the basis of three data points, which are laid out in Table 13.

Table 13 Determining freight train mileages based on Ecoinvent v2.0, (Railway Association of Canada, 2018) *and* (Messmer & Frischknecht, 2016a)

Source	**Locomotives**	**Vehicle kilometres per year for all trains**	**Mileage** (vkm per train per year)
Ecoinvent v2.0, SBB (Swiss federal railway) for the year 2000	307	28,000,000	91,205
(Railway Association of Canada, 2018) Average taken form 2008-2017	2,808	106,666,700	37,989
(Messmer & Frischknecht, 2016a) SBB for the year 2014	327	33,600,000	102,752
Input used for the model:			67,484

First an average will be taken from two years data covering two years supplied by the Swiss federal railway. Next, this will be averaged with the Canadian data, because this data is already averaged over 10 years. The resulting mileage is then 67,484 vehicle kilometre per year for freight trains.

The mileage of regular trains, calculated by using an average of the mileages from Table 13, is 138,489.5. The last relevant number for calculating the amount of regular trains is the number of rail carriages per train. For this, we have chosen the average number of carriages of the trains in Table 10, mentioning the regular trains which were used for the calculation. This gives an average of 4.5 carriages per train. As for high-speed trains, the numbers are rather similar in Europe and Asia: 391,358 vehicle km per year for European trains and 395,323 for Asian trains (Doomernik, 2015). The mileages are significantly higher for high-speed rail than they are for regular rail. This should be no surprise, as these trains go faster and make less stops.

4.2.2.4 Graph of number of trains

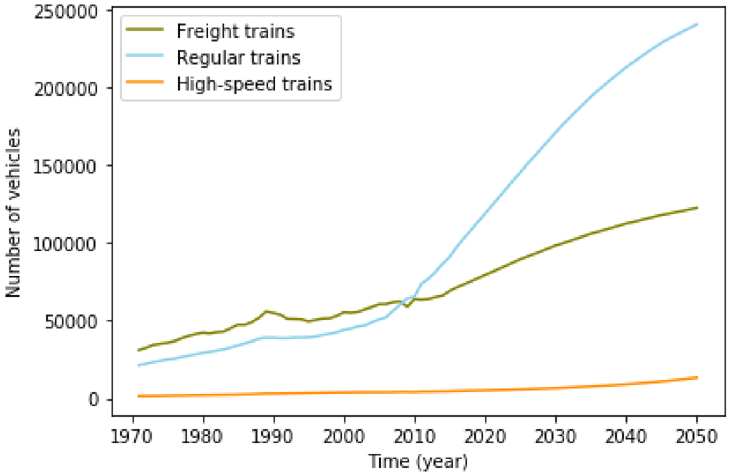

Figure 10 Amount of trains calculated with the IMAGE data and mileage and load calculated above

4.2.3 Vehicle calculation validation

Using the data compiled in the paragraphs above the following vehicle amounts can be calculated. The amounts for 2017 and the tonne/passenger-kilometres from the respective sources are shown in Table 14 below.

Table 14 Global train stock calculated with the tonne-kilometres of the three respective sources for the year 2017 calculated with the mileage and load originating from the calculations in the paragraphs above

	Regular trains (number)	**Regular train coaches**	**High-speed trains** (number)	**Freight trains** (number)	**Freight railcars** (number)
IMAGE	102,896	463,032	4,701	73,177	4,354,027
IEA	55,961	251,625	7,051	83,517	4,969,270
UIC	50,184	225,828	6,503	71,507	4,254,642
IEA/UIC average	53,073	238,829	6,777	77,512	4,611,956

Firstly, as for regular trains, the combined number of regular train coaches from Table 7 is 246,834. There are, however, several regions missing, so we need to identify which relevant regions are still missing and try to establish there share in the total number of trains. The IEA report mentions as other significant regions in terms of rail usage Korea and Russia. Together with the regions in table 7 these would make up more than 90% of train movements (IEA, 2019a). The number of Tera passenger-km that Korea and Russia represent is 0.152 (World Bank, n.d.). This would be approximately 5.2% of the global passenger-km. So approximately 15% of regular trains is not accounted for in the 246,834 value, which is already higher than the IEA/UIC average of 238,829. However, the accuracy of IEA and UIC is also questionable, since various regions could underreport or overreport the passenger-kilometres. However, the model calculates the global number based on a global average of mileage and load; we consider that for the purpose of this research some inaccuracy is acceptable. Future research should seek to determine a more accurate global number.

Secondly, the UIC placed the global number of high-speed trains at 4,959 (UIC, 2020). This is significantly lower than the 6,777 of the IEA/UIC average. However, this is calculated with the European high-speed train, which has a lower seating average per train. In China, where trains are on average 1.5 times longer than European trains, there are approximately 2,600 trains (UIC, 2020)(Lawrence et al., 2019). When we count the Chinese trains 1.5 times, the calculation results in 6,256 trains, which is much closer to the IEA/UIC average of 6,777. The material differences between more and shorter European trains or less and larger Chinese trains are unclear due to a lack of data regarding specifics on the trains. Future research should determine whether there is a significant difference and what the material efficiency is of shorter versus larger high-speed trains.

Lastly, with regard to freight trains, the number of wagons that is the sum of the regions for which data was found, is 4,972,166 with 125,155 locomotives. We learn from the UIC data that we do not miss relevant other regions, since rail freight transport in Africa and South-America appears to be almost negligible (UIC, 2018b). The calculation, in terms of wagons, thus appears to be acceptable, while the amount of locomotives seems to be underestimated when assuming one locomotive per freight train. It was already noted in the literature that longer trains meant more than one locomotive (Dick et al., 2019). Therefore, the weight of half a locomotive will be added to the freight trains to correct the number.

4.2.4 Vehicle to kilograms

With regard to high-speed rail Appendix C shows various types of trains, mostly TGV, to obtain an idea of how heavy high-speed rail vehicles are. The average weight that can be taken from the high-speed trains mentioned below is 424 tons. For regular trains Table 11 sums up the main facts about various regular trains. The average weight that we have taken for regular trains is 252 tonnes with an average of 4.5 railcars per train. Finally, in Table 12 the average weight of a freight train containing an average amount of rail cars is determined to be 1,765 ton. Using the data from Table 15 below the average weight of trams and metros is determined to be 101 ton for metros and 37 for trams.

Table 15 An average of the two light rail vehicle types, the full table is in appendix C (GVB, n.d.)*,* (City of Helsinki, 2015) *and* (HKL/HST, n.d.)

Model	**Weight in tons**	**Passenger seating capacity**
Average tram	37	70
Average metro	101	123

4.2.5 Kilogram of vehicle to material

Silva et.al. have published an article about methods of recycling rolling stock, including an inventory of the components embedded within regular, freight and high-speed trains (Silva & Kaewunruen, 2017). This source makes the problem evident that not all trains use the same building materials for the components. The primary the difference is whether components of the train are made from aluminium or steel. It is beyond the scope of this research to determine exactly what percentage of trains world-wide uses mostly aluminium and what percentage uses steel. Therefore, we have chosen to split it in half aluminium / half steel when we cannot decide whether the body (or other component) of a train is constructed from aluminium or steel. Furthermore, the material type ‘other’ is composed of materials such as silicone-coated fabric, which lines the gangway bellows. In Table 16 the material fractions according to Silva and Kaewunruen (2017) are laid out. Furthermore, Table 16 includes a study by a consultancy firm commissioned by the UK government, which analysed rolling stock (Network Rail, 2009). The weight of the rolling stock that was analysed indicates that this concerned light stock such as trams or metros.

Table 16 Material shares in various rolling stock types (Silva & Kaewunruen, 2017)(Network Rail, 2009)

Material type	**Regular train**	**High-speed train**[9]	**Freight train**	**Light rail**
Steel	60.30%	47.32%	91.72%	57.33%
aluminium	31.46%	25.17%	5.41%	26.71%
plastics	2.09%	3.28%	0.00%	7.27%
copper	0.14%	1.31%	0.15%	2.54%
glass	0.37%	1.85%	0.00%	1.74%
iron	0.20%	12.32%	2.73%	0.00%
other	5.41%	16.01%	0.03%	4.41%

The material fractions shown above combined with the average weight and the current vehicle stock determination gives the following current material stock in vehicles.

Table 17 The current global material stock in all rail vehicle types

Material type	**Regular train** (in Mton)	**High-speed train** (in Mton)	**Freight train** (in Mton)	**Light Rail** (in Mton)
Steel	36.29	1.36	125.48	7.61
aluminium	18.93	0.72	7.40	3.54
plastics	1.26	0.09	0.00	0.96
copper	0.08	0.04	0.21	0.34
glass	0.22	0.05	0.00	0.23
iron	0.12	0.35	3.73	0.00
other	3.26	0.46	0.04	0.59

Using the material fractions from Silva and Kaewunruen (2017) and the data from IMAGE, the materials embedded within the rolling stock can be determined. This is shown in the following figures 11, 12 and 13.

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[9] It is important to note that in the article by Silva and Kaenwunruen one of the components of the high-speed train, named the brake control unit, has been given a weight that appears to be too high. The result is that in the material fractions steel and aluminium have been given a lower value than we should expect and the components iron and other are higher than they should be.

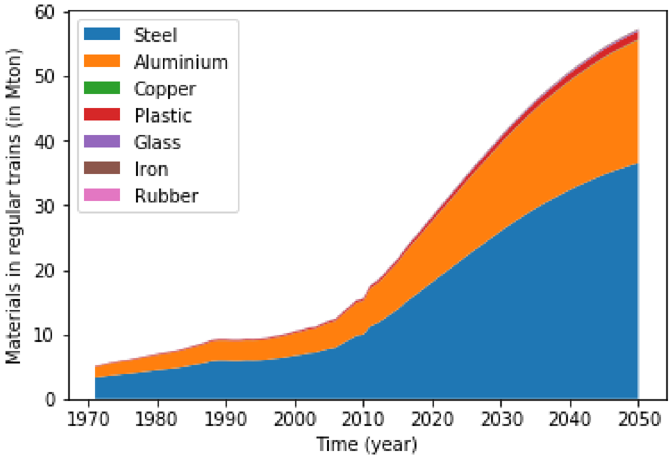


Figure 11 Materials in the stock of regular trains determined using the IMAGE/TIMER model

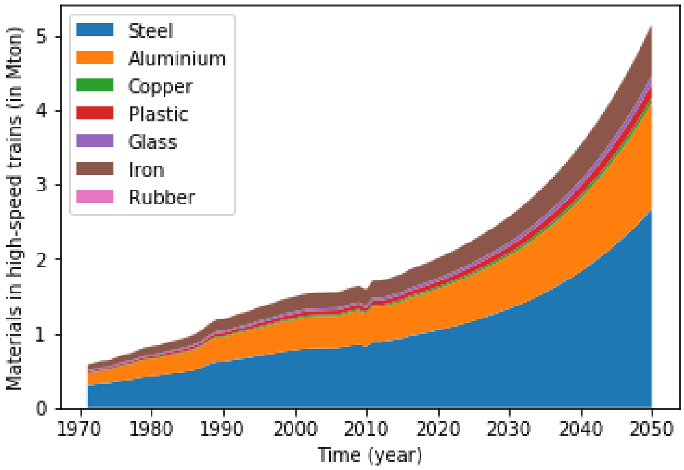


Figure 12 Materials in the global stock of high-speed trains determined using the IMAGE/TIMER model

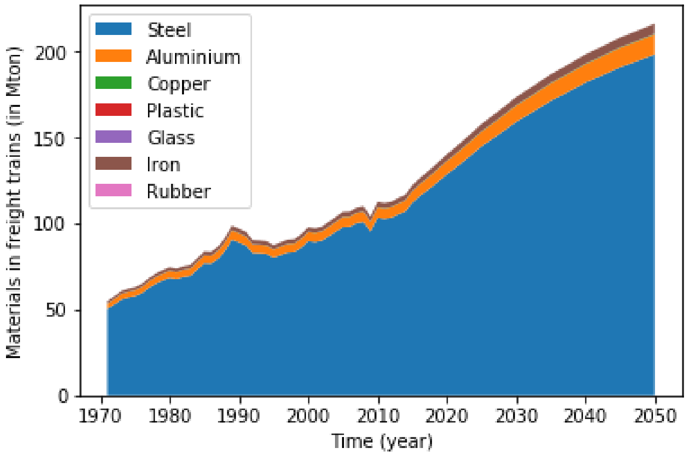


Figure 13 Materials in the global stock of freight trains determined using the IMAGE/TIMER model

4.3 Sea freight

4.3.1 Assessment of the current situation

4.3.1.1 Global number of maritime vessels

According to UNCTAD (United Nations Conference on Trade and Development) at the beginning of 2019 the number of ships in the world was 95,402 (UNCTAD, 2019). The ships are divided into five categories: oil tankers, bulk carriers, general cargo ships, container ships and other types. The other types contain: gas carriers, chemical tankers, offshore vessels, ferries and passenger ships (UNCTAD, 2019). Another estimate is made by the organisation Equasis, set up by the European Commission and the government of the United Kingdom with the aim of improving the shipping industry in terms of safety and transparency (Equasis, n.d.-a). Equasis estimates the total number of ships in 2017 at 90,715 and in 2018 at 92,251 (Equasis, 2018, 2019). The numbers exclude fishing vessels, which for 2018 were 24,606 vessels. Fishing vessels are not considered in the IMAGE/TIMER model and constitute only a very small fraction of the weight of ships, 0.8% of the weight of the global fleet (Equasis, 2019).

Table 18 Number of shipping vessels according to UNCTAD and Equasis

Source	**year**	**Number of ships**
(UNCTAD, 2019)	2019	95,402
(Equasis, 2019)	2018	92,251
Average		93,827

4.3.1.2 Estimate of global tonne-kilometres

The number of nautical ton miles that were estimated to have been shipped in the year 2018 is 58.8 Tera ton-miles, which is equal to approximately 108.9 Tera ton-km. This is much higher than the value determined by IMAGE/TIMER which put the number of Tera ton-km at 73.5.

4.3.2 Translating tonne-kilometres to vessels

4.3.2.1 Load capacity

UNCTAD determined an average load capacity for the entire maritime shipping fleet of 24,256 DWT in the year 2018 (UNCTAD, 2019). This is expressed in DWT (Dead Weight Tonnage), which means the amount of tonnes the vessel can carry. The problem with using an average load and mileage for the entire fleet is the great disparity within the fleet. Oil tankers that were built in the past 4 years have an average capacity of 82,577 DWT, while those that were built 20 or more years ago only had an average capacity of 8,241 DWT (UNCTAD, 2019). In order to give a more realistic depiction of the world fleet, the vessels need to be differentiated not just in types but also in sizes. Therefore, using the partition determined by EQUASIS the fleet is differentiated into small, medium, large and very large. These category sizes represent a size group in Gross Tonnage (GT), which is a volumetric measure of a ship. The following volumes correlate with the sizes: small vessels to all ships below 500 GT, medium is 500 until 25,000 GT, large is between 25,000 and 60,000 and very large is above 60,000 (Equasis, 2019). In Table 19 below the composition of the fleet is laid out. We have used the numbers from Ecoinvent to determine a load factor and mileage for the respective ship sizes. Subsequently, the respective share of tonne-kilometres of the vessel size group is determined using the capacity, mileage and load factor. The calculation can be found in appendix D.

Table 19 Fleet composition based on Ecoinvent v2.0 and own calculations using the Equasis reports from 2005-2018 (Equasis, n.d.-b) *and UNCTAD data* (UNCTAD, 2005, 2006, 2015, 2016, 2017, 2018, 2019, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014)

	Small	**Medium**	**Large**	**Very large**	**Sources**
Average load capacity (DWT)	375	8,215	53,051	147,805	Own calculation based on (Equasis, n.d.-b) and all the UNCTAD reports
Share of ships in the fleet	0.374	0.428	0.130	0.068	(Equasis, n.d.-b)
Load factor	0.71	0.71	0.65	0.50	Ecoinvent v2.0
Mileage (vkm/year)	27,000	27,000	100,000	150,000	Ecoinvent v2.0
Share of goods transported by shipping per year	0.002	0.054	0.358	0.586	Own calculation based on (Equasis, n.d.-b) and all the UNCTAD reports

4.3.2.2 Load factor and mileage

Ecoinvent v2.0 was the only available source for the load factor and mileage, which are given in table 19 above. This provided three load factors; it was assumed that the small and medium category have the same load factor. For maritime shipping we have presumed that regional data will not differ significantly, since, like air transport, maritime shipping is very global business.

4.3.2.3 Graph of number of vehicles

For maritime shipping some extra info was added to the model. There is extensive information available regarding the fleet composition for the period of 2005-2018, which makes several trends visible. This was added to the model by determining an average annual growth or decline rate of ship sizes, making a forecast on the basis of the trends in the period 2005-2018. Here we see a stark rise in the number of very large boats and a significant decline of small and medium ships. If this trend were to continue, we may presume that almost all small and medium boats will be replaced by very large ships. In appendix D the various steps taken are laid out as well as the tables of data that were used to determine the growth rate. The decline of small and medium boats in this graph is, most likely, starker than it will be in real life. This graph is presented here to give an idea of how very large boats are on the rise and how the fleet composition has been modelled.

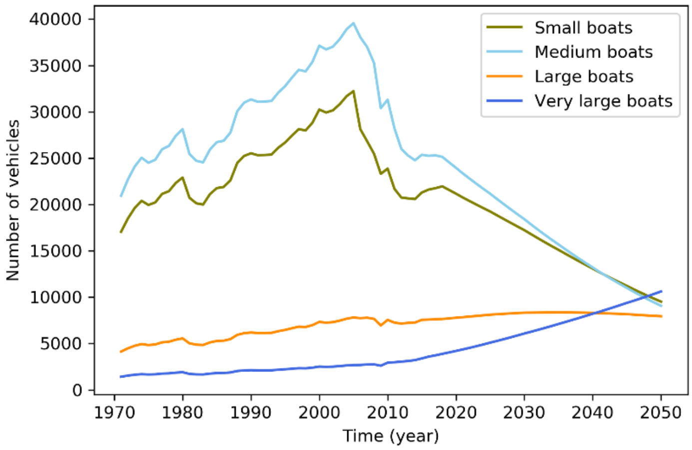


Figure 14 Number of boats based on IMAGE/TIME applied to 2005-2018 growth rates

4.3.3 Vehicle calculation validation

Initially the fleet average DWT was used as load capacity with an average of loads and mileages with the tonne-km as given by UNCTAD of 108.9 tera ton-km. This produced a world fleet of 62,476 vessels as result. This is rather far from the average number from UNCTAD and Equasis of 93,827. This is why the fleet was split up in four categories. We have applied the different mileages and loads to the four categories, assigning to each a share of the amount of the tonne-kilometres equal to the share that the categories shipped. This calculation resulted in 87,059 ships, which is much closer to the UNCTAD/Equasis average.

4.3.4 Vehicle to kilograms

Ships vary significantly in size and in the tonnage they can carry, which is expressed in GT (Gross Tonnage) or DWT (Dead Weight Tonnage). GT means the volume of the entire ship and therefore the size. DWT regards the amount of cargo that a ship can carry, this means how heavy all the containers the ship caries are (UK Department for Transport, 2019). Collective data about the world fleet is mostly expressed in GT or DWT and therefore a conversion factor must be found to determine LDT (Light Dead Weight Tonnage) from GT or DWT. LDT represents the actual weight of the ship without fuel, crew or cargo. A report on the end-of-life of the shipping industry, made by the consultancy firm COWI for the European Commission, has determined such conversion factors (COWI et al., 2011). Applying these conversions to the total number of GT for the various types of ships in the world fleet gives the numbers in Table 20.

Table 20 The GT(Gross Tonnage) and LDT(Light Dead weight Tonnage) of the various types of ships in the world fleet and the conversion factor given (COWI et al., 2011) (Equasis, 2019)

Ship type	**Total GT**	**Total LDT**	**GT/LDT**
General cargo	58,429,000	29,659,391	1.97
Specialized cargo	4,834,000	1,810,487	2.67
Container ship	232,877,000	105,374,208	2.21
Ro-Ro cargo ship	49,815,000	15,567,188	3.2
Bulk carrier	447,892,000	174,957,813	2.56
Oil and chemical tanker	334,738,000	117,451,930	2.85
Gas tanker	73,588,000	38,128,497	1.93
Other tanker	2,346,000	13,71,930	1.71
Passenger ship	40,453,000	32,888,618	1.23
Offshore vessels	43,102,000	14,561,486	2.96
Service ships	11,032,000	6,895,000	1.6
Tugs	5,199,000	3,249,375	1.6
Total	1,304,305,000	541,915,922	

4.3.5 Kilogram of vehicle to material

One study made a determination of what a ship is made of by examining the manual of a ship (Jain et al., 2016). Because not many other reliable sources can be found with regard to the material composition of ships, we have made the assumption that the material composition is roughly the same for most types of ships. This assumption makes the determination of the material composition of the world fleet less accurate, as not all ships have the same material shares and these will change over time. Therefore, it is there important that in future research differing material shares are found to make a more accurate analysis of the variety in the material composition of ships. This falls beyond the scope of this paper, so the material fractions as shown in Table 21 will be applied to all ship types. Some of the components differentiated by Jain et al. (2016) are not materials but components or a combination of materials. Therefore, the material types joinery, ship machinery, electrical and electronic equipment and non-ferrous metals have to be differentiated in singular material groups, resulting in the material shares in Table 21. For more information on this, please see table 53 in appendix D.

Table 21 Material shares of boats (Jain et al., 2016)(A. B. Andersen et al., 2001)(Jeong et al., 2018)(Oguchi et al., 2011)(Hess et al., 2001)

material type	**share**
Steel	87.98%
Aluminium	0.63%
Copper	0.87%
Iron	3.38%
Glass	0.06%
Plastics	1.66%
Wood	1.30%
Other	4.13%

The material fractions of Table 21 are multiplied with the weight of the total current fleet that is calculated using the conversion factors, as shown in table 20. Combining the information of these tables will give the current fleet the following material stock, as shown in Table 22 below (Equasis, 2019).

Table 22 Material composition of the world fleet using the Equasis fleet composition and the material fractions of Table 21 (Equasis, 2019)

material type	**weight (in Mtons)**
Steel	476.8
Aluminium	3.4
Copper	4.7
Iron	18.3
Glass	0.3
Plastics	9.0
Wood	7.0
Other	22.4

The changing fleet is multiplied by the material fractions as determined in Table 22 above. This gives the following shares of materials in the global freight fleet stock. It should be noted that the calculation of the material stock was done slightly differently from the determination of the vehicle number. Two factors, the number of vehicles and the change in load capacity, were interpolated in order to forecast the change in the fleet composition. The reason for this is, that it has allowed us to apply more trends to give a more realistic result. It should also be noted that the weight conversion shown in 18 we applied to the fleet to relate the DWT sizes of different types of ships to weight. The end result was an average gram of vehicle per tonne-km and this is the value that we modelled with. The conversions were thus used but only to calculate intermediate values.

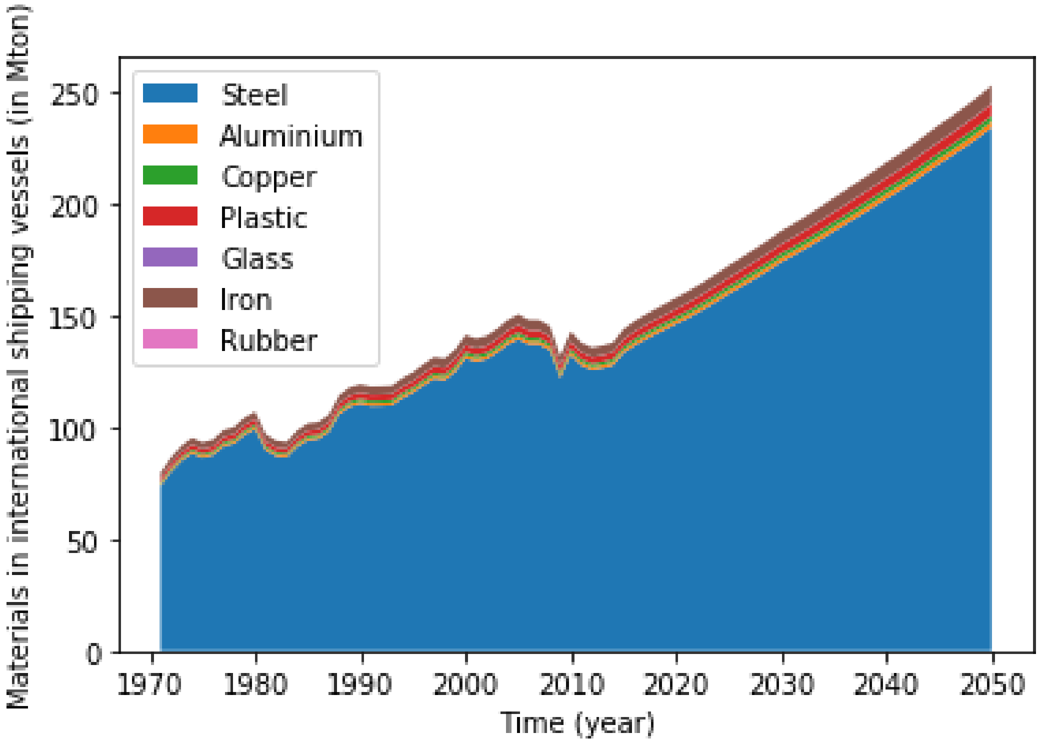


Figure 15 The material stock in all maritime shipping vessels using the IMAGE/TIMER

4.4 Road freight

4.4.1 Assessment of the current situation

4.4.1.1 Number of trucks

A recent IEA study estimated the global freight vehicle stock and forecasted its future. These estimates divided the vehicles in three categories, the HFTs (Heavy Freight Truck), MFTs (Medium Freight Truck) and LCVs (Light Commercial Vehicle) (IEA, 2017). The categories are divided in terms of GVW (Gross Vehicle Weight), which refers to the empty weight of the vehicle plus the maximum load it can carry. The LCV category is every freight van below 3.5 tonnes of GVW, the MFT is between 3.5 and 15 tonnes of GVW and the HFT is above 15 tonnes of GVW. The number of vehicles is based on the IEA mobility model, which combines national and regional data about vehicles with energy consumption, emissions and other data related to energy use. The estimated numbers of vehicles in the world stock for the year 2015 are: 130 million LCVs, 32 million MFTs and 24 million HFTs, thus a total of 186 million (IEA, 2017).

4.4.1.2 Tonne-kilometres

With this model, the IEA also estimated the number of tonne-kilometres transported by trucks in 2015 and 2050. In Table 23 below the estimates by IEA and IMAGE/TIMER are compared. The IEA model places the number of tera-tonne-kilometre at 28 for 2015, while IMAGE/TIMER considers it to be a total of 12.9 tera-tonne-kilometre, comprised of 11.05 for heavy trucks and 1.85 for medium trucks. Clearly, the IEA model estimates much more freight traffic by truck than IMAGE/TIMER. The estimated growth of truck freight until 2050 by IMAGE/TIMER is also lower than that of the IEA, although to a lesser extent as it is approximately 117%, compared to a growth of 139% forecasted by the IEA.

Table 23 IEA and IMAGE/TIMER tonne-kilometres compared for the year 2015 and 2050 in Tera tonne-kilometres (10^{12} tonne-kilometres)

Source	**2015 Tera-tonne kilometres**	**2050 Tera-tonne kilometres**
(IEA, 2017)	28	67
IMAGE/TIMER	12.9	28.7

4.4.2 Translating tonne-kilometres to vehicles

4.4.2.1 Load capacity, load factor and mileage

The distribution of tonne-kilometres per vehicle group for the year 2015 is, according to the IEA, 63 percent by HFT, 33 percent by MFT and only 4 percent by LCV, which equals 1.12 tera-tonne kilometres. This low percentage for LCV can be explained by the fact that much less kilometres are traversed by LCV than by MFT and HFT, and the relatively light load of LCV vehicles. The average mileages found were 13 (thousand kilometres per year) for LCV, 37 for MFT and 52 for HFT. The corresponding loads are on average 0.74 tonne for LCV, 7.95 for MFT and 14.03 for HFT. These numbers are also shown in Table 24. They are averaged from the IEA regional data, which can be found in appendix E.

Table 24 Characteristics of global truck transport (IEA, 2017)

	LCV	**MFT**	**HFT**
Share of global road freight transport	4%	33%	63%
Mileages in thousand kilometres per year per vehicle	13	37	52
Average load of vehicle in tonnes	0.74	7.95	14.03

The values given by IEA will be used for the model. Since the load is already given, calculating a load factor and load capacity is unnecessary.

4.4.2.2 Graph of number of trucks

Because IMAGE does not differentiate between LCV, MFT and HFT as IEA does, a manner must be found to equate the average load and mileages from IEA to the IMAGE data. We have solved this by using the 4 percent of total tonne-kilometres going to LCV as given by IEA. In the model, the 4 percent is subtracted from the total and applied to LCV. The remaining 96 percent is then divided among medium and heavy freight along the lines of the original distribution as determined by IMAGE/TIMER. They are thus added up and each category is subtracted from the total to recreate the original fractions. Figure 16 shows the resulting vehicle numbers.

Some aspects have not been considered in this analysis: the changes in fractions of medium trucks and heavy trucks and improvements in efficiency (load factor). The accuracy of this scenario is therefore questionable. However, it is difficult to determine how trucking will increase in terms of efficiency and to what extent the various modes of transport will increase in terms of their use. The IEA (2017) truck scenario does make a determination about efficiency improvements. Furthermore, in the IEA model the number of heavy freight trucks overtakes the medium freight trucks by 2050 as opposed to the IMAGE/TIMER model. In appendix E some of the efficiency improvements of the IEA model are outlined.

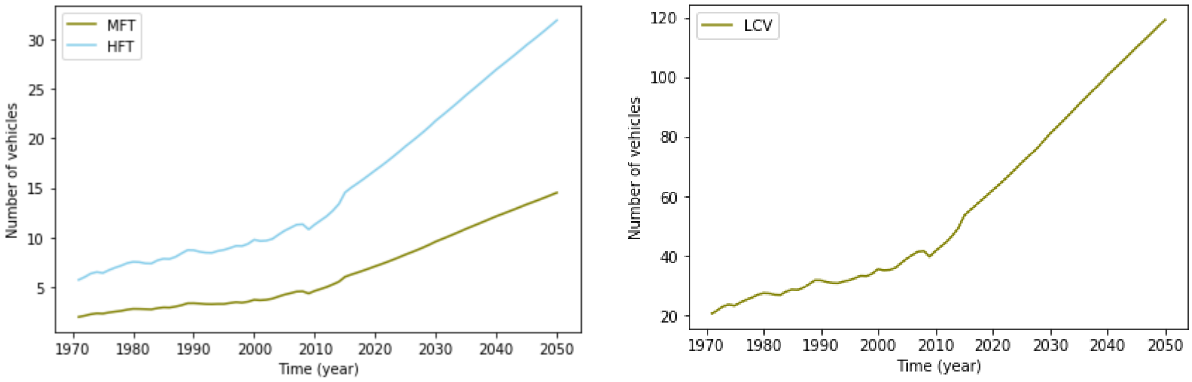


Figure 16 Number of LCV, MFT and HFT vehicles based on the IMAGE/TIMER model (in millions)

4.4.3 Vehicle calculation validation

When applying the global average mileage and load to the percentages of the tonne-kilometres and the tonne-kilometres themselves of the IEA. The following numbers of vehicles are calculated: 174,343,443 vehicles in total of which 120,180,466 LCV, 30,512,901 MFT and 23,650,075 HFT. This is close to the number of vehicles determined by IEA: 130 million LCV, 32 million MFT and 24 million HFT. The global average of load and mileage that have been calculated using the regional mileages and the loads of the IEA can thus be applied in the model.

4.4.4 Vehicle to kilogram

Not all vehicles have the same weight and within categories a variety of vehicles exists. Therefore, an average has to be found for the weight of the three categories. In Table 25 the average LCV curb weight (the weight of the truck minus driver or load) of the US, China and the EU are laid out. We have used the average of this value as an average weight of LCV vehicles in the global fleet.

Table 25 Averages of LCV weight in three global regions: EU, US and China (Tu et al., 2014).

Region	**Weight (in kg)**
China	1348
EU	1681
US	2154
average	1728

For medium and heavy freight we have used a study about vehicles on the Dutch roads to determine an average size for the respective medium and heavy category (Ligterink, 2016). From this analysis we have derived average empty weights of 8,229 kg for medium freight and 15,947 kg for heavy freight. Source calculations can be found in appendix E.

4.4.5 Vehicle kilogram to material

Trucks exist in a wide variety as they can serve a large variety of purposes. Because exact material composition for each of the type of truck is not available, we have applied a general material content to the vehicles. In order to make a more precise determination of what materials the truck vehicle is comprised of, further study is required on the fleet composition and the materials in the various types of trucks. The material composition used for this paper is a study done for the European Commission, DG for Climate Action (Hill et al., 2015). The material content outlined in this study considers three types of vehicles: a reinforced van, a rigid truck and an artic truck. Data from this study have been used to determine the material fraction in a LCV, MFT and HFT. The material content of the trucks is laid out in Table 26. The original table from which the fractions have been taken can be found in appendix E.

The van considered is slightly larger than the description of LCV by the IEA. However, a more accurate source determining material content of freight vehicles is lacking. It is beyond the scope of this research to create an exact match for the LCV and therefore the assumption is made that this van will be largely similar to the average LCV. Future research should determine the exact material content of the various types of vehicles.

Table 26 Material fractions of the three road freight vehicle types (Hill et al., 2015)

material	**LCV**	**MFT**	**HFT**
Steel	56%	56%	63%
Aluminium	6%	1%	4%
Copper	1%	0%	1%
Plastics	11%	4%	6%
Glass	1%	1%	0%
Iron	10%	8%	11%
Titanium	0%	0%	0%
GFRP or CFRP	0%	16%	0%
Wood	0%	0%	0%
Rubber	3%	6%	6%

Using these fractions the current stock of road freight vehicles contains the following materials.

Table 27 The current stock of materials in the global road freight fleet based on the IEA stock of vehicles and kilograms and fractions of the tables above

Material	**LCV current stock** (in Mton)	**MFT current stock** (in Mton)	**HFT current stock** (in Mton)
Steel	124.68	147.20	242.27
Aluminium	13.70	2.37	13.78
Copper	2.25	0.79	1.91
Plastics	24.26	9.22	21.43
Glass	1.35	1.84	1.15
Iron	22.69	21.86	40.57
Titanium	0.00	0.00	0.00
GFRP or CFRP	0.00	42.40	0.00
Wood	0.00	0.00	0.00
Rubber	6.74	14.75	22.20

If the fractions, load and mileage are applied to the IMAGE/TIMER model, the following material stocks in the global freight fleet can be determined.

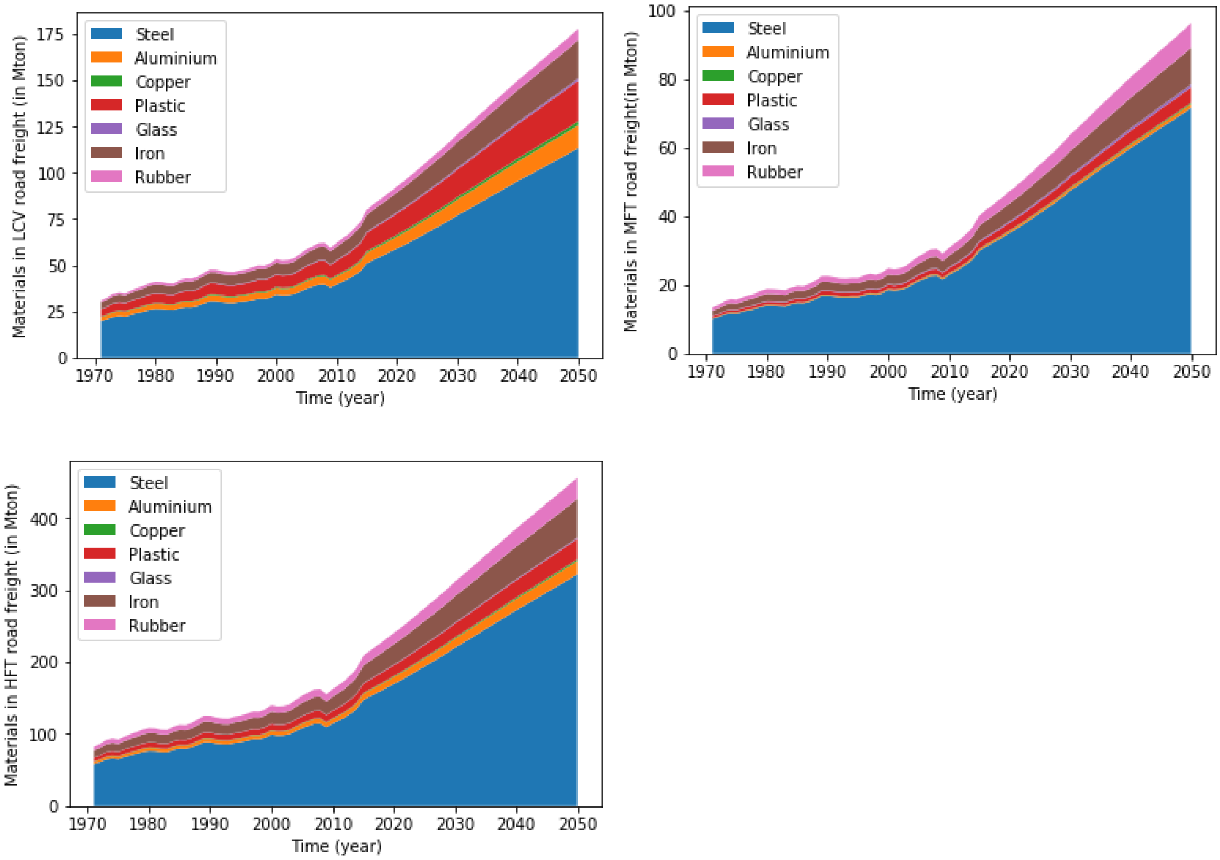


Figure 17 The material stock in LCV, MFT and HFT using the IMAGE/TIMER model

4.5 Road public transport

4.5.1 Assessment of the current situation

4.5.1.1 Number of buses

Only one source is available to determine the global number of buses. This is a study by a German consultancy firm, which gives a number of 10.4 million buses (including minibuses) for 2016, up from 10.3 in 2014 (SCI Verkehr, 2017). Table 28 gives an estimate of the composition of the current global bus fleet distributed over various types of buses (UITP, 2019a).

Table 28 Composition of the current bus fleet (UITP, 2019a)

Type	**Fraction of total**
Standard bus	67.7%
Articulated bus	12%
Midibus	8.4%
Minibus	5.2%
Double deck bus	5%
Trolley bus	1.7%

4.5.1.2 Passenger-kilometres

Estimates of bus passenger miles are scarce, especially on a global scale. One factor contributing to this is the fact that Chinese national statistics count bus and car travel as one category. This makes it difficult to isolate bus travel in this region (Cox, 2014). However, an estimate of global freight an passenger transport can be found in a report by the OECD (Organisation for Economic Co-operation and Development) and the ITF (International Transport Forum) (ITF, 2017). This estimate placed urban bus travel at approximately 7.3 Tera passenger-kilometres. However, this estimate excludes non-urban bus travel. For this, they give only data for total non-urban road travel: 14.6 Tera passenger-kilometres, including car and motorcycle transport (ITF, 2017). According to the modal shift for the EU, 9.4 percent of inland passenger transport is done with the various types of buses (Eurostat, 2019b). If we would apply this fraction, approximately 1.4 Tera passenger-kilometres could be attributed to bus travel. However, this is a highly uncertain number because the EU is not representative for global transport. The ITF makes no estimate for global passenger-kilometres, but it does give an estimate for vehicle kilometres. When the vehicle kilometres are multiplied by the average load factor of 43% and a load of 57 (passengers) of buses, global Tera passenger-kilometres would be 10.3 (ITF, 2019). It has to be noted, however, that this is a very rough estimate, which makes this number by no means certain. IMAGE/TIMER has placed the number of passenger-kilometres for 2015 at 13.14 tera tonne-kilometres. This is relatively similar to that of the ITF.

4.5.2 Translating passenger-kilometres to buses

4.5.2.1 Load capacity

As shown in Table 28 above, buses exist in a variety of categories. Specific material fractions for every type of bus vehicle have not been studied until now and calculating these fractions falls beyond the scope of this research. Therefore, in terms of material content we have divided buses into the categories for which data on material fraction exists: regular buses and mini-/midibuses. For these two categories an average load capacity must be found. The category midibus is not an official category of buses. However, the term is used by the UITP and by transport industry to describe a bus between a minibus (up to 18 seats) and a coach or standard bus (above 40 seats). For the combined category of mini-/midibuses the average load capacity is calculated as a weighted average for minibuses and midibuses, based on their respective shares in the global fleet: 5.2% minibuses 8.4% midibuses. In the mini-/midibus category approximately 38% is minibus and 62% is midibus. For regular buses a source has been used that compiles data on a variety of buses and coaches in four European countries: The

United Kingdom, The Netherlands, Austria and Luxemburg (Schoemaker, 2007). The averages are outlined in Table 29. In appendix F the tables can be found from which the averages were taken.

Table 29 Average weights and load capacity of buses (Ford, 2019a),(IVECO, 2010), (Mercedes-Benz, 2020), (Hill et al., 2015), (BYD, 2019), (Mercedes-Benz, 2018), (ISUZU, n.d.) *and* (Schoemaker, 2007)

Bus category	**Weight** (in kg)	**Max load** (in passengers)
Minibuses	2,804	15
Midibuses	10,125	28
Mini-/midibuses average	7,324	23
Regular buses	14,855	57

4.5.2.2 Load factor

For bus occupancies or load factors a wide variety of sources is available from various world regions. All available occupancies were averaged. For the United States we found only occupancies for three separate bus types: school buses, coaches and transit buses. We determined the occupancy for the United States on the basis of a weighted average of the three bus types. This seems fair because of the uneven spread of bus travel in the United States. In the period between 2014 and 2018 the US bus fleet consisted of approximately 476,150 school buses, 36,155 coaches and 57,987 transit buses (ABA Foundation, 2016; Pupil Transportation Statistics, 2020; Tang et al., 2018). The average load factor was applied to both mini-/midibuses and regular buses. This is not entirely valid, because the use of smaller buses is often different from that of larger buses, which will most likely impact the occupancy. There are, however, limited sources available on the differing occupancy, so for the purpose of this research the assumption is made that they are similar. Future research should study whether and how smaller buses differ in occupancy from larger buses. The occupancy that was determined for buses is 43.1%., All sources and intermediate assumptions can be found in appendix F.

4.5.2.3 Mileages

As with the load factor, a wide array of sources from around the world is available regarding bus mileages. From all of these mileages an average was taken, which has been applied to both mini-/midibuses and regular buses. This resulted in a mileage of 47,843.6. All sources can be found in appendix F.

4.5.2.4 Graph of number of buses

In order to graph the number of buses, the tonne-kilometres had to be divided between mini-/midibuses and regular buses. The percentages shown in Table 28 regarding percentages of buses refer to numbers of vehicles, not tonne-kilometres. Therefore, using the mileage and load, we have calculated what percentages of tonne-kilometres go to the respective categories. This gave 5.2 + 8.4 = 13.6% for midi-/minibuses and 86.4% for regular buses (UITP, 2019a). This results in 5.97% of tonne-kilometres for midi-/minibuses and the remaining 94.03% for regular buses. This can be seen in Figure 18.

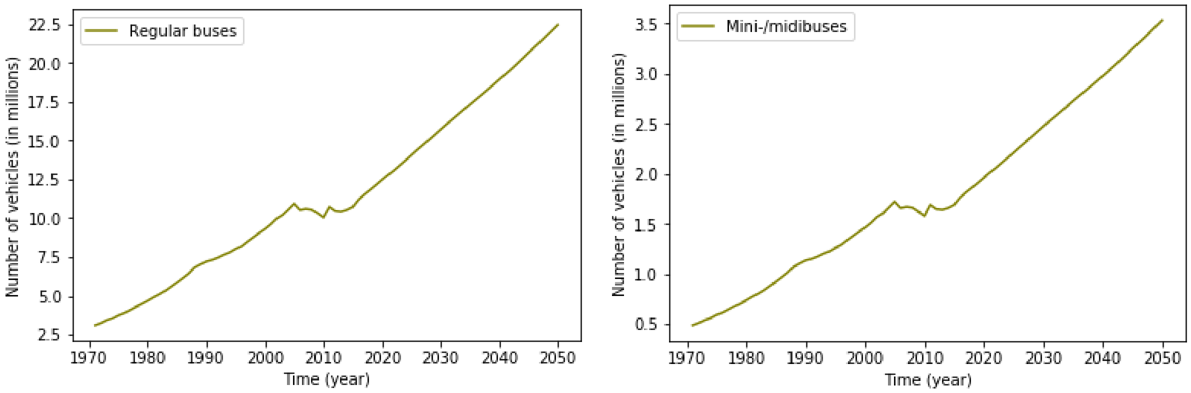


Figure 18 The number of buses using the IMAGE/TIMER model

4.5.3 Validation of calculation

When applying the mileage of 47,843.6 and the load factor of 43.1 on the determined approximate number of global tonne-kilometres from the ITF data of 10.3 Tera tonne-kilometres (ITF, 2019), we get a number of 8,243,467 regular buses and 1,297,540 mini-midibuses, giving a total of 9,541,006 buses. This is quite close to the 10.4 million determined by the German consultancy firm (SCI Verkehr, 2017).

4.5.4 Vehicle to kilogram

The sources used to determine the load capacity of the buses also provided a tare weight, meaning the weight minus fuel and passengers. The average weight of the mini-/midibus was determined with a weighted average for minibuses and midibuses based on their respective prevalence in the world fleet. This resulted in an average weight o 7,324 kg for mini-midibuses and 14,855 kg for regular buses. In appendix F the tables can be found on which the calculation of the average weight was based.

4.5.5 Kilogram of vehicle to material

The same article from which we derived the material fractions of trucks, supplied us with data on the material content of two types of buses (Hill et al., 2015): a midibus with a 12 tonne GVW (Gross Vehicle Weight) and a coach with a 19 tonne GVW. Table 30 below gives the material distribution for a midibus and a coach that will be used to determine the material content of buses.

Table 30 Material fractions of buses extracted from (Hill et al., 2015)

Material	**Mini-/midibuses**	**Regular buses**
Steel	26.29%	45.84%
Aluminium	36.52%	18.98%
Copper	0.25%	0.25%
Plastics	14.91%	8.76%
Glass	4.56%	2.24%
Iron	5.58%	9.50%
Rubber	2.62%	2.90%

Applying these fractions to the vehicle stock of 10.4 million buses in 2016 (SCI Verkehr, 2017) gives the following numbers for the material stock in the global bus fleet (Table 31).

Table 31 Material stock in mini-midibuses in 2016

Material	**Mini-/midibuses** (in Mton)	**Regular buses** (in Mton)
Steel	2.723	61.188
Aluminium	3.783	25.335
Copper	0.026	0.334
Plastics	1.545	11.693
Glass	0.472	2.990
Iron	0.578	12.681
Rubber	0.271	3.871

Using the mileage, load capacity, load factor and material fraction on the IMAGE/TIMER data gives the following global material stock in buses.

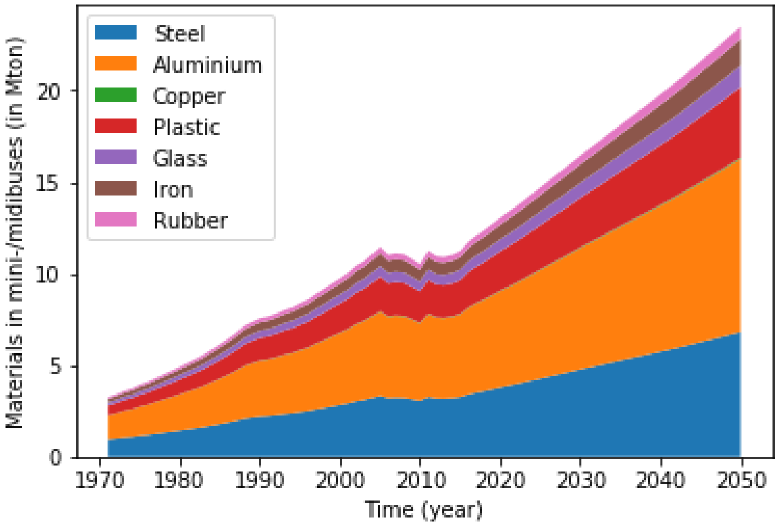


Figure 19 Material content of mini-/midibuses in the global fleet using the IMAGE/TIMER scenario

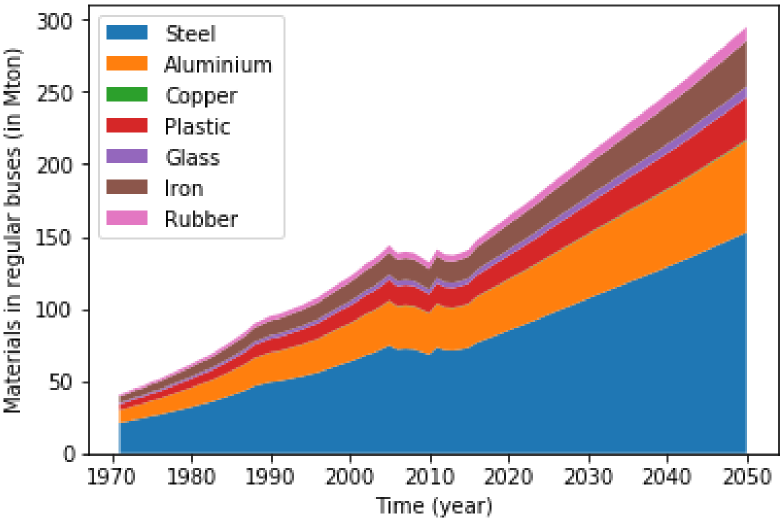


Figure 20 Material content of regular buses in the global fleet using the IMAGE/TIMER scenario

4.6 Inland freight shipping

4.6.1 Assessment of current situation

4.6.1.1 Number of vessels

No global stock assessment of inland shipping vessels exists. Only several regional numbers can be found. One estimate for Europe gives approximately 15,000 inland shipping vessels in 2015 (Rail Freight Forward, n.d.). An estimate for China gives the number of 137,000 inland shipping vessels for 2018 (Wong, 2019). In a hearing in the United States it was reported that the country counted approximately 40,000 inland shipping vessels (Buzby, 2018). Lastly, an older report from 2010 stated that Russia contained approximately 30,000 inland shipping vessels, although passenger vessels are included in this number (Klyavin, 2010).

Table 32 Number of inland shipping vessels in various regions

Source	Country/region	year	Number of vessels
(Rail Freight Forward, n.d.)	Europe	2015	15,000
(Wong, 2019)	China	2018	137,000
(Buzby, 2018)	United States	2018	40,000
(Klyavin, 2010)	Russia	2010	30,000

4.6.1.2 Number of tonne-kilometres

In terms of tonne-kilometres there is no global estimate of inland waterway freight shipping. There is a report which estimates the percentage of inland waterway transport on total freight transport in the EU, the US and China. This report states that in 2013 8 percent of freight transport in China was done in inland waterways, also 8% in the US and 6% within the EU (Beyer, 2018). In the EU in 2013 this means 0.153 tera tonne-kilometres of freight travel (Eurostat, 2019a). For the US this means 0.47 Tera tonne-miles (nautical) thus approximately 0.85 Tera tonne-kilometres (Bureau of Transportation Statistics, n.d.-b). However, this number includes coastwise and lakewise shipping. Without coastwise shipping the number would be 0.576 Tera tonne-kilometres. (Coastwise shipping means sea shipping, but along the coast rather than going out to open sea.) Russia, which also has a relatively large inland freight system, moved 0.074 tera tonne-kilometres in 2014 (Ministry of Transport of the Russian Federation, 2016). A recent report by the ITF (International Transport Forum) estimated a very stark rise in Chinese inland shipping. The report stated that in 2017 China moved 4.35 Tera tonne- kilometres of freight via inland shipping, while the US moved 0.44 and the EU 0.14 Tera tonne-kilometres (ITF, 2019). Adding up the numbers for the EU, the US, China and Russia we come to a global total of 5 Tera tonne-kilometres, assuming that inland shipping in other world regions is negligible. However, it is clear that this estimate is not very accurate as the US statistical bureau reported a higher number than the ITF report. The amount estimated by IMAGE/TIMER in 2017 is 6.75 tera tonne-kilometres and China accounted for 1.73 of these tonne-kilometres.

4.6.2 Translating tonne-kilometres to vessels

4.6.2.1 Load capacity

A study modelled a variety of ships that could pass through the Danube based on EU determined classification (Bačkalov et al., 2014). An average weight and load capacity of inland freight ships is derived from the four types outlined in this study. The average load of inland freight vessels that will be used in this report is 646 tons of ship weight with an average load capacity of 1,816 tons.

4.6.2.2 Load factor and mileage

The load factor and mileage used in our research are the numbers given by Ecoinvent v2.0: a load factor of 71% and a mileage of 26,677 kilometres per year.

4.6.2.4 Graph of number of vessels

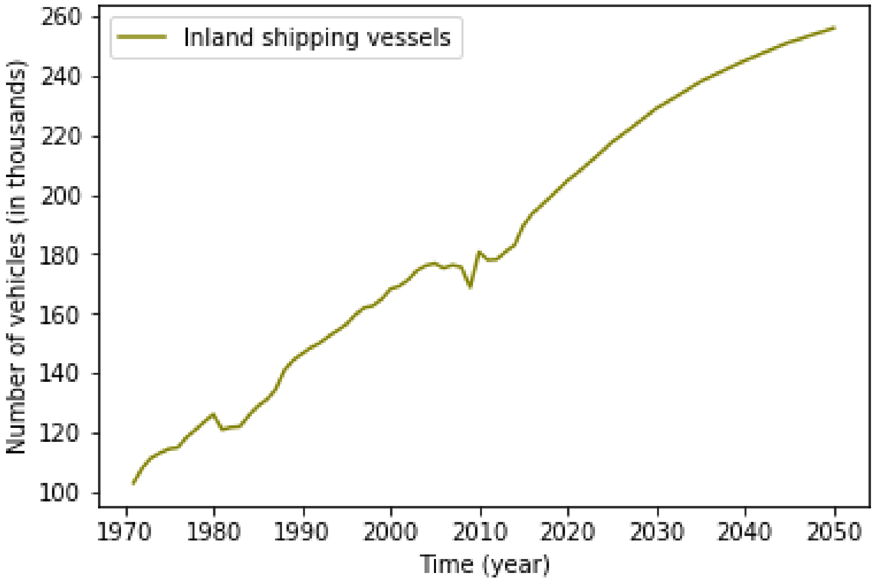


Figure 21 Global number of inland shipping vessels calculated withe the IMAGE/TIMER model

4.6.3 Vessel calculation validation

Applyingthe mileage and load factor to the 5 Tera tonne-kilometres of the ITF report, we come to 145,365 inland shipping vessels. This number is lower than the 222,000 vessels in the US, China, Russia and the EU that we calculated on the basis of the sources mentioned in the first paragraph of this chapter. However, the data regarding inland shipping is quite limited and often inaccurate. The number of tonne-kilometres given by ITF appears inaccurate, as it reported 0.136 tera tonne-kilometres less than the US transport statistics for the same year. Secondly, the number of vessels is also inaccurate as some sources include passenger vessels. Because of the lack of data and inaccuracies of the reports it was difficult to verify the calculations for the mileage and load factor used in our model. However, it is clear that future studies should seek to portray more accurately global inland shipping.

4.6.4 Vessel to kilogram

The above-mentioned article about inland shipping vessels in the Danube also gave us an average vessel weight that could be used in our model: 646 tons per inland shipping vessel.

4.6.5 Kilogram of vessel to material

Since there is no separate source available outlying the material content of inland shipping vessels, we have used the material fractions of maritime vessels. This material fraction is determined using various sources and can be found in Table 53 of appendix D. In Table 33 below the material fractions are lined out.

Table 33 Material fractions of ships (Jain et al., 2016)(A. B. Andersen et al., 2001)(Jeong et al., 2018)(Oguchi et al., 2011)(Hess et al., 2001)

material type	**share**
Steel	87.98%
Aluminium	0.63%
Copper	0.87%
Iron	3.38%
Glass	0.06%
Plastics	1.66%
Wood	1.30%
Other	4.13%

Using these fractions on the 145,365 vessels calculated with the ITF Tera tonne-kilometres, the current global stock of inland shipping vessels contains the following materials.

material type	**Material content of inland shipping vessels** (in Mton)
Steel	82.618
Aluminium	0.592
Copper	0.817
Iron	3.174
Glass	0.056
Plastics	1.559
Wood	1.221
Other	3.878

The global material stock of inland shipping vessels in IMAGE/TIMER gives the following graph.

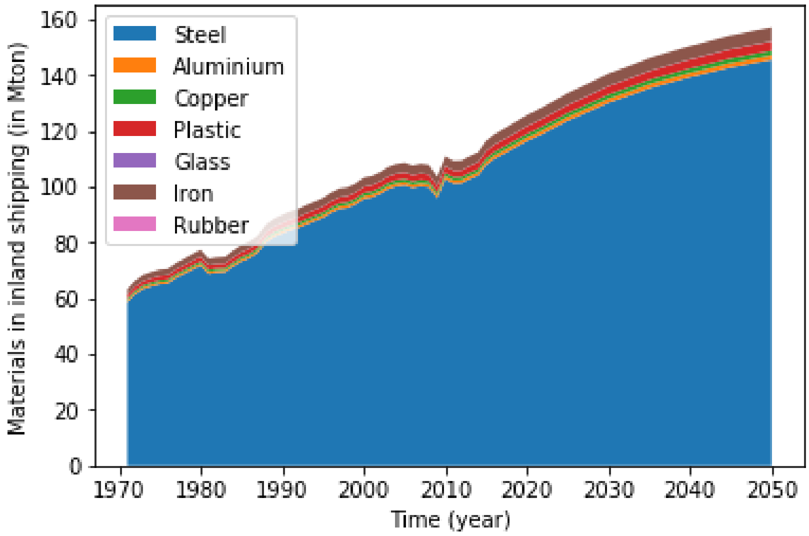


Figure 22 Materials in global inland shipping vessels using IMAGE/TIMER

5. Stock results and implications

In this chapter the intermediate results of the stock analysis are discussed. First, the combined materials in the current stock of vehicles is shown. the passenger- and tonne-kilometres are compared, then the variables for kg/passenger- and tonne-kilometre are determined and lastly the material distribution in the current stock of vehicles is determined.

5.1 Current global material stock in vehicles

In the figure below the findings regarding the material stock of the various vehicles of chapter 4 are combined.

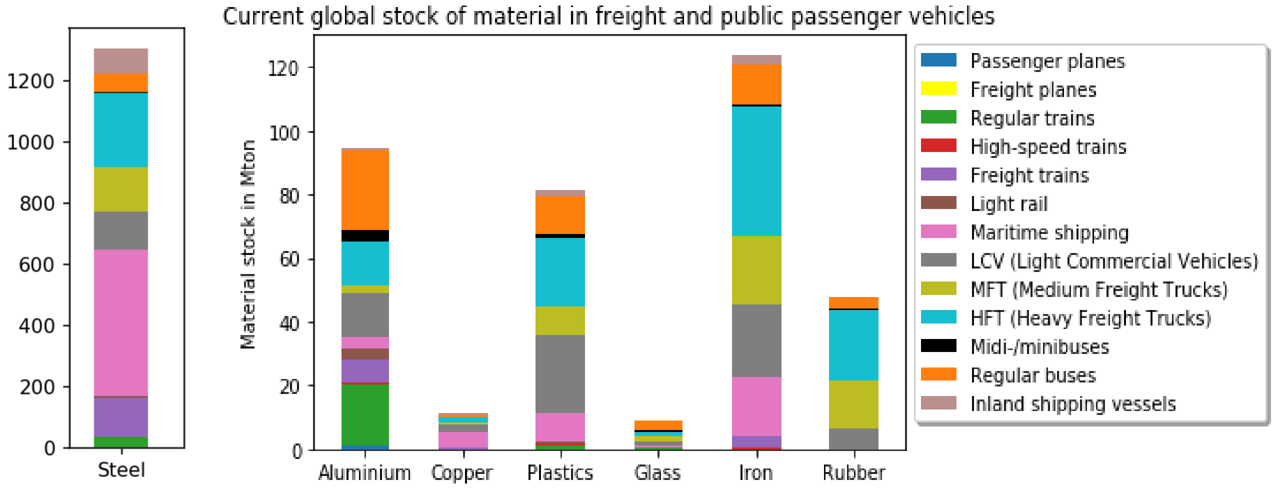


Figure 23 Current global material stock in public passenger and freight vehicles

We can see that steel makes up the bulk of the materials. To allow the other material categories to show which vehicles make up the largest parts steel was placed in a separate graph. In steel maritime shipping makes up the largest fraction followed by HFT and then MFT. It is clear that maritime shipping and freight trucks make up the largest fraction of materials global transport. When only looking at the public passenger transport vehicles, buses make up the largest fraction followed by trains.

5.2 Comparison of passenger and tonne-kilometres of IMAGE/TIMER

As is apparent from the previous chapter, the passenger- and tonne-kilometres found in the data analysis did not always coincide with the values of IMAGE/TIMER. In Table 34 a comparison is made between the IMAGE/TIMER data and the other sources that were used in our research. It should be noted that not all of these values are for the same year for lack of comparable data for the same years and that the sources differ in terms of accuracy. The least accurate values for other sources than IMAGE/TIMER are those of bus and inland shipping, which had to be based on incomplete numbers and rough estimates.

Table 34 Comparison of the IMAGE/TIMER Tera passenger- and tonne-kilometres and other sources (which include IEA, ITF, UIC, UNCTAD, IATA). The most recent year that was available in the sources was used as well as the corresponding value of IMAGE/TIMER.

Tera Passenger-kilometres (not all years are the same in terms of pkm but the IMAGE value corresponds with the year of the other studies)			**Tera tonne-kilometres (not all years are the same in terms of tkm but the IMAGE value corresponds with the year of the other studies)**		
Transport mode	**IMAGE/TIMER**	**Average of other studies**	**Transport mode**	**IMAGE/TIMER**	**Average of other studies**
Plane	4.23	8.3 (IATA, 2019b) for the year 2018	Rail freight	9.2	9.75 average of (UIC, 2018b) and (IEA, 2019a) for the year 2017
Train	5.7	2.94 average of (UIC, 2018b) and (IEA, 2019a) for the year 2017	Maritime shipping	73.5	108.9 (UNCTAD, 2019) for the year 2018
High-Speed train	0.6	0.87 average of (UIC, 2018b) and (IEA, 2019a) for the year 2017	Road freight	12.9	28 (IEA, 2017) for the year 2015
bus	13.14	10.3 (ITF, 2019) for the year 2015	Inland shipping	6.75	5 (ITF, 2019) for the year 2017
			Air freight	0.57	0.26 (IATA, 2019b) for the year 2018
Total	23.67	22.41	**Total**	102.92	151.91

It becomes apparent that the total amount of passenger transport estimated by IMAGE/TIMER is comparable to that of the other sources. However, the modal distribution is rather different. With regard to freight transport IMAGE/TIMER appears to have made a significant underestimation of road freight and maritime transport. This leads to the other sources estimating total freight transport to be 50 percent higher than IMAGE/TIMER. The modal distribution of the two global tonne- and passenger-kilometres of IMAGE/TIMER and the other sources can be seen in the following Figures 24 and 25.

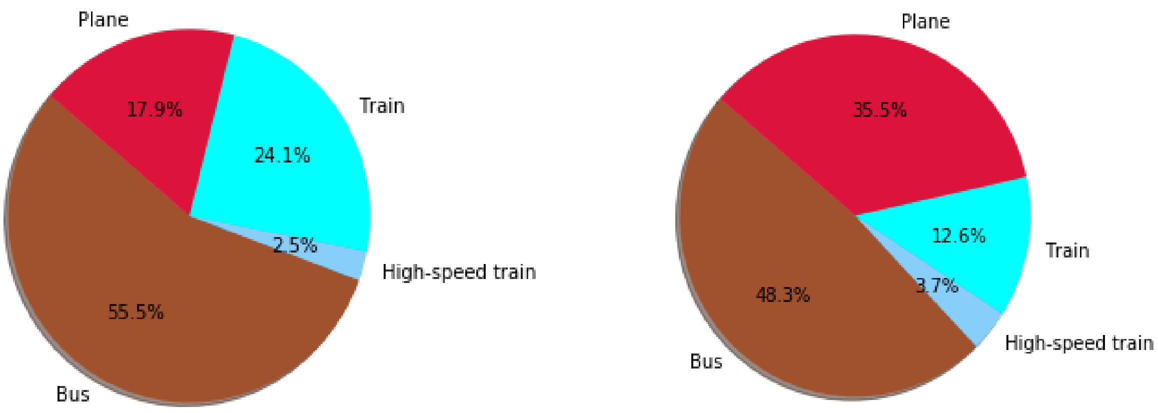


Figure 24 Comparison of the modal distribution in terms of passenger km between IMAGE/TIMER (left) and other sources (right)

Figure 25 Comparison of IMAGE/TIMER (left) modal freight transport distribution and other sources (right) in terms of tonne-kilometres

Figures 24 and 25 show the information from Table 34 above in pie charts to visualize the differences and similarities of the modal distribution given by IMAGE/TIMER and the various other sources. We can see that the international shipping fraction is remarkably similar in both pie charts. Overall, freight transport, in terms of modal shift, is relatively similar. Passenger transport has bigger differences, mainly the overestimation of train transport and underestimation of flying by IMAGE/TIMER. Other differences can be seen in the overestimation of inland shipping and underestimation of road freight by IMAGE/TIMER.

5.3 Determining the gram/tonne- and passenger-kilometre variable

For policy decisions it is interesting to determine the efficiency of a transport mode in comparison with other transport modes. Therefore, a variable such as kg/tonne-kilometre is relevant. This is calculated by dividing the weight of the fleet in kilograms by the total number of tonne-kilometres and then applying the material fractions of the various transport modes. It should be noted that this comparison alone cannot be the deciding factor in determine the sustainability of a vehicle. Other environmental implications, such as the emissions of the burning of fuels should also be accounted for.

5.3.1 Passenger transport vehicles

In the table below the passenger transport modes are examined and compared in terms of the material required to supply one passenger kilometre (pkm) in the various transport modes.

Table 35 Comparison of passenger transport modes in terms of material use using the variable g/pkm (gram per passenger-kilometre)

	Passenger planes (g/pkm)	**Regular trains (g/pkm)**	**High-Speed trains (g/pkm)**	**Midi/mini-buses (g/pkm)**	**Regular buses (g/pkm)**
Grams of vehicle/ passenger-kilometre	0.172	4.549	3.322	14.61	11.96
Steel	0.015	2.743	1.572	3.840	5.481
Aluminium	0.117	1.431	0.836	5.335	2.269
Plastic	0.009	0.095	0.109	2.178	1.047
Copper	0.002	0.006	0.044	0.037	0.030
Glass	0	0.017	0.061	0.666	0.268
Iron	0	0.009	0.409	0.815	1.136
Titanium	0.010	0	0	0.000	0.000
CFRP	0	0	0	0.000	0.000

Rubber	0	0	0	0.383	0.347

5.2.2 Freight transport vehicles

In the table below the freight transport modes are examined and compared in terms of the material required to supply one tonne-kilometre (tkm) in the various transport modes.

Table 36 Comparison of freight transport modes in terms of material use using the variable g/tkm (gram per tonne-kilometre)

	Freight planes (g/tkm)	**Freight trains (g/tkm)**	**Maritime freight (g/tkm)**	**Inland waterway freight (g/tkm)**	**Light Commercial Vehicle (g/tkm)**	**Medium Freight Truck (g/tkm)**	**Heavy Freight Truck (g/tkm)**
Grams of vehicle/tonne-kilometre	0.727	14.039	4.976	18.781	200.571	30.521	21.697
Steel	0.065	12.876	4.378	16.524	111.317	17.061	13.734
Aluminium	0.494	0.760	0.031	0.118	12.235	0.275	0.781
Copper	0.084	0.021	0.043	0.162	2.006	0.092	0.108
Plastics	0.038	0	0.083	0.312	21.662	1.068	1.215
Glass	0	0	0.003	0.011	1.203	0.214	0.065
Iron	0	0.383	0.168	0.636	20.258	2.533	2.300
Titanium	0.044	0	0	0	0	0	0
GFRP or CFRP	0	0	0	0	0	4.914	0
Wood	0	0	0.065	0.244	0	0	0
Rubber	0	0	0	0	6.017	1.709	1.258

It is interesting how inefficient the light commercial vehicles are in terms of material used per tonne-kilometre. Comparatively, maritime freight is very efficient in material use.

5.4 Material distribution in passenger and freight transport

In the graphs below the use of various materials in the world fleet is shown, assigned to the respective modes of transport.

5.4.1 Passenger fleet materials

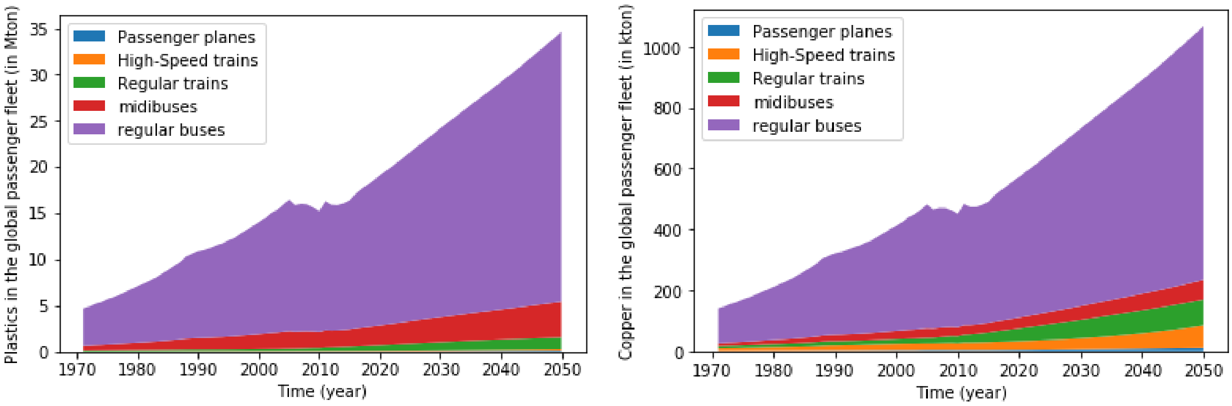


Figure 26 Plastics (left) and copper in the trains of the world passenger fleet (right)

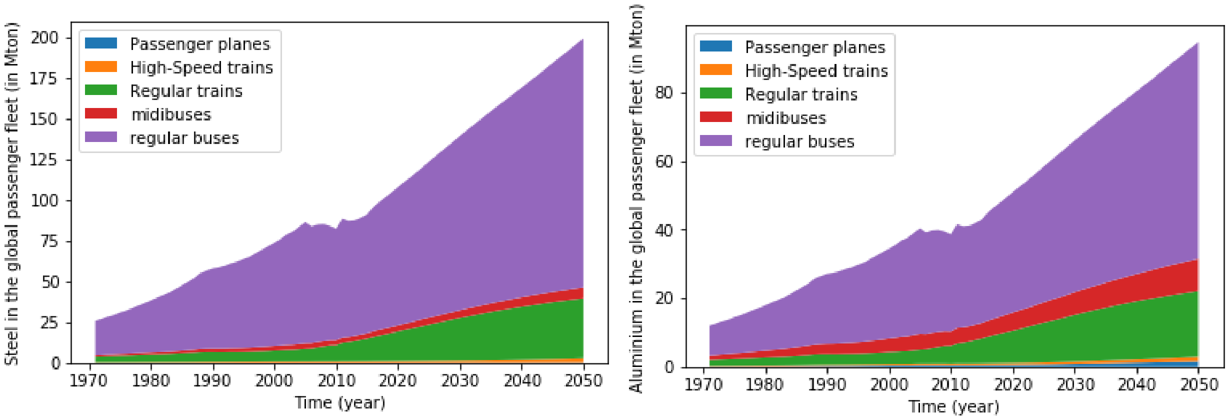


Figure 27 Steel (left) and aluminium (right) in the vehicles of the world passenger fleet

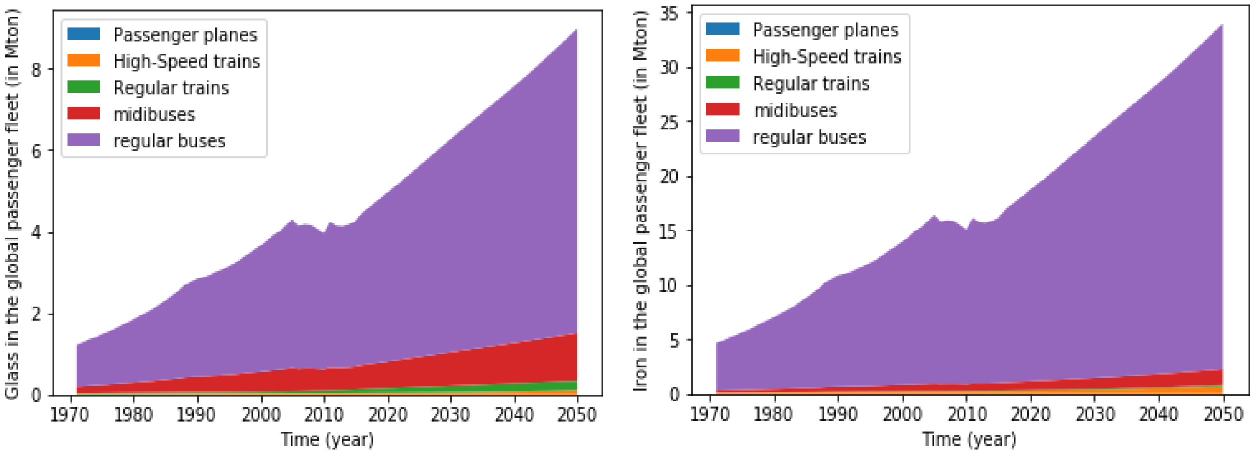


Figure 28 Glass (left) and Iron (right) in the global passenger fleet

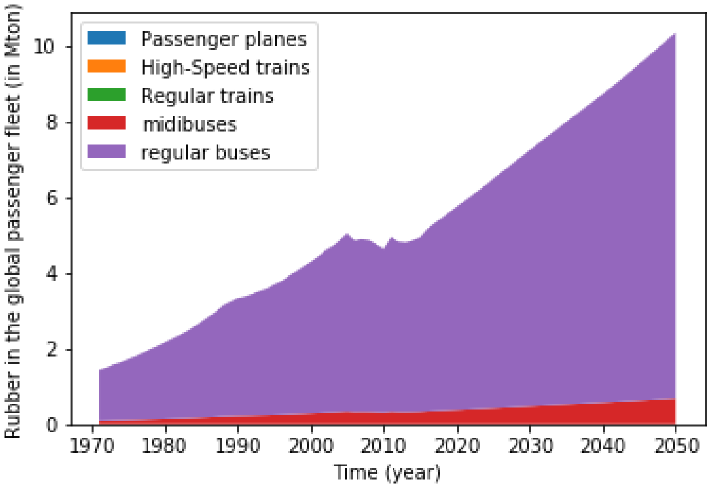


Figure 29 Rubber in the global passenger fleet

These graphs show that buses stand out as containing the majority of the material. Trains turn out to be quite efficient, especially considering that IMAGE/TIMER attributes more passenger-kilometres to trains than the IEA and UIC did. Trains have approximately half the passenger kilometres of buses while containing much less material. Overall, the rule seems to be, that the larger the vehicle, the higher it's material efficiency is. An exception should be made for airplanes, which are, in terms of materials, the most efficient form of transport. This is not to say, however, that flying has the greatest environmental benefits, since fuel emissions and other environmental impact have not been addressed here.

5.4.2 Freight fleet materials

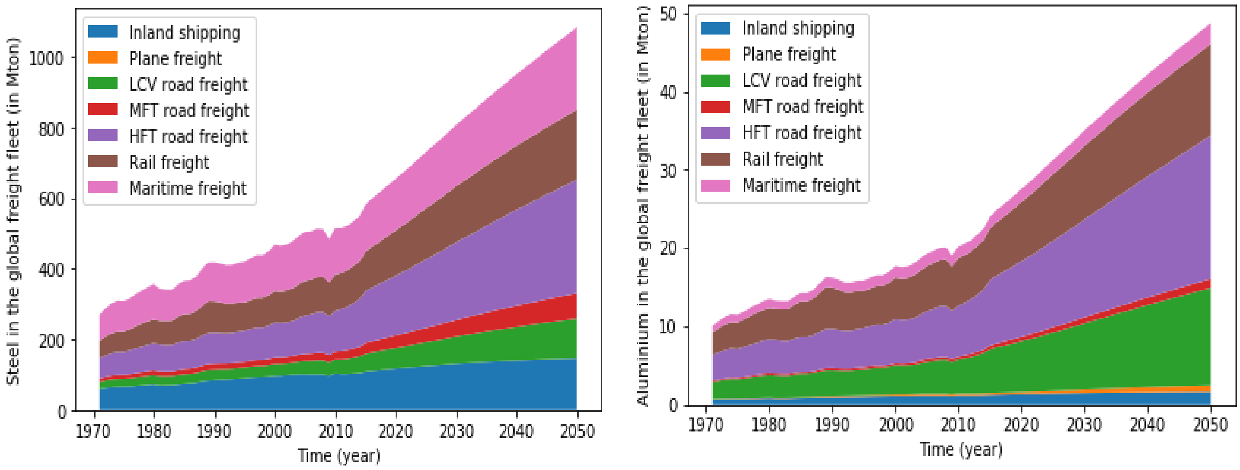


Figure 30 Steel (left) and aluminium (right) in the global freight fleet

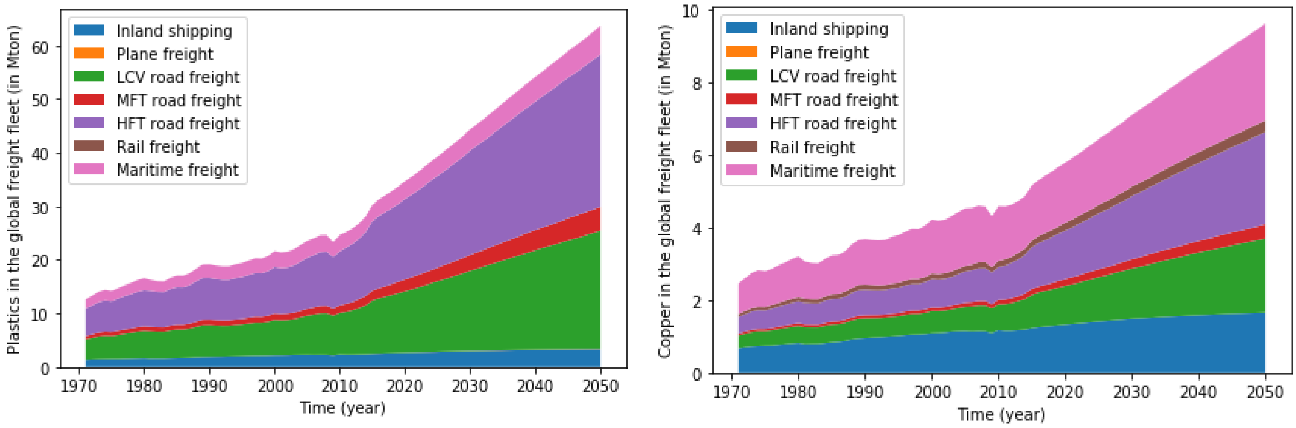


Figure 31 Plastics (left) and copper (right) in the global freight fleet

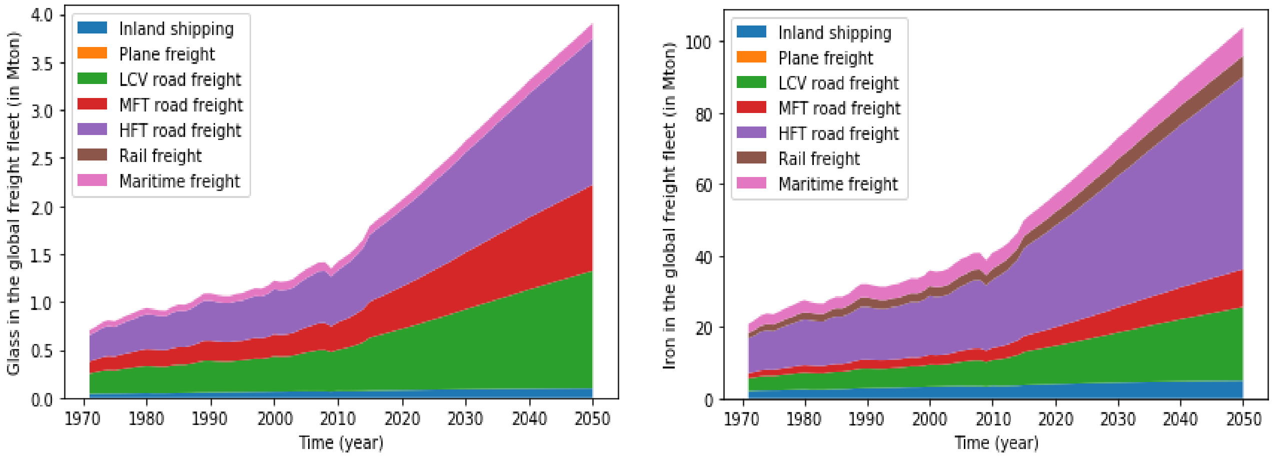


Figure 32 Glass (left) and Iron (Right) in the global freight fleet

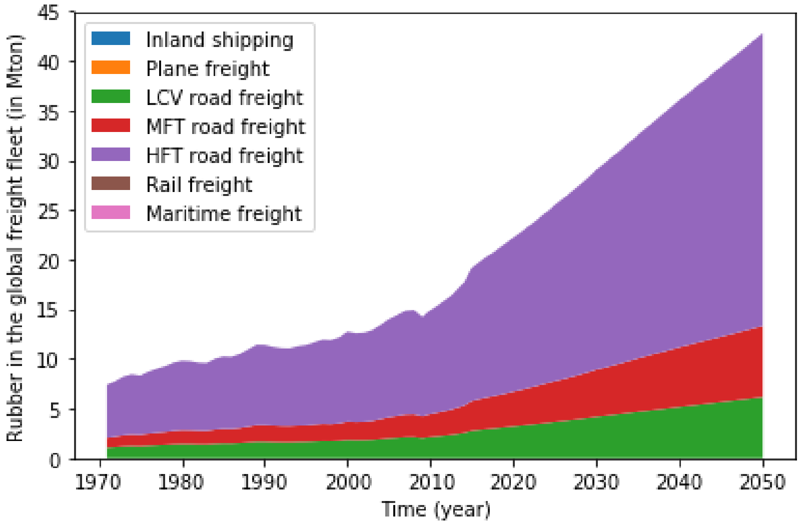


Figure 33 Rubber in the global freight fleet

The most remarkable trend that can be seen in these graphs is how material inefficient road freight is in terms of material requirements. Considering that the maritime fleet transports by far the most tonne-kilometres it is remarkable that in several material categories it does not constitute the large fraction. It would seem that maritime transport, in terms of materials, is a relatively efficient transport mode.

5.4.3 Comparison with the global building stock

On the basis of the above-mentioned article of Marinova et al. we have compared the development foreseen for the global stock of materials in buildings for the period from 2018 to 2050 to the forecasted developments in material use in vehicles in this period. (Marinova et al., 2020). For steel, we see that the material use in vehicles is rather limited compared to steel in buildings. In 2018 steel stocks in buildings are approximately 12 Gt, rising to more than 18 Gt in 2050. All steel in both passenger and freight vehicles rises to a stock of a little over 1.2 Gt in 2050. Copper in the vehicles studied here represents an even smaller quantity compared to the global stock of copper in buildings. The copper stock in buildings rises from approximately 190 Mt to approximately 260 Mt, whereas copper in vehicles rises to approximately 11 Mt. For aluminium, the stock in vehicles rises from approximately 60 Mt to 140 Mt. In buildings this is from approximately 1.2 Gt to 1.4 Gt. Finally, for glass vehicles go from 5.5 Mt to 13 Mt, while buildings go from 1.25 to 2.25 Gt from 2018 to 2050 (Marinova et al., 2020). It should be no surprise that there are less materials embedded in vehicles than in buildings. However, it is interesting to see how much bigger or smaller certain fractions are. Aluminium is relatively the largest material fraction in vehicles compared to buildings. In 2050 it represents a quantity equal to a tenth of the stock in buildings. Glass is in this comparison the material least used in vehicles: the use of glass in vehicles represents only 0.6% of the stock of buildings.

Another interesting comparison would be between the inflow and outflow for vehicles vs. buildings Vehicles have shorter lifetimes than buildings, so we may expect developments in inflow and outflow to come closer here. We will come back to this in Ch.6.2.3.

6 Inflow and Outflow

This chapter examines the inflow and outflow of vehicles and materials. First we have to determine the inputs that are needed for this calculation: the average lifetime of the various vehicles.

6.1 Inputs to the inflow/outflow model

6.1.1 Table of all the vehicle lifetimes

The lifetimes of the vehicles will be determined by combining a variety of sources to create one aggregate number for the global average lifetime of the respective vehicles. In appendix G the description of these sources can be found. For each vehicle type, all the available sources were averaged in order to determine a lifetime.

Table 37 Lifetimes of the various vehicles and the sources

Vehicle category	Sources	Vehicle type	years
Planes	(IATA, 2016) (Howe et al., 2013) (Lopes, 2010) (IATA, 2018)	Passenger	20
		Freight	21
Trains	(Stripple & Uppenberg, 2010) (Nahlik et al., 2015) (Yue et al., 2015) and Ecoinvent v2.0	Regular	35
		High speed	30
		Freight	38
Boats	(Dinu & Ilie, 2015) (Chatzinikolaou & Ventikos, 2015) (Messmer & Frischknecht, 2016b) (Fan et al., 2018) and Ecoinvent v2.0	Maritime	26
		Inland	40
Road freight	(Yang et al., 2018) (Law et al., 2011) (Sen et al., 2017)	LCV	14
		MFT and HFT	8
buses	(Nordelöf et al., 2019) (Law et al., 2011)	Midi and Regular buses	13

6.1.2 Vehicle history

In order to use the Industrial Ecology python module for the determination of the inflow and outflow, an initial year must be determined. For this, we have taken the year that the first of the respective vehicle type appeared on earth. Table 38 outlines the starting year for the various vehicles.

Table 38 The year of invention of the modern conception of the vehicle types

Vehicle	year	what	Source
Planes	1940	First airliner with pressurised cabin takes flight	(Capoccitti et al., 2010)
Trains	1825	First completely mechanised rail transport system is built	(Fava-Verde, 2018)
Boats	1807	First successful demonstration of a steamboat	(Woods, 2009)
Road freight	1896	The world's first truck is built	(Daimler, 2006)
Buses	1895	The first motorized bus is produced	(Daimler, 2008)

6.1.3 Lifetime distributions of the vehicles

The concept of a set lifetime of a vehicle is unrealistic, because not all vehicles reaching their average lifetime immediately stop working. Therefore, we have applied a folded normal distribution in the model and calculated for each vehicle the standard deviation as a percentage of the mean.. We could calculate this for those vehicles for which a vehicle distribution was found. For the vehicles for which no data on distribution was available, we applied the average of the other vehicles. The standard deviation of the lifetime distribution is calculated with the following formula:

$$\sigma^2 = \frac{\sum f x^2}{n} - \bar{x}$$

σ is the standard deviation of where f the frequency is where data x occurs and n is the sum of occurrences of f. The $\bar{x}$ is the mean which is calculated as follows:

$$\bar{x} = \sum \frac{f_x}{n}$$

Table 39 gives the percentages of the mean calculated on the basis of the various sources. The tables from which these are calculated can be found in appendix G.

Table 39 The standard deviation as a fraction of the mean of buses LCV trucks and planes and the average of the three

	Source	**Value** (standard deviation as fraction of mean)
Buses	(Laver et al., 2007)	0.322
LCV trucks	(Dun et al., 2015)	0.196
Planes	(IATA, 2018)	0.281
Average for other vehicles		0.266

6.2 The material content of the vehicle inflow and outflow

In the graphs below the inflow and outflow of vehicles is shown. These are calculated using the above-mentioned inputs to the module developed by Stefan Pauliuk, which available open source on Github (Pauliuk & Heeren, 2019). The module is loaded into Python and determines the in and outflow based on the stock. The graphs below show the total inflow and outflow of all the vehicles studied in this report , which helps us to determine what the yearly material demand is. This is based on the material content of the vehicles as shown in previous chapters. In appendix G the graphs can be found showing the number of vehicles that flow in per vehicle type as well as how the materials are distributed per vehicle type.

6.2.1 Graphs of the inflow/demand and outflow of materials each year to produce the vehicles

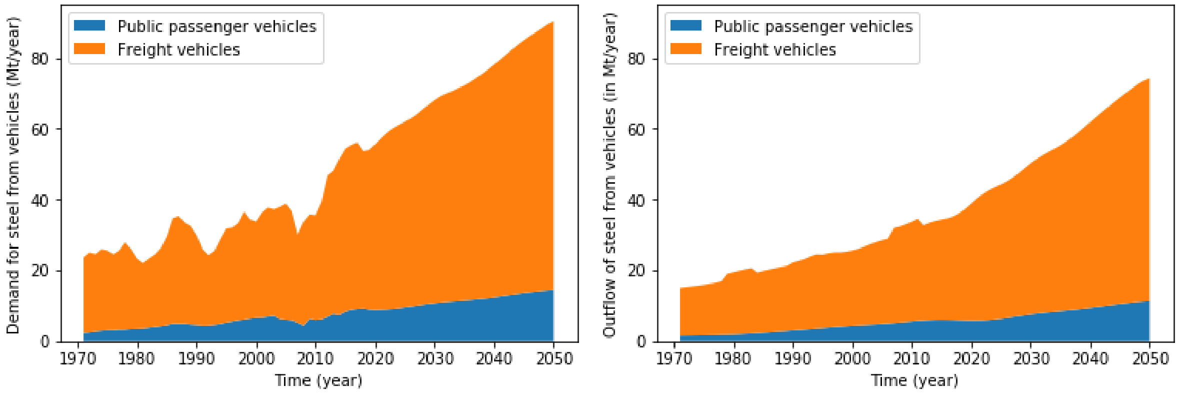


Figure 34 Demand (left) and outflow (right) of steel in the SSP2 baseline scenario

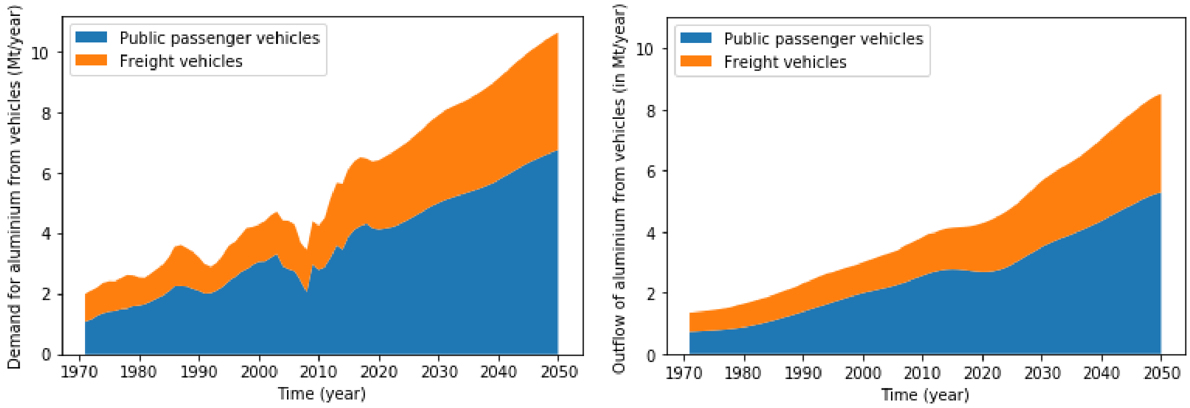


Figure 35 The demand (left) and outflow (right) of aluminium in the SSP2 baseline scenario

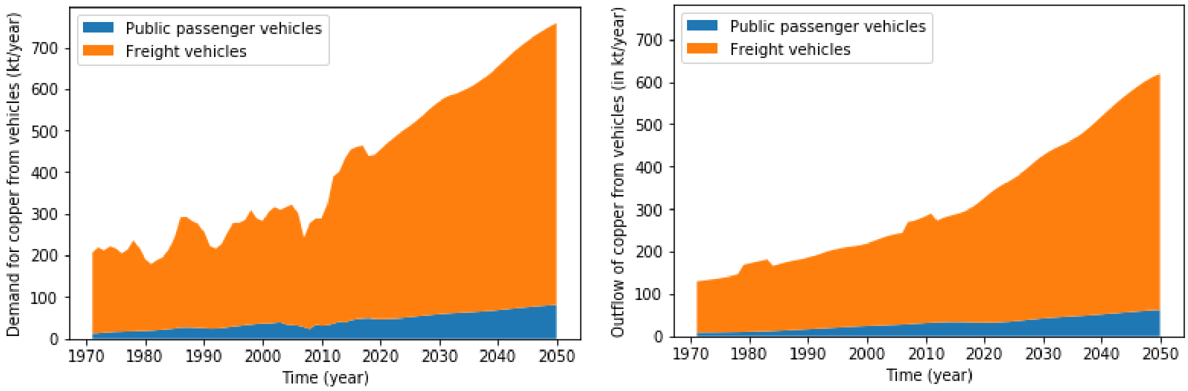


Figure 36 The demand (left) and outflow (right) of copper in the SSP2 baseline scenario

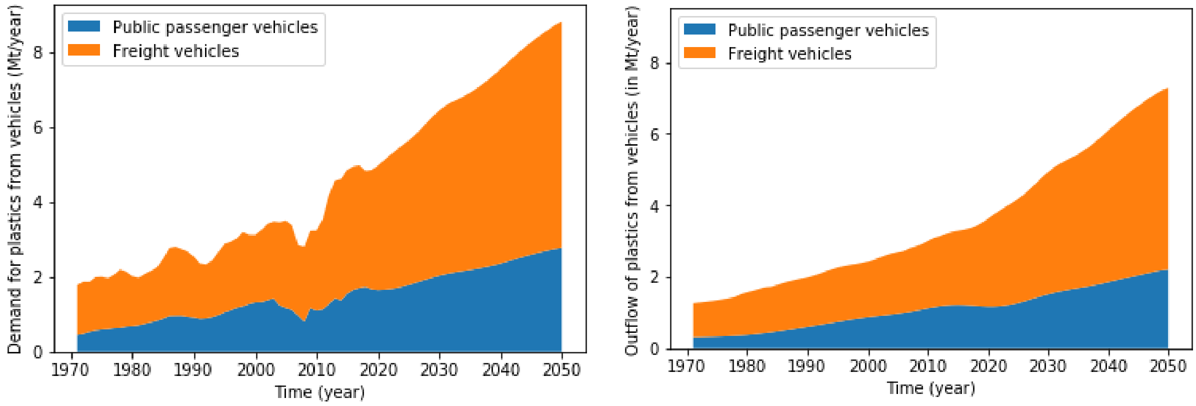


Figure 37 The demand (left) and outflow (right) of plastics in the SSP2 baseline scenario

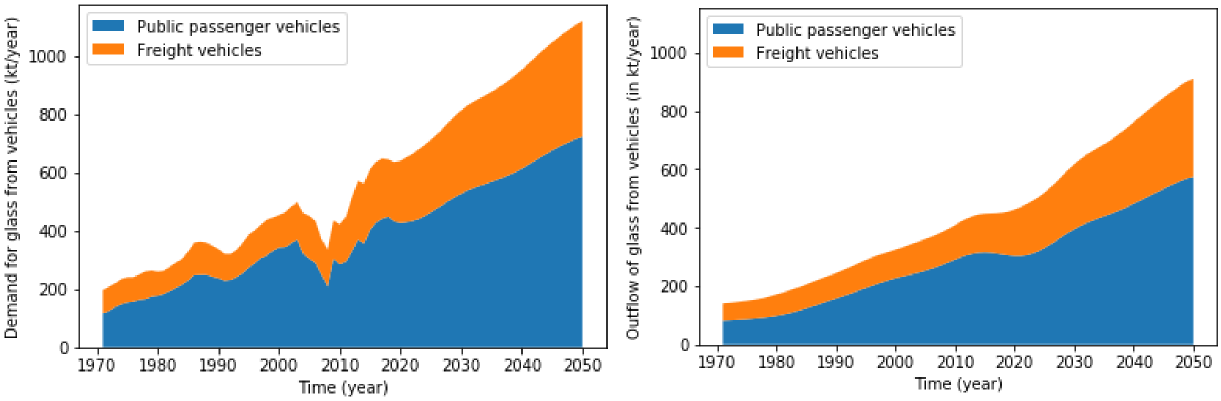


Figure 38 Demand (left) and outflow (right) of glass in the SSP2 baseline scenario

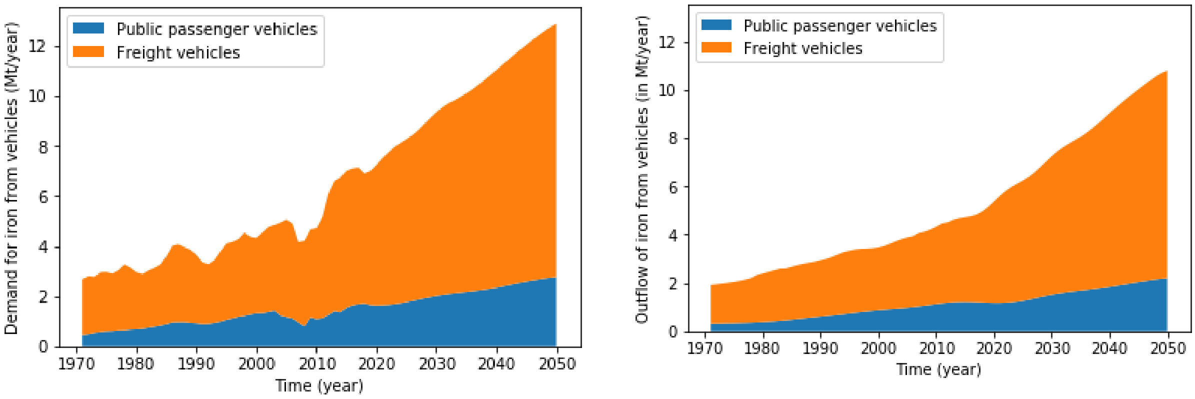


Figure 39 Demand (left) and outflow (right) of iron in the SSP2 baseline scenario

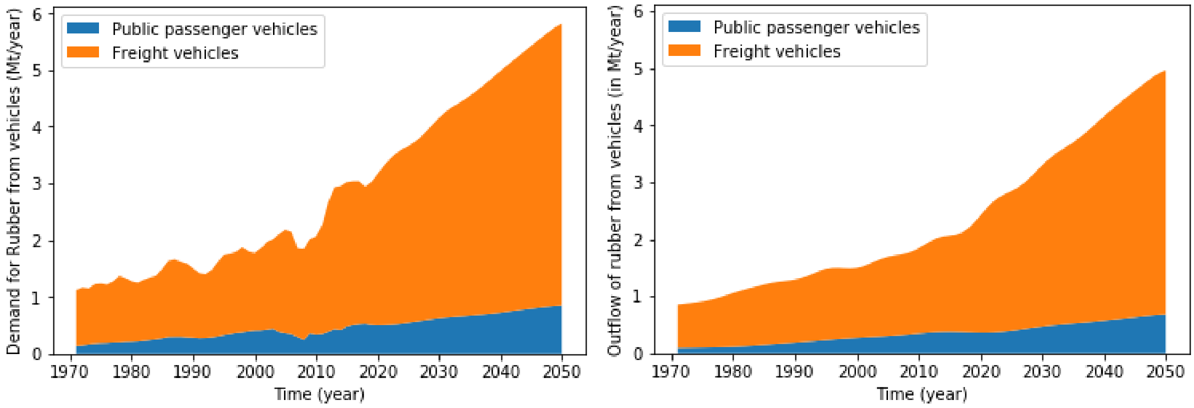


Figure 40 Demand (left) and outflow (right) of rubber in the SSP2 baseline scenario

6.2.2 Comments regarding inflow and outflow and comparison of results

To recapitulate, in the graphs shown above the inflow means the materials required to create the vehicles that will be added to the global fleet and thus the demand. The outflow means the vehicles that have reached their end-of-use and will thus be discarded or recycled. In the graphs we see a very striking dip in the inflow of the materials. This is the result of a stark decrease in passenger- and tonne-kilometres in the period around 2010. This is most likely a result of the 2007-2008 financial crisis. Furthermore, the comparison in made between public passenger vehicles and freight vehicles. The reason why these are passenger vehicle category is called public passenger is to clearly note that cars are not part of the analysis. Cars have already been analysed in previous research and have therefore been left out of this analysis (Deetman et al., 2018). The first conclusion that we can take from the graphs shown above is that a complete circular economy is not possible in the demand for transport continually rises. The demand for materials is, at every point, higher than the outflow. The only way the economy could, theoretically, be circular by 2050 is of other sectors would decline over the period from now until 2050. This would leave extra material of the outflow of these sector which can be used to fill the shortcomings of the outflow of the transport sector. The market for transport thus shows no signs of saturation until 2050.

The demand for copper in cars, electrical appliances and energy technologies is approximately 5000 kt/year in 2010-2015 and rises to approximately 13,000 kt/year in 2045-2050 (Deetman et al., 2018). This is much higher than the approximate 400 kt/year in 2015 to 800 kt/year in 2050 for freight vehicles and public transport vehicles. The flows of materials for buildings are, , much larger than for the vehicles analysed in this study, like we have seen with the stock. The global inflow of steel in buildings is almost 800 Mt/year and the outflow is a little over 400 Mt/year in 2050 (Deetman et al., 2020). The respective inflow of steel in the vehicles is near 90 Mt/year and the outflow is approximately 70 Mt/year in 2050. The fact that buildings have a comparatively lower outflow than the vehicles, is most likely due to longer lifetimes of buildings. The approximate inflow of glass, aluminium and copper in buildings is approximately 90 Mt/year for glass, 50Mt/year for aluminium and 17.5 Mt/year for copper. The outflow of building materials in the respective categories is approximately 57 Mt/year for glass, 37 Mt/year for aluminium and approximately 9.5 Mt/year for copper (Deetman et al., 2020). The correlating values for the vehicles of this study are for glass 1100 kt/year in and 850 kt/year out, for aluminium 10.5 Mt/year in and 8.5 Mt/year out and for copper 600 kt/year out and the already mentioned 800 kt/year in. For copper, glass and steel the flows of the buildings are much larger than for freight and public transport vehicles, whereas for aluminium the flows of the vehicles are relatively large, approximately a fourth of the size of the flows of the buildings. As we see from this comparison is that building flows also continually increase until 2050. Retrieving material from the outflow of the building sector to input into the transport sector would therefore also not result in a circular economy.

7 The 2°C SSP 2 IMAGE scenario and fleet electrification

This chapter looks at the SSP2 2°C scenario and investigates how the values from this scenario differ in terms of vehicle and thus material requirements. This chapter specifically addresses the additional material requirements from society when more electric vehicles would enter the world fleet. We will do this on the basis of the vehicle shares given by the IMAGE/TIMER scenario, which depict what fuel type the vehicles would use.

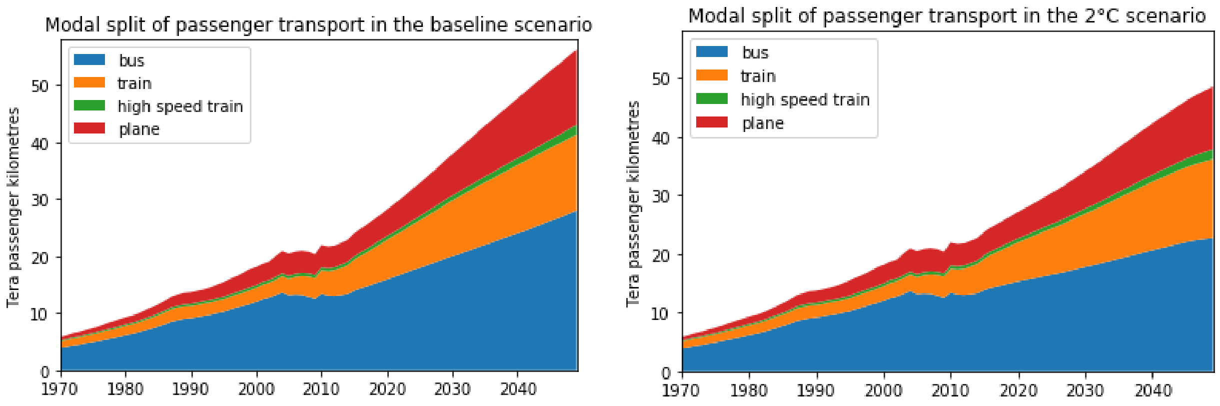
7.1 The SSP2 2°C IMAGE scenario

The narrative of the SSP2 as the middle of the road scenario is a world based on past trends. The world remains quite divided and the population rises steadily, although levelling off after 2050 (which is not visible in this model as it stops at 2050). In terms of climate mitigation, some actions are being taken, but no drastic measures. International institutions attain only moderate successes in achieving sustainable development goals. As education and access to health care and water improve, some technological improvements occur, but no discoveries result in wide societal changes. In terms of economic development emerging economies increase rapidly in population and wealth, but after reaching a certain level both these factors level off (O'Neill et al., 2015).

The SSP2 initially falls short of preventing some of the more dire effects of global warming. The baseline has an approximate CO_2 ppm of 785 by 2100 with 2.6 W/m^2 radiative, forcing an approximately 3.8°C warming above pre-industrial levels (Fricko et al., 2017). The worst effects of climate change are thought to be abated when global warming would be limited to below 2°C of the pre-industrial level. Climate policy has therefore been steered towards this goal (Y. Gao et al., 2017). Therefore, within the narrative of the SSP2 scenarios were developed wherein emissions were significantly reduced. The measures taken in this scenario are mostly situated in the supply side of energy and thus aimed at a move away from fossil fuels and an increase in the use of renewables. Furthermore, emissions are abated by implementing Carbon Capture and Storage (CCS). In a way the SSP2, even in its more stringent climate scenario, is a 'fossil intensive scenario'.

7.2 Modal split comparison of the SSP2 baseline and SSP2 2°C

The model is built in python, which makes it easy to look at other IMAGE scenarios as well and to determine what the differences are to the currently used baseline scenario of SSP2. We have compared the stringent SSP2 2°C scenario with the baseline in terms of material requirements of transport. A lot of the measures taken in such a scenario are therefore not visible in this comparison, but the differences in this respect could be limited. Firstly, we have assessed the modal split: what percentage of global travel is done by which mode. The percentages are in percentage of total Tera passenger-/tonne-kilometres.


Modal split of passenger transport in the baseline scenario

Modal split of passenger transport in the 2°C scenario

Figure 41 Modal split development between 1970 and 2050 of passenger transport in the SSP2 baseline and 2°C scenario

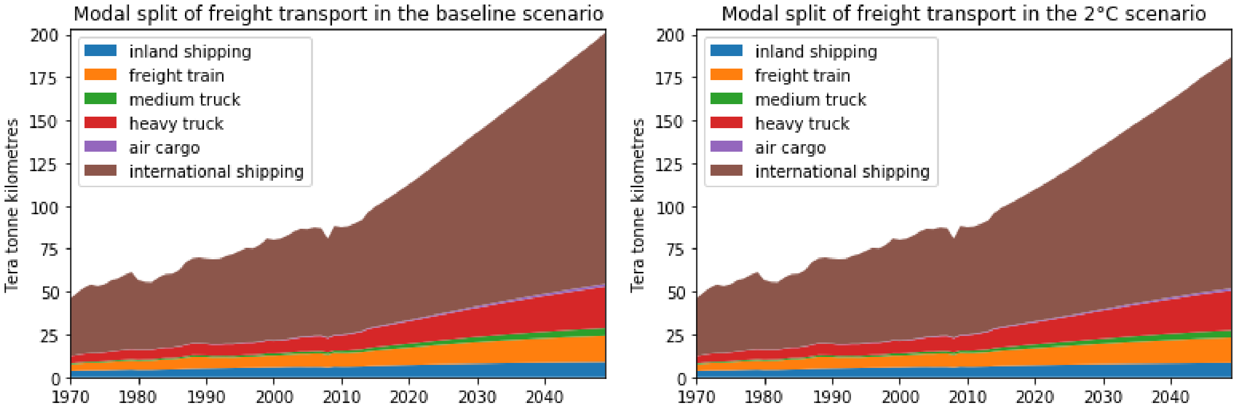


Figure 42 Modal split development between 1970 and 2050 of freight transport in the SSP2 baseline and 2°C scenario

In terms of modal split the difference in the scenarios can be seen in figure 38 and 39. In both cases the modal split remains relatively similar, with the exception of a slight increase in train usage as opposed to the other passenger transport modes. One interesting difference that can be seen in the freight transport decrease is that mostly seems to originate from international shipping. Other categories are relatively similar. The assumption is thus that when transport demand needs to decrease this is most easily done in international shipping. Decreasing the amount of freight vehicles is more difficult and happens to a lesser extent. This will be interesting for this chapter as, when looking at fleet electrification, the only vehicles that will be looked for freight are the trucks as these are the vehicles that could be electrified in the IMAGE scenario. This could therefore result in there being little difference between the baseline and the 2°C scenario. In the following paragraphs we will see where the baseline and the 2°C scenario differ in terms of vehicle types of the various transport categories.

7.3 Fleet electrification

The vehicle fleet is not constant in terms of its composition. As time progresses, technological developments could lead to new fuel and vehicle types. IMAGE/TIMER therefore bases the emission scenarios on the adoption of novel vehicle technologies and fuels. In terms of material requirements this is most relevant for the electrification of the fleet. The component in electric vehicles that makes the greatest difference, is the battery.

7.3.1 Battery material content

In order to determine the material requirements for the various electrification scenarios, we must determine the material content of the batteries. Not all batteries are alike and development in battery technology changes the material composition of batteries and thus material requirements. However, as the developments in material use in batteries are not easily predicted, we have based ourselves on an article which gives a generic model of the composition of a battery for electric vehicles. This will be used for all the batteries of electric vehicles now and in the future. Table 40 below outlines the material fractions determined by this article (Diekmann et al., 2017). The full table on which Table 40 below is created, can be found in appendix H.

Table 40 Material fractions of a battery for electric vehicles (Diekmann et al., 2017)

Material	**Fraction**
Steel	9.0%
Aluminium	34.5%
Copper	9.2%
Plastics	11.0%
Lithium	1.0%
Nickel	3.1%
Cobalt	3.1%
Manganese	2.8%
Other	26.3%

7.3.2 Battery weight

Different vehicle types require different sizes of batteries. Furthermore, electric vehicles come in two major categories, the Plug-in Hybrid Electric Vehicle (PHEV) and the Battery Electric Vehicle (BEV). The first of these uses a much smaller battery than the full electric vehicles (Plötz et al., 2012). Capacity of electric vehicles is often expressed in kWh. Therefore, because of a lack of data regarding battery weight, we have used an average specific energy density of batteries in Wh/kg in order to calculate the weight of batteries. Specific energy density is continually improving, as the following graph of an analysis by CE Delft in 2011 shows (Duleep et al., 2011).

Table 41 Specific energy densities of various battery technologies (Duleep et al., 2011)

Battery type	**Year**	**Specific Energy Density in Wh/kg**
Lithium Mn Spinel	2012	105
Lithium Mn Spinel	2020	125
Silicon Lithium	2020	160
Silicon Lithium	2025	190
Silicon Lithium Sulfur	2030	300

The Chinese specific energy density goal for 2020 is to achieve al least 250 Wh/kg for all battery packs produced in China (Duan et al., 2020). Japan and the US also set the goal of 250 Wh/kg battery energy density, although the US aims to achieve the goal two years later in 2022 (Hao et al., 2017). The current

Tesla model S has already achieved this energy density goal and the company seeks to increase it to 330 Wh/kg in the coming years (Hawkins, 2019). Therefore, we have used 250 Wh/kg, assuming that most electric vehicles in the future will have al least this energy density. The vehicles which are electrified in the scenarios above are buses and trucks. The battery weight thus needs to be determined for the categories: LCV, MFT, HFT, mini-/midibuses and regular buses. In Table 42 and 43 below you will find the capacity as given by manufacturers of electric vehicles and other available sources.

Table 42 Average battery sizes for trolley, PHEV and BEV batteries of mini-/midibuses and regular buses

Bus averages					
Vehicle type	**BEV regular bus**	**PHEV regular bus**	**Trolley**	**BEV mini-/midibus**	**PHEV mini-/midibus**
kWh	314.0	48.5	29.5	136.5	19
kg	1256.0	194.1	118.0	546.0	76
Source	(Ebusco, 2020) (U.S. Department of transportation, 2017)	(Bisschop et al., 2019) (U.S. Department of transportation, 2017)	(U.S. Department of transportation, 2017) (J.-B. Gallo et al., 2014)	(Z. Gao et al., 2017) (J.-B. Gallo et al., 2014)	(Volvo, n.d.)

Table 43 Average sizes of batteries of various truck types

Truck averages						
type	**LCV BEV**	**LCV PHEV**	**MFT BEV**	**MFT PHEV**	**HFT BEV**	**HFT PHEV**
kWh	63.5	13.8	135	21	225.4	34.6
kg	254	55.2	540	84	901.6	138.4
Source	(Pelletier et al., 2014) (California Air Resources Board, 2015)	(Gnann et al., 2013)(Ford, 2019b)	(den Boer et al., 2013)	(Ippoliti & Tomić, 2019)	(Pelletier et al., 2014)(den Boer et al., 2013)(Scania, 2020)(DAF, n.d.)	(J. Gallo, 2016)(Bisschop et al., 2019) (DAF, n.d.) (National Research Council, 2012)

In the appendix H all the different sources can be found from which the average battery capacities shown in table 42 and table 43 that are used as input for the model. The capacity is multiplied by 250 Wh/kg to obtain a weight, which is applied to the material fractions of a battery in order to determine the material requirements. It should be noted that the average battery capacities as determined above are not constant and could change rapidly. Future research should therefore seek to determine changes in capacities and the material consequences thereof.

7.3.3 Vehicle shares in the SSP 2 baseline and 2°C scenario

Applying the vehicle shares in terms of Tera tonne-kilometres and Tera passenger-kilometres to the mileages and loads of chapter 4, the number of vehicles can be determined, as can be found in the graphs below.

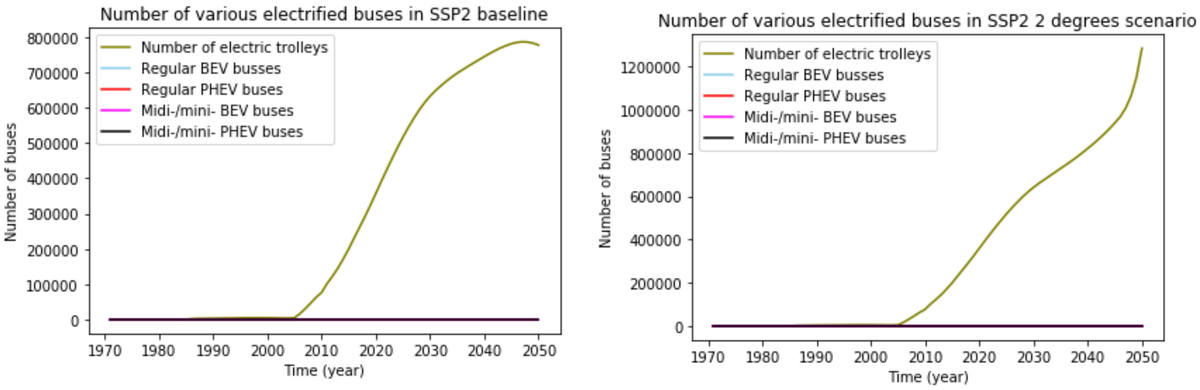


Figure 43 The number of electric passenger vehicles in the stock of SSP 2 baseline and the 2°C scenario

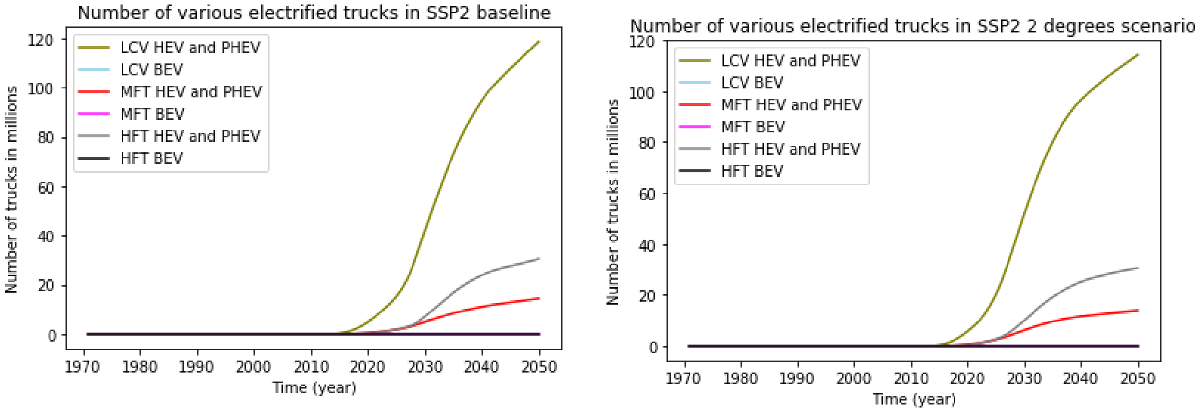


Figure 44 The number of electric freight vehicles in the stock of SSP 2 baseline and the 2°C scenario

It becomes clear that the SSP2 baseline and the 2°C scenario do not differ significantly in terms of BEV projections. Both scenarios make little use of full electric vehicles. With regard to buses there are no hybrids used. Freight, on the other hand, will turn almost all of its vehicles into hybrids by 2050. There is a slight difference between the baseline and the 2°C scenario with regard to freight in the sense that the shift to hybrids happens a bit earlier in the 2°C scenario. On the whole, the only significant difference between the two scenarios regards electric trolley buses for passenger transport.

7.3.4 Materials in the stock of batteries in electric vehicles

Using the generic battery material fractions and combining it with the battery weight of the various vehicles and their numbers, an estimate can be made of the material content of the batteries (Diekmann et al., 2017).

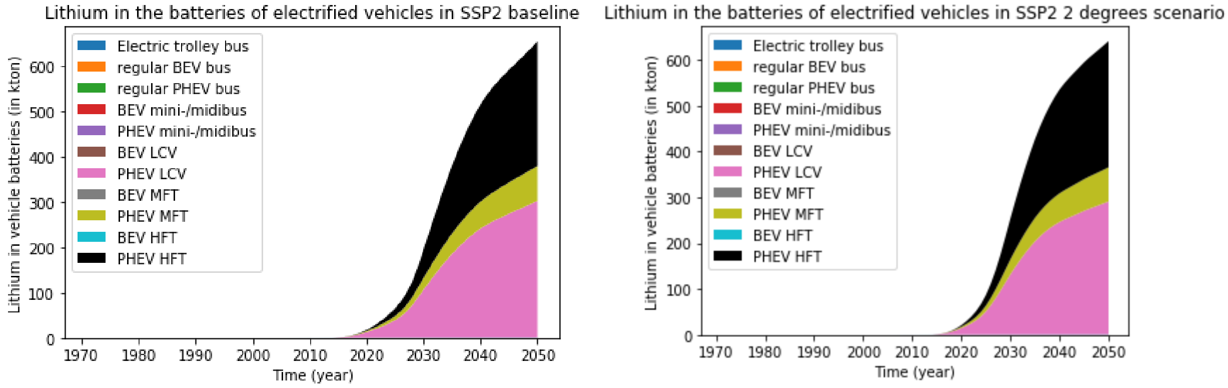


Figure 45 Stock of lithium in the batteries of the electric vehicles in SSP2 baseline and the 2 degrees scenario

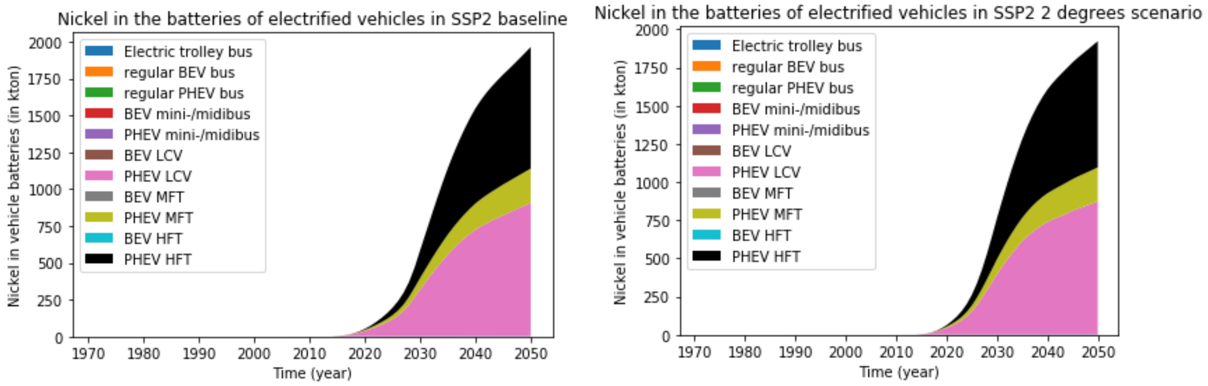


Figure 46 Stock of nickel in the batteries of the electric vehicles in SSP2 baseline and the 2 degrees scenario

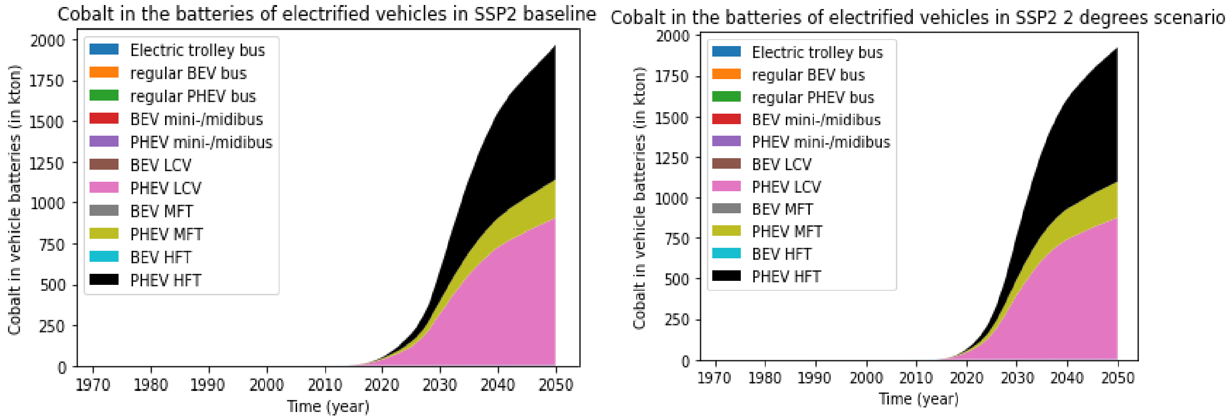
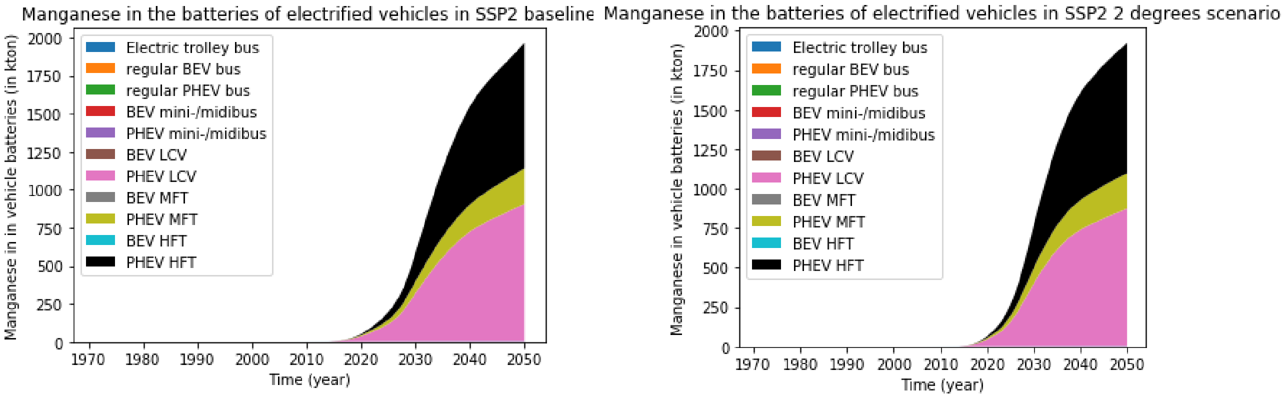


Figure 47 Stock of cobalt in the batteries of the electric vehicles in SSP2 baseline and the 2 degrees scenario



Manganese in the batteries of electrified vehicles in SSP2 baseline

Manganese in the batteries of electrified vehicles in SSP2 2 degrees scenario

Figure 48 Stock of manganese in the batteries of the electric vehicles in SSP2 baseline and the 2 degrees scenario

The graphs show that the majority of material requirements are found for hybrid trucks. This is not surprising as IMAGE/TIMER shows that these vehicles will become predominantly hybrids by 2050. This is the case for both the baseline and the 2°C. The material requirements of the batteries are slightly higher for the baseline scenario, not because a higher degree of electrification, but because the scenario expects slightly more transport and thus more vehicles in total. In both scenarios by 2050 practically all of the trucks are either hybrid or plug-in hybrid.

It becomes clear that, in terms of battery material requirements the SSP2 baseline and the 2°C scenario do not differ greatly. The material requirements do show a significant use of metals with limited proven reserves. Would batteries indeed all use cobalt, the SSP2 scenario and baseline show that this would put a significant stress on the global cobalt reserves. The reserves are approximated at 7.1 million tonnes (Duleep et al., 2011). This means that only to create the PHEV freight vehicles of the world, approximately a third of all global cobalt reserves would be required. Moreover, this scenario is already outdated, as it does not account for any BEV busses or trucks, of which there are already 400.000 in the world (Sustainable Bus, 2019). On top of that, passenger cars and electronic appliances will also require a significant amount of cobalt in the SSP2 baseline and 2°C scenario (Deetman et al., 2018). The same applies to lithium, nickel and manganese, although the global supply of these three metals is less limited. Lithium has 28 million tonnes, nickel 70 million tonnes and manganese 500 million tons of reserves (Duleep et al., 2011). In addition to limited reserves, we have to face other problems, such as public health risks and environmental degradation that accompany the extraction of these materials. For example, it was found that in the Democratic Republic of Congo, the country where most cobalt is extracted, , accounting for 60% of global reserves, populations living in the vicinity of mines are subject to high concentrations of this toxic metal (Nkulu et al., 2019).

7.3.5 Materials in the flows of electric vehicles

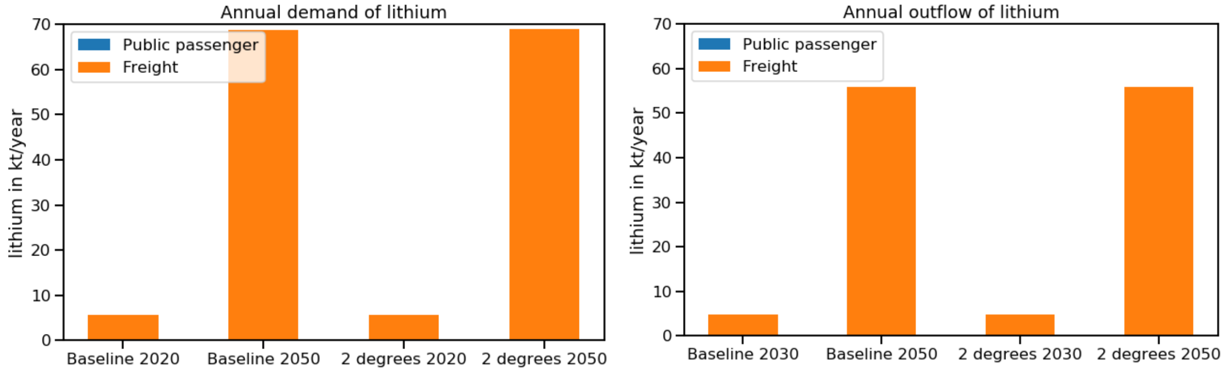


Figure 49 Annual demand in 2020 and 2050 and outflow in 2030 and 2050 of lithium in the baseline and the 2°C scenario

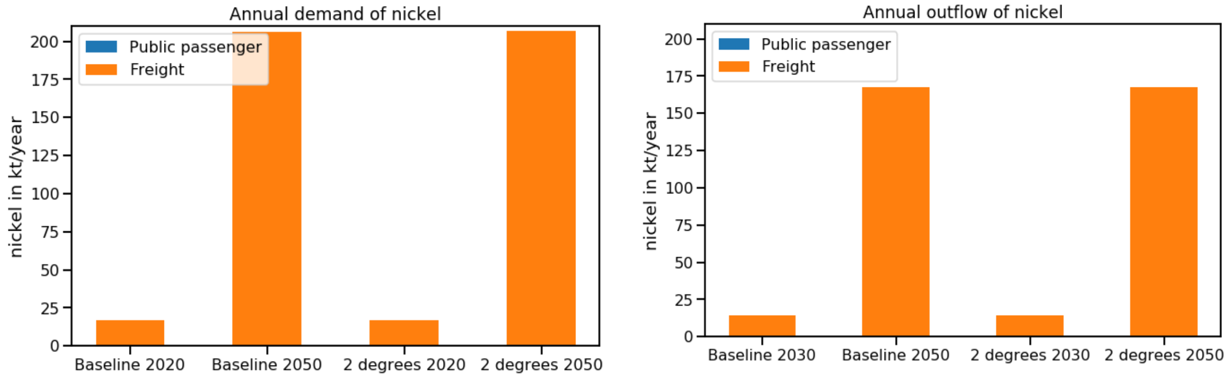


Figure 50 Annual demand in 2020 and 2050 and outflow in 2030 and 2050 of nickel in the baseline and the 2°C scenario

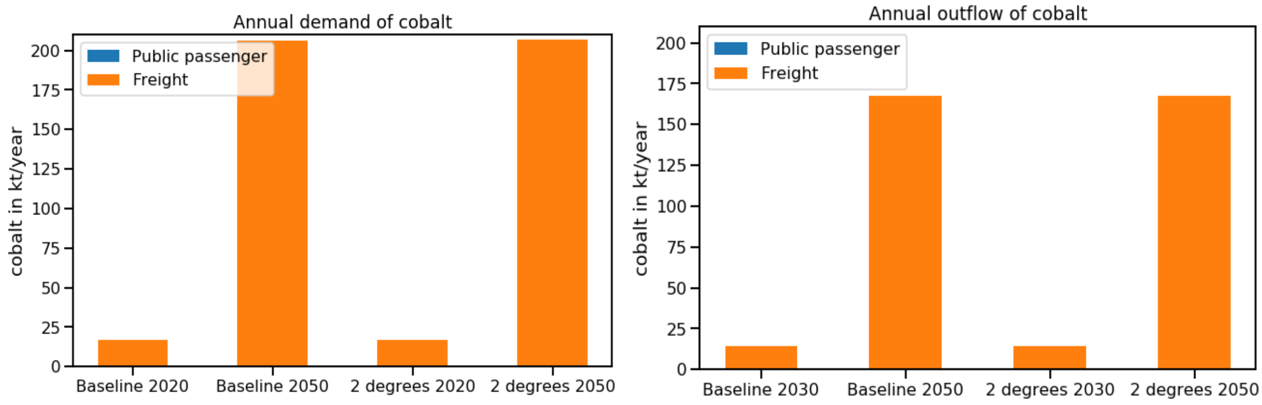


Figure 51 Annual demand in 2020 and 2050 and outflow in 2030 and 2050 of cobalt in the baseline and the 2°C scenario

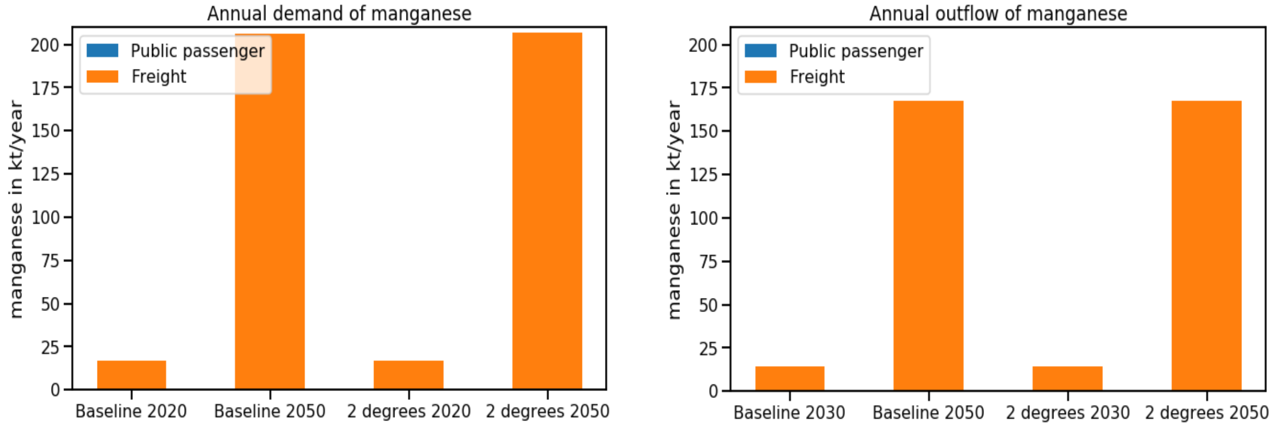


Figure 52 Annual demand in 2020 and 2050 and outflow in 2030 and 2050 of manganese in the baseline and the 2°C scenario

7.3.6 Comparing the flows

The outflow calculated in the graphs shown above show the outflow of 2030 rather than 2020 of which the inflow is shown. The reason we have chosen to show 2030 rather than 2020 is that in 2020 there is no outflow to speak of since a significant amount of batteries only started appearing in the two scenarios around 2020. In order to give a better idea of how the outflow develops we chose to show 2030 rather than 2020 for the outflow. What we can conclude is the outflow of 2030 comes very close to the inflow or demand of 2020. By dividing the demand of 2020 by the demand of 2050 we determined a demand growth rate. The growth rate with which the demand increases that the flows above portray are 12 for the baseline and 12.1 for the 2°C scenario. As can be seen in the following figure 53.

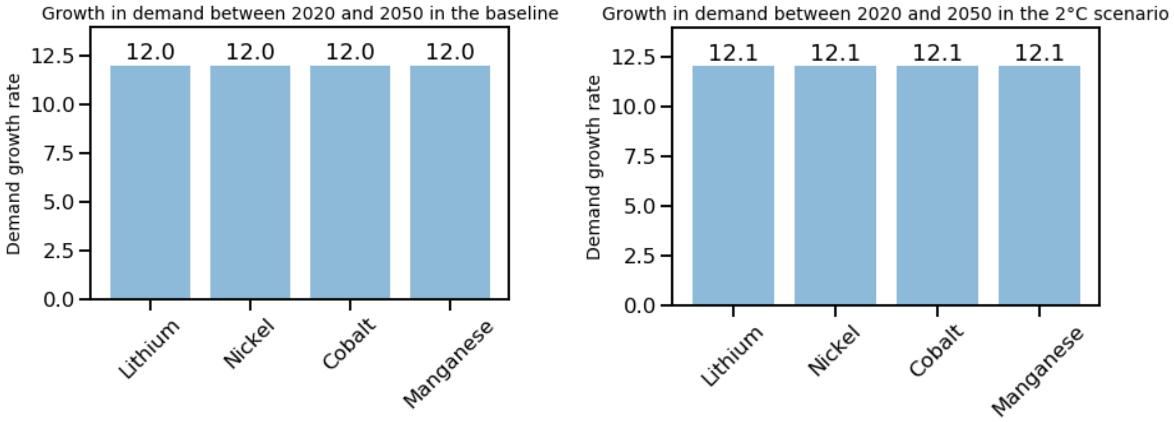


Figure 53 Demand growth of metals used for batteries in fleet electrification

When we compare the flows of cobalt and lithium for the transport vehicles, studied in our research, to the study by Deetman et al. (2018). We find that they are quite close to the flows of cobalt and lithium in cars, appliances and green energy technologies. The article by Deetman et al. (2018) makes three content estimates regarding the cobalt and lithium demand: low, medium and high demand. The cobalt flow calculated in our research is quite similar to the low cobalt estimate for cars, appliances and energy technologies, which is approximately 20kt/year in 2020 and increases to 90 kt/year in the baseline and to 210 kt/year in the 2°C scenario in 2050. In the medium content scenario cobalt demand rises between 2020 and 2050 from approximately 90 kt/year to 260 kt/year in the baseline and from 90 kt/year to 460 kt/year (Deetman et al., 2018). The cobalt demand in our research, which is approximately the same for both scenarios, rises from approximately 20kt/year to 200kt/year between 2020 and 2050. With regard to lithium, demand for lithium in cars, appliances and green energy technology rises from approximately 10 kt/year in both scenarios to 60 kt/year in the baseline and to approximately 370 kt/year in the 2°C scenario between 2020 and 2050. This is the low content estimate, which is nearest to the increase in demand from approximately 5 kt/year in 2020 to 70 kt/year in 2050 for the vehicles of this study. It is remarkable, that when only determining that all trucks become hybrid or plug-in hybrid by 2050, we already see such a stark demand increase for these metals. Of course, it should be noted that we have considered the material fractions and weight of the batteries as constant factors in this study, which is not realistic. However, it is beyond the scope of this study to determine such changes and model them. This should be addressed in future research.

7.4 Comparing material in- and outflows of the baseline and the 2°C scenario

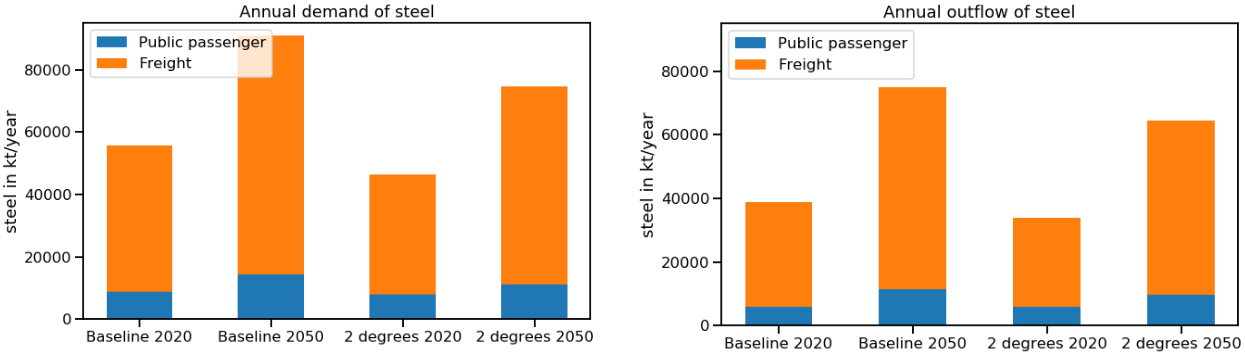


Figure 54 The annual demand (left) and outflow (right) of steel in the baseline and the 2°C scenario in 2020 and 2050

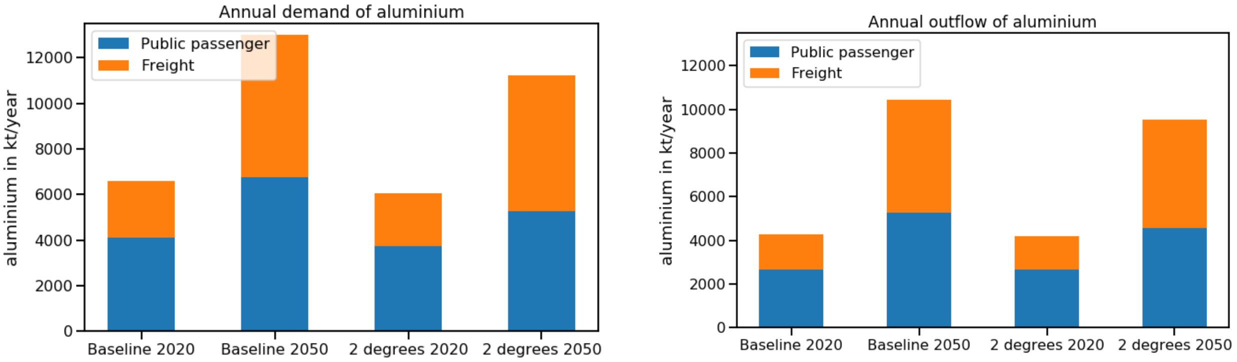


Figure 55 The annual demand (left) and outflow (right) of aluminium in the baseline and the 2°C scenario in 2020 and 2050

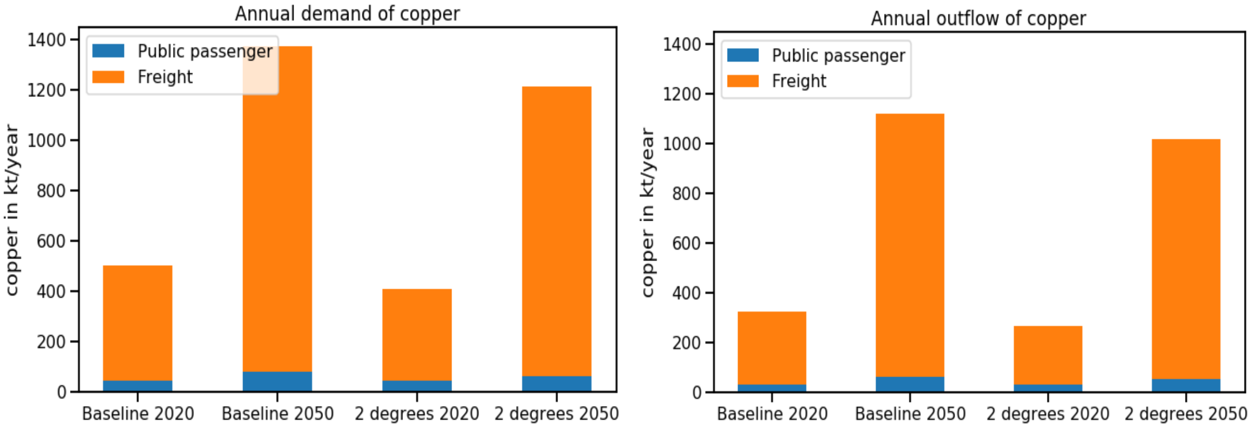


Figure 56 The annual demand (left) and outflow (right) of copper in the baseline and the 2°C scenario in 2020 and 2050

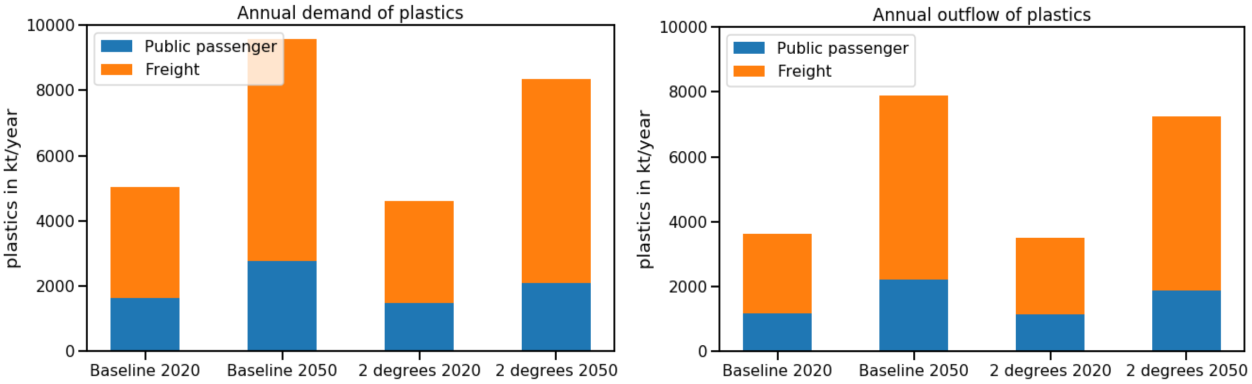


Figure 57 The annual demand (left) and outflow (right) of plastics in the baseline and the 2°C scenario in 2020 and 2050

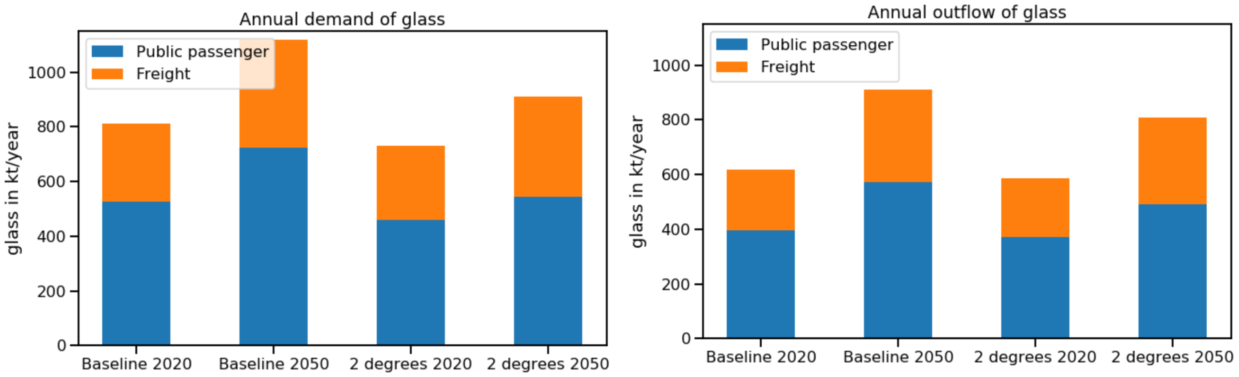


Figure 58 The annual demand (left) and outflow (right) of glass in the baseline and the 2°C scenario in 2020 and 2050

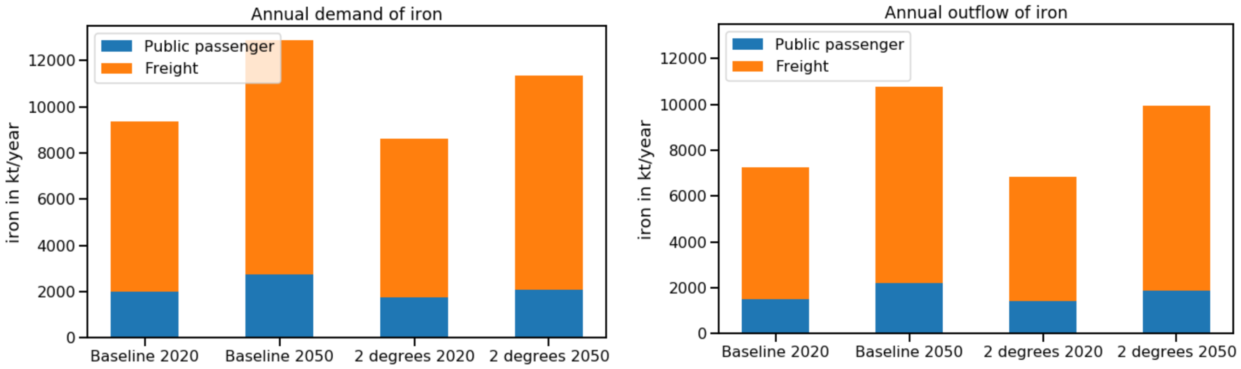


Figure 59 The annual demand (left) and outflow (right) of iron in the baseline and the 2°C scenario in 2020 and 2050

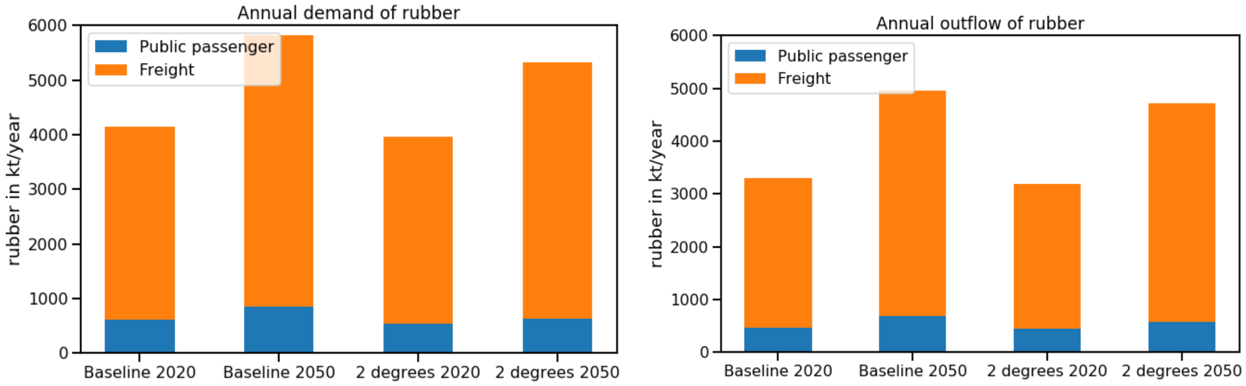


Figure 60 The annual demand (left) and outflow (right) of rubber in the baseline and the 2°C scenario in 2020 and 2050

7.5 Discussing the difference between between the baseline and the 2°C scenario

To commence, it is important to realise that the SSP scenario output that this report works with has been made several years ago. This is the reason why the values for 2020, thus the current year, still differ significantly.

When we compare the flows they show that the annual inflow and outflow of material in the 2°C scenario is lower - in varying degrees - than in the baseline. This means that material demand of the 2°C scenario will not increase compared to the baseline scenario for the vehicles studied in this report. More material will there be required in the baseline scenario. Secondly what we did, since we now know the demand and the outflow, is to calculate by what degree the various materials increased in the two scenarios. We did so by dividing the demand of 2020 by the demand of 2050 the demand growth rate is calculated as shown in figure 61 below. The demand growth of the 2°C scenario is slightly higher for copper, this is, most likely, due to the fact that the starting point of the 2°C scenario is lower because less vehicles are needed in the scenario. Adding the copper from the batteries of the electric vehicles will therefore, proportionally have a greater effect than in the baseline. It is interesting to see that in both scenarios the demand for copper almost triples and demand for the other materials almost double. With the exception of steel which experiences in increase in demand of 60%.

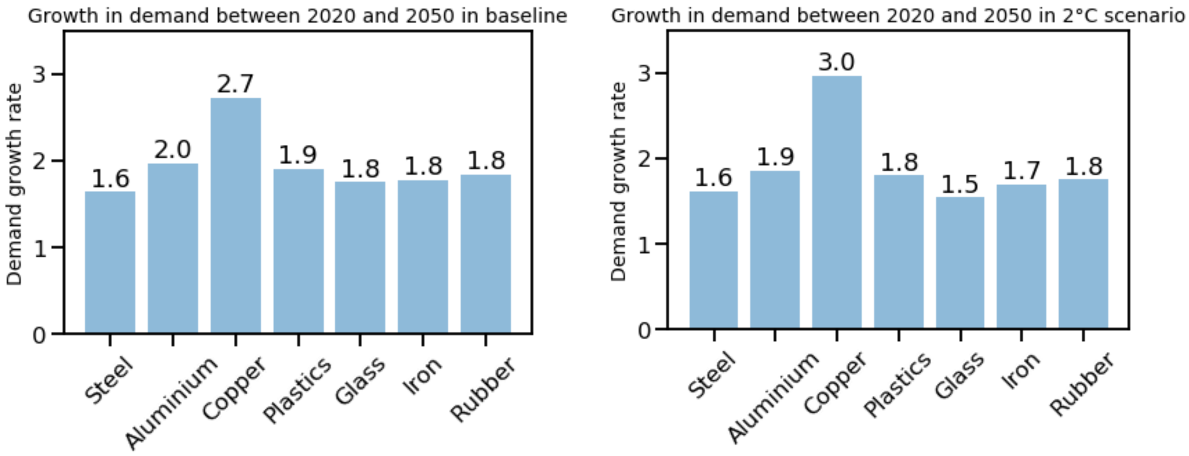


Figure 61 Demand growth in the two scenarios

It should be noted that in the flows depicted in figures 54 through 60 above, the steel, aluminium, copper and plastics of the batteries have been added. Especially for copper this made quite a significant difference. For copper in batteries there is a significant additional demand. The new demand in 2050, however, is still approximately fifteen times lower than the combined demand for copper in cars, electrical appliances and green energy technologies (Deetman et al., 2018). The same applies for copper in buildings (Deetman et al., 2020).

Considering the development of the material flows for vehicles, the narrative of SSP2 seems to fit at first, although recent developments have already shown the SSP2 to be unrealistic. Both scenarios assume that there will be no fully electric buses or trucks until at least 2050. All extra material in batteries that was found originated from hybrids and plug-in hybrid vehicles. Currently, however, there are 400.000 electric buses in the world fleet and the number continues to rise (Sustainable Bus, 2019). This discrepancy might be explained by the fact that this model was developed already some time ,when electric buses seemed a distant technological advancement in a more remote future, unlike it turned out to be. The narrative of the model states that some technological advancement will happen, but no grand breakthroughs. Apparently, one has underestimated the speed of the breakthrough of electric buses and trucks. Secondly, a lot of the developments in transport happen in China at a very rapid pace which those who developed SSP2 have failed to foresee.

Another aspect of the narrative is the globalising economy and growth in developing countries until at least 2050. This is visible in the increased use of freight vehicles. Particularly the growth of maritime shipping and of the size of ships is clear example. This model assumes a significant efficiency improvement in maritime shipping vessels, which counterbalances the growth in maritime transport and makes the total material impact of developments in the maritime sector limited, although it still constitutes a significant fraction.

Overall, the main difference between the baseline and the 2°C scenario for the vehicles studied in this report, is a slight decrease in the number of tonne- and passenger-kilometres, with less vehicles as a result. In other areas, such as improvements in carbon intensity of energy production, the difference between these scenarios may be expected to be more visible.

8 Policy recommendations

Three themes stand out when it comes to the question how the insights of this thesis could be helpful in conceiving new policies. The first regards data. Our research shows that there is still a lot of relevant data lacking. Improving on this will allow us to make more accurate scenarios in the future. Secondly, we will consider what can be said about the scenarios studied in this report and what it teaches us for policy making for a circular economy. Lastly, we will see what lessons we can learn in terms of material efficiency and the reduction of material use.

As we stated in the current report, there are various areas where assumption had to be made due to a lack of data. This is particularly apparent in the material composition of vehicles. It is understandable that such data is difficult to compile, since each company makes its vehicles differently, giving it a different material composition. However, in order to know the material demands of the future, accurate data on the material composition of vehicles is necessary. This includes an accurate number for the empty weight of the vehicles, which for many vehicles was very difficult to find. Ideally, we would have data on the approximate material content of vehicles over time. If clear trends can be discerned, these can be modelled in order to make more accurate forecasts of material requirements in the future.

The second point where we were faced with a lack of data regards the development of fleet compositions. Such data was only available for maritime vessels. Data on these developments could help to make an extrapolation for possible future developments of the fleet. The report shows that the bigger the vehicle, the more efficient its material use. Therefore, understanding whether the relative number of smaller and larger vehicles within the fleet is expected to change over time, is an important variable for the determination of material requirements. Other points for which data could be improved, are lifetime and lifetime distribution. Calculating the outflow and inflow is dependent upon these values and therefore it is important to make sure these values are accurate. A higher lifetime means lower material requirements, but also, if demand increases over time, a long lifetime means that the inflow (demand) will be significantly higher than the outflow. Lastly, there are the values necessary to relate tonne- and passenger-km to vehicles numbers. The mileage and the load, or the combination of load capacity and load factor, are clear indicators of the efficiency of a vehicle. Getting accurate information on these values will, most likely, serve a purpose beyond determining the material content of transport demand scenarios. The lack of accurate datapoints thus impacted the accuracy of this paper. However, it also clearly shows, which values can be improved to make more accurate scenarios for the future.

Regarding the scenarios assessed in this report, several critical remarks can be made. Firstly, it should be noted that the model output that was used for this report, dates from some time ago. Although new output will be generated relatively soon, it is not yet available and therefore there was no choice but to use the older output. Secondly, it is important to keep in mind, that the model output cannot pretend to give an accurate prediction of the future. Rather, it creates a logical narrative of what a future world could look like and what the implications could be. The narrative used for this report is the second Shared Socio-economic Pathway, in particular the baseline and the 2°C scenarios. Considering this, the scenario output is at times relatively close to reality, while at other times quite distant from it. It is interesting to note that the complete amount of travel (in passenger-km) by the passenger vehicles studied in this report is quite close to the number reported by various other sources. The area where the model output differed most from the quantity of passenger travel reported by other sources, is air transport. The scenario output predicted half the quantity of air travel that was reported by the IATA. The same is true for high-speed train transport, which also appears to be underestimated by the IMAGE output. Most likely, this underestimation is caused by the speed with which China develops. In the IMAGE output, there was almost no high-speed train transport predicted for 2019. However, the IEA report estimated that China accounts for approximately 55% of all global high-speed train transport. In terms of freight transport, the IMAGE scenario significantly underestimates the quantity of goods transported currently. The IMAGE second SSP baseline calculates approximately one third less freight transport than the combined other sources. The two freight transport modes that are underestimated most significantly are maritime shipping and freight trucks. Lastly, in terms of fleet electrification, two assumptions seem to have been at the centre of the second SSP narrative. Firstly, the assumption that the technology of fully battery electric vehicles would be too expensive or difficult to be attained before 2050. Secondly, that the number of hybrid vehicles will increase significantly and that by 2050 practically all trucks will be hybrid or plug-in hybrid. Looking at the current developments, these assumptions seem questionable. A stark increase in hybrid trucks could still happen. However, counting out battery electric buses and trucks before 2050 seems unrealistic seeing as there are already 400,000 electric buses operational (Sustainable Bus, 2019). In summary we may say that, although the scenario shows some serious discrepancies with the current situation, there are still relevant conclusions that can be drawn from analysing the IMAGE output. Studying a scenario is an exercise in answering a ‘what if’ question. No one can accurately predict the future, so studying an imperfect scenario is the best we have got. Moreover, an notable factor is the significant growth predicted in the scenario. Growth in transport use is also predicted by various other reports on specific categories of vehicles, such as the IEA report on trucks and market analyses of airplanes by Airbus (IEA, 2017)(Airbus, 2019b). If growth were to increase like in the two scenarios we studied, demand for steel, aluminium, iron, plastics, rubber and glass would almost double for the manufacture of the vehicles studied in this report. The demand for copper in these vehicles would almost triple. Because the growth is relatively fast, the outflow will not match the inflow. Therefore, even if a hundred percent of end-of-life products would be recycled, virgin material will still be required. Therefore, if the policy objective is to achieve a circular economy, it should be aimed at reduction of transport demand and/or improve the material efficiency of vehicles.

As expressed by the waste hierarchy of the Dutch politician Ad Lansink and currently adopted in the EU directive on waste: first reduce, then reuse, then recycle (Gharfalkar et al., 2015). As much could be said for the use of transport vehicles. In terms of material efficiency, in other words the material needed to produce a unit of transport, not all vehicles in this report score equally. If one wishes to reduce the material requirements of society, focus could be given to the promotion of vehicles with a high material efficiency. For freight transport, we see that Light Commercial Vehicles (LCV) are found to be quite inefficient in terms of their material requirements per goods moved. The question should be asked, whether these vehicles should be promoted, even if they were electric. When companies such as DHL boast that their fleet of electric delivery vans has increased, it is questionable whether this is an improvement in terms of sustainability (Blaauw, 2017). Rather, when looking at material use in vehicles, the focus should be on delivering packages with larger vehicles and realising pick-up points instead of door-to-door delivery. Maritime vessel, on the other hand, are quite efficient in terms of materials. From this perspective airplanes are the most efficient vehicles for passenger transport. However, most likely this will not weigh against the higher emissions that accompany the planes (Hill et al., 2019). Second comes the train, which combines low emissions per passenger kilometre with high material efficiency. Policy should be aimed at promoting vehicles with this combination of low emissions and high material efficiency. Finally, we studied the material requirements of batteries for battery electric vehicles and hybrid vehicles. We found that, even when not accounting for battery electric vehicles, demand for the materials in batteries will increase twelve-fold for the vehicles of this study due to a rise in the use of hybrid vehicles. Demand for lithium, cobalt, nickel, copper and manganese could thus increase significantly. Therefore, supply and production capacity should be continuously monitored to determine whether they will be able to meet these increased demands.

9 Discussion and conclusion

The aim of this thesis is to outline what the current material stock and future material stocks and flows are in the global freight fleet and the motorised global passenger transport fleet. Notably, we exclude cars a because cars have already been outlined in another study. The future and past stocks and flows were determined on the basis of the baseline and the 2°C scenario of the second Shared Socio-Economic Pathway in the integrated assessment model IMAGE for the period 1970-2050. The current stock was determined by first analysing available data documenting the current stock of vehicles. Secondly, we calculated the material in the vehicles by multiplying the fractions of materials in the vehicles with the an average weight of the vehicle types. The vehicles were divided into broad categories; for freight vehicles: inland shipping vessels, maritime vessels, planes, trains, medium trucks and heavy trucks; for passenger vehicles: high-speed trains, regular trains, planes and buses. These were based on the categories used by the IMAGE model. For the assessment of the material content of vehicles, these categories were found to be too broad, because most vehicles have significantly varying sizes, which impacts the weight as well as the load these vehicles can carry. This was solved by dividing the vehicle categories into subcategories or types. This also influences the second part of this thesis, which is the calculation of the stock and flows of vehicles based on tonne- and passenger-kilometres. This impacted the second part because the passenger- and tonne-kilometres determined by the two SSP 2 scenarios of IMAGE had to be divided into smaller categories.

For some vehicle categories calculating an average weight of the various vehicle sizes sufficed, for the following categories the fleet had to be divided into various sizes. Maritime vessels were divided into small, medium, large and very large, trucks were divided further from large and medium into LCV (Light Commercial Vehicles), MFT (Medium Freight Truck) and HFT (Heavy Freight Trucks). buses were divided into mini-/midibuses and regular buses. Once the fleet composition was determined as well as the weight, the last step was the determination of the material fractions of the vehicles. These fractions were taken from studies which separated and weighed one specific model of a vehicle type. This is not very accurate, since each manufacturer of a vehicle will use different fractions of materials to create their product. However, the alternative is to have the material fractions of every vehicle brand as well as changes in the material fractions over time. Such data, however, does not exist and studies outlining the material content of a vehicle are very rare. Therefore, the material fractions of vehicles given by these specific studies were applied to the whole fleet. It would be useful to improve the accuracy of data on material fractions of the vehicles in future research. This could significantly improve the accuracy with which material requirements of society can be calculated. The specific materials that are studied in this thesis are those with the highest fractions of the total and those that occur in more than one of the categories. These materials are steel, aluminium, copper, iron, plastics, glass and rubber. It should be noted that we decided to consider steel and iron separately, because cast iron is often used in vehicle engines, which makes it a significant fraction in the total material stock.

Applying the fractions and the weight of the vehicles to the current stock, we found the following results. In terms of kilograms of material the global fleet of maritime vessels contains the most material, followed by heavy freight trucks, medium freight, light commercial vehicles, freight trains, inland shipping vessels and lastly freight planes. Weights are expressed in hundreds of Mega tonnes and the largest material fraction is steel. With regard to passenger vehicles, buses are by far the largest category in terms of tons of material in the current fleet, followed by regular trains, mini-/midibuses, high-speed trains and planes. The numbers are largely in tens of Mega tonnes rather than hundreds, except for buses. Like for freight vehicles, steel is the largest fraction of the materials. However, the aluminium fraction is higher in passenger vehicles than in freight and comes a close second. The total kilograms of the fleets were divided by the number of tonne- or passenger-kilometres to determine the material efficiency of the vehicles. In this respect, planes scored best, since the vehicles are kept light and have a high occupancy. With regard to freight, the most efficient, in terms of material of vehicle per good transported, vehicle types are maritime vessels, followed by freight trains, inland shipping vessels, heavy freight trucks, medium freight trucks and lastly light commercial vehicles. When ranking the passenger vehicles from most to least efficient, airplanes come first, followed by high-speed trains, regular trains, regular buses and lastly mini-/midibuses.

The second part of this thesis relates to the determination of the numbers of vehicles based on tonne- and passenger-kilometres. This is the measure used by IMAGE. For this, we divided the tonne- and passenger kilometres by the load multiplied with the mileage of the vehicles. The load can either be given in sources or can be calculated by multiplying the load capacity with the load factor. Loads and mileages are difficult numbers to pinpoint, because they differ per country or region as well as within vehicle categories. Furthermore, they change over time. Moreover, mileages and loads are not always recorded. Therefore, a global average is not the most accurate representation of the values. However, it is beyond the scope of this research to determine accurate loads and mileages for all world regions and this should therefore be addressed in future studies. Combining the mileages and loads with the passenger- and tonne-kilometres of IMAGE gives us the numbers of vehicles, which can be multiplied by kilograms per vehicle and material fractions. This allows us to determine the stock of material in vehicles for the period of 1970 until 2050.

On the basis of the stock of vehicles the inflows and outflows of the vehicles are calculated. This is done by applying a python module designed to calculate inflows and outflows from a stock. The additional values that were put into the model were average lifetimes, the year of conception of the vehicle and the standard deviation from the average lifetime, in order to determine the lifetime distribution within the fleet. In the stock and flows can be seen that in the SSP2 narrative of IMAGE the number of vehicles in the world fleet and the material requirements more than double between 2020 and 2050.

Subsequently, the following scenarios of the second SSP narrative were examind. The first scenario that was studied is the baseline and the second scenario is the 2°C scenario. The 2°C scenario applies various measures which would limit global warming to 2°C above pre-industrial level. Secondly, the electric vehicle fractions of these two scenarios are applied to the stocks and flows to assess the material consequences of electrification of the vehicle fleet. This was calculated by determining the average weight of the batteries of electric vehicles as well as their material fractions. This is also a very inaccurate number as battery technology is changing rapidly and the composition of batteries changes as well. Moreover, this method only addresses the weight of the battery, which is added to the total weight of the vehicle. Except for battery size, the material differences between an internal combustion engine and an electric traction motor or hybrid vehicles are not addressed. In future studies more accurate material fraction should be assessed.

We found that in both SSP2 scenarios there will be no or a negligible number of battery electric trucks or buses. Furthermore, in both scenarios all trucks will become either hybrid or plug-in hybrid. This leads to significant growth in demand for lithium, cobalt, manganese and zinc, if the composition of batteries will not change significantly. So even without any battery electric vehicles the demand for these materials and their outflow later in time will increase significantly.

It is remarkable, that there are no electric buses or trucks until 2050 in any scenario , considering that already now there is a significant number of these vehicles on the road. Various reasons could explain this, but most importantly it should be noted that it is not the goal of the SSP to predict the future. The scenarios seek to portray the likely outcomes of various policy choices and to assess possible directions of future developments.

However, if a scenario strays too far from reality, one could question whether it has surpassed its purpose. Various discrepancies were found between the findings of the SSP 2 scenario and the information given by various sources about the current state of global transport. In particular for maritime and truck freight transport, the scenario underestimated the global transport significantly. For passenger transport, IMAGE SSP 2 underestimated plane and high-speed train transport.

Furthermore, it is important to note that the method of this thesis also has its shortcomings. Calculating vehicles on the basis of the number of tonne- and passenger kilometres in the world, does not works when there are stark decreases in these kilometres, such as occurred in the 2007-2008 financial crisis. According to the method, a decrease in the number of kilometres translates into a decrease in the number of vehicles, which means a large outflow of vehicles from the stock. Although it can be expected that such a crisis leads to a slower demand for new vehicles, it is hardly realistic to expect such a large outflow, followed by an equally large inflow after the crisis. One could expect that the vehicles are stored until they are necessary again.

This study aims at finding the material requirements of global transport, but it does not account for cars as a related paper already examined cars in the second SSP scenario (Deetman et al., 2018). Moreover, several other categories remain outside the scope, including bikes, motorbikes, construction vehicles, fishing vessels and farm vehicles. It remains to be seen whether these categories and perhaps others are significant for a complete overview, but we have to realize that a complete account of all the vehicles in the world is still lacking.

This study does show, however, that in order to improve the IMAGE model by adding material content, vehicles should be defined in more narrow categories than is currently done. In terms of energy use and emissions, sizes of vehicles might not be significant, but in terms of material use the size of a vehicle is important. Especially in the vehicle category Light Commercial Vehicles this is apparent. LCV is currently one of the most prevalent vehicle types in the world, yet IMAGE does not differentiate for this category. Another important addition would be to make a clear differentiation within rail transport. The number of metros in the world is rising rapidly and when assessing the global material requirements, this category cannot be lacking. Considering the stark increases in transport and the materials demand of transport, as shown in this study, it be clear that an assessment of material requirements is a relevant and important element in IAM scenarios is. When we use IAMs to measure human impact on the environment, we cannot exclude the material dimension, since large increases in the demand for materials impact the environment significantly. The rising demand from society for materials within planetary boundaries, means that these materials must be used more efficiently. Assessing the scope of the requirements from the inflow side as well as identifying opportunities for better reuse and recycling from the outflow side, is an important step towards a more circular economy.

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Appendix A: Methodology

The calculation for the inflow and outflow can be described as follows. To the module an initial year for a vehicle type is given, this year determined based on the first modern invention of the type. For example, with regards to boats the first year that is chosen is the steamboat rather than the invention of a wooden boat. This initial year is used to interpolate a historic vehicle number which is necessary as otherwise the module will make the inflow the total stock of 1970. This would lead to large inflow and outflow spikes at the end-of-life of the vehicles. Another input that was added is a standard deviation from the mean. This creates a lifetime distribution of the vehicles in order to produce a realistic intersection of the vehicle fleet. The ages are folded normally distributed, the reason it is not a normal distribution is because in a normal distribution the outer cohorts can become negative. With a vehicle inflow of more than a million this would lead to negative lifetimes of the vehicles. Lastly a rolling average is applied to reduce large spikes of inflow and outflow as such spikes would be unrealistic. Spikes a generated when, as a result of for example an economic crisis, the tkm or pkm decreases sharply to later increase significantly. With the calculation of stock that is applied of dividing the tkm or pkm by load and mileage the stock decreases significantly because less vehicles are needed to create these tkm or pkm. These vehicles would not be immediately destroyed in order to rebuild them two years later which such spikes would suggest. Furthermore, is can be assumed that production and demolition/recycling capacity would not be able to capable to meet this demand.

Appendix B: Airplanes

In this appendix the calculations done to arrive at some of the values are laid out.

Firstly, According to Boeing the world fleet of freighter airplanes is 1870 and accounting for 8 percent of the total global commercial fleet, a quick calculation would then place the global fleet at 23375 (Boeing, 2018).

Secondly, not every source makes a distinction between passenger and freight aircrafts. However, when averaging the 8 percent freight of Boeing and, when dividing the 1812 Airbus freight estimate by the total, the 7.4 percent of airbus, an average of 7.7 percent freight is found.

In table X the freight planes that were used to determine an average load capacity are laid out. Using a weighted average. In table 40 the calculated average weight for the three weight categories is laid out which were used to determine an average weight of freight planes. Table X also show the fractions of the weight categories based on the amount of planes of the study by Cananova et al. (2017).

Table 44 All freight planes in service in the year 2018-2019 (Casanova et al., 2017)

Plane	in service	fraction	Capacity in lb	cap in ton
Bombardier CRJ 100/200PF	10	0.0065	14800	7
McDonnell Douglas MD-80SF	9	0.0059	46600	21
Boeing 737-300SF/300C	109	0.0710	42800	19
Boeing 737-300QC	29	0.0189	40550	18
Boeing 737-400SF/400C	124	0.0808	45550	21
Boeing 757-200PF	79	0.0515	84120	38
Boeing 757-200SF	205	0.1336	69500	32
Boeing 757-200Combi	6	0.0039	69500	32
Airbus A310-200F/300F	10	0.0065	87350	40
Airbus A300-600F	103	0.0671	113050	51
Airbus A300-600 converted	68	0.0443	108910	49
Airbus A330-200F	37	0.0241	147050	67
Boeing 767-200	59	0.0384	92700	42
Boeing 767-300F	126	0.0821	115700	52
Boeing 767-300(ER)BCF/SF	56	0.0365	115350	52
McDonnell Douglas MD-11F	34	0.0221	191095	87
McDonnell Douglas MD-11BCF	85	0.0554	189700	86
Boeing 777 Freighter	129	0.0840	224900	102
Boeing 747 400(ER)F	143	0.0932	261600	119
Boeing 747-400BCF/BDSF	43	0.0280	237750	108
Boeing 747-8F	71	0.0463	298700	135

Table 45 Categories and average weight (Casanova et al., 2017) *and* (Airliners.net, n.d.)

Weight category	Fraction	Average weight
Small	0.38	46618
Medium	0.29	86679
Large	0.33	160625

Regarding material compositions the assumption is made that according to the research by Timmis et al. (2015) CFRP is 35% plastic and 65% carbon fiber. Furthermore, a study on airplane recycling showed that a boeing 777 has approximately 100 miles of cable and a boeing 787 has approximately 60 miles of cable (Asmatulu et al., 2013). An LCA on copper and aluminium wiring showed that per kilometre of wire there is 4.124 kg copper (Bao et al., 2017). When discussing aircrafts the type of miles that are usually referred to is nautical miles, thus that is assumed to be the miles discussed in the article by Asmatulu et al. (2013). Thus that would mean 185.2 km cable in a Boeing 777 and 111.12 km cable in a Boeing 787. The average weight of the 777 s 149,550 and of the 787 is 110,000. The weight of the copper cable for the 777 is approximately 763 kg and for the 787 is 458 kg. This would give the following fractions for copper in airplanes when assumed that all the cable used in the planes are copper cables. 763/149550 = 0.0051 is the fraction of copper in the 777 and 458/110000 = 0.0042 is the fraction of copper in the 787. Lastly the assumption is made that this copper is part of the 'other' section in the LCA study of a plane which calculated material fractions (Howe et al., 2013). It will therefore me subtracted from this fraction.

Table 46 Materials in aircrafts calculate new fractions (Howe et al., 2013)*,* (Timmis et al., 2015)*,* (Asmatulu et al., 2013) *and* (Bao et al., 2017)

Material	Fraction	Material	Fraction
Aluminium	0.68	Aluminium	0.68
Composites (mostly CFRP, thus Carbon Fibre Reinforced Polymer)	0.15	Steel	0.09
Steel	0.09	Plastics	0.053
Titanium	0.06	Titanium	0.06
Copper	0.0		0.0046
Other	0.02	Other	0.113

Appendix C: Rail transport

Appendix C.1: Light rail

Below the calculation is laid out which was done to arrive at the approximately 0.57 tera passenger kilometres in global light rail travel in 2018. This is calculated using an average trip length of 8.4 km as derived from United States travel statistics and multiplying it by the UITP ridership data (APTA, 2019). Ridership stands for the number of trips that were made with a transport mode in a year. According to the UITP data ridership for light vehicles is on the rise, especially considering the metros. Between 2015 and 2018 the light rail ridership increased from approximately 14,000 million passenger trips to 14,658 million passenger trips (UITP, 2019b). Metro ridership increased from 45,051 million passenger trips to 53,768 passenger trips between 2012 and 2017 (UITP, 2018b). Furthermore, in recent years a stark increase can be detected in the building of additional light rail tracks with an average yearly increase in growth of 36% (UITP, 2018a). With regards to types of light rail vehicles and their weight table X will elaborate on a various models.

Appendix C.2: Tables of regular and high speed trains and light rail

Table 47 Various high speed trains from which an average is taken (UNECE, 2017)

Train type	**Seats**	**Weight of train (in tons)**
TGV Sud-Est	345	385
TGV Atlantique	485	444
TGV Réseau	377	383
Eurostar	794	752
TGV Duplex	512	380
Thalys PBKA	377	285
TGV POS	377	383
TGV 2N2	509	383
Average	472	424

Table 48 Various regular trains from which an average is taken (Connor, 2011) (Railfaneurope.net, n.d.)(NS, n.d.)

Train type	**Seats**	**Cars (carriages per train)**	**Weight in tons**
British Rail Class 365	263	4	152
British Rail Class 444	392	5	227
ICM-IV	257	4	192
DDZ 'Double-decker'	384	4	350
DD-IRM VIRM-VI	571	6	349
DD-IRM VIRM-IV	391	4	236
Average	**376**	**4.5**	**252**

Table 49 A variety of light rail vehicles (GVB, n.d.), (City of Helsinki, 2015) *and* (HKL/HST, n.d.)

Model	**Weight in tons**	**Passenger seating capacity**
Combino tram	34	59
Tram 12G	34	63
CAF (M4) metro	48	66
Metropolis (M5) metro	190	178
M200 Bombardier metro	65	124
Helsinki Arctic tram	43	88

Appendix C.3: Calculation for Japanese trains

The Japan number of trains was calculated as follows. The amount of passenger-km reported by the Japanese Ministry of land Infrastructure, Transport and Tourism for 2016 is 0.432 Tera passenger-km (MLIT, n.d.). Of these rail passenger-km 0.101 were travelled by high-speed (UIC, 2018b). The percentage of the trains that can be considered regular rail is thus 1 - 0.101/0.432 = 76.6% of total. In the annual report of the largest Japanese train company it states that is has 12,876 rolling stock and that it accounts for 31.5% of the Japanese train market (JR East, 2017). This would mean that there are 12,876/31.5 * 100 = 40876 carriages of which 40876 * 76.6 = 31,319 regular train carriages.

Appendix C.4: Freight rail

Below the calculation is laid out which was done to determine the weight and load of freight trains. Determining the weight of freight trains is a different subject because globally the length of a freight train varies greatly. This is significant because the material requirements in terms of kg per ton km decreases if trains increase in length. The reason is that less locomotives are required. An interesting trend with regards to train length that can be observed is that increasingly freight trains are increasing the number of rail cars. The average number of railcars in the western United States during the 1980s was 68.9, in 2000 it was 72.5 and since 2010 it is 81.5 (Dick et al., 2019). Furthermore, the European industry group, representing European rail freight companies, is advocating for increasing freight trains in Europe (CER, 2016). The question then is what the average weight is of a locomotive and the average weight and capacity of freight rail cars. With regards to locomotives the region where the locomotive is used is significant. In the United States two general locomotive types can be discerned, the larger road locomotives weighing between 415,000 and 432,000 pounds (thus 188241 and 195951 kg). The smaller yard and local locomotives weigh between 250,000 and 390,000 pounds (thus 113398 and 176901 kg) (Norfold Southern, 2014). The average weight of a US locomotive is thus 168623 kg or 169 tons. In Europe smaller, often electric, locomotives are used and these vary between 80 tons and 129 tons averaging at 120 tons (G&W, n.d.). The EU and US average freight locomotive thus weighs 145 tons. The length of the cars vary between 16 meter and 28 meters (CSX, n.d.). The weight of the freight cars is dependent upon the type and number of axles that the cars have, in table X the various rail wagons are deliberated upon as well as their weight. The prevalence was determined using the US trade commission report which gives a number for all the rail cars in use in the US, Canada, China and Russia (P. Andersen et al., 2011). The weight and capacity was determined using Ecoinvent v2.0 data and various industry sources which give an average capacity and empty weight of rail cars (Searates, n.d.), (BNSF Railway, n.d.), (Transatlantic, 2016) and (DJJ, 2018). The car type other was calculated using a weighted average of the other cars.

Table 50 Rail freight car types, average weight and capacity (P. Andersen et al., 2011)*,* (BNSF Railway, n.d.)*,* (Searates, n.d.)*,* (Transatlantic, 2016) *and* (DJJ, 2018).

Car type	**Box**	**Open hopper**	**Closed hopper**	**gondola**	**Flat**	**Tank**	**refrigerated**	**Other**
Average tare weight in tons	26	23	23	28	27	29	48	25
Average capacity in tons	68	70	66	79	70	62	82	68
Percentage of fleet	5.1%	16.9%	23.7%	26.6%	9.3%	13.4%	1.1%	3.7%

The previously mentioned average number of railcars of 81.5 per is rather different from that of the European Union as the average number of containers per train in Europe is between 25 and 50. This partly has to do with regulations and EU infrastructure not having the capacity to handle the freight train sizes that are common in the US. The typical length of a European train is therefore approximately 500 meter while in the US it is approximately 2000 meter. The number of tons that are shipped on average per train is 400 net tons for Europe and 2500 for North America (Rail Freight Forward, n.d.). If only looking at heavy bulk trains the amount is between 1200 and 2000 for the EU and between 9000 and 12000 for the US (Furtado, 2013). This paper will therefore make an average of the EU and US train length and capacity and apply it for this analysis of global rail freight transport.

Appendix D: Maritime shipping

Appendix D.1: Calculating load capacity and fleet characteristics

Firstly, the total GT (Gross Tonnage), thus the volume of all the ships combined, was divided by the DWT (Deadweight Tonnage), the carrying capacity to determine a factor of DWT per GT. This is done because the data by Equasis measures the ships in GT and the division of the fleet in size in extracted from Equasis (Equasis, 2019).

Table 51 The fleet total GT per year and the fleet total DWT for the years 2005-2018 retrieved from (Equasis, n.d.-b) *and UNCTAD data* (UNCTAD, 2005, 2006, 2015, 2016, 2017, 2018, 2019, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014)

Year	Fleet total GT (Gross Tonnage) (in 1000 ton)	Total DWT (Dead weight Tonnage) (in 1000 DWT)	DWT per GT
2018	1350508	1926183	1.43
2017	1304305	1862340	1.43
2016	1270284	1805279	1.42
2015	1210422	1745992	1.44
2014	1166485	1689462	1.45
2013	1094026	1625750	1.49
2012	1048336	1536868	1.47
2011	1008119	1395743	1.38
2010	932935	1276137	1.37
2009	853276	1192317	1.40
2008	833437	1117779	1.34
2007	778911	1042328	1.34
2006	729108	959964	1.32
2005	600614	895843	1.49

Now an average DWT/GT factor of 1.41 is determined this is multiplied by the average GT of the four ship weight categories of the Equasis reports.

Appendix D.2: Determining material content of ship from combining various sources

Table 52 Material components of ship (Jain et al., 2016)

Materials and components	share
Steel	85.48%
Non-ferrous metal (copper, aluminium, brass, zinc and lead)	1.05%
Ship machinery	6.25%
Electrical and electronic equipment	1.25%
Minerals	2.55%
Plastics	1.20%
Joinery	1.30%
Miscellaneous	0.93%

Table 53 Determining material content of various part of a ship from the study by (Jain et al., 2016)

Material category	Designated as specific material		Source
Joinery	**Material**	**fraction**	

	Wood	100%	(A. B. Andersen et al., 2001)
Ship machinery	Steel Cast iron Aluminium Plastic Copper Other	40.0% 46.0% 8.0% 0.9% 0.1% 5.0%	(Jeong et al., 2018)
Electrical and electronic equipment	Iron Aluminium Copper Plastic Glass Other	40.7% 35% 5.7% 3.24% 4.8% 12.9%	(Oguchi et al., 2011)
Non-ferrous metals[10]	Copper Aluminium Other (zinc and bronze)	75% 8% 17%	(A. B. Andersen et al., 2001) (Hess et al., 2001)

Appendix D.3 Creating an average growth rate of ship sizes within the global fleet from 2005-2018

Below some of the data found in the various reports of UNCTAD and Equasis are laid out.

Table 54 Average gross tonnage and ship number for small and medium ships (Equasis, n.d.-b)

Year	GT small ships	Number of small ships	GT medium ships	Number of medium ships
2018	9159	34495	229690	39452
2017	8943	33752	227774	39141
2016	8828	33356	226040	39017
2015	8508	32136	222033	38351
2014	8281	31240	218305	37719
2013	7883	29682	211295	36728
2012	7648	28843	209923	36144
2011	7587	28286	216282	36927
2010	7490	27831	215192	37165
2009	7270	27084	207697	36285
2008	7071	26307	214413	37335
2007	6841	25515	206685	36028
2006	6721	25122	199179	34794
2005	6251	23660	168131	29710

Table 55 Average gross tonnage and ship number for large and very large ships (Equasis, n.d.-b)

Year	GT large ships	Number of large ships	GT very Large ships	Number of very large ships
2018	451034	11997	660625	6307

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[10] No exact estimate of the material content of non-ferrous scrap was found, however one study on the recycling of military vessels suggested that the majority of non-ferrous scrap is copper. Therefore the material types of Andersen et al. (2001) were used and a fraction of 0.75 was designated to copper and the other 0.25 divided in the other non-ferrous metal types in this scrap.

2017	443398	11783	624190	6039
2016	438128	11615	597288	5816
2015	427041	11309	552840	5437
2014	413388	10924	526485	5211
2013	390160	10317	484688	4857
2012	372865	9867	457901	4617
2011	359067	9540	425183	4321
2010	335072	8930	375182	3842
2009	306837	8183	331472	3399
2008	300839	7995	311114	3177
2007	280920	7472	284464	2914
2006	261544	6974	261663	2682
2005	214319	5700	211913	2157

Based on the two tables above the percentage of the size categories in the fleet could be determined in terms of number of boats. This is seen in the table below.

Table 56 The percentage of the ship size group in the fleet (Equasis, n.d.-b)

Percentage of small boats in the fleet	**Percentage of medium boats in the fleet**	**Percentage of large boats in the fleet**	**Percentage of very large boats in the fleet**
0.373925	0.427659	0.130047	0.068368
0.372066	0.431472	0.12989	0.066571
0.371431	0.434468	0.129337	0.064763
0.368393	0.439639	0.129641	0.062327
0.367123	0.443263	0.128376	0.061238
0.363821	0.450186	0.126459	0.059534
0.362937	0.454807	0.124158	0.058097
0.357716	0.466993	0.120646	0.054645
0.357872	0.477896	0.114829	0.049403
0.361356	0.484116	0.109178	0.04535
0.351632	0.499038	0.106865	0.042465
0.354725	0.500883	0.10388	0.040512
0.361094	0.500115	0.100241	0.03855
0.386431	0.485243	0.093096	0.03523

Now that the percentage of boats in the fleet is determined. For each year, using the load capacity, load factor, mileage and percentages the share of the tonne-kilometres for each respective category calculated for each year. Thus the formula is as follows:

$$tkm\ small\ boats\ year\ x = mileage * loadcapacity * loadfactor * \%small\ boats\ year\ x$$

Once this is applied to all four categories then the shares of each category of the total tonne-kilometres can be determined which are seen in the table below.

Table 57 Using data from Equasis and UNCTAD the share of tonne-kilometres of each of the four ship sizes was determined

years	**Share of total tonne-kilometres of small ships**	**Share of total tonne-kilometres of medium ships**	**Share of total tonne-kilometres of large ships**	**Share of total tonne-kilometres of very large ships**
2018	0.00214666	0.053834082	0.358439408	0.58557985
2017	0.002180789	0.055543673	0.366619385	0.575656153
2016	0.002218453	0.056803262	0.373319115	0.56765917
2015	0.002257166	0.05890518	0.384146408	0.554691246
2014	0.002287944	0.060315126	0.387268045	0.550128886
2013	0.002335589	0.062602856	0.391957443	0.543104111
2012	0.002379879	0.065323131	0.393414022	0.538882968
2011	0.002488043	0.070926456	0.399258913	0.527326587
2010	0.002696441	0.0774703	0.409014305	0.510818954
2009	0.002897598	0.082781628	0.414670092	0.499650681
2008	0.002924123	0.08866779	0.42183261	0.486575478
2007	0.003051464	0.092192941	0.424876405	0.479879189
2006	0.003227653	0.095652551	0.425881733	0.475238063
2005	0.003671614	0.098754133	0.426834389	0.470739864

The growth rates of percentage of tonne-kilometre found from this data is then used to extrapolate future growth and thus forecast how the shares of boats in the fleet will develop. In Python this extrapolation is done. What should be noted is that some percentages grow or decline faster than others, therefore a calculation is applied to make the values shares of a total. The extrapolated future growth rates are thus summed to a total and then divided of that total to remain a percentage. To validate that the share of tonne-kilometre by very large ships is indeed increasing the following graph and table are added for illustration.

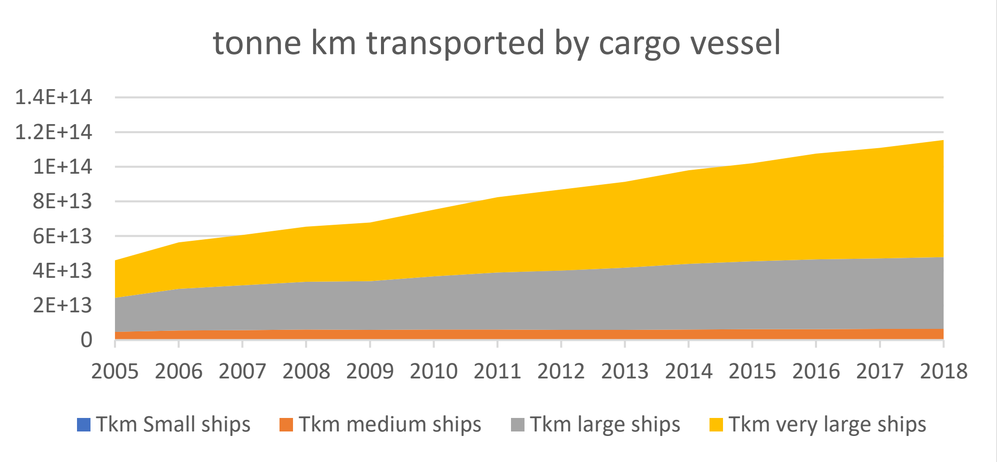


Figure 62 Share of tonne-kilometres per vessel size group over the period 2005-2018, using UNCTAD and Equasis data (Equasis, n.d.-b) (UNCTAD, 2005, 2006, 2015, 2016, 2017, 2018, 2019, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014)

Table 58 UNCTAD and Equasis data regarding vessel amount and tonne-miles for the year 2005-2018 to determine a tonne-km/vessel relation (Equasis, n.d.-b) (UNCTAD, 2005, 2006, 2015, 2016, 2017, 2018, 2019, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014)

Years	**UNCTAD data tonne-km**	**Equasis Vessel amount**	**UNCTAD Data tonne-miles**	**Tonne-km/vessel**
2018	1.0892E+14	92251	5.8812E+13	1180689900
2017	1.07596E+14	90715	5.8097E+13	1186084374
2016	1.02454E+14	89804	5.5321E+13	1140867801
2015	9.90376E+13	87233	5.3476E+13	1135322091
2014	9.74652E+13	85094	5.2627E+13	1145382800
2013	9.35075E+13	81584	5.049E+13	1146149735
2012	9.06313E+13	79471	4.8937E+13	1140432661
2011	8.67366E+13	79074	4.6834E+13	1096903761
2010	8.26048E+13	77768	4.4603E+13	1062194682
2009	7.46504E+13	74951	4.0308E+13	995989593.2
2008	7.80933E+13	74814	4.2167E+13	1043832491
2007	7.62598E+13	71929	4.1177E+13	1060209429
2006	7.39689E+13	69572	3.994E+13	1063198988
2005	7.01241E+13	61227	3.7864E+13	1145313799

Appendix E: Trucks

Appendix E.1 : Various tables regarding trucks

The differing payloads in various world regions from which a global average is calculated can be seen in the following table 59.

Table 59 Loads of trucks in various regions of the world (IEA, 2017)

County / region	**LCV**	**MFT**	**HFT**
United States	0.55	6.4	15.4
European Union	0.62	7	14.5
China	0.82	8.7	13.3
India	0.96	9.7	12.9
Global average	0.74	7.95	14.03

Calculation the average weight of medium and heavy freight trucks.

	Vehicle type	**Weight**	**Percentage in fleet**
Medium trucks	GVW <10 above	4669	14%
	GVW 10-20	8820	85%
	GVW <10 below	6947	2%
	Average	8229	
Heavy trucks	>20	15583	6%
	GVW 10-20	15605	3%
	>20	18379	9%
	Tractor trailer	15729	83%
	Average	15947	

Table 60 Material content of three types of road transport vehicles (Hill et al., 2015) *The vehicles are determined by GVW which means Gross Vehicle Weight (GVW). GVW refers to the total combined weight of the vehicle including cargo, driver and fuel.*

Material type	**Van (5t GVW)**	**van%**	**Rigid Truck (12t GVW)**	**Rigtruck%**	**Arctic Truck (40t GVW)**	**arctictruck %**
Iron	232	0.101	517	0.083	1543	0.106
Steel	1011	0.439	3198	0.516	8750	0.601
HS Steel	268	0.116	268	0.043	465	0.032
Aluminium	141	0.061	55	0.009	519	0.036
Copper	23	0.010	20	0.003	70	0.005
Plastics	249	0.108	214	0.035	815	0.056
Rubber	69	0.030	350	0.056	844	0.058
Glass	14	0.006	41	0.007	43	0.003
Water	15	0.007	0	0.000	60	0.004
Lead	16	0.007	25	0.004	156	0.011
GFRP (Glass-fibre Reinforced Plastics)	0	0.000	1000	0.161	0	0.000
Other	263	0.114	512	0.083	1285	0.088
total	2301	1.000	6200	1.000	14550	1.000

Appendix E.2: Trends in global freight transport according to IEA

As mentioned in the road freight chapter, IEA modelled various trends in global road transport into the scenario for future road freight use. The rapid growth that is modelled for the future is based on significant road freight growth in various regions. In the US road freight doubled between 1980 and 2010, in the EU in the same period growth was four-fold. In India the increase was ten-fold and in China between the period of 1975 and 2015 roadfreight increased thirty times (IEA, 2017). The drivers behind the rapid growth in India, China as well as the ASEAN region. Firstly, there is the globalisation of suply chains and production activity in Asia combined with stark growth in economic development and instrialisation in this region. Secondly, the market and geographical location of raw materials which mean that goods need to be transported to areas with high economic and industrial activity. Thirdly, the growth in these countries was based to a large extent on an export economy, thus requiring the infrastructure for large scale global trade. In terms of efficiency, both in fuel use per tonne-kilometre and tonne-kilometre per vehicle. Moreover, technological improvements such as use of routing algorithms and geographic information systems as well as coordination of freight operations will lead to efficiency improvements (IEA, 2017). These factors will thus, according to the IEA scenario, lead to an increase in the growth of HFT and decrease in the growth of MFT. This will also decrease the number of vehicles needed to supply a growing global transport need. The challenge is to put such trends to numbers and thereby make the current scenario which relates vehicles to the IMAGE/TIMER tonne kilometres more realistic.

Appendix F: Buses

F.1 Tables for bus weights and load capacity

Table 61 Various minibuses (Ford, 2019a),(IVECO, 2010) *and* (Mercedes-Benz, 2020)

Vehicle	**Weight** (in kg)	**Max load** (in passengers)
Ford 350 L2 H2	2544	12
Ford 410 L3 H2	2620	15
Ford 460 L4 H3	3198	18
IVECO A42.13	3070	17
VS30 sprinter Mercedes-Benz	2589	15

Table 62 Various midibuses (Hill et al., 2015)*,* (BYD, 2019)*,* (Mercedes-Benz, 2018) *and* (ISUZU, n.d.)

Vehicle	**Weight** (in kg)	**Max load** (in passengers)
BYD K7 bus (electric)	10200	23
ISUZU citibus (diesel)	8000	24
Mercedes Benz Citaro 12m	11500	35 (average of 31 and 38)
Mercedes Benz Citaro K	10800	28 (average of 30 and 26)

Table 63 Buses in use in the UK and Austria (Schoemaker, 2007)

United Kingdom			**Austria**		
Bus brand	**Weight**	**Seats**	**Bus brand**	**Weight**	**Seats**
B10M 6096	11134	58	Mercedes-Benz Tourismo	12980	55
N112/3 Skyliner	18860	86	Neoplan N316SHD	13850	52
Volvo Plaxton B12M	12460	51	Mercedes-Benz O404 15R	13350	53
Scania Irizar 1	13760	50	IRIBUS/Karosa Axer C956.1076	11900	55
Scania Irizar 2	12170	53	Mercedes-Benz Tourismo O350	13900	50
Volvo B12B6050	13040	51	Neoplan N1116	13775	48
Volvo Plaxton B12B6050	13040	51	Mercedes O 350RHD	13200	53
Van Hool DAF Alizee	13040	48	Jonkheere/Volvo B12 Mistral 70	13130	51
Leyland Olympian	14520	93	Neoplan N122L	18745	78
Volvo Jonckheere B12B	13340	51			
Average	**13536**	**59**	**Average**	**13870**	**55**

Table 64 Buses in use in The Netherlands and Luxembourg (Schoemaker, 2007)

The Netherlands			**Luxembourg**		
Bus brand	**Weight**	**Seats**	**Bus brand**	**Weight**	**Seats**
Bova XHD 139 D430	15487	63	VDL Bova D40XS SBR 4005	18840	67
Van Hool T916 Astron	14800	51	Bova XHD120.D340	13370	38
Van Hool 927 SD3	17132	66	MAN/Berkhof 24.460	18140	71
EVOBUS Travego	13880	51	Mercedes-Benz Tourismo O 350/E	13300	50
Bova PHD 15 430	15800	51	VDL Berkhof Scania Axial 100	19260	69
Setra S 328 DT	16750	69	Van Hool TD927 Astromega	17400	61
Volvo B12B	15710	44	SETRA Evobus D8553	19200	84
Scania average bus	16200	54	Scania Irizar K124 EB4X2	13752	58
DAF/Berkhof SB 4000	12920	50	Van Hool 927 SD3	17000	68
BOVA FHD 13.380	13710	40	Van Hool T917	16760	52
VDL Bus SB 4000	13380	36	Van Hool TD927 Astromega	18370	67
Van Hool 927 SD3	17132	66	Van Hool TD927 Astromega	18040	69
Scania K124 IB	14600	56			
BOVA FHD 13.340	13362	40			
Average	**15062**	**53**	**Average**	**16953**	**63**

Appendix F.2: Tables for bus occupancies and mileages

Table 65 Occupancy sources and assumptions

Sources	**Occupancy rate**
The average occupancy of India's bus transport for the years 2014-2016 (UITP, 2017)	70.2%
A study on the main road in the Philippines estimated an average occupancy of buses in 2007 (Domingo et al., 2015)	52%
A European average in 1999 for buses and coaches in terms of passengers per vehicle (Adra et al., 2004)	17 passengers, which is 29.8% when using the average of 57 seats per vehicle
A study on the U.S. bus occupancy (U.S. Department of transportation, 2019)	Thus study determined an average 40 passengers per motorcoach, 18 per school bus and 10 per transit bus. This would give a respective 70.3% occupancy for motor coaches, 31% for school buses and 17.4% for transit buses. (assuming an average maximum load for buses of 57 passengers). A weighted average of these occupancies gives an occupancy of 32.1%.
A study in 2008 regarding occupancy in Chinese bus lines (Özdemir et al., 2015)	44%

Ecoinvent v2.0 Has the data for Swiss bus transport	14 passengers in regular buses and 21 in coach buses. If these are averaged the load is 17.5 passengers which is 30.7% and thus very close to the EU average.

Table 66 All bus mileage sources

Source	**Mileage** (km/year)
United States average in recent (U.S. Department of Energy, 2018) in the year 2017 and (ABA Foundation, 2016) in the year 2014	19312 for school buses 54737 for transit buses 51700 for motor coaches
United states estimate of bus mileages in various countries in 2005-2007 (U.S. Department of transportation, 2010)	28810 for Japan 30120 for France 41892 for Germany 30901 for the United Kingdom 22625 for Mexico 13462 for the U.S.
A more recent estimate for the year 2014 in Germany (Kuhnimhof et al., 2017)	51309
The Dutch national statistical agency estimated average mileage of bus travel of coaches and transit buses in the period between 2013 and 2018 (CBS, 2019)	60344
Calculated average of 2013-2018 in Norway (Statistics Norway, 2020)	30969
A study on mileages of buses in China and estimated the average over the period of 2002 until 2009 (Huo et al., 2012)	105463
An estimate of bus mileage in the city Delhi in India (Goel et al., 2015)	71175
An estimate the average mileage of buses in Manilla in the Philippines in 1997 (Domingo et al., 2015)	62061
An estimate of mileages in four Southeast Asian cities (Oanh & Van, 2015)	50005 for Bangkok 35040 for Kathmandu 77380 for Hanoi 71723 for Ho Chi Minh City

What becomes clear from the previous tables is that in India and China buses travel much more per day than in Europe and the United States. A large portion of bus travel in the U.S. is from school buses which have a relatively low yearly mileage. A possible explanation of the higher mileage in these countries as opposed to Europe and the U.S. is that there is more long distance bus transport in these countries. Another is that less vehicles are used for the bus lines. However, this is speculation and no clear explanation is found in the literature. With regards to occupancy rates the table 65 outlines the various global estimates.

Making sense of all these datapoints is difficult as they are quite disparate. The overall trend appears to be that in the EU and the U.S. load factors (or occupancy rates) are lower than in India or the Philippines. In terms of occupancy China seems to be quite in the middle. With regards to mileage, the buses in China make significant amount of extra miles compared to Europe or even other Asian countries. The average occupancy and mileage that is calculated from the values in the table above are 43% and a mileage of 47843.6.

Table 67 Fractions of materials in a midibus and coach (Hill et al., 2015)

Material type	Fractions in midibus	Fractions in a coach
Iron	5.58%	9.50%
Steel	26.29%	45.84%
Aluminium	36.52%	18.98%
Copper	0.25%	0.25%
Plastics	14.91%	8.76%
Rubber	2.62%	2.90%
Glass	4.56%	2.24%
Water	0.45%	0.90%
Lead	1.12%	1.16%
Other	7.71%	9.47%

Appendix F.3: Regarding electric bus projections

The current global electrical bus fleet is mostly situated in China, with a fleet of 460000 vehicles, however the market for electric buses in growing in Latin America, India and Europe (IEA, 2019b). The number of electric buses will most likely increase significantly in the future making up significant percentages of the global fleet. What percentage exactly is difficult to pinpoint as this will differ per country and a variety of other factors which could impact the growth of electric buses. What can be said is that many cities and countries make commitments to phase out petrol and diesel vehicles. Various European Cities, for example, have stated to only buy electric buses starting 2025 (Pereirinha et al., 2018). A study on fleet electrification by the market research firm Bloomberg NEF made the assessment that in 2040 between 60% and 70% of the global bus fleet would be electric (Bloomberg NEF, 2019). Such an increase would impact the material requirements of buses significantly in terms of the batteries of electric vehicles.

Appendix G: Inflow and outflow

Appendix G.1: Tables of vehicle of vehicle lifetimes

Planes

In a guide by the IATA a variety of airlines laid out the depreciation that was used for the aircrafts in their fleet (IATA, 2016). In the table below the data published by the various airlines is summarised. One LCA of and Airbus A320 assumed an average lifetime of 20 years (Howe et al., 2013). In another LCA study the estimate lifetime of an Airbus A330-200 was placed at 24 years (Lopes, 2010). Another IATA study determined the average end of life for passenger airplanes to be 25.9 and for freight aircrafts

Table 68 Depreciation years given by various airlines compiled in an IATA guide (IATA, 2016)

Airline	**Aircraft type**	**years**
Air France-KLM group	All aircrafts	20 - 25
Cathay pacific	Passenger	20
	Freighter	20 - 27
Easyjet	All aircrafts	23
Emirates	All aircrafts	15
Kenya Airways	Boeing 787, 777, 737-300 and 737-700	17
Lufthansa	All aircrafts	20
Qatar Airways	Passenger	12
	Executive	10
	Freighter	7
Singapore Airlines	Passenger	15-20
	Freighter	20
South African Airways	All aircrafts	20
Turkish Airlines	Passenger	20
	Freighter	20

Trains

In a LCA report the average lifetime of freight locomotives is assumed to be 40 years and for passenger trains the lifetime was assumed to be 30 years (Stripple & Uppenberg, 2010). Another LCA used 35 years as the lifetime for freight trains (Nahlik et al., 2015). The Ecoinvent v2.0 database determined the lifetime of passenger trains at 40 years. For high speed trains one source was found which gave a lifetime of 20 years, this is averaged with the other sources of trains giving a lifetime for passenger trains (Yue et al., 2015).

Boats

A study on the recycling of maritime vessels estimated that the average lifetime of shipping vessels was between 25 and 30 years (Dinu & Ilie, 2015). In an LCA study the average was placed between 20 and 25 years (Chatzinikolaou & Ventikos, 2015). In a third life cycle study a differentiation was made regarding shipping vessels in that container and bulk carrier vessels had a life span of 20 years while tankers had a life span of 30 years (Messmer & Frischknecht, 2016b). In another study the life span of shipping vessels was placed at 30 years on average (Fan et al., 2018). With regards to inland shipping, the Ecoinvent v2.0 database gives a significantly higher life span for inland shipping with barge tankers having a lifetime of 32.5 and barges 46.5 years.

Road freight vehicles

A life cycle assessment of the Light Commercial Vehicle category (LCV) determined the average lifetime of the vehicles to be 10 years (Yang et al., 2018). With regards to other trucks the application of a truck impacts the lifetimes (Law et al., 2011). In the table below the various uses of this study and the respective lifetimes are laid out.

Table 69 Lifetimes of road freight vehicles differentiated in different application (Law et al., 2011)

Use	**Lifetime in years**
Service trucks	10
Urban delivery	19
Municipal utility	17
Regional delivery	12
Long haul delivery	8
Construction	19

As study on heavy duty trucks in the United States averaged the lifetime of the trucks between 6.6 and 10 years (Sen et al., 2017). Both of the vehicle types Medium Freight Truck (MFT) and Heavy Freight Truck (HFT) can be considered as the category heavy duty. Another study placed the average lifetime of an LCV at 14.5 years (Dun et al., 2015).

Road public vehicles

One LCA placed the average lifespan of buses at 12 years (Nordelöf et al., 2019). In the study also outlining the lifetimes of trucks an average lifetime for buses and coaches was placed at 13 years (Law et al., 2011). The ecoinvent v2.0 report places the average lifetime of buses at 12.5 years.

Appendix G.2: Tables for lifetime distributions

Table 70 End of life of a dataset taken from a graph of buses in the United States (Laver et al., 2007)

Age	**frequency**	**Age continued**	**frequency**
1	0	14	1180
2	160	15	1200
3	250	16	1220
4	240	17	1200
5	230	18	1050
6	130	19	300
7	100	20	510
8	190	21	580
9	180	22	175
10	250	23	25
11	390	24	50
12	595	25	30
13	710		

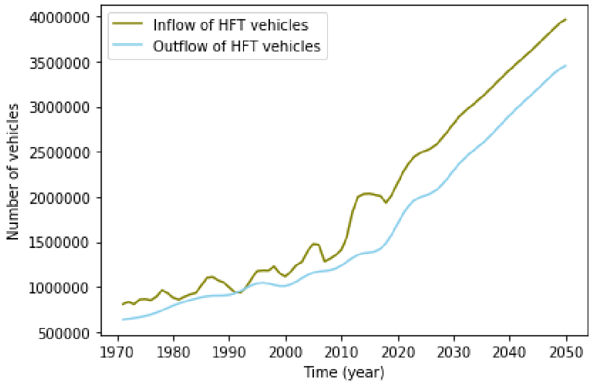
Table 71 Percentages of retirement age of LCV truck (Dun et al., 2015)

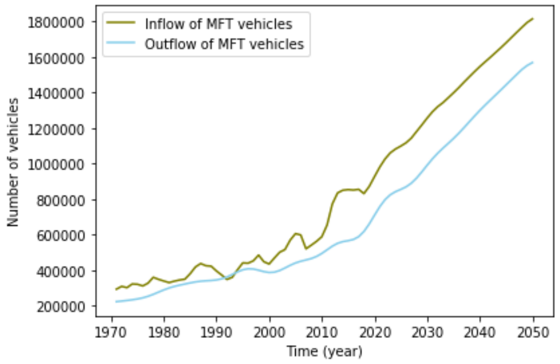
Age	Percentage	Age continued	Percentage
1	0	14	20.45
2	0.05	15	14.6
3	0.03	16	11.53
4	0.15	17	7.3
5	0.2	18	4.78
6	0.23	19	2.6
7	0.45	20	1.33
8	0.88	21	1.15
9	1.18	22	0.68
10	2.25	23	0.4
11	4.05	24	0.55
12	7.08	25	0.28
13	17.38	26	0.33

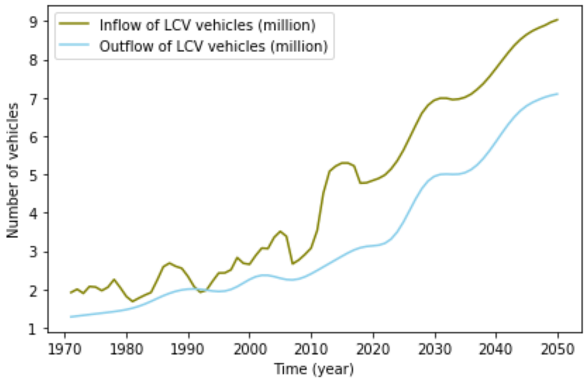
Table 72 Ages and numbers of aircraft decommissioning dataset taken from a graph (IATA, 2018)

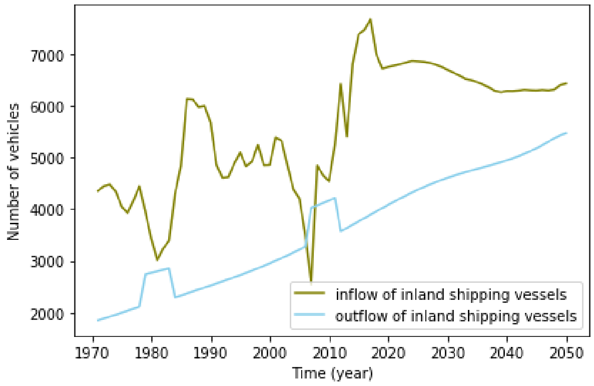
Age	Number of planes decommissioned	Age	Number of planes decommissioned
6	5	30	550
8	10	32	400
10	30	34	300
12	110	36	220
14	150	38	200
16	200	40	150
18	420	42	120
20	480	44	80
22	600	46	40
24	700	48	20
26	750	50	10
28	610		

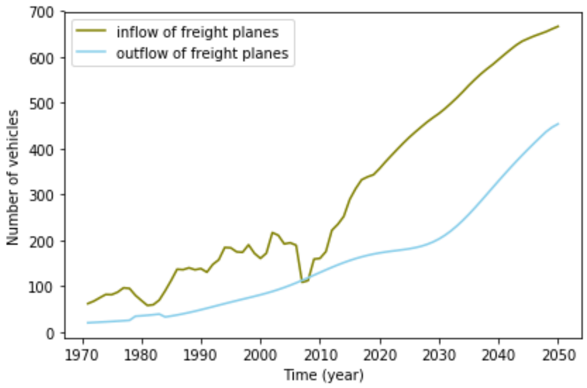
Appendix G.3 In- and outflow of vehicles graphs

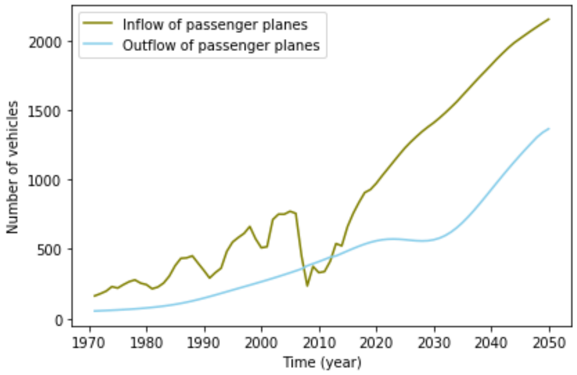


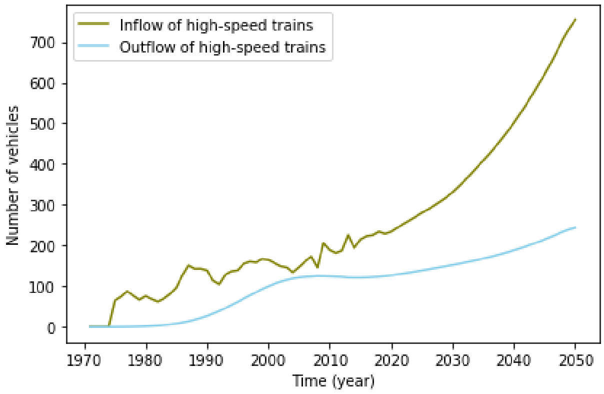


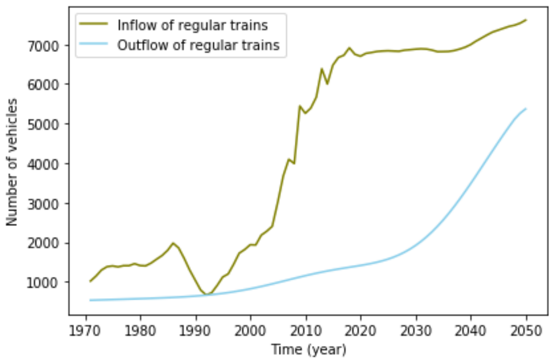


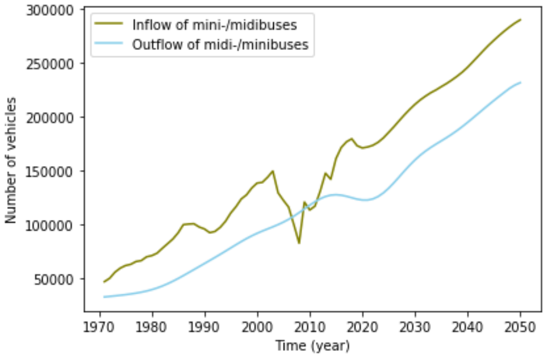


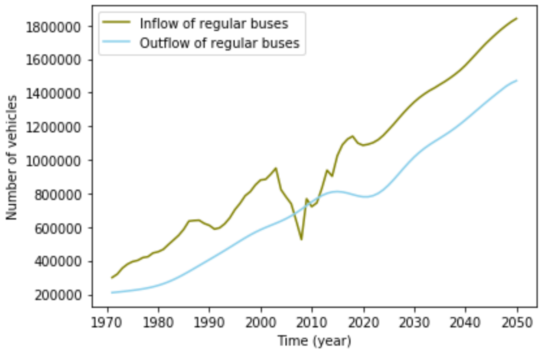


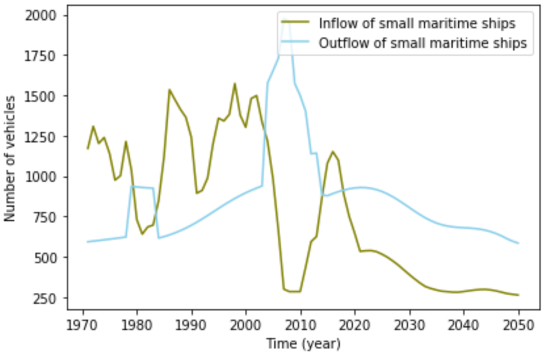


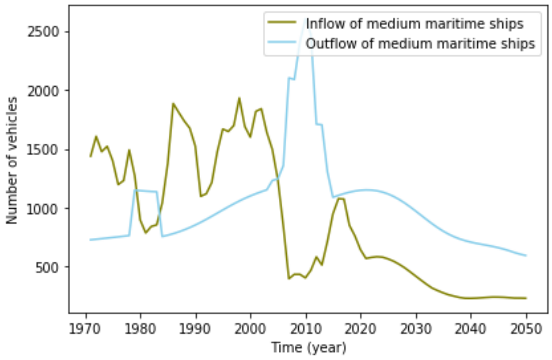


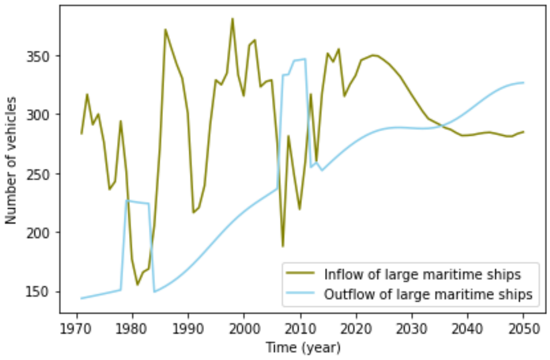

Inflow of regular trains
Outflow of regular trains
Number of vehicles
1000
2000
3000
4000
5000
6000
7000
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)

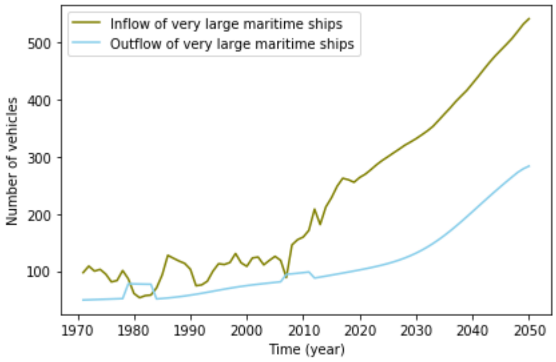

Inflow of mini-/midibuses
Outflow of midi-/minibuses
Number of vehicles
50000
100000
150000
200000
250000
300000
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)


Inflow of regular buses
Outflow of regular buses
Number of vehicles
200000
400000
600000
800000
1000000
1200000
1400000
1600000
1800000
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)

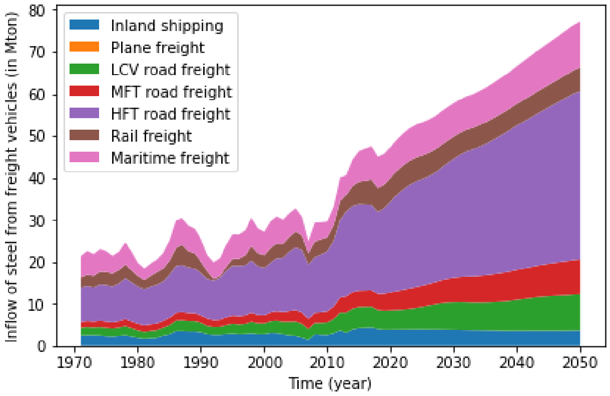

Inflow of small maritime ships
Outflow of small maritime ships
Number of vehicles
250
500
750
1000
1250
1500
1750
2000
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)

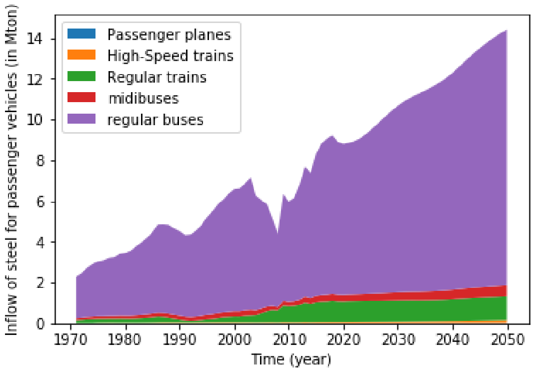

Inflow of medium maritime ships
Outflow of medium maritime ships
Number of vehicles
500
1000
1500
2000
2500
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)

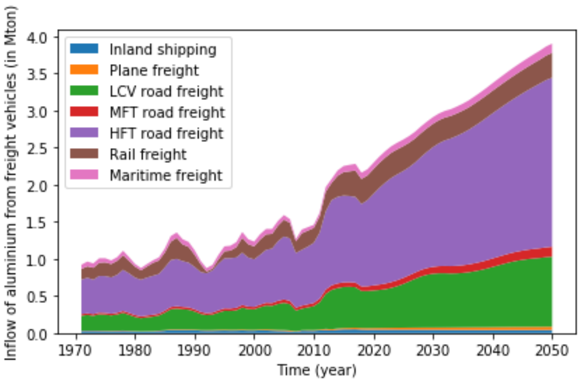

Inflow of large maritime ships
Outflow of large maritime ships
Number of vehicles
150
200
250
300
350
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)

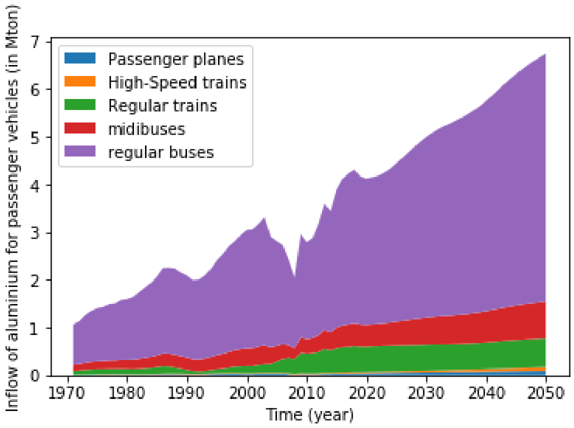

Inflow of very large maritime ships
Outflow of very large maritime ships
Number of vehicles
100
200
300
400
500
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)

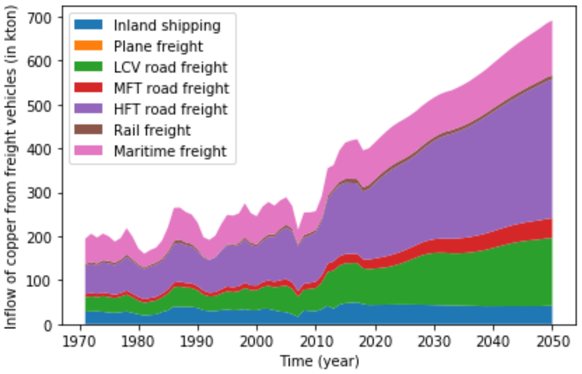
Appendix G.4 Materials in inflow

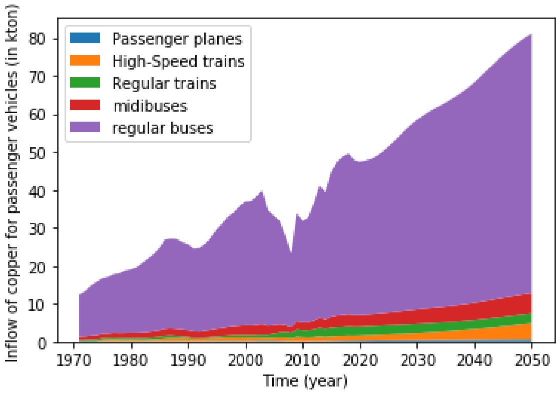


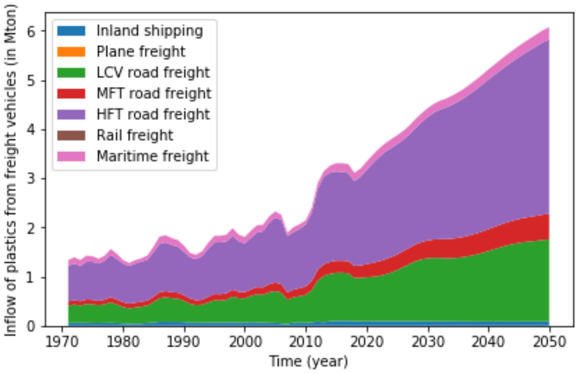


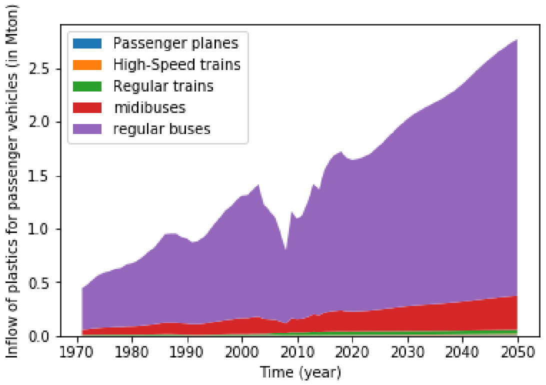


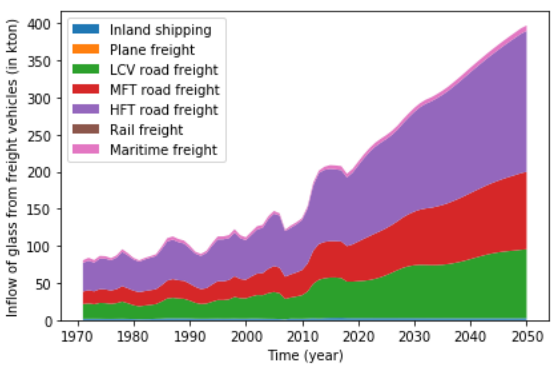


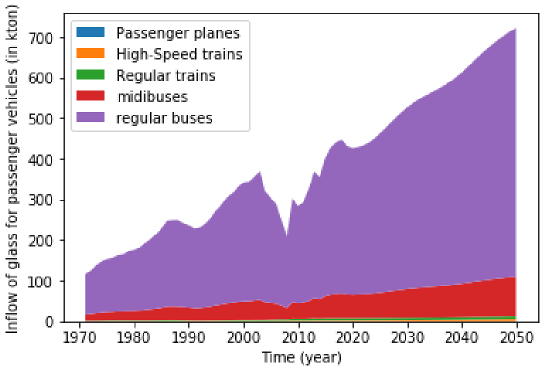


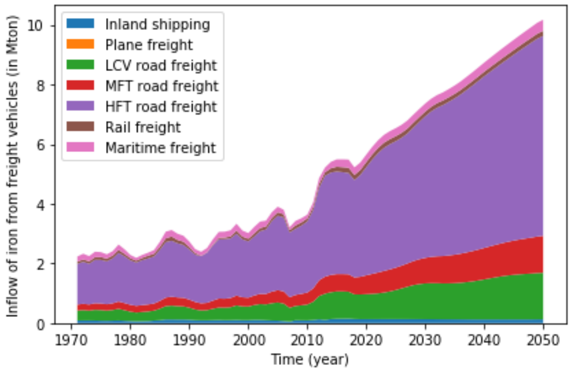


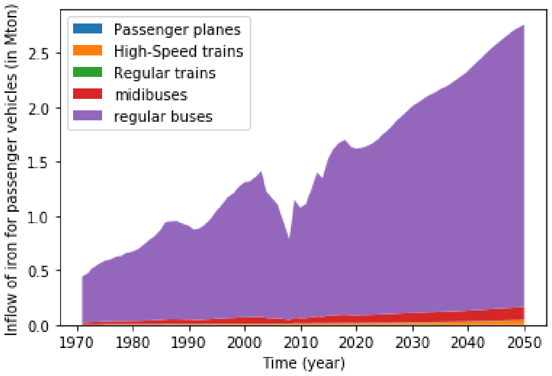


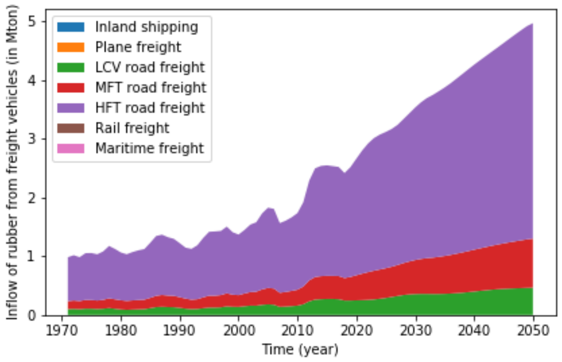


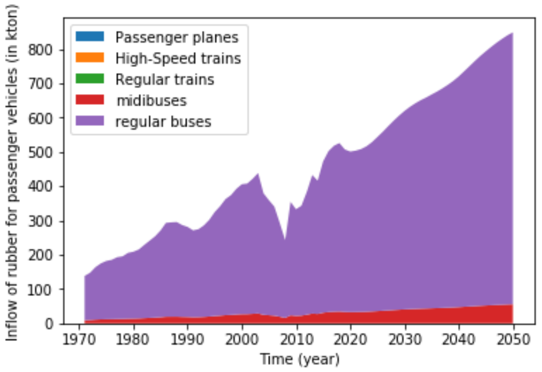




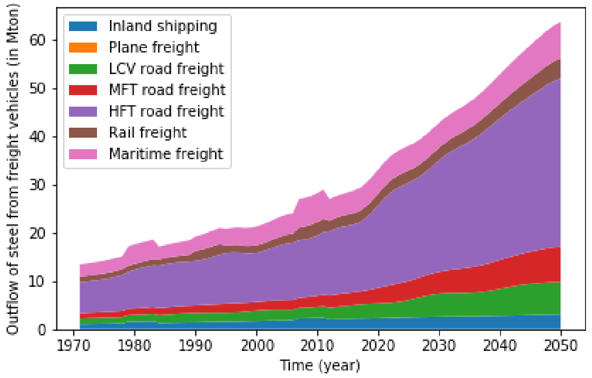


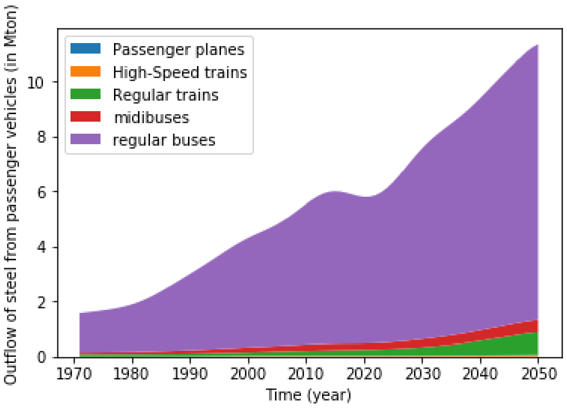


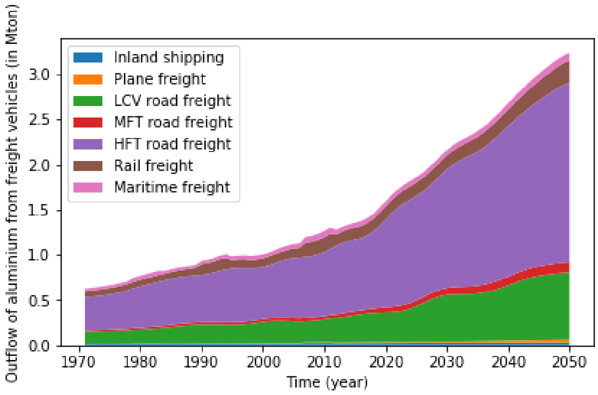


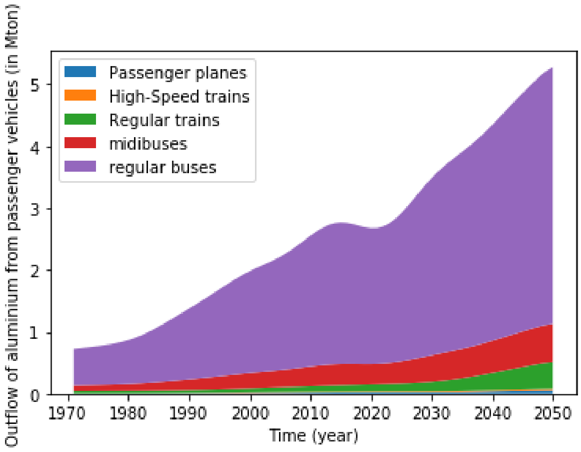


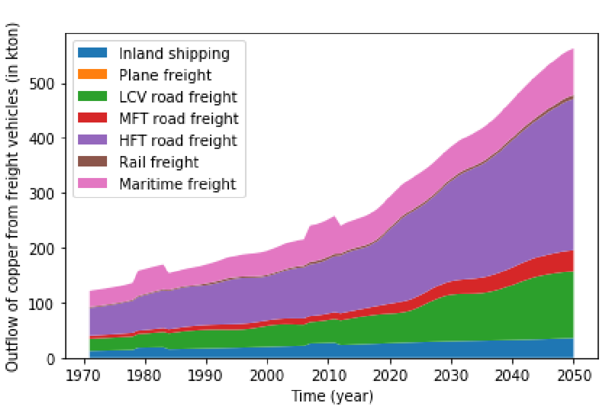
Appendix G.5 Materials in outflow

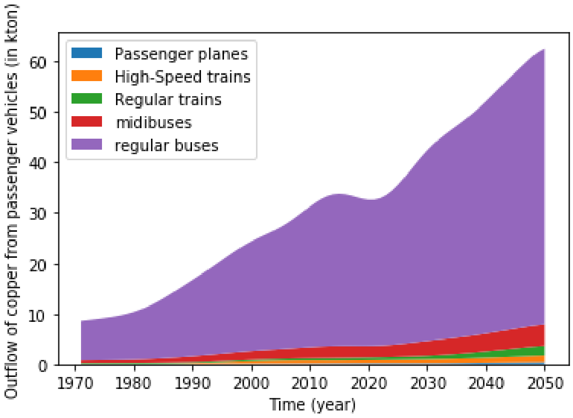


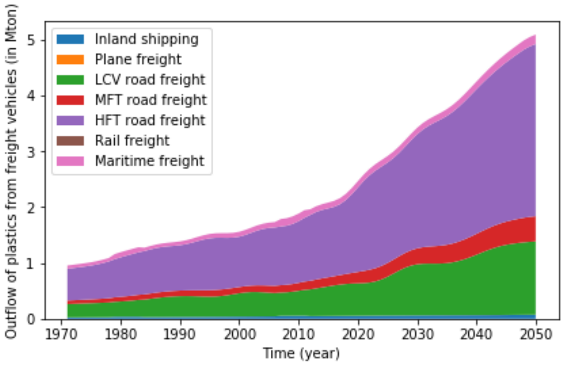


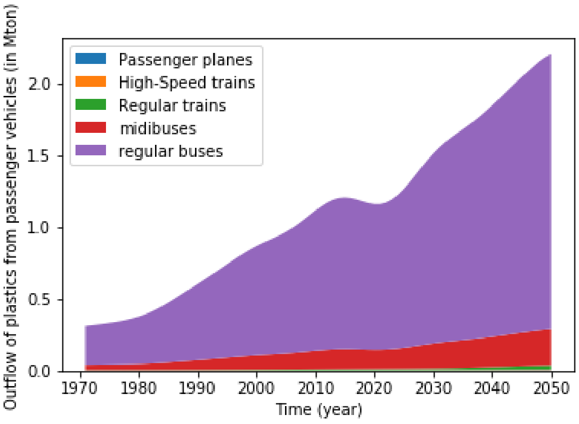

Outflow of aluminium from freight vehicles (in Mton)
Inland shipping
Plane freight
LCV road freight
MFT road freight
HFT road freight
Rail freight
Maritime freight
0.0
0.5
1.0
1.5
2.0
2.5
3.0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)

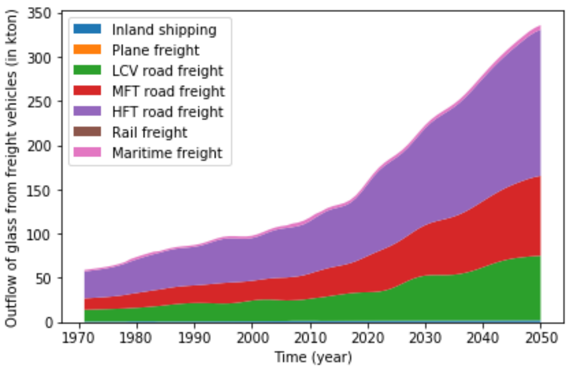

Outflow of aluminium from passenger vehicles (in Mton)
Passenger planes
High-Speed trains
Regular trains
midibuses
regular buses
0
1
2
3
4
5
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)

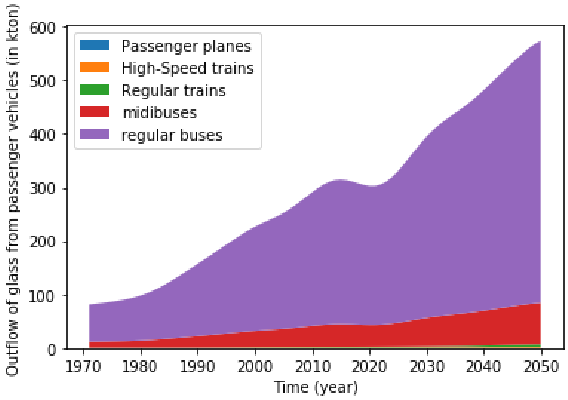

Outflow of copper from freight vehicles (in kton)
Inland shipping
Plane freight
LCV road freight
MFT road freight
HFT road freight
Rail freight
Maritime freight
0
100
200
300
400
500
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)

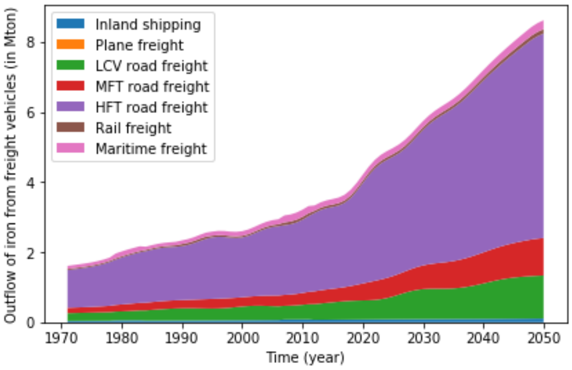

Outflow of copper from passenger vehicles (in kton)
Passenger planes
High-Speed trains
Regular trains
midibuses
regular buses
0
10
20
30
40
50
60
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)

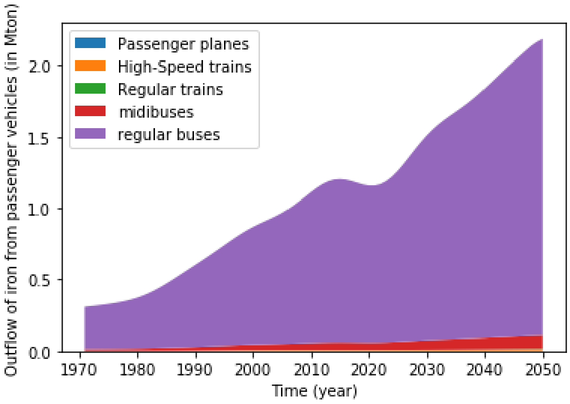

Outflow of plastics from freight vehicles (in Mton)
Inland shipping
Plane freight
LCV road freight
MFT road freight
HFT road freight
Rail freight
Maritime freight
0
1
2
3
4
5
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)

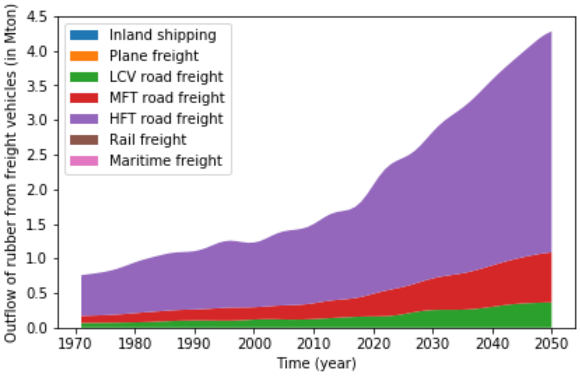

Outflow of plastics from passenger vehicles (in Mton)
Passenger planes
High-Speed trains
Regular trains
midibuses
regular buses
0.0
0.5
1.0
1.5
2.0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)

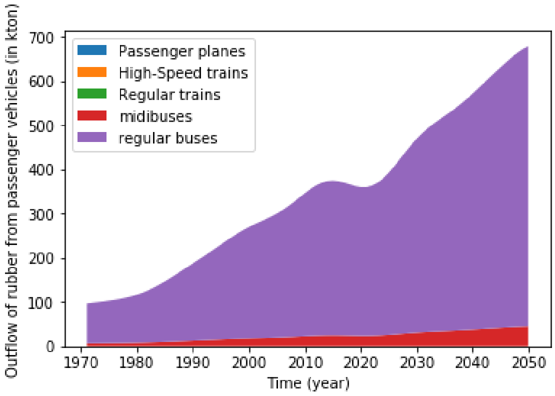

Outflow of glass from freight vehicles (in kton)
Inland shipping
Plane freight
LCV road freight
MFT road freight
HFT road freight
Rail freight
Maritime freight
0
50
100
150
200
250
300
350
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)


Outflow of glass from passenger vehicles (in kton)
Passenger planes
High-Speed trains
Regular trains
midibuses
regular buses
0
100
200
300
400
500
600
1970
1980
1990
2000
2010
2020
2030
2040
2050
Time (year)


Outflow of iron from freight vehicles (in Mton)
Time (year)
0
2
4
6
8
1970
1980
1990
2000
2010
2020
2030
2040
2050
Inland shipping
Plane freight
LCV road freight
MFT road freight
HFT road freight
Rail freight
Maritime freight


Outflow of iron from passenger vehicles (in Mton)
Time (year)
0.0
0.5
1.0
1.5
2.0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Passenger planes
High-Speed trains
Regular trains
midibuses
regular buses


Outflow of rubber from freight vehicles (in Mton)
Time (year)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
1970
1980
1990
2000
2010
2020
2030
2040
2050
Inland shipping
Plane freight
LCV road freight
MFT road freight
HFT road freight
Rail freight
Maritime freight


Outflow of rubber from passenger vehicles (in kton)
Time (year)
0
100
200
300
400
500
600
700
1970
1980
1990
2000
2010
2020
2030
2040
2050
Passenger planes
High-Speed trains
Regular trains
midibuses
regular buses

Appendix H: Scenarios and fleet electrification

Table 73The original table from where the material fractions of a battery for electric vehicles are determined (Diekmann et al., 2017)

Battery component	Material fractions		Material type	Fraction
Battery system periphery	Steel	5.7%	Steel	9.0%
	Electronics	2.7%		
	Aluminium	18.0%		
	Plastics	5.7%	Aluminium	34.5%
	Cables	2.3%		
Module periphery	Aluminium	5.2%	Copper	9.2%
	Plastics	1.5%		
	Steel	3.3%		
Cathode	Aluminium	5.5%	Plastics	11.0%
	Lithium	1.0%		
	Nickel	3.1%		
	Cobalt	3.1%	Lithium	1.0%
	Manganese	2.8%		
			Nickel	3.1%
	Oxygen	4.8%		
Anode	Graphite	8.2%	Cobalt	3.1%
	Copper	9.2%		
Cell housing	Aluminium	5.8%	Manganese	2.8%
Electrolyte separator, others	Plastics	3.8%	Other	26.3%
	Volatile components	8.3%		

Table 74 Sources used to determine an average battery capacity of the truck types

Vehicle category	Vehicle type	Brand	Source	Vehicle capacity (in tonnes GVW or US class)	Battery capacity (in kWh)
LCV	BEV	Zenith	(California Air Resources Board, 2015)	-	57
	BEV	EVI	(California Air Resources Board, 2015)	-	99
	BEV	Peugeot	(Pelletier et al., 2014)	-	56
	PHEV	Ford	(Ford, 2019b)		13.6
	PHEV	-	(Gnann et al., 2013)		14
	BEV	Edison	(Pelletier et al., 2014)		42
MFT	BEV	-	(den Boer et al., 2013)	10	120
	BEV	Renault	(den Boer et al., 2013)	16	150
	PHEV	Odyne	(Ippoliti & Tomić, 2019)	-	28
	PHEV	Odyne	(Ippoliti & Tomić, 2019)	-	14
HFT	BEV	DAF	(DAF, n.d.)	-	222

	BEV	DAF	(DAF, n.d.)	37	170
	PHEV	DAF	(DAF, n.d.)	37	85
	Hybrid	-	(National Research Council, 2012)	Class 8	25
	BEV	Scania	(Scania, 2020)	27	165
	PHEV	Scania	(Bisschop et al., 2019)	-	18.4
	PHEV	Volvo	(J. Gallo, 2016)	Class 8	10
	BEV	Balqon	(den Boer et al., 2013)	55	250
	BEV	Nautilus	(Pelletier et al., 2014)	-	320

Table 75 Sources to determine the battery sizes of the various bus types

Vehicle category	**Vehicle type**	**Brand**	**Source**	**Vehicle capacity (in passengers)**	**Battery capacity (in kWh)**
Regular buses	BEV City transit bus	EBUSCO	(Ebusco, 2020)	55	444
	PHEV bus	Xcelsior	(U.S. Department of transportation, 2017)	41	11.6
	BEV City transit bus	EBUSCO	(Ebusco, 2020)	41	393
	BEV city transit bus	Catalyst	(U.S. Department of transportation, 2017)	43	105
	Trolleybus	ABB TOSA	(J.-B. Gallo et al., 2014)	135	38
	Trolleybus	Xcelsior	(U.S. Department of transportation, 2017)	41	21
	PHEV	VDL	(Bisschop et al., 2019)	-	60
	PHEV	Volvo	(Bisschop et al., 2019)	-	76
Mini-/midibuses	BEV bus	PRIMOVE	(J.-B. Gallo et al., 2014)	36	60
	BEV bus	Proterra	(J.-B. Gallo et al., 2014)	35	74
	PHEV bus	Volvo	(Volvo, n.d.)	32	19
	BEV Shuttle	Balqon	(Z. Gao et al., 2017)	-	312
	BEV Shuttle	Motiv	(Z. Gao et al., 2017)	-	100