Material stocks and flows in the circular economy,

a prospective material flow analysis for vehicles in the Netherlands for 2000-2050

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Executive Summary

To keep society within planetary boundaries, it is essential to reduce primary material consumption. The Dutch government has set goals to limit the primary extraction by half in 2030 and to be a fully circular economy by 2050.

To be able to achieve this without reducing our standards of living, the only way is to extract the materials we need from the urban mine. Knowledge of the urban mine for the vehicles in our society is incomplete, and this research aims to contribute by studying the material stocks and flows for the most important road, rail, air, and water vehicles by weight in the Netherlands.

An inventory is made for the materials in these vehicles between 2000 and 2017, and several sustainable transportation developments are identified which influence the material composition: (i) vehicle electrification, (ii) more effective utilisation of the vehicle fleet, (iii) lifespan elongation for vehicles, (iv) capacity enlargement of vehicles, and (v) modal shift towards low emission modes of transportation. These developments are categorised according to typologies from socio-technical transitions analysis which allow for the quantitative results to be placed in a socio-technical context and to be better interpreted. These 'transition pathways' are then compared to a reference pathway.

Bottom-up, stock-driven, prospective, dynamic material flow analysis was conducted based on exogenous driving factors describing the required transportation service for passenger-, freight-, sea- and air transportation in passenger-kilometres and ton-kilometres. These driving factors were based on the WLO-low projections for the future of Dutch transportation, and therefore the results for primary material demand should be interpreted as a minimum. Outflow was modelled using Weibull distributions based on statis-

tical data for the demographics of vehicles.

The historical stock of materials in vehicles in the Netherlands was found to have grown from 28 megatons in 2000 to 36.3 megatons in 2017. Ships contribute two thirds to total mass, cars a quarter, and the rest is in order of reducing mass: road utility vehicles, bicycles, transit vehicles, and aircraft. Ferrous metals contribute most to the total mass (82%) followed by Polymers (5.6%), Copper (3.4%), and Aluminium (3.4%). A small but important contribution is made by Critical Raw Materials, which only contribute 0.8% but the total mass of 74 thousand tons is significant.

Of all studied developments, lifespan elongation reduces the primary material demand most by around 40% and the available material from the urban mine, but vehicle stock size is not influenced. Improving the effective utilisation of vehicles does reduce the stock size significantly (by 20%) and primary material demand is reduced by 35%, whilst the amount of material available in the urban mine is reduced by only 10%. Electrification of the vehicle fleet and vehicle capacity enlargement increases the vehicle stock by mass by 11% because of the introduction of heavier vehicles. The primary material demand increases strongly by 43% and the materials available from the urban mine are increased by 35%.

Important steps required to continue in developing the understanding of the urban mine for the circular economy, are to interpret which proportion of the material outflows are available for reuse, and for which parts of the inflows secondary materials can replace primary materials. Other important objectives are to expand the knowledge for material content of objects in society, and the knowledge on the lifespan of materials and objects in society, because these limit the interpretation of the results the most.

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Contents

1
Introduction

To be able to make informed strategies for a circular economy, it is essential to know the quantity and characteristics of materials residing in society. This allows for the design of end-of-life strategies to improve resource efficiency and reduce environmental impact (*Krausmann et al.*, 2017). This holds especially true for vehicles in society, as they contain high proportions of valuable materials and are expected to undergo radical transitions to allow for a sustainable and low-carbon future and to comply with climate agreements and commitments (*Rijksoverheid*, 2019). Learning from studies on the material basis of the renewable energy transition, it is essential to understand the material impact of choices for the future of mobility and transportation (*Kleijn et al.*, 2011).

> *Accounting methods need to be advanced to provide a comprehensive and consistent picture of all flows of materials through society including stocks and outflows of wastes and emissions to better support waste management and recycling policy.*
>
> – First of eight key recommendations by *Krausmann et al.* (2017)

1.1 Background

The primary material demand of society needs to be minimized to ensure that we operate within the earth's planetary boundaries. Instead of discarding used products and materials, reusing them retains their inherent value. Transitioning to a circular economy means to improve resource efficiency by closing material loops and transitioning to renewable forms of energy, and it would allow human society to prosper whilst minimizing the impact on the environment and ecosystems on which it depends (*MacArthur*, 2013; *Geissdoerfer et al.*, 2017).

To still be able to produce goods without depending on primary material extraction, materials need to be delved from other sources. By accessing the Urban Mine through extracting end-of-life mat4rials from society instead of the extraction of raw materials, the value of the materials used in society is not lost by discarding them, and the environmental impacts of waste disposal and primary resource extraction are reduced (*Van der Voet et al.*, 2017). The Dutch government has recently adopted goals to strongly reduce primary material input into the economy within the coming years, by 50% as of 2030, and by achieving full circularity by 2050. To achieve this is impossible without either reducing the standard of living or resorting to secondary extraction from the Urban Mine. Circular economy policies have since been adopted in order to achieve these goals (*Rijksoverheid*, 2019). The Netherlands owns a disproportionate proportion of the worlds cars (0.9%) (*Bosch et al.*, 2019), of the worlds seafaring ships (0.6%) (*UKDOT*, 2019), and of the worlds wealth (1%) (*UNSD*, 2017), compared to its population (0.2%) (*United Nations*, 2019) or its land area (0.03%) (*World Bank*, 2019). With great wealth and great footprint, comes great responsibility.

The knowledge of the Urban Mine is fast-growing but still incomplete (*Van der Voet et al.*, 2017; *Müller et al.*, 2014; *Wiedenhofer et al.*, 2019), as we still do not know what materials circulate in large parts of our society. Vehicles are essential to delivering transportation service and they contain high proportions of valuable and high environmental impact materials like metals and polymers which can potentially be reused or recycled at a reduced environmental cost compared to primary extraction (*Li et al.*, 2016). To be able to develop resource-efficient and low environmental impact ways to deliver transportation without depending on primary resource extraction and effective end-of-life strategies for vehicles, a comprehensive long term understanding is needed of the materials needed in transportation (*Krausmann et al.*, 2017).

1.2 Problem statement

To be able to effectively design a Circular Economy and access the Urban Mine so that secondary materials can replace primary materials, knowledge of the Urban Mine needs to be expanded. It should include the whole of society, but as of now most of the knowledge is focused on the urban and built environment (*Müller et al.*, 2014; *Augiseau and Barles*, 2017), and relatively little is known about materials in vehicles. Vehicles contain large amounts of valuable materials which can often be recycled with lower environmental impacts compared to primary extraction (*Mathieux and Brissaud*, 2010), thus it is essential to develop this knowledge, and that is what this research aims to do.

Few accounts have yet been made of the material quantities and characteristics of the vehicle fleets of the Netherlands, yet transportation is expected to undergo transitions in order to reduce emissions which are expected to have significant material requirements (*Bosch et al.*, 2019). These material flows need to be understood to know what the impact is on the primary extraction of raw materials, and if there are possibilities for reusing secondary raw materials from the urban mine to develop circular economy practices.

1.3 Research questions

How have the material stocks and flows of vehicles in the Netherlands developed, and how might they change for different transition pathways considering sustainable transportation?

1. What is the academic state of the art for analysing material stocks and flows for vehicles, in terms of methods used and results generated?
2. How has the historical material stock of vehicles in the Netherlands developed, and what are its characteristics in terms of material composition and stock demography*?
3. Which developments are relevant to the stock of vehicles, their demography, and their material characteristics for distinct sustainable transportation transition pathways?
4. How will material stocks and flows of vehicles in the Netherlands evolve in 2020-2050 for different pathways, and how much material will become available from the urban mine?

1.4 Scope

This research is designed to add to the current state of the art (*Müller et al.*, 2014; *Augiseau and Barles*, 2017) by adding a new case study all vehicles in the Netherlands, using driving factors that are case-specific to transportation, using a bottom-up accounting approach, stock driven modelling of flows, and by using MFA as a comparative tool to analyse the future material impact of sustainable transportation developments. The goal is to include the most important road, rail, water, and air vehicles in the Netherlands. For as many vehicles as possible, material content data will be collected which together should form the material stock of vehicles in the Netherlands.

**material stock demography* is a concept borrowed from human population studies to describe the age composition of materials in systems in material flow analysis (*Cabrera Serrenho and Allwood*, 2016)

This thesis will focus on a wide range of materials instead of a selection. The goal is to make the most comprehensive material account for the most important vehicles on a national scale, but as no similar account was made before, the goal is restated: to make a material account that is as comprehensive as possible within the given time frame for this thesis of 6 months.

2

Literature review

The field of Industrial Ecology is an interdisciplinary science that integrates social, natural and engineering perspectives to understand complex adaptive systems in society. A broad systemic perspective needs to be adopted to understand the most relevant aspects for the historical, current, and future state of transport and mobility (*Allenby*, 2006; *Lifset and Graedel*, 2002). Industrial Ecology provides a variety of analytical tools which have been developed to identify environmental problems and their sources in society, compare and quantify the impacts of service systems and detect problem shifting for potential solutions (*Van der Voet*, 2011).

This chapter will be introduced by a short background of the field of Industrial Ecology (2.1). The conceptualisation (2.2) will consider prospective material flow analysis, transition pathways and stock-flow modelling. These topics will then be placed in the context of the literature gap (2.3), and concluded (2.4).

2.1 Theoretical background: Industrial Ecology

The academic field of Industrial Ecology (IE) emerged from various disciplines at the end of the 20^{th} century with the recognition of the problem of waste and pollution in industry (*Ayres*, 1989), resource efficiency in chemistry (*Garner and Keoleian*, 1995), and to explore the possibilities of cleaner production (*Garner and Keoleian*, 1995; *Frosch and Gallopoulos*, 1989).

The term *Industrial Ecology* draws a parallel between natural ecosystems and industry, which juxtaposes current industry in society as inefficient ecosystems with ever-accumulating waste and pollution in contrast to natural ecosystems where waste flows are rather by-products which are never lost but are indefinitely used as resources by a network of actors in a cyclical chain of interdependent organisms (*Lifset and Graedel*, 2002). Another modern and important concept associated with the implementation of Industrial Ecology practices is the concept of Circular Economy (CE). This concept can be traced back to the *Boulding* (1966) conceptualisation of *spaceship earth* but only emerged into policy in the 1980s (*Pearce and Turner*, 1990) which since has been widely embraced and recognised as a paradigm to improve resource efficiency and reduce environmental impact by closing material and energy loops (*MacArthur*, 2013). A short critical reflection on the concepts *Industrial Ecology* and *Circular Economy* are included in Appendix A.1.

Following the development of these concepts that focus on recycling and resource efficiency, a realisation has occurred that we do not understand the quantities and characteristics of materials residing in society (*Krausmann et al.*, 2017). To be able to develop strategies for materials in society, it is essential to gain an understanding of this topic. The concept of *Urban Mining* has emerged which aims to prospect for- and mine secondary materials from society, as opposed to traditional mining and prospecting, which aims to extract primary resources from the environment (*Van der Voet et al.*, 2017). Reusing materials from society has three key advantages as compared to primary extraction: it reduces waste which pollutes the environment, it reduces reliance on finite primary raw materials, and in some cases can significantly reduce life cycle emissions, like in the important case of concrete which accounts for a significant proportion of global emissions (*Alnahhal et al.*, 2018; *Andrew*, 2018).

In order to understand the complex interrelations of society (i.e. production, wellbeing, etc.) and nature (ecosystems, resources, etc.), the field of IE has developed analytical tools which aim to quantify the flows of energy and materials and their environmental impact at different scales in society. *Clift and Druckman* (2015) describes the traditional analytical tools of Industrial Ecology to be Life Cycle Assessment (LCA), Material Flow Analysis (MFA), and Input-Output Analysis (IOA), and how modern interpretations of these traditional tools aim to include a dynamic factor which allows for the assessment of the expected effects of certain developments in the future.

2.2 Conceptualisation

In the context of this thesis, it is required to understand the materials used in vehicles in the Netherlands in the past and in the future and the state of the art is to use Prospective Material Flow Analysis which is discussed in chapter 2.2.1. Interconnected with the growing understanding of societies' metabolism and its impact on the environment, are the *design* and *implementation* of interventions which intend to improve the social, economic, and environmental sustainability of society (*Clift and Druckman*, 2015). One key concept which aids in the design and implementation of interventions and developments is *socio-technical systems*, which is discussed later on in chapter 2.2.2. Chapter 2.2.3 discusses the future of passenger and freight transportation in the Netherlands.

2.2.1 Prospective Material Flow Analysis

To understand the material flows in society, MFA can be conducted for a single substance or chemical or element, in which case it is referred to as a *substance flow analysis* as opposed to an MFA which would analyse one or more materials, which are made up of a combination of substances or elements (*Elshkaki et al.*, 2005).

Where static MFA excel in providing insight into hot spots of material demand or emission within a system. A dynamic MFA is more applicable to answer the research questions in this thesis, as it allows to explore the historical or prospective evolution of material stocks and flows for a system. (*Clift and Druckman*, 2015).

The most Closely related to material flows are material stocks. When conducting an MFA, it is important to explicitly discuss the principles used for stock modelling. Two important distinctions are *top-down* and *bottom-up*. The top-down (equation 2.1) approach infers the addition to stock as the difference in mass between in- and outflow, whereas the bottom-up (equation 2.2) approach would multiply the quantity of a commodity with its mass and sum the total mass of all commodities. The latter is accepted as being more accurate, but requires harder to find data (*Gerst and Graedel*, 2008; *Müller et al.*, 2014)

For the following equations: S_t is stock at time t: , S_0 is initial stock level at initial time step T_0, and T is current time step, N_{it} is the quantity of final commodity i in use at time t, m_{it} is the mass of final commodity at time t, and A is the number of different types of commodities in use.

$$S_t = \sum_{t=T_0}^{T} (inflow_t - outflow_t) + S_0 \qquad (2.1)$$

$$S_t = \sum_{i}^{i=A} N_{it} \cdot m_{it} \tag{2.2}$$

In the context of a circular economy, where the focus lies on the reuse and recycling of discarded materials, one aims to quantify the outflow of materials from society. This outflow is not dependant on demand for second-hand materials, as few markets exist for discarded or waste products. Instead, the in- and outflows are a product of how much material (the stock) is required in society, and the lifespan (or residence time) of that material (eq. 2.2). This is referred to as a stock-driven approach for modelling flows. (*Van der Voet et al.*, 2002; *Müller*, 2006)

The economic and environmental value of making end-of-life strategies for these stocks of in-use materials that are locked away in society has been underlined by many studies (*Müller*, 2006; *Augiseau and Barles*, 2017). Broad adoption of the term *Urban Mine* in academics and society acknowledges this change of mentality (*Cossu and Williams*, 2015; *Van der Voet et al.*, 2017).

Another more widely used approach exists, the flow-driven approach, where the outflows and stocks are a product of the inflow of materials (eq. 2.1). This is the preferred approach for cases where there is a high material turnover, or when lifespans are short. In this case, statistical data can be used for inflows, and estimations can be avoided. The disadvantage of this method is that the level of stocks and outflows are more uncertain, especially so for materials with long life spans like with vehicles, which trades off with the advantage of fewer and more easily accessible data required for analysis compared to stock-driven modelling. (*Clift and Druckman*, 2015; *Wiedenhofer et al.*, 2019)

Concluding, to quantify the historical material quantities and characteristics of vehicles in the Netherlands a bottom-up, dynamic, and stock-driven approach for making an inventory is preferred. But if one aims to explore the future material stocks and flows, modelling is essential, and additional data and assumptions need to be made.

Dealing with the future (I): scenarios and sensitivity in prospective MFA

When conducting prospective MFA, assumptions are made about the state of the future. Because the future is uncertain, often studies test their assumptions to sensitivity, or sometimes even compare different scenarios. Two important publications review the methodologies used in published MFA studies; *Müller et al.* (2014) analyses 60 MFA studies about metals and *Augiseau and Barles* (2017) analyses 31 MFA studies about construction materials. Both find that modelling principles are relatively similar but that extrapolation/prospecting models vary considerably between studies.

Very few MFA studies consider or compare different scenarios, instead, most conduct sensitivity analysis (SA) on key assumptions and driving forces like lifespan or material intensity, as the

Publication	Scenarios	Sensitivity	Year
Kleijn2000Dynamic	-	Lifespan	2000
Elshkaki2005Dynamic	-	-	2005
Muller2006Stock	-	Lifespan; Concrete intensity; Floor area	2006
Hu2010Iron	-	Lifespan; Steel intensity; Floor area	2010
Zhang2011Predicting	-	Lifespan; peak waste moment	2011
Hou2015Greening	Baseline; Recycling	Lifespan; Consumption; Recycling	2015
Sandberg2016Dynamic	-	-	2016
Wiedenhofer2019Integrating	Resource stabilisation; Sustainable circularity	all (Monte Carlo Sampling)	2019

Table 2.1: Comparison of selected studies on the basis of considering (a) different scenarios and (b) sensitivity analysis.

literature review of seven relevant studies in Appendix A.2 shows.

If studies do consider distinct future scenarios, most did so according to a single development (e.g. recycling yes/no), instead of systematically comparing outcomes of different options. If such a scenario comparison was included it was done because this was explicitly part of the research objective, which indicates that a systematic comparison of material impacts using MFA is not very common.

Dealing with the future (II): Driving forces in MFA

Driving factors can be understood in the context of MFA as exogenous inputs which govern the amount of material required in a future scenario.

Many MFA studies use generic and widely applicable driving forces like GDP and population to make future projections (*Augiseau and Barles*, 2017). Whilst this approach has been shown to be effective (*Hu et al.*, 2010), some studies prefer to use more case-specific driving factors because they allow for more granularity and accuracy for the case at hand (*Müller et al.*, 2014). For the case of vehicles, where projections indicate that the development of passenger transportation will be different to that of freight transportation, choosing case-specific driving factors for each sector would allow for a better modelling of the future (*CPB/PBL*, 2015).

A more comprehensive discussion regarding driving forces for this thesis can be found in Appendix A.3, but the main argumentation is presented here in the main text.

Most prospective studies do not explicitly report the difference between exogenous and endogenous variables in their modelling. The *Müller* (2006) method was replicated in many studies, which was also the study with the highest level of transparency. This is confirmed by the

Publication	Inflow	Stock	Outflow	Year
Kleijn2000Dynamic	Several	-	LifetimeSeveral	2000
Elshkaki2005Dynamic	ScenarioGDP, ScenarioPop, Substitution, Reuse	-	LifetimeWeibull, LeachingRate	2005
Muller2006Stock	MaterialPerUnit,	ScenarioPop, UnitPerCap	LifetimeNormal	2006
Hu2010Iron	MaterialPerUnit,	ScenarioPop, UnitPerCap, Urbanisation	LifetimeNormal	2010
Zhang2011Predicting	HAperHH	HouseHoldPrediction	LifetimeWeibull	2011
Sandberg2016Dynamic	Modernisation	ScenarioPop, Cap/Dwelling	LifetimeWeibull	2016
Wiedenhofer2019Integrating	PrimaryMaterials, Remanufacturing, Construction	-	LifetimeWeibull, ProcessingLosses	2019

Table 2.2: Description of ***exogenous*** driving factors used in selected studies. Driving factors are categorised with their relation to either *inflow, stock* or *outflow*.

Augiseau and Barles (2017) literature review. One reason might be that few standardised methods of MFA reporting exist or are applied which shows that transparency in MFA modelling can be improved *Müller* (2006).

All of the seven studies model outflow according to lifespan, and most agree on a preference for the Weibull distribution, if data allows for it (table 2.2). Many studies use exogenous input of population or GDP growth (either directly or indirectly through derived variables like floor area per capita) to model future stock levels and govern the inflows according to expected material intensity per stock unit. Fewer studies use more case-specific exogenous inputs like predictions for the number of households, which is preferred, but also dependent on the availability of such specific information.

Even though the findings of *Augiseau and Barles* (2017) were confirmed that many different case studies use many different driving forces for prospective modelling methods, several main themes were identified and presented in the following paragraph:

Prospective Material Flow Analysis: conclusions from the literature review

Modelling practices vary strongly between studies, but common themes were identified. Few studies quantitatively compare material impacts of distinct scenarios, even though its importance has been recognised. Most prospective MFA studies include sensitivity analysis on lifespan assumptions by assuming a slightly lower and higher likely lifespan, which gives a bandwidth for results. Generally, driving forces used in prospective material flow studies are categorised as follows: *stocks* are generally governed by exogenous projections for e.g. population, GDP, or more case-specific themes like number of households; *outflows* are generally governed by the lifespan of materials in the stock; *inflows* are generally governed by compensation of output and change in stock.

It is striking that very few prospective MFA studies systematically compare the material requirement of different options for the future, even though the importance of integrating material impact with factors relevant to societal transition has been recognised in literature reviews (*Hod-*

son et al., 2012), and is illustrated by studies describing the expected material impact of e.g. the renewable energy transition (*Kleijn et al.*, 2011).

2.2.2 Scenarios, transitions, and pathways

Several fields of study aim to understand transitions in order to inform current decisions. A recent special issue in the journal *Technological Forecasting & Social Change* highlights the friction in the traditional interpretation of transitions in quantitative modelling compared to the interpretation of socio-technical transition analysis (*Hof et al.*, 2019), and argues that model-based studies can be enriched by engaging with socio-technical transition studies which allow for a more refined interpretation of institution and actor behaviour. In the context of this thesis, two interpretations are discussed: the *multi-level perspective approach towards transition pathways*, and *comparative pathways in quantitative systems modelling*.

Transition pathways from the multi-level perspective approach

To understand how systems in society develop and transition, a prominent approach is a three-level model for transitions (*Rip and Kemp*, 1998; *Geels*, 2002; *Köhler et al.*, 2019). This approach aims to understand the complex interactions in society that contribute to the emergence, development and adoption of transitions.

It focuses on interaction of processes at three scales; *the micro scale*, or niches, which are protected spaces where radical transitions can emerge and be nurtured, which build momentum and can influence *the macro scale*, or socio-technical regimes, where existing systems are structured, which in turn can influence and destabilise the *meso scale* (exogenous socio-technical landscapes, large scale patterns in society), which in turn creates openings where niche innovations can emerge.

From the perspective of *Geels and Schot* (2007), the understanding of transition pathways is that transitions, system changes and innovations can be understood according to four different typologies, which describe multi-level interactions in the sense of timing (how transitions behave according to interactions with landscape pressure at a certain level of development) and nature (the extent to which an innovation might disrupt or reinforce a regime).

Another interpretation is that of (*Berkhout et al.*, 2004) which develops typologies according to the axes of high vs. low coordination and internal vs. external resources. These typologies are a first schematic attempt at developing ideal types and are less well supported by examples and characteristics than the the typologies presented by (*Geels and Schot*, 2007).

Transition pathways in quantitative modelling

The interpretation of *transition pathways* is ambiguous, as the following example shows. Within the context of quantitative systems modelling like Integrated Assessment Models (IAM), pathways have been used to point out likely consequences of specific choices (*Moss et al.*, 2010). Examples of the use of pathways following this description are the IPCC 1.5- and 2-degree pathways (*Rogelj et al.*, 2018), which aim to describe different options for keeping below certain global warming levels. This approach uses the following definition: Future transition pathways are projections, or distinct combinations of options, to achieve long-term goals which radically depart from a 'reference future' and are characterised by endpoints or a set of policies, and can describe technological or behavioural options that contribute to these goals. (*Krausmann et al.*, 2017).

The understanding of transition pathways used in quantitative systems modelling (*Turnheim et al.*, 2015) is that a *pathway* allows for comparison of a hypothesis through long term goals or politically defined end-points that radically depart from a *reference future* represents how future would result if the present way of conducting society would stay the same. This approach underlines that the value of integrated assessments is not that they can, or attempt to, accurately forecast innovation and transition; instead, it aims to understand the future implications of current choices.

Interpreting the concept of transition pathways

The above paragraphs confirm the observation by (*Hof et al.*, 2019) that the concept of *transition pathways* used in quantitative models like IAM (*Moss et al.*, 2010) have similarities but are not identical to *transition pathways* in the context of the multi-level-perspective as described by (*Geels and Schot*, 2007).

This thesis would propose to bridge these two approaches by holding the definition of transition pathways described in quantitative modelling (ch. 2.2.2), but to then characterise these transition pathways according to the typologies described by (*Geels and Schot*, 2007) or (*Berkhout et al.*, 2004). This is valid as the two definitions do not contradict each other, but instead, describe similar phenomenon from different perspectives. This is interesting for discussion purposes so that a connection can be made between a typology and the expected impact of a transition.

This could be done by developing several *transition pathways* which can be compared to a *reference future* (*Turnheim et al.*, 2015), both qualitatively through the typologies and quantitatively through modelling the material impact in a prospective Material Flow Analysis. In the context of this thesis, it would allow exploring what the implications are of different pathways for the material demand and secondary material release for vehicles in the Netherlands.

In this thesis, the concept of *transition pathways* is understood to be different from the concept of *scenarios*, and is understood as follows: a *scenario* is a projection of overarching developments (projections for population, demand for mobility, or GDP). Different pathways describe how various developments like electrification or lifespan elongation progress over time.

Existing scenarios for the future of mobility

For decades, scenarios have been a tool to inform decision making for both governments (*United Nations*, 2015; *Oberthür and Ott*, 1999) and private industries (*Kolk and Levy*, 2001) for a wide range of topics including climate change. This chapter discusses how a scenario will inform the exogenous input factors for the prospective MFA in this thesis. Two scenarios were considered, The WLO projections which focus on just the Netherlands and similar projections done by the IPCC which focus on the global situation. Appendix A.4 and A.5 include a longer discussion of the IPCC and WLO scenarios with regards to transportation, but the conclusions are presented here.

CPB/PBL (2015) provides a low and a high projection for different sectors, based upon low and high projections for population and GDP. Detailed cohorts from this study examine the role of passenger transportation, freight transportation, sea freight transportation, and air transportation in the future and provide projections for the performance of passenger and freight vehicles in the future (in passenger-kilometres for mobility, ton-kilometres for freight transportation, and passenger movements for flying). A disconnect was noticed regarding the compatibility of the scenarios with the Dutch governments' climate commitments, but this is further discussed in Appendix A.5. Some implicit information could be found regarding the modality of the future of transportation. These implied that modality would not change by alot, but because these were not explicitly stated, these were not considered. For the reference scenario, the current modal split and vehicle performance was assumed to stay constant through 2050, under the WLO scenario.

2.2.3 The future of freight and passenger transportation in the Netherlands

This section will discuss developments for sustainable transport and mobility in the future and will propose a set of themes which will serve as the transition pathways for this thesis. The endpoints for each pathway are described in the Methodology section (ch. 3.3.1).

Haghshenas and Vaziri (2012) provides an extensive literature review discussing Sustainable Transport Indicators (STI), and show that vehicle ownership, urban area, and private share negatively correlate with environmental performance. The strongest positive correlations for the environmental performance of regions are urban density, public share, and non-motorised share. From the perspective of this study, urban area and density are out of scope. The focus is laid on the public share, non-motorised share, and vehicle ownership. This is supported by data describing emission factors for different vehicles, where transit vehicles like trains and buses perform significantly better per person-kilometre than privately owned motor vehicles, see figure 2.2. Next to having an impact on emissions, shifting from private car ownership to other modes of transport has an impact on required materials, as is illustrated in the famous photograph (fig. 2.1).

(*Hannon et al.*, 2016) discusses the future of mobility and transport, and a lot of focus is laid on the role of electrification of the vehicle fleet, and the role of autonomous transport and ride-sharing. Explosive growth in initiatives for sharing cars and especially bikes has been described by (*Shaheen et al.*, 2010). Also, on-demand transportation services like Uber and Lyft have grown with the internet age (*Cramer and Krueger*, 2016).

2.3 Research gap and synthesis

This chapter will place the concepts discussed in the previous chapters into context with the research questions of this thesis, identifying the research gap that this thesis addresses.

Research gap: dynamic MFA and vehicles

The publications discussed in the previous chapters suggest that few dynamic MFA studies were conducted for vehicles. Most of the selected cases describe the stocks and flows of buildings in urban environments, and other topics include the lead in cathodes, household appliances, PVC, wastewater infrastructure.

To find whether this also holds for a larger selection of case studies a search strategy is proposed using Web of Science. Appendix A.6 details the exact search strategy and results, but the main results are shared here. Most studies focusing on prospective material flow analysis described cases related to buildings, and only a few were found which deal with prospective material flow analysis in the case of vehicles. The most relevant publication is the PROSUM project (*Huisman et al.*, 2016), which provides high quality and extensive analysis of passenger cars in the European Union. However, vehicles other than cars are not considered, and although total mass is accounted for, material content for the 28 metals which were considered was based on few electronic components only (magnets, motors, battery cells, etc.) so important materials like polymers are not considered.

The cases described in the field of (dynamic) material flow analysis remain very focused on the urban domain; cities, infrastructure, building, and construction, as shown in figure 2.3. Far fewer publications consider cases with topics like waste management, metals in products, mobility, and food.

Only a few of the MFA publications that were found that do consider vehicles as a case study are prospective. The studies are mostly static analyses of geographic regions (Japan, UK, EU) and consider a subset of materials which are mostly metals. The most extensive analysis found so far

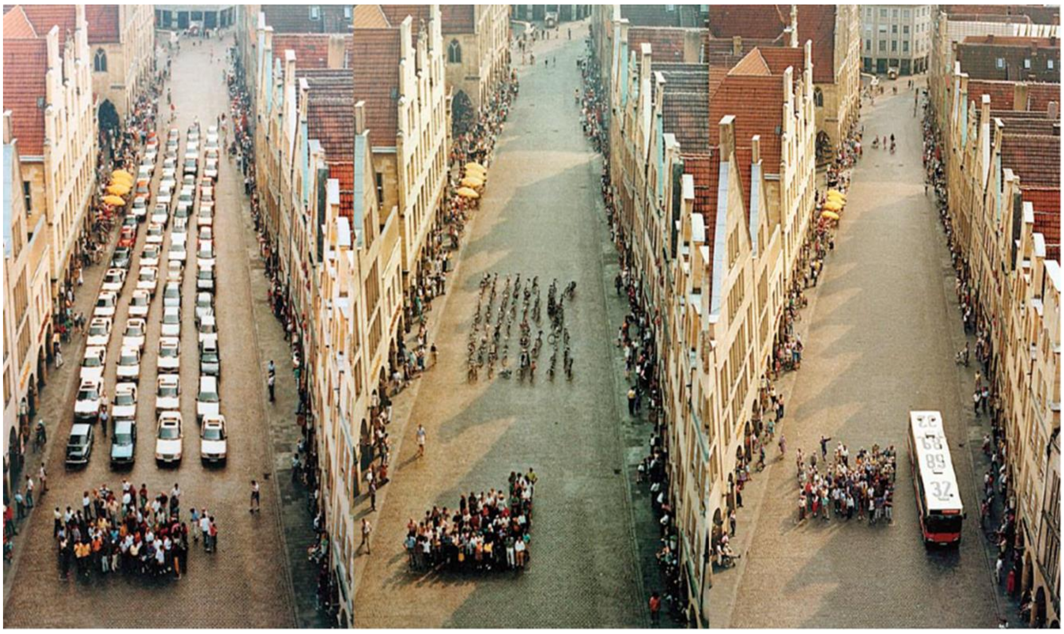


Figure 2.1: Three photos showing the impact of modal shift between car, bikes and a bus for 72 people commissioned by the City of Münster Planning Office in 1991. Image: public domain.

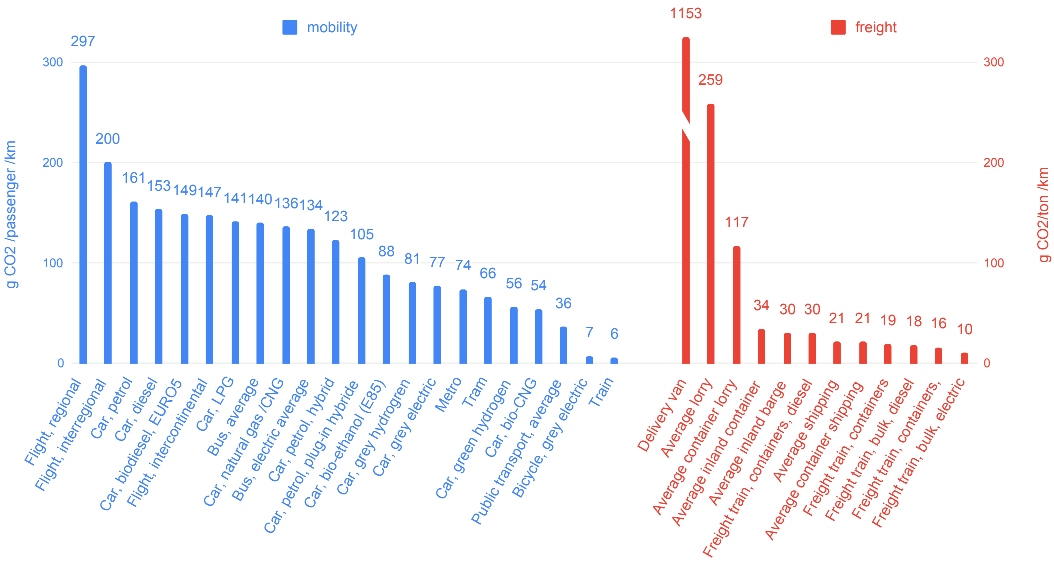


Figure 2.2: Emission factors for selected vehicles. The reference unit for mobility: passenger-kilometer, and for freight:ton-km. Data from (*Ministerie EZK*, 2019)

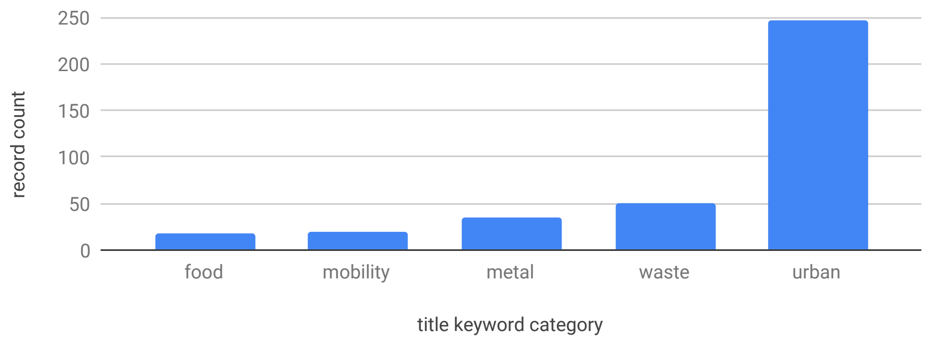


Figure 2.3: Count of publications after manual categorisation of title keywords into five categories from the search strategy shown in listing 1.

state	methodology	topic	scope	geography	prospective
state of the art	dynamic mfa	all buildings	all materials	multiple countries and continents	yes
state of the art	dynamic mfa	road (cars & larger vehicles)	steel, aluminium	Japan, UK, EU	no
thesis	*dynamic mfa*	*raod, water, air, railroad vehicles*	*all materials*	*Netherlands*	yes

Figure 2.4: Positioning of this thesis relative to the state of the art for dynamic prospective MFA for buildings and for vehicles.

is that of the European PROSUM project (*Huisman et al.*, 2016) which accounts for 28 (critical) metals in a 15-year historical time series for selected components of passenger cars, and a study on critical raw materials in Dutch cars (*Deetman et al.*, 2018). Table 2.4 describes the positioning of this thesis relative to dynamic prospective MFA for the state of the art for buildings and for vehicles.

2.4 Conclusions from literature

A suitable method to answer the research questions is a bottom-up, stock-driven, prospective material flow analysis, and is best documented through (*Müller*, 2006). However, answering the research questions in chapter 1.3 would require to extend the method in different ways.

Prospective MFA studies generally describe a single future scenario and explore the sensitivity of different assumptions on the results. Few studies explore distinct future scenarios which are based on paradigm-shifting factors like policy or introduction of new technology. This is a particularly interesting opportunity where MFA can be used to inform policy decisions which aim to contribute to achieving climate goals. This thesis would explore several pathways aiming to achieve zero-emissions mobility in line with current climate commitments.

Dynamic MFA has proven to be extremely informative in the planning of future outflows of building sector materials for waste management or resource recovery. Even though the built environment contains a larger proportion of societies' materials compared to vehicles, vehicles contain relatively valuable and critical materials. Few studies have focused on vehicles in transportation, of which most only consider passenger cars and not other vehicles like ships, bicycles, or utility cars. The state of the art of dynamic MFA for vehicles still lags behind that for the building sector.

Of all the material studies of vehicles in society, the main focus is the valuable and critical metals. However, in a circular economy, one would aim to recycle all materials found in vehicles. To the best knowledge, this thesis is the first attempt to account for a full bill of materials for vehicles.

The most often studied vehicle category in MFA is the passenger car, which is arguably the heaviest on-land vehicle category in society. To best of knowledge, no accounts of materials have been made for other road vehicles like bicycles, buses, motorcycles. Furthermore, no material accounts were found for vehicles that operate in different domains: air, water, and railroad. If one way to achieve zero-emission transportation, a modal shift is a factor which has to be considered. To fully inform decisions made regarding the transportation of freight and passengers in a sustainable way, it makes sense to also consider the material demand of all modes of personal and freight transportation.

3 Methodology

The fundamental method supporting this thesis is a prospective, bottom-up, stock driven, material flow analysis (*Müller et al.*, 2014). This work will be built upon in several ways, firstly by aiming to include an exhaustive set of materials in the scope, secondly by conducting the analysis for several distinct pathways for the future, and thirdly by basing the stock-flow modelling upon lifespan distributions which are informed by a combination of Weibull distributions and empirical data.

The accounting of the vehicle stocks and the materials contained in it are described in the first chapter (ch. 3.2). The method for applying a comparative prospective MFA using Weibull lifespan distributions and transition pathways is described in the second chapter (ch. 3.3). Finally, the chapter is concluded (ch. 3.4).

3.1 Modelling using Python

The Python programming environment was chosen for managing data and conducting material flow analysis over alternatives like spreadsheets which are likely to struggle with the large quantities of data required for this thesis. Alternatives like Vensim are available, which are commonly used by material flow analysis practitioners, but one drawback is that the method is only reproducible for people with access to academic (free) or commercial (expensive) licenses to this software. Python, on the other hand, is free and open-source (*Python Software Foundation*, 2020).

All data and calculations are published in a GitHub repository (*Van der Zaag*, 2019), which allows those interested to easily reproduce but also provides transparency as it is possible to examine the entire history of its development.

The results from this thesis will become available through an interactive online ipython notebook, which requires no setup and allows to explore the data in great detail, and is hosted at: `https://colab.research.google.com/github/grimelda/urmive/blob/master/hstockplots.ipynb`. Comparison of future pathways described in this section can be explored via a separate interactive ipython notebook hosted at: `https://colab.research.google.com/github/grimelda/urmive/blob/master/Pathways_Comparison.ipynb`. (*Van der Zaag*, 2019)

3.2 Historical stocks of materials in vehicles in the Netherlands

To explore the possibilities of aiming to include an exhaustive set of materials in a Material Flow Analysis (MFA), a case study of the Netherlands vehicles between 2000 and 2017 are considered.

The following paragraphs summarise the data collection required to answer the first research subquestion and is split into two parts regarding (a) accounting for all vehicles, and (b) accounting for the materials in these vehicles. For detailed descriptions of data collection, the reader should refer to Appendix B.1.

3.2.1 Counting all vehicles and their mass in the Netherlands

The Dutch bureau of statistics provides the most comprehensive accounts for different types of vehicles, including count and mass data for all registered road vehicles (cars, vans, motorbikes, trucks, etc.) (*CBS*, 2019a) - (*CBS*, 2019f). Data for bicycles was published by (*BOVAG-RAI*, 2019b,a).

Data for the aircraft fleet was supplied by (*CBS*, 2019c), but categorisation was unclear and no mass data was available, which was found by reviewing source data from (*ILENT*, 2019) and manual lookup of manufacturer data on mass.

Data for seagoing ships were provided by (*MI&W*, 2019), which reports on individual ships and their Gross Tonnage, categorised by 27 categories. Weighted averages were taken per category for Gross Tonnage, which was converted to lightship mass following the method described in (*EC DG Environment*, 2011). A dataset was found describing the mass of all recreational boats in the Netherlands (*Waterrecreate Advies BV*, 2015) for 2014.

Important gaps in available data are that for rail vehicles, including trains, metro and trams. Because of the relative importance of trains in personal mobility and the transformation pathways conducted in this thesis, a dataset of unreliable quality was used to account for the number of trains in the Netherlands (*Treinenweb.nl*, 2019). This was the best available source, and even official data from the Dutch government was not of sufficient quality to be able to validate this dataset (*ILENT*, 2019). Eurostat data was found to be unavailable, perhaps because the Netherlands has overlooked to report this to the European Commission, as their membership would require (*Eurostat*, 2019). Trams and metro were excluded from this research because not even unreliable datasets could be found.

3.2.2 Accounting for materials in vehicles

The best available material composition data for vehicles were supplied by the Argonne National Laboratory through the updated specifications for the Vehicle-Cycle model (*Burnham*, 2012). This was the only reviewed data set available, but only covers various types of passenger cars. Utility vehicles are not included. Importantly, some critical raw materials are accounted for. All batteries in vehicles in this study relied on battery data supplied by this data set.

Best available data for Aircraft was of low quality as it accounted for a limited set of materials (*Lopes*, 2010), and no other dataset was found that could validate its application.

Best available data for ships was of low quality as it accounted for only a very select set of materials (*Jain et al.*, 2016), but a private interview with an engineer at Damen Shipyards confirmed its validity for a range of different ship types (*Prins*, 2019)

For all other included vehicles, data from EcoInvent 3.5 (*Wernet et al.*, 2016) was used. Mostly, good estimations were found regarding the Data quality varies strongly, for several vehicles (cars, bicycles) the data is of acceptable quality, but others (aeroplanes) are of unacceptably low quality, so other sources were found.

3.2.3 Combining materials and vehicles.

Material content is expressed as a dimensionless mass fraction per unit $[fraction/unit]$, which is multiplied by vehicle mass $[kg]$, and vehicle count $[unit]$, resulting in a final mass in kilograms.

Because of a mismatch between the number of vehicle categories with weights, and material content datasets, mapping was required. Because the mapping file is even too large to publish in the appendix, the reader should refer to the *Urmive* GitHub repository, where the mapping file (datamap.csv) can be inspected at `https://github.com/grimelda/urmive/blob/master/data/datamap.csv` (*Van der Zaag*, 2019).

95 different reported materials were grouped into 16 Material Groups for convenience, but results can be explored with originally reported individual material data. The material groups are *Aluminium; Ceramics; Chemicals; Composites; Copper; Critical Raw Materials, CRM; Glass; Insulation; Metals, ferrous; Metals, other nonferrous; Minerals; Organic; Paint; Polymers; Textiles;* and *Unknown*.

3.3 Prospective material stocks and flows for vehicles in the Netherlands

3.3.1 Sustainable transportation developments

To describe sustainable transportation developments in the Netherlands, a set of endpoints are chosen which describe the total system of the vehicles described in this thesis. These developments have been introduced in the literature review chapter, and the endpoints for each pathway are presented in the Results chapter 4.1.1. To confirm the relevance of the chosen developments, an interview was conducted with professor Bert van Wee (*Van Wee*, 2019).

In order to bridge the gap between the quantitative modelling interpretation and the socio-technical transitions analysis interpretation of *transition pathways*, this thesis chooses to categorise the developments under the transition typologies presented by (*Geels and Schot*, 2007). These typologies were chosen over the earlier typologies presented by (*Berkhout et al.*, 2004) because the former provides more historical examples and characteristics which form a more coherent description of the sustainable transportation developments described in this thesis.

3.3.2 Describing the total system of vehicles in the Netherlands

If one assumes that vehicles exist to deliver an amount of service, the total system of vehicles in the Netherlands can be described by the share of transportation service delivered by different vehicles. The main categories for passenger transportation vehicles are Cars, Bicycles, Walking and Mass Transit. Cars are composed of electric, conventional, and hybrid, Bicycles are composed of the different two-wheeled vehicles like bicycles, motorcycles, mopeds, etc., and Mass Transit is composed of buses, trains, etc. Walking requires no vehicles (one could assume that shoes are vehicles, but for this thesis, shoes are assumed to be part of clothing which people require for everyday life and not specifically for transportation). The main categories for freight transportation are seagoing ships, inland ships, road freight and rail freight, each which compose of different types of vehicles of that category.

3.3.3 Transition pathways

One of the aims of this thesis is to extend the *Müller* (2006) method to use several distinct future transition pathways relevant to the research question for the MFA. This allows for the exploration of the development of the portfolio of Dutch vehicles. This could give insight into the material demand and release following modal shifts (e.g. increased share of public transport), or the introduction of new low emission technologies (e.g. electric vehicles).

In order to be able to compare the material impacts of possible future developments, several different transition pathways will be compared with a reference future in this thesis. The WLO-laag scenario delivers the exogenous inputs into the model: passenger-kilometres for passenger transportation, ton-kilometres for freight transportation, and passenger movements for flying.

Reference pathway: the WLO-laag scenario

This chapter discusses how a scenario will inform the exogenous input factors for the reference pathway for the prospective MFA in this thesis. For decades, scenarios have been a tool to inform decision making for both governments (*United Nations*, 2015; *Oberthür and Ott*, 1999) and private industries (*Kolk and Levy*, 2001) for a wide range of topics including climate change.

The basis selected for the projections in this thesis is the WLO-low scenario (*CPB/PBL*, 2015). This source describes the future of the Netherlands in terms of bandwidth (low and high outlooks) for different modes of passenger transportation, different modes of freight transportation and air traffic. These projections are based on expected developments for population and economic growth. Whilst the value of using general driving forces like GDP and population has been recognised (*Hu et al.*, 2010), the more case-specific approaches are sometimes used because they allow for better granularity regarding different types of vehicles (**?**)g, and the WLO scenarios provide just that for vehicles.

The low scenario was selected because this represents a minimum in terms of material consumption, as material use increases with both population growth and economic growth (*Krausmann et al.*, 2017). The results of this thesis should, therefore, be interpreted as a minimum regarding the amount of material needed in the future and the minimum amount of materials expected to be released from materials, according to various future scenarios.

This pathway aims to serve as a reference to the other pathways explored in this thesis. This pathway represents a situation where the share of modes in transportation stays the same as it currently is, and that the current transitions we are going through stagnate. These transitions will instead be explored in the pathways as a comparison. This reference pathway does not represent *business-as-usual*, as that implies that current trends are extrapolated and that a prediction is made to what the future will look like. Because this is impossible, it is chosen to stay away from trying to predict the impossible but rather to inform the impact of likely transitions.

Implementing transitions

The transitions will be described from the theory of diffusion of innovations (*Loorbach and Rotmans*, 2006). This theory argues that certain transitions follow a characteristic S-shaped curve instead of e.g. a linear transition. The function generally used to describe such an S-shaped transition is the logistic curve. A logistic curve can be interpreted as the cumulative distribution function of adoption with a particular probability density. This curve incorporates the passage of time required to adopt innovations and a steepness which reflects the quickness of adoption.

The curve is interpreted as a function describing the share of a unit at a certain time. Variables are the expected transition midpoint, and the curve steepness (analogous to growth rate), as seen in equation 3.1, where f_x represents the share of a unit at time x; with x = time, L = endpoint share, x_0 = midpoint time, k = steepness.

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}} \tag{3.1}$$

If the shares of delivered service (e.g. share of person-kilometres) are modelled towards the endpoints defined in the previous paragraph, the shares can be multiplied with the exogenous input from the WLO-laag scenario, which would result in the amount of delivered service (e.g. person-kilometers) per vehicle type. Finally, the delivered service per vehicle, in person-kilometres, can be multiplied by the number of vehicles needed per unit of service, the result is the number of vehicles required to deliver a certain amount of service.

3.3.4 Prospective Material Flow Analysis

The stock-driven prospective Material Flow Analysis from (*Müller*, 2006) is selected as the fundamental method, as described in the literature review in chapter 2. The method is extended on three fronts: (a) to base lifespan distributions on empirical data, (b) by conducting the MFA for distinct transition pathways in order to compare the material implications, and (c) by disaggregating the total mass into its material components in as much detail as possible.

To extend upon the *Müller* (2006) method, lifespan distributions for vehicles are based on empirical data, using the Weibull distribution to model the stochastic behaviour of deprecating vehicles.

3.3.5 Dynamic flow modelling

To track the age of individual vehicles at an aggregated level over time, a histogram is constructed for each year. Each bin of the histogram represents the count of vehicles of a certain age cohort. This is referred to as a demographic histogram. The term *demography* is commonly used to describe the age composition of people, however, it is certainly not unusual in academic literature describing vehicles or material stock. Several publications describe material demographics using histograms, as is illustrated by the article titled: *Material Stock Demographics: Cars in Great Britain*, published in *Environmental Science & Technology* (Cabrera Serrenho and Allwood, 2016).

This demographic histogram will be noted in the equation as a vector, which allows it to be algebraically manipulated. In this notation, the magnitude of the histogram (sum of all cohorts) is equal to the scalar value of the stock at a certain time step. A generic two-term Weibull Survival Function (SF), with lifespan=λ and shape factor=k is used as a basis (eq. 3.2).

$$F_{(\lambda,k)}\left(i\right) = e^{-\left(\frac{i}{\lambda}\right)^{k}} \tag{3.2}$$

This demographic histogram ($F\left(t, i\right)$ at time t) is found by scaling the SF by the vehicle fleet size divided by the vehicle lifespan. The stock size is represented by the magnitude of the demographic histogram vector ($F\left(t, i\right)$) at year=t for vehicle=v, and vehicle fleet size=z: age cohort=i, lifespan=λ, and shape factor=k (eq. 3.3):

$$F_{(v,z,\lambda,k)}\left(t_0, i\right) = \frac{z_v}{\lambda_v} \cdot e^{-\left(\frac{i}{\lambda_v}\right)^{k_v}} \tag{3.3}$$

For dynamic behaviour, a separate discretized Weibull function with the same shape factor=(k) and a different lifespan=λ_d is subtracted from the demographic histogram of the previous time step. This is then shifted using a lower shift matrix ($\mathbf{L}$). Depending on whether the stock change (external factor) is positive, births are added, or if negative, the entire histogram is scaled according to the magnitude of deaths, as shown mathematically in the following equation 3.4.

$$F_{(v,z,k,m,\lambda_d)}\left(t, i\right) = \begin{cases} \mathbf{L}_i \times \left(F_{(t-1,i)} - m \cdot \left(e^{-\left(\frac{i}{\lambda_d}\right)^{k}} - e^{-\left(\frac{i-1}{\lambda_d}\right)^{k}}\right)\right) + \delta s_t \times \mathbf{q} & \text{if } \delta s_t \geq 0 \\ \mathbf{L}_i \times \left(F_{(t-1,i)} - m \cdot \left(e^{-\left(\frac{i}{\lambda_d}\right)^{k}} - e^{-\left(\frac{i-1}{\lambda_d}\right)^{k}}\right)\right) \cdot \frac{|\mathbf{s}|-\delta s_t}{|\mathbf{s}|} & \text{if } \delta s_t < 0 \end{cases} \tag{3.4}$$

The values of m and λ_d are unknown, and parameter estimation should find the proper input for the discretized Weibull distribution that describes the deaths during a timestep. A full description of this method and the results from this exercise are given in Appendix B.4.

With a lower shift matrix $\mathbf{L}_i$ (eq. 3.5) defined as a matrix with ones on the subdiagonal, as described by *Beauregard* (1973): a 4×4 example is shown in 3.5. The queue vector q (eq. 3.6)

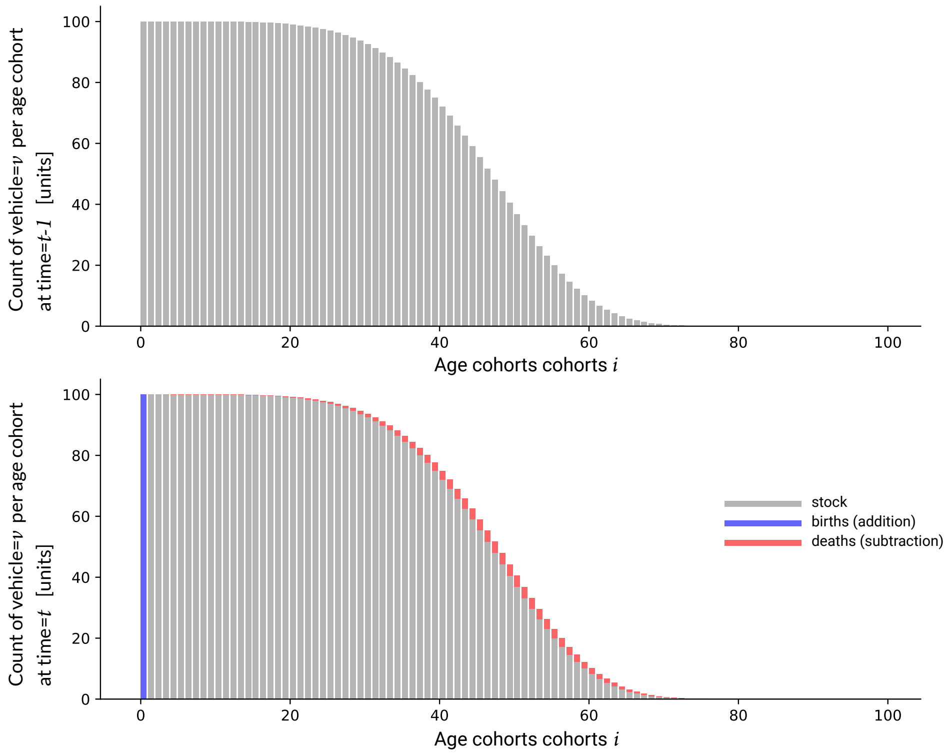


Figure 3.1: Demographic histogram at time t, which shows new births in blue and deaths in red compared to previous timestep $t-1$ for a hypothetical vehicle v, with lifespan $\lambda = 50$, and shape factor $k = 5$.

simply places the births in the first age cohort of the histogram.

$$\mathbf{L} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \tag{3.5}$$

$$\mathbf{q} = \begin{bmatrix} 1 & 0 & 0 & 0 & \dots & i \end{bmatrix} \tag{3.6}$$

3.4 Conclusions from methodology

The prospective material flow analysis method described in (Müller, 2006) was used in this thesis, but was extended in three ways: (a) to aim to consider an exhaustive bill of materials for vehicles,

(b) to conduct the analysis for several different pathways which would allow for quantitative comparison of the material impact, and to group the chosen developments under four typologies for transition pathways (*Geels and Schot*, 2007) which places the developments and results within a socio-technical framework, and (c) to model lifespan used in stock driven flow modelling upon a combination of Weibull distributions based on empirical demographic data of vehicles.

4

Results

THE FIRST PART OF THIS CHAPTER describes how sustainable transportation developments are implemented for the different pathways explored in this thesis (section 4.1), and the findings from applying the Weibull distribution to stock and flow modelling are presented in section 4.2.

The second part presents the results that answer the research questions of this thesis, the historical material stocks will be presented in section 4.3, and the prospective stocks and flows are presented per transition pathway in section 4.4. Finally, a cross-comparison between pathways is presented in 4.5.

4.1 Modelling sustainable transportation developments

4.1.1 End points for developments

In this chapter, endpoints are presented for developments discussed in the literature review section, following the method described in the methodology section. A more comprehensive background is given for each development and endpoint in Appendix B.2. The eight developments for transportation are then each categorised according to four transition pathways typologies (*Geels and Schot*, 2007), and a summary is shown at the end of this chapter in table 4.1.

These reason for choosing these developments were if they contribute to: (a) lower emissions, and (b) better material efficiency. Note that none of the described developments even potentially allow compatibility with the commitment to net-zero emissions from transportation. Arguably, no transportation technology has the potential to achieve net-zero life cycle emissions, but with green fuel/electricity, in-use emissions can be eliminated or compensated. The different developments are chosen to explore different possibilities for the mobility sector to comply with climate agreements and commitments made by the Dutch government (*Rijksoverheid*, 2019). A personal interview with professor Bert van Wee (*Van Wee*, 2019) confirmed the following developments were interesting to consider for vehicles and the materials used in the future: *Low emissions vehicle rollout*, *Enlarging of freight vehicle capacity*, *Passenger transportation as a service*, *Two-way freight trade*, *lifespan elongation through refurbishment/modernisation*, and *Modal shift*.

- *Low emission vehicle roll out*

  One of the few replacements for current vehicles that allow independence from fossil fuels are hydrogen Fuel Cell Vehicles (FCV) and Electric Vehicles (EV). FCV are not considered as their fleet has stayed constant and has never risen above 30 cars for the last decade in the Netherlands (*BOVAG-RAI*, 2019a). EV reduces life cycle CO_2 emissions by around 15% on the current electricity grid, but potentially 75% with a green grid (*Hawkins et al.*, 2013; *Helms et al.*, 2010). Assuming that the Dutch grid transforms into a fully green grid, a radical adoption of EV is needed to significantly reduce emissions. A downside to this transition is that there is a higher material requirement for the production of EV, so other solutions are required to compensate for the increase in material demand.

  This development is categorised under the Substitution (ST) typology (*Geels and Schot*, 2007) because how the transition has rolled out until now is characterised by the main actors being incumbent or new vehicle manufacturers rolling out substitution at a component level, with the overall market for vehicles remaining relatively unchanged compared to before the introduction of electric vehicles.

  Endpoint: EV share for electric vehicles is 90% by 2050.

- *Passenger transportation as a service*

Recent developments like autonomous transport and ride-sharing services like Uber, Lyft, Swapfiets, or Greenwheels achieve higher occupancy and utilisation of vehicles, which in turn reduces the resources needed for the production of vehicles. From the literature review, it remains unclear whether autonomous transportation will reduce or increase life cycle emissions. But from the perspective of resource efficiency, as it requires fewer vehicles, it remains interesting to explore. An indication of the theoretical amount of cars needed to provide mobility service come from looking at extreme situations on the road. During peak traffic, at most 2.6m out of 7.7m total vehicles were on the road in 2014, indicating an effective utilisation of 33% (*CBS*, 2011).

This development is categorised under the De- and Realignment (RA) typology (*Geels and Schot*, 2007) as it is characterised by new actors rapidly disrupting existing markets, which delegitimize incumbent actors (similar to how the Uber service has disrupted the taxi business (*Cramer and Krueger*, 2016)).

Endpoint: Smarter sharing of resources and services to a more achieve effective utilisation could allow the car vehicle fleet to shrink by 50%, and the bicycle fleet to shrink by 25% requiring fewer resources for production.

- *Lifespan elongation through modernisation and refurbishing*
  For at least the past 20 years, passenger cars were observed to have increasingly longer lifespans (Appendix, figure B.4). If the trend continues, this would indicate that vehicle turnover would decrease and fewer materials are needed to deliver transportation service. This development would assume that all vehicles would undergo a similar trend.

  This development is categorized under the Reconfiguration (RC) typology (*Geels and Schot*, 2007), as this most accurately describes how the lifespan of trains is elongated using refurbishing (*Wikipedia contributors*, 2019), where incumbent actors together with established partners very slowly over time adopt practices that achieve long term goals.

  Endpoint: Vehicles increase lifespan linearly by 49% in 2050 compared to 2020.

- *Enlarging of freight vehicle capacity*
  The capacity of a wide range of freight vehicles has shown to be increasing over time (appendix figures B.6(a) and B.6(b)), which potentially allows for fewer trips, more efficient transportation, and using fewer materials in vehicles.

  This development is categorised under the Substitution (ST) typology (*Geels and Schot*, 2007) because the enlarging of freight vehicles is characterised by the main actors being incumbent or new vehicle manufacturers rolling out larger vehicles with the overall market for vehicles remaining relatively unchanged.

  Endpoint: Current trends are extrapolated linearly

- *Two-way freight trade*

Recent studies have shown that at least 20% of road freight and 45% of sea freight transportation is empty. Even though this is mostly due to the inherent incompatibility of two-way trade in a globalised economy (as raw materials are shipped to a producing country like China as bulk, but products are shipped around the world in container ships), significant improvements can be made. (*Ambel*, 2017; *Brancaccio et al.*, 2017)

This development is categorised under the De- and Realignment (RA) typology (*Geels and Schot*, 2007) as it is characterised by new actors rapidly disrupting existing markets, which delegitimize incumbent actors (similar to how the Uber service has disrupted the taxi business (*Brancaccio et al.*, 2017).

Endpoint: The freight vehicle fleet efficiency is increased by 25% by 2050.

- *Modal shift for passenger transportation*
  The backdrop for this storyline is that the transportation system of the Netherlands is overhauled because the increasing growth of road infrastructure cannot keep up with increasing demand for transport, especially considering the quick metropolisation of the Randstad. Mobility systems in other regions are analysed and are taken as a model for a radical reinvention of the Dutch mobility system from the perspective of a modal shift. Driving is radically reduced to slightly lower than the levels of the Tokyo region. Use of public transport is increased to approach levels of Paris. Slow transportation is doubled to accommodate for an increase in public transport, and the already strong cycling infrastructure is expanded to double cycling at a national level. This implies that emissions in 2050 could be reduced by 67% compared to the current situation (75% if assuming EV rollout, and even more if assuming green electricity production), see Appendix B.2 for calculation.

  This development is categorized under the Transformation (TF) typology (*Geels and Schot*, 2007) as it would require large scale transformations of existing behaviour, infrastructure, and regulations, which would take a long time.

  Endpoint: Modal share of 65% public transport, 20% cycling, 5% walking, and 10% driving, by person-kilometres in 2050.

- *Modal shift for freight transportation*
  The backdrop for this storyline is that few alternatives exist for sea transportation, and to reduce emissions and to reduce congestion on roads, a shift towards inland and railroad shipping is achieved. Half of road freight capacity is redistributed over inland and railroad shipping, and sea shipping is left as-is. The potential emissions reduction are impossible to estimate using available data.

  This development is categorized under the Transformation (TF) typology (*Geels and Schot*, 2007) as it would require large scale transformations of existing behaviour, infrastructure, and regulations, which would take a long time.

Table 4.1: Eight developments for passenger and freight transportation identified in chapter 2.2.3, are categorised by the four transition pathway typologies from (*Geels and Schot*, 2007).

		Pathways				
Transportation	*Development*	**REF: Stagnation**	**Substitution**	**Realignment**	**Reconfiguration**	**Transformation**
Passenger	Low-emission vehicles		x			
Passenger	Transport as-a-service			x		
Passenger	Lifespan elongation				x	
Passenger	Modal shift					x
Freight	Vehicle enlargement		x			
Freight	Two-way-trade			x		
Freight	Lifespan elongation				x	
Freight	Modal shift					x

Endpoint: Modal share of 29% road, 27% inland, 24% sea, and 20% train, by shipped tons in 2050.

4.1.2 Transition pathways

The transition pathways are tools which are used to describe how the number and weight of vehicles will develop in the future, for different assumptions. For detailed descriptions for each transition for passenger-, freight-, sea vessel-, and aircraft transportation, under the five transition pathways (reference: REF, substitution: ST, de- and realignment: RA, reconfiguration: RC, and transformation: TF) please refer to Appendix B.3. One example will be shown in the main text for the Transformation transition pathway for passenger transportation which describes the developments for modal shift. Other transition pathways follow the same method, but in the main text, only the implementation of the main assumptions will be highlighted.

Implementing transitions for the Transformation (TF) pathway

First, the delivered service (passenger-kilometres) for passenger transportation is extrapolated based on historical data and data for future projections (figs 4.1). Following this, the current modal split is shifted over time towards the endpoints, using a logistic function as described in the methodology chapter (figures 4.2(a) and 4.2(b)). This results in a shifted modal share through 2050 shown in figure 4.1. This is multiplied with a factor: the number of vehicles required per delivered unit of service (assumed to be constant for this pathway), which gives the final result for vehicle count (fig. 4.1). The last step, to combine vehicle unit counts by material content, is similar to the method for the historical vehicle count data described in chapter 3.2.

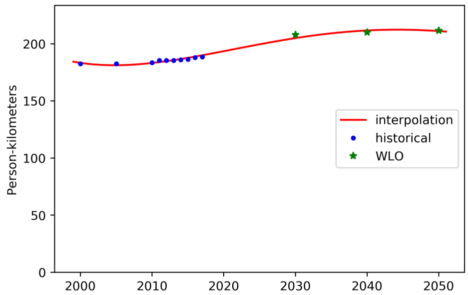
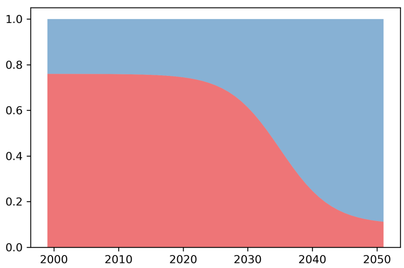


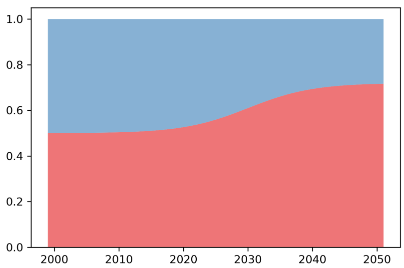
Figure 4.1: Delivered service by passenger transportation, in person-kilometers. WLO-low scenario (green stars) and historical data (blue points) are fitted with a fourth order polynomial (red line). Data from (*CPB/PBL*, 2015) and (*KIM*, 2019).

Table 4.2: Current modal split (*KIM*, 2019) compared to chosen modal split under transformation (TF) pathway.

Mode	Current share (REF)	2050 share (TF)
driving	76%	12%
transit	12%	63%
cycling	10%	20%
walking	2%	5%



(a) Binary shift between share of driving (red) and non-driving (blue) modes of transport.



(b) Binary shift between share of public (red) and slow (blue) modes of transport.

Figure 4.2: Binary shifts from current starting points to chosen end points using the logistic function

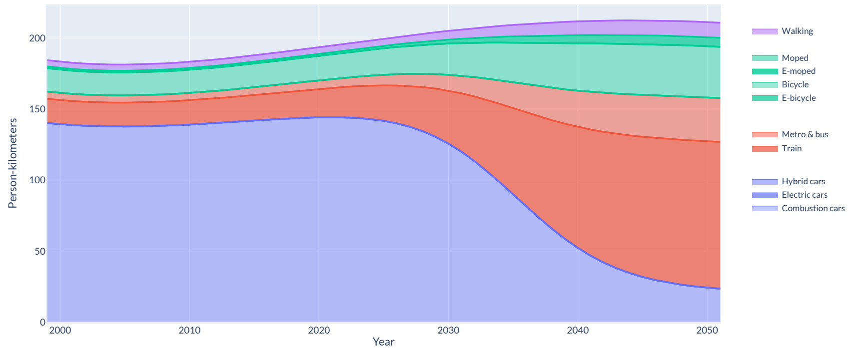


Figure 4.3: Delivered service by passenger transportation, in person-kilometers under the transformation (TF) pathway.

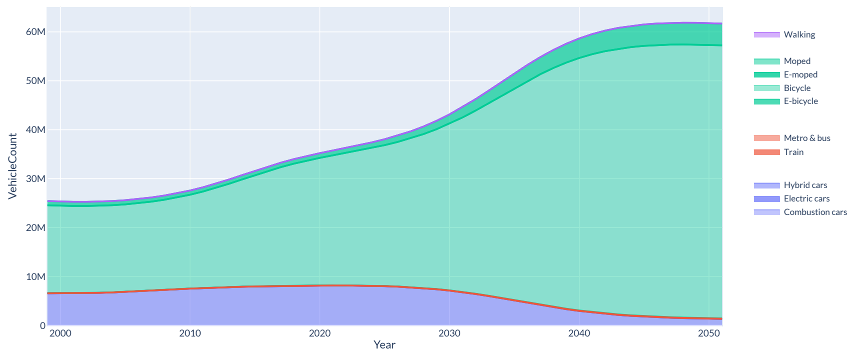


Figure 4.4: Vehicle count for passenger transportation vehicles under the transformation (TF) pathway. The number of public transport vehicles are order of magnitudes smaller than for bicycles and cars. Walking is included in the legend, but the mode of transport requires no vehicles.

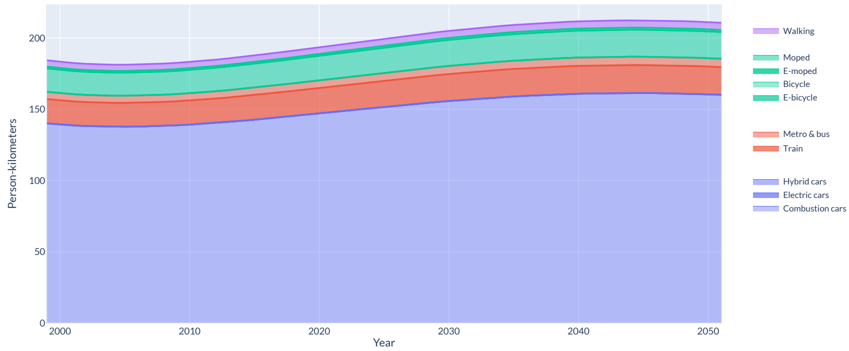


Figure 4.5: Share of passenger-kilometers by vehicle mode under the reference (REF) pathway

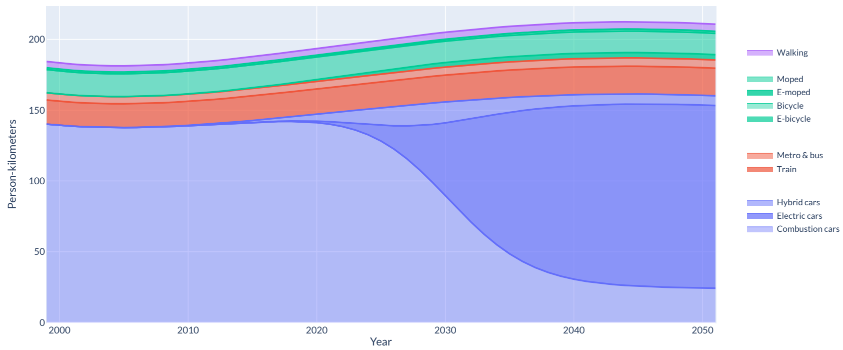


Figure 4.6: Share of passenger-kilometers by vehicle mode under the substitution (ST) pathway

Implementing transitions for the other pathways

The projection for the number of passenger-kilometres and freight ton-kilometres for the reference (REF) pathway are shown in figures 4.5 and 4.7. These figures also represent the situation for the reconfiguration (RC) pathway as here the vehicle composition stays the same compared to REF only the lifespan of vehicles is gradually increased. These figures also represent the situation for the de- and realignment (RA) pathway as here the vehicle composition stays the same compared to REF only the effective utilisation of vehicles is gradually increased.

Projections for the substitution pathways for passenger- and freight transportation represent the replacement of conventional cars with electric cars, and freight vehicles with higher capacity freight vehicles, and are shown in figures 4.6 and 4.8. Projections for the transformation pathway for freight vehicles is given in figure 4.9, for passenger transportation it is given in the previous section in figure 4.4. The whole datasets describing the exact shares, number of vehicles, and weight of all vehicles, for all pathways, can be found in the Urmive GitHub repository (*Van der Zaag*, 2019). A spreadsheet that summarizes the most important data can be found accompanied by this thesis via Appendix C.3.

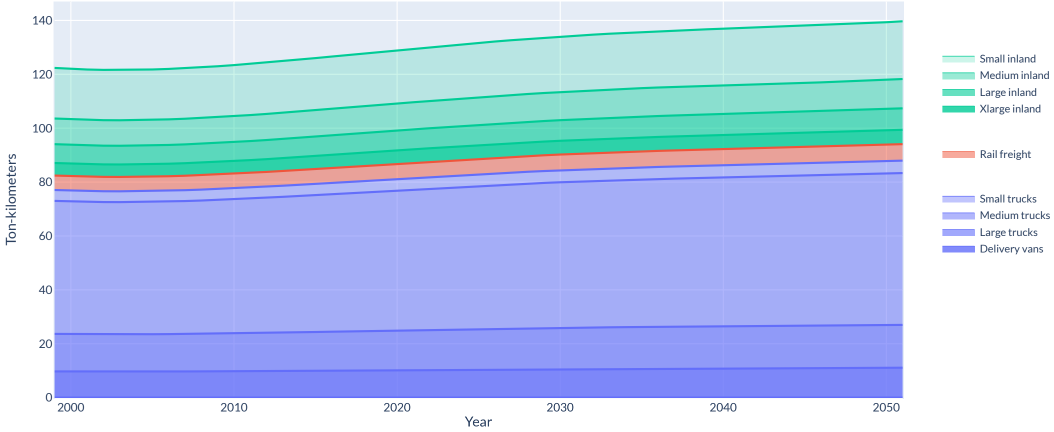


Figure 4.7: Share of ton-kilometers by freight vehicle mode under the reference pathway

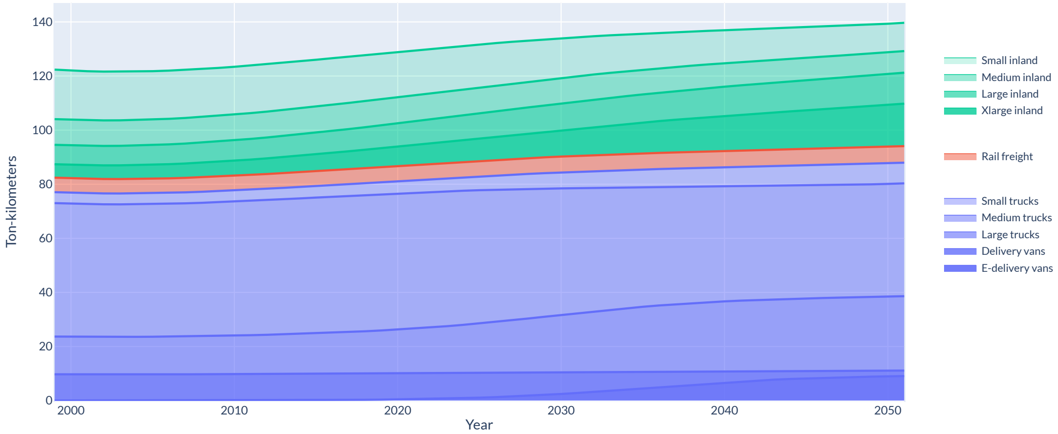


Figure 4.8: Share of ton-kilometers by freight vehicle mode under the substitution pathway

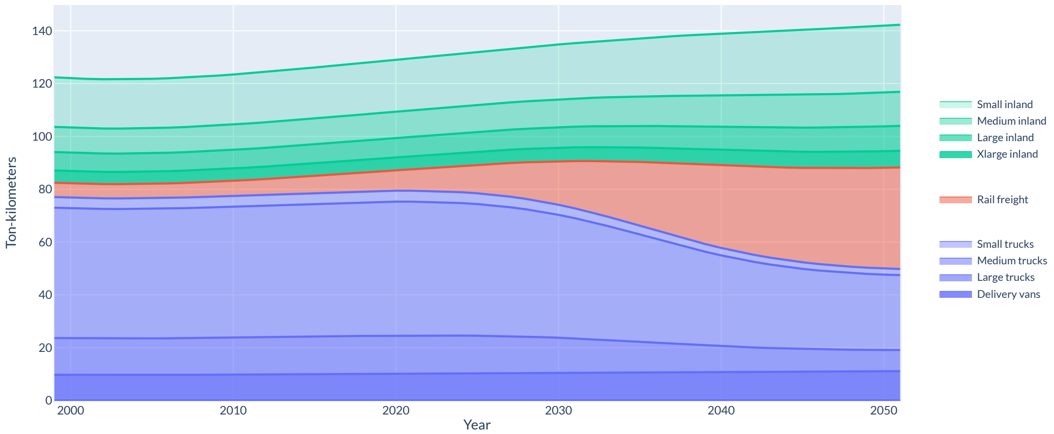


Figure 4.9: Share of ton-kilometers by freight vehicle mode under the reference pathway

4.1.3 Material composition of vehicles

Detailed material composition data were collected for 43 different vehicle types. The quality varies strongly, from good for vehicles like cars using the GREET vehicle cycle data (*Burnham*, 2012) to medium for most data sets from ecoinvent (*Wernet et al.*, 2016), to mediocre for ship and train data from ecoinvent and other sources (*Wernet et al.*, 2016; *Jain et al.*, 2016).

All data is published on the Urmive GitHub repository (*Van der Zaag*, 2019), but the most important data is summarised in an excel sheet accompanying this thesis via Appendix C.2.

4.2 Stochastic lifespan and demography in stock and flow modelling

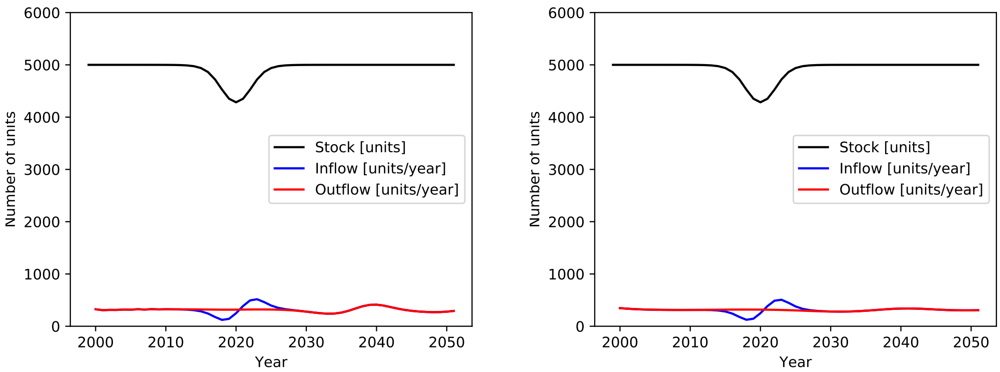
When modelling stocks and flows, the lifespan of the unit under study is important as it represents a delay between inflow and outflow. The most straightforward method to model this is without a lifespan distribution, but this results in noise from changes in stock which persists throughout the model. In this thesis, lifespan was modelled as a stochastic process using a Weibull distribution describing the chance of survival of units in a certain age cohort. To be able to do this, parameters were estimated for distributions describing the outflow of information was gathered describing the demography of the units under study, and these were fitted with a Weibull survival function.

4.2.1 Dynamic stock modelling (I) Flow modelling

The equation presented in the methodology chapter (**??**) is shown below and describes the number of cars in a certain year (*t*) and different age cohorts (*i*). The function requires two known inputs, an external function describing stock and its change (δs_t), the demographic histogram ($F_{(t-1,i)}$). This leaves two unknowns: the multiplication factor (m) regulating the magnitude of deaths in a timestep, and the lifespan (λ_d) distribution of the deaths. These parameters are estimated manually after which good results are found for shape factors between 1.4 and 6.5. A full description of this method and the results from this exercise are given in Appendix **??**

$$F_{(v,z,k,m,\lambda_d)}\left(t,i\right) = \begin{cases} \mathbf{L}_i \times \left(F_{(t-1,i)} - m \cdot \left(e^{-\left(\frac{i}{\lambda_d}\right)^k} - e^{-\left(\frac{i-1}{\lambda_d}\right)^k}\right)\right) + \delta s_t \times \mathbf{q} & \text{if } \delta s_t \geq 0 \\ \mathbf{L}_i \times \left(F_{(t-1,i)} - m \cdot \left(e^{-\left(\frac{i}{\lambda_d}\right)^k} - e^{-\left(\frac{i-1}{\lambda_d}\right)^k}\right)\right) \cdot \frac{|\mathbf{s}|-\delta s_t}{|\mathbf{s}|} & \text{if } \delta s_t < 0 \end{cases}$$

Assuming that the lifespan of vehicles follow distributions (the next chapter will provide evidence that this is indeed the case), implies that an effect on the response of stock changes to the in- and outflows can be expected. This is tested by comparing the in- and outflows responding to a change in stock level, using a narrowly distributed lifespan (which approaches the behaviour of using no lifespan distribution) with a widely distributed lifespan. The spread in demography has a marked effect on in- and outflows, where a wide spread in lifespan significantly dampens the long term responses (fig. 4.10(a) & 4.10(b)). This means that when modelling using a fixed lifespan, impulses from changes in stock are not dampened, and thus persist throughout the modelling time domain. This overestimates the dynamic response of stock changes. This provides evidence that assuming a fixed lifespan is especially problematic for subjects where there is evidence that lifespan shows even a small amount of stochastic behaviour, as was found with most vehicle types in this study.



(a) Hypothetical response for stock with unnaturally narrow spread for lifespan (high shape factor; $k = 7$) shows a strong dynamic response.

(b) Hypothetical response for stock with a more evidence based spread for lifespan (medium shape factor; $k = 3$) shows a dampened dynamic response.

Figure 4.10: The response to in- and outflows following a change in stock level

4.2.2 Dynamic stock modelling (II) Stock demography

When (a) detailed and high-quality data is available describing the demographics of a vehicle stock, (b) the vehicle stock is relatively constant over time, and (c) there is reason to believe that inflow and outflow would follow stochastic (randomly distributed according to lifespan) behaviour, a Weibull survival function scaled to the expected outflow (stock over expected lifespan) shows a convincing proxy for demographic data.

Vehicle lifespans were found to be widespread after inspecting demographic data for 11 vehicle types. Empirical demographic data is shown for cars in figure 4.11. In this year, the average stock size was $z_{car} = 8.2 \cdot 10^6$ (*CBS*, 2019e) and in the same year, BOVAG-RAI described cars

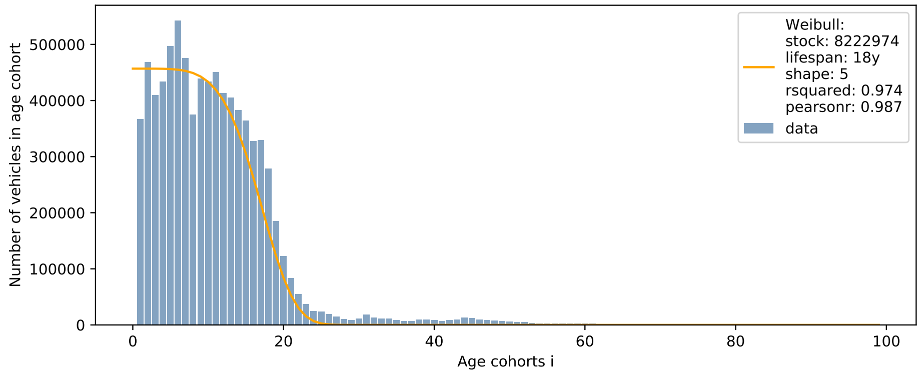


Figure 4.11: Demographic data for passenger cars from (*CBS*, 2019e) fitted with adapted Weibull survival function (eq. 4.1).

to deprecate after an average of $\lambda_{car} = 18$ years, figure 4.11 (*BOVAG-RAI*, 2019a). A good fit was found for shape factor $k_{cars} = 5$ (eq. 4.1):

$$F_{(z,\lambda,k)}\left(t_0, i\right) = \frac{z_{cars}}{\lambda_{cars}} \cdot e^{-\left(\frac{i}{\lambda_{cars}}\right)^{k_{cars}}} = \frac{8.2 \cdot 10^6}{18} \cdot e^{-\left(\frac{i}{18}\right)^5} \qquad (4.1)$$

Validation was done for several other registered road vehicles, which can be found in Appendix **??**. For many vehicles, no lifespan data was found, and both lifespan λ and shape factor k were manually estimated based on demographic data only, which resulted in the values shown in table 4.3.

For vehicles that are managed as assets, e.g. trains and aircraft, demographic data shows evidence of vehicles being bought in batches. If different models of the same type of vehicle have similar lifespans, it makes sense to assume a constant lifespan, however, if different models within the same vehicle category have a wide range of lifespans, it makes sense to use a lifespan distribution.

If this method does not provide satisfying results like in the above example of trains and jets, this indicates that other factors have a high influence on the demographics of the vehicle. Three examples of factors that can influence: (a) foreign import/export of second-hand vehicles, (b) that stock is not constant over time, and (c) evidence of non-stochastic behaviour of inflow and outflow e.g. when vehicles are managed as assets. In these cases, both the lifespan and the shape were varied to find the best fit. This does mean that there is no way to discern which part of the outflow comprises of exports and which of the dismantling of vehicles, which would be possible if lifespan data was available.

Based on three characteristics: lifespan, stock size, and estimations for Weibull shape factors,

Table 4.3: Shape factors (k) and lifespan values (λ) for various vehicle categories for which demographic data was found for reference year 2017. Stock data came from *CBS* (2019a)- *CBS* (2019f). Demographic histograms for each are shown in in Appendix **??** - **??**

vehicle	**stock**	**shape**	**lifespan**
bus	9 822	5	18
cars	8 222 974	5	18
utility cars	2 252 000	2	21.5
jets*	240	7	20
ships	1 250	2	30
trucks	58 159	2.5	17
trains*	1 069	7	40
mopeds	1 178 300	5	18
motorbikes	655 991	3.6	38
delivery vans	852 622	4.5	16

it was found to be possible to accurately model the demography of vehicles. If lifespan information was not available, demographic data allows for a reasonable estimation of lifespan and Weibull shape factors, as shown for 10 vehicles in table 4.3. Note that for jets and trains demographic data did not show convincing results, most likely because these are vehicles for which stochastic behaviour cannot be assumed because they are managed in batches as assets, and their outflow is governed by planned obsolescence.

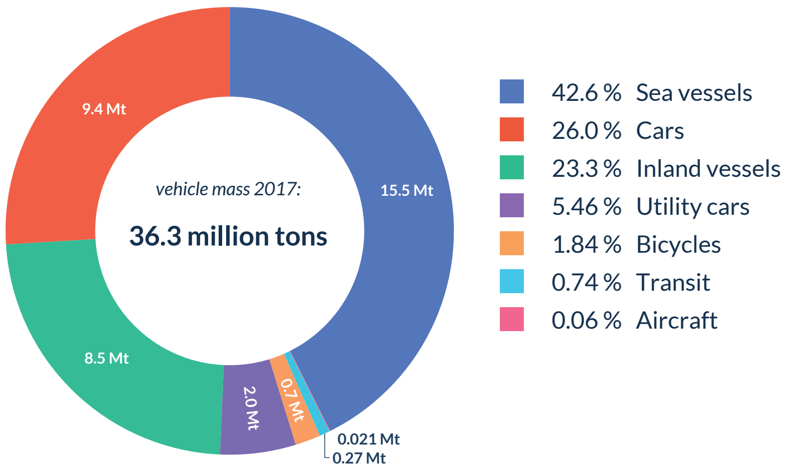


Figure 4.12: Contribution of different vehicle classes to the total mass of vehicles in the Netherlands. Historical data from different sources described in chapters 3.2.1 and 3.2.3, or summarized in Appendix spreadsheet C.1 and C.2.

4.3 Historical material stocks in vehicles in the Netherlands

4.3.1 The overall material stock of vehicles in the Netherlands

Ships and cars together represent the most significant contribution to the mass of vehicles in the Netherlands (fig. 4.12). In 2017, the 1.4 thousand sea- and 5.0 thousand inland vessels accounted for 66% of vehicle stock. In the same year, the 8.2 million passenger cars weighed roughly 5 times as much as the 0.92 million Utility cars which represent delivery vans, trucks, and other company-related vehicles. A table with the counts of vehicles aggregated by vehicle class is shown in table 4.4 and 4.5, and a full table of all data can be found in the spreadsheet accompanied in Appendix C.1.

Interesting to see is that the mass of the bicycles class (includes 23 million (e-) bicycles, 1.1 million (e-) mopeds, and 0.66 million motorbikes) is similar in magnitude to the Transit class (9.8 thousand buses and 1.1 thousand trains), but it is important to note that metros and trams are not counted through lack of data.

When the total mass is disaggregated into material groups (fig. 4.13), the contribution of Ferrous metals (different types of steel and iron) is by far the largest, followed by Polymers, Copper and Aluminium. This is unsurprising as most vehicle types' main material component is steel, except for lightweight vehicles like aeroplanes.

Copper and aluminium are reported separately from other nonferrous metals. The minerals material group is expected to consist mostly of insulation used in ships (*Prins*, 2019), and to a lesser extent, minerals like barium and silica.

Table 4.4: Counts of 170 different vehicle types aggregated by vehicle class. Historical data from different sources described in chapters 3.2.1 and 3.2.3, or summarized in Appendix spreadsheet C.1.

Class	Vehicles in class	Count 2000	Count 2005	Count 2010	Count 2014	Count 2017
Bicycles	6	17 831 800	18 041 300	20 003 760	24 852 800	25 824 200
Cars	7	6 339 091	6 989 708	7 622 255	7 931 270	8 225 750
Utility cars	33	752 402	957 883	943 221	884 875	926 308
Transit	67	12 757	12 613	12 996	11 099	10 757
Inlandvessels	4	0	0	5 386	5 224	5 067
Seavessels	29	898	883	1 288	1 225	1 458
Aircraft	3	499	556	592	556	535
Pleziervaartuigen	21	0	0	0	210 988	0

Table 4.5: Mass for 170 different vehicle types aggregated by vehicle class. Historical data from different sources described in chapters 3.2.1 and 3.2.3, or summarized in Appendix spreadsheet C.1.

Class	Vehicles in class	Mass [Mt] 2000	Mass [Mt] 2005	Mass [Mt] 2010	Mass [Mt] 2014	Mass [Mt] 2017
Seavessels	29	11 748	12 081	14 904	16 423	15 484
Cars	7	7 109	7 838	8 579	9 008	9 438
Inlandvessels	4			8 514	8 589	8 482
Utility cars	33	1 431	1 860	1 932	1 870	1 983
Bicycles	6	377	406	535	641	668
Transit	67	278	268	305	283	268
Aircraft	3	24	22	23	22	21
Pleziervaartuigen	21				185	

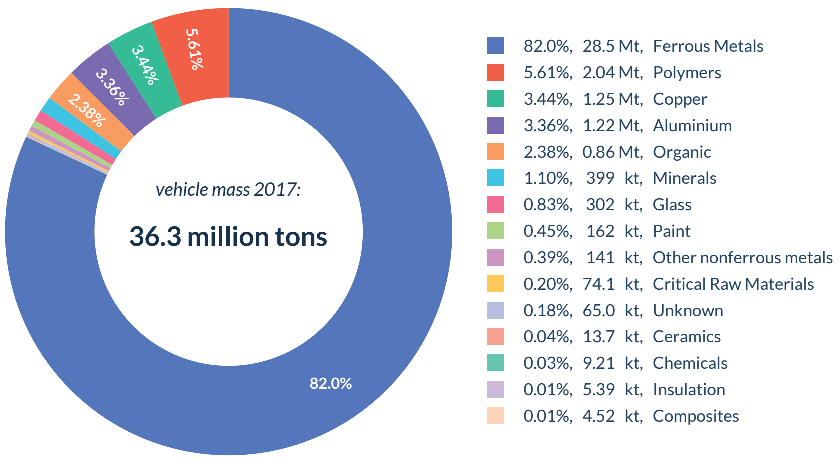


Figure 4.13: Contribution of different material groups to the mass of vehicles in the Netherlands. Historical data from different sources described in chapters 3.2.1 and 3.2.3, or summarized in Appendix spreadsheet C.1 and C.2.

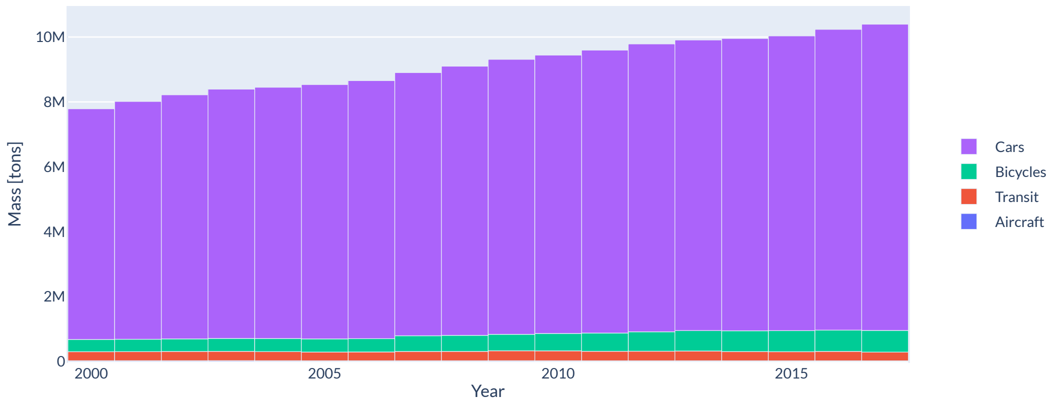


Figure 4.14: Mass of passenger transportation vehicles over time, grouped by vehicle class. Historical data from different sources described in chapters 3.2.1 and 3.2.3, or summarized in Appendix spreadsheet C.1 and C.2.

The mass of vehicles in personal transportation is growing over time, largely because of an increase in the number of cars, and an increase in the proportion of heavier cars which include (hybrid-)electric vehicles (fig. 4.14). The mass of other vehicle classes remains more constant over time, with bicycles showing a small increase. Note the slight jump in 2007 for bicycles represents that data for motorbikes was only available from this moment onwards.

The mass of freight transportation vehicles shows a slight increase over time (fig. 4.15), which is due to the slightly increasing numbers and increasing the average mass of individual vehicles. This enlargement trend was found in inland shipping, sea shipping, and road transportation.

No data were found regarding the number and material content of freight trains, but the contribution is expected to be small because the number of vehicles is estimated to be an order of magnitude lower than that of inland ships, and the mass also to be an order of magnitude lower than that of inland ships.

4.3.2 Aluminium stocks in vehicles in the Netherlands

The stock of aluminium shows a relatively strong growth compared to other materials (fig. 4.16), as newer and heavier vehicles like electric bicycles and electric cars use larger proportions of this material to reduce vehicle mass by replacing steel. Most vehicles use only a little bit of aluminium, and their contribution to the stock is less important than the vehicles mentioned. Importantly, large freight vehicles like ships and trains use a relatively low amount of this material and their contribution to the total stock is low.

Surprising is the relative importance of bicycles in the stock of aluminium. The dataset describing the material content of (e-) bicycles was obtained from Ecoinvent 3.5 (*Wernet et al.*,

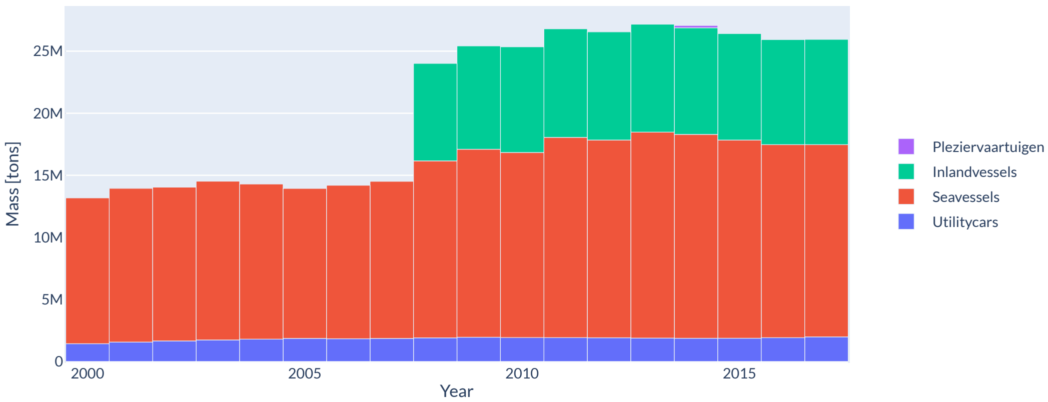


Figure 4.15: Mass of freight transportation vehicles over time. Historical data from different sources described in chapters 3.2.1 and 3.2.3, or summarized in Appendix spreadsheet C.1 and C.2.

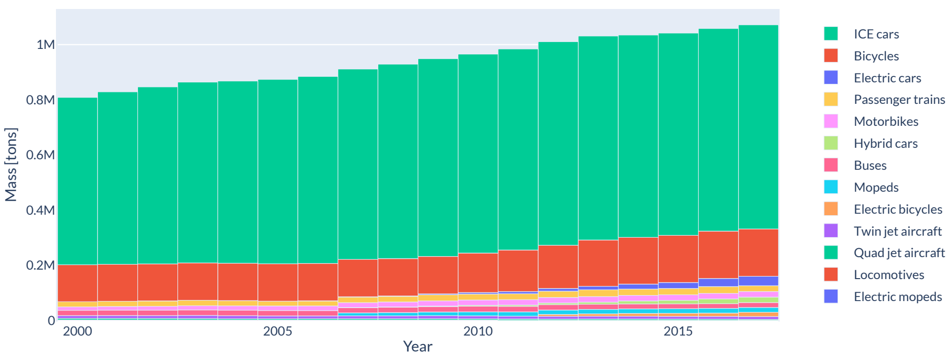


Figure 4.16: The stock of aluminium in passenger vehicles over time. Historical data from different sources described in chapters 3.2.1 and 3.2.3, or summarized in Appendix spreadsheet C.1 and C.2.

2016), and this reports that the content of an average bicycle is 42%. This could not be verified with data for material content of bicycles in the Netherlands, so this remains uncertain. However, aluminium is an increasingly cheaply available metal so it is reasonable to believe that more of it will be used in the future as people prefer lighter bicycles, and mass reduction for electric bicycles improves their performance.

Importantly, no data sets were found that describe the material content of ships. Even though the proportions used are expected to be low, the overall mass of ships means that even a low proportion contributes significantly to the total. The aluminium stock shows a very slight jump around 2007 and 2008, which is explained by the absence of data for motorbikes before this date.

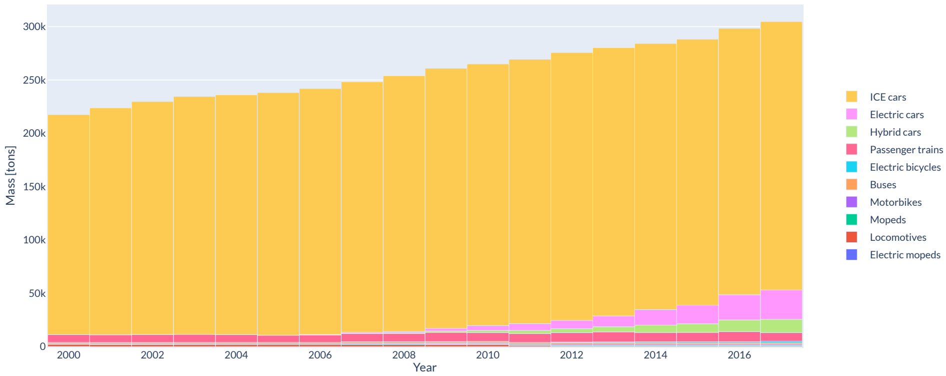


Figure 4.17: The stock of Copper in passenger vehicles over time. Historical data from different sources described in chapters 3.2.1 and 3.2.3, or summarized in Appendix spreadsheet C.1 and C.2.

4.3.3 Copper stocks in vehicles in the Netherlands

The stock of copper shows a strong and steady increase over time, with an important role for conventional cars, electric cars and hybrid electric cars. The contribution is surprising, as the 245 thousand electric cars contribute 8% compared to 239 thousand hybrid cars contributing 4% to the total in 2017 (fig. 4.17). This underlines

4.3.4 Critical raw material stocks in vehicles in the Netherlands

Critical Raw Materials (CRM) contribute only 0.32% to the total but the absolute mass of this material group at 74 120 tons is very significant. This is unsurprising, as vehicles are one of the main applications of CRM. Their mass was found to be strongly increasing and is mainly contained in the lithium oxides, cobalt and graphite used in batteries for electric personal cars, as can be seen in figure 4.18.

Other CRM stock does not show growth and includes Platinum used in combustion engines and Niobium and tantalum used in aeroplane jet turbines. The contribution of hybrid electric cars to the total is lower than that of electric vehicles even though their numbers are almost equal, simply because their CRM content is lower. Palladium and Neodymium show up in negligible quantities (<1 ton) and are contained mostly in electronic sub-components of vehicles as reported by the EcoInvent database, so it is difficult to verify the validity of these results.

Whilst lithium oxides and graphite are not in the EU communication for critical materials (*EC*, 2017), these materials were of importance in the (*EC*, 2018) Report on Raw Materials for Battery Applications, and recently were reported to be supply-critical in electrification transition (*Ballinger et al.*, 2019). For this reason, they are included in this chapter.

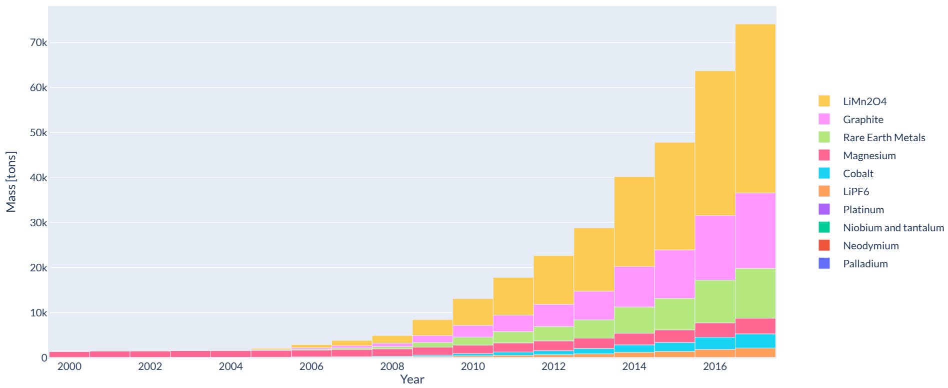


Figure 4.18: Mass of critical raw materials (and graphite and lithium oxides) used in vehicles over time, grouped by materials. In 2017, around 95% of CRM mass was contained in electric vehicles. Historical data from different sources described in chapters 3.2.1 and 3.2.3, or summarized in Appendix spreadsheet C.1 and C.2.

4.3.5 Mass of vehicles over time

Many vehicle types show a trend of increasing mass (see figures B.6(a) and B.6(b)). For cars and bicycles this is illustrated by the fact that their electric counterparts are heavier vehicles, but each vehicle type for which data was available shows this trend. This can be explained in two parts: for freight transportation, there is an economy of scale advantage for capacity enlargement. For passenger transportation electrification is one reason, but greater affluence might increase the demand for more expensive and heavy cars.

4.3.6 Conclusions from the historical stock of materials in vehicles

The stock of materials in vehicles appears to be increasing over time. This can be explained mostly by the increase in the number of vehicles over the past 17 years. However, another factor significantly contributes: the types of vehicles are undergoing a transition. On one hand, vehicles are becoming larger both for freight transportation and passenger transportation. On the other hand, vehicles with alternative powertrains are entering the transportation domain, and electric vehicles require larger amounts of valuable and supply-critical materials than the vehicles that they are replacing.

4.4 Prospective material stocks and flows in the Netherlands

Four different pathways will be contrasted with the 'Reference' (REF) pathway. This pathway is informed by the WLO-laag scenario (*CPB/PBL*, 2015). It represents a future where the current

Table 4.6: Material stocks and flows for vehicles in the Reference (REF) pathway. Data Appendix C.3.

	absolute			*relative increase to 2020*		
	Inflow [t/y]	Outflow [t/y]	Stock [t]	Inflow	Outflow	Stock
2020	1 445 000	1 196 000	36 810 000	0%	0%	0%
2030	1 595 000	1 339 000	39 350 000	10%	12%	7%
2040	1 632 000	1 384 000	41 860 000	13%	16%	14%
2050	1 758 000	1 499 000	44 380 000	22%	25%	21%

modal split stays the same as it has, and developments like electrification, transport as a service, and lifespan elongation stagnate. This was done for two reasons, (a) to reflect that this pathway does not aim to be a prediction, and (b) to better contrast the contribution of a single transition to material impact as a whole. Table 1 reminds us of the four pathways, as described in the Methodology chapter. The definition used to describe transition pathways is that of (*Turnheim et al.*, 2015) from the perspective of quantitative systems modelling, and the four typologies for transition pathways are used from (*Geels and Schot*, 2007).

4.4.1 Reference pathway

The 'Reference' (REF) pathway represents a future where the current share of modes and vehicles would remain constant through 2050. Transitions we are currently undergoing like vehicle enlargement and low emission vehicle replacement, are not represented in this pathway but are considered in the following pathways.

Under the assumptions for the REF pathway, the material stock for vehicles steadily increases by 21% by 2050 (table 4.6 and figures 4.19-4.21). The main contributors to growth are sea vessels and personal cars, and most of the growth is accounted for by steel. To achieve this level, the yearly inflow of steel contained in vehicles needs to grow by 24% in 2050 compared to 2020 (table 4.6).

In order to sustain the service delivered by vehicles in this pathway between 2020 and 2050 (30 years), the total cumulative inflow is estimated at 50 million tons of material; 40.4 Mt of Steel, 3.4 Mt of Polymers, 2.4 Mt of Aluminium, and 1.2 Mt of Copper. This number is disaggregated into all material groups in the Appendix table C.1. The magnitude of outflows in the same period was generally in the range of 75-95% of inflows. An estimation of the material turnover was made by counting the cumulative in- and outflows required to sustain the stock in the period 2020-2050.

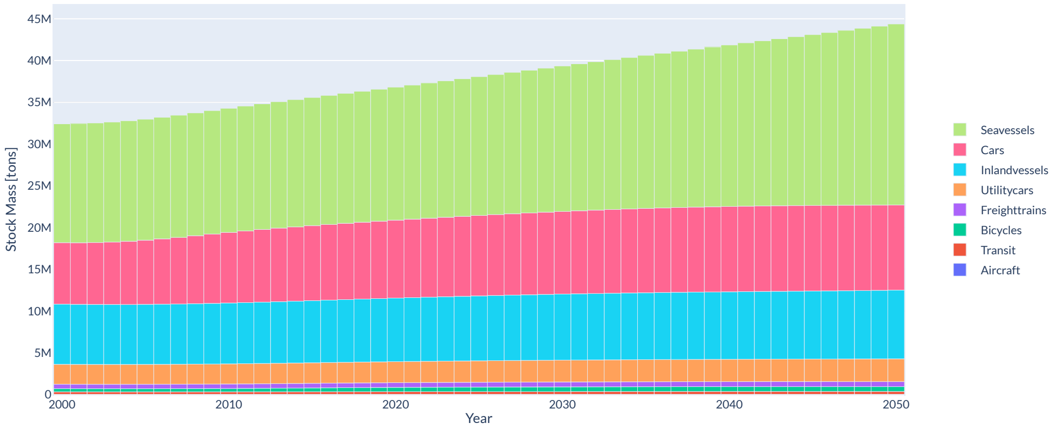


Figure 4.19: Stock of materials in vehicles under the Reference (REF) pathway. Data Appendix C.3.

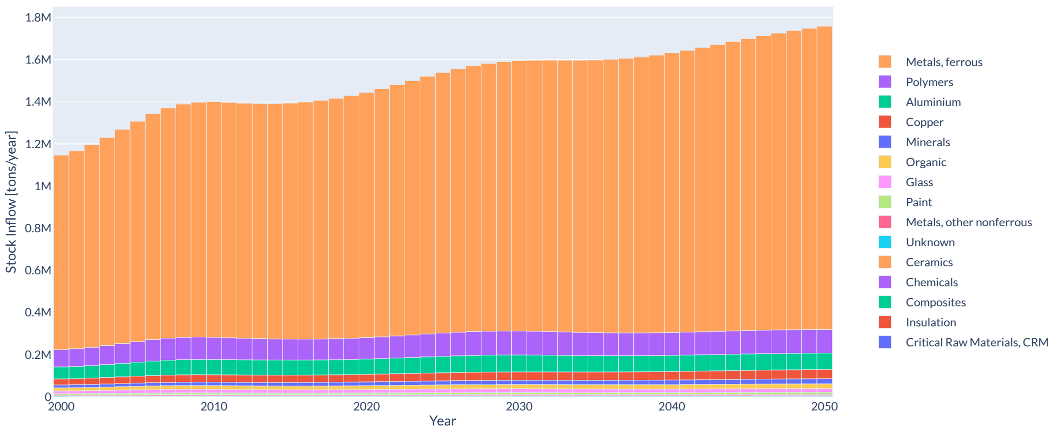


Figure 4.20: Inflow of materials in vehicles under the Reference (REF) pathway. Data Appendix C.3.

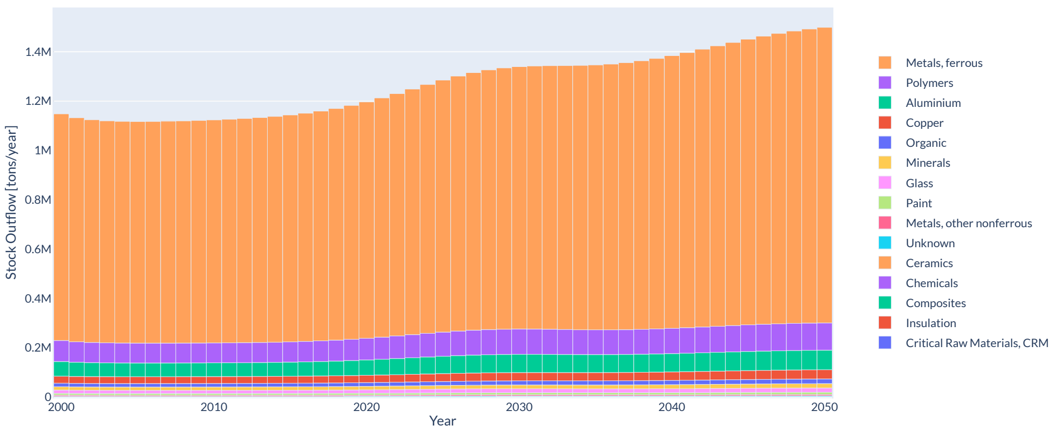


Figure 4.21: Outflow of materials in vehicles under the Reference (REF) pathway. Data Appendix C.3.

Table 4.7: Material stocks and flows for vehicles in the Substitution (ST) pathway. Data Appendix C.3.

	absolute			*increase relative to REF*		
	Inflow [t/y]	Outflow [t/y]	Stock [t]	Inflow	Outflow	Stock
2020	1 469 000	1 200 000	36 820 000	2%	0%	0%
2030	2 188 000	1 532 000	41 340 000	37%	14%	5%
2040	2 670 000	2 309 000	46 630 000	64%	67%	11%
2050	2 593 000	2 337 000	49 450 000	47%	56%	11%

4.4.2 Substitution pathway

This pathway is characterised by rapid developments undertaken by incumbent actors like existing vehicle producers, who 'substitute' parts of their existing practices (e.g. a new electric motor instead of a conventional petrol motor), whilst their business model remains largely the same. The endpoints for this pathway are 85% of passenger cars, 85% of delivery vans, and 20% of bicycles replaced by electric counterparts by 2050. Other freight vehicles are replaced by larger capacity counterparts following current trends.

The developments described under the 'Substitution' transition are projected to result in a stock increase of 14% compared to the REF pathway, with especially strong growth in the period 2020-2040 (table 4.7). Because of the large number of vehicles being replaced in this pathway, the yearly material in- and outflow rates are significantly higher than in the reference scenario. Cumulatively between 2020 and 2050, the material inflow is a factor 1.4x larger than the reference scenario. The developments especially reflect the substitution of internal combustion engine (ICEV) cars with electric cars (EV) (figure 11a).

Substitution of small capacity freight vehicles with larger capacity vehicles does reduce the mass of freight vehicles, but this reduction offset by the overall increase in the number of vehicles due to the expected increase in demand for freight transport.

The outflow of materials from vehicles is higher than inflow after 2030 when vehicles are projected to be deprecated before end of effective life due to replacement, and the first generation of substituted vehicles are deprecated. Important note: the only electric vehicle transitions modelled were those of passenger cars and delivery vans. Trucks were not included because of lack of data, and if a transition would happen for these vehicles, the material requirements would be even higher for the electric-related material groups.

The main materials required for this projected transition are in order of the size of yearly inflow: Steel, Polymers, Aluminium, Critical Raw Materials, Other nonferrous metals, and Copper. The pathway requires a cumulative inflow 1.4x larger compared to the REF pathway, of which the strongest change is for the material groups CRM (>1000x), Aluminium (2x), and Copper (2.5x) (Table C.2). That the required amount of materials is so high in this pathway, is not inherently

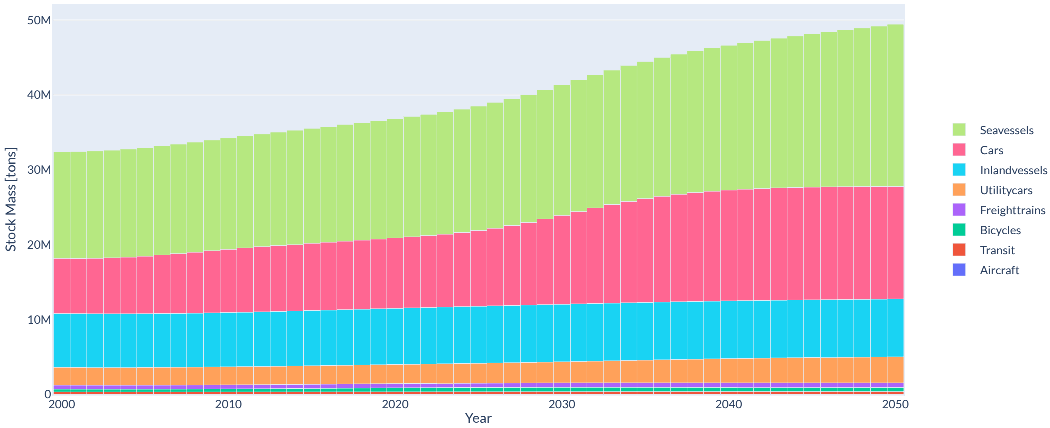


Figure 4.22: Stock of materials in vehicles under the Substitution (ST) pathway. Data Appendix C.3

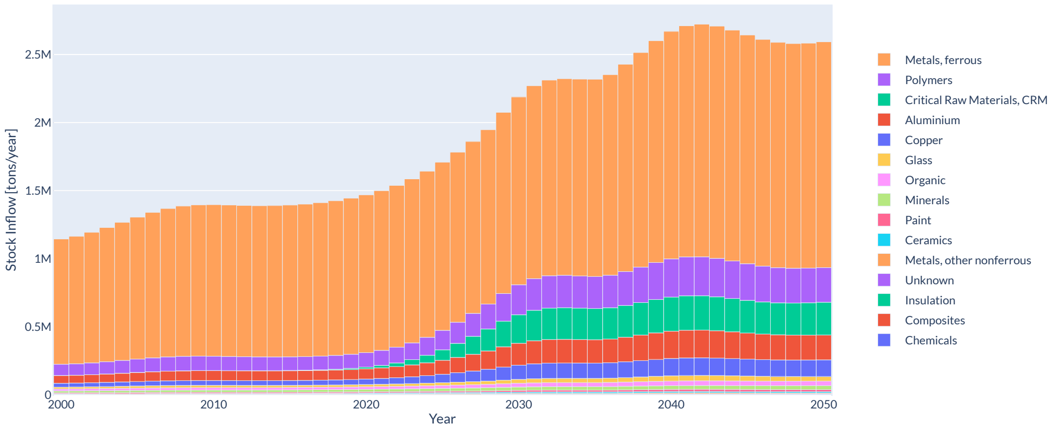


Figure 4.23: Inflow of materials in vehicles under the Substitution (ST) pathway. Data Appendix C.3

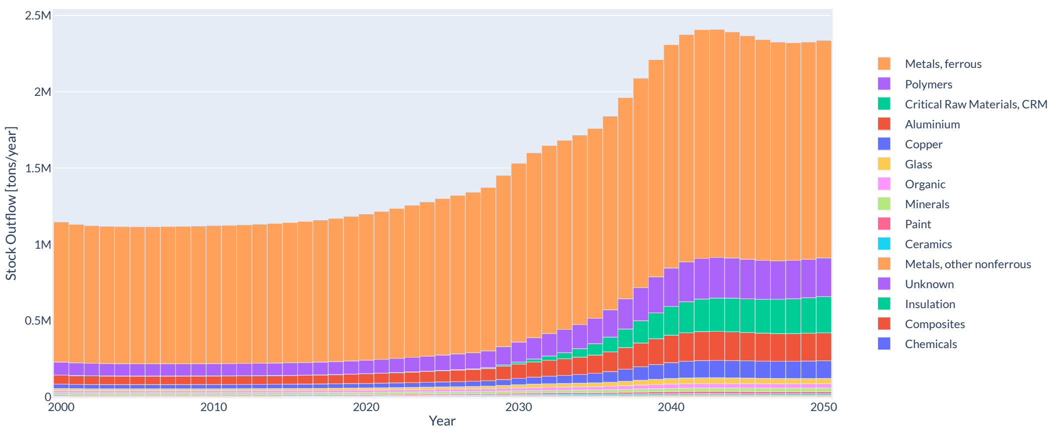


Figure 4.24: Outflow of materials in vehicles under the Substitution (ST) pathway. Data Appendix C.3

Table 4.8: Material stocks and flows for vehicles in the De- and Realignment (RA) pathway. Data Appendix C.3.

	absolute			*relative increase to REF*		
	Inflow [t/y]	Outflow [t/y]	Stock [t]	Inflow	Outflow	Stock
2020	1 370 000	1 195 000	36 500 000	-5%	0%	-1%
2030	1 130 000	1 327 000	36 350 000	-29%	-1%	-8%
2040	1 337 000	1 271 000	35 470 000	-18%	-8%	-15%
2050	1 383 000	1 147 000	37 230 000	-21%	-23%	-16%

bad or undesirable because although there is an upfront environmental impact of requiring more primary material, a proportion of this material is secondary, and it enables lower emission use of vehicles.

Surprisingly, in this pathway, the third-largest material group by inflow is Critical Raw Materials (CRM), which consists mainly of Lithium oxides and graphite anodes used in batteries. Of this material group, inflows are projected to surpass the 100 thousand tons per year in 2026, whilst outflows are only expected to hit 100 thousand tons per year around 3036, which has implications for the potential reuse of these supply critical materials. This highlights the importance of exploring production methods which rely on less valuable and supply critical materials or exploring other less resource-intensive ways of producing low emissions vehicles like retrofitting older vehicles.

4.4.3 De- and realignment pathway

This pathway represents a situation where new players enter the transportation sector and achieve rapid deployment and challenge the status quo, similar to how vehicle-sharing business models like 'Swapfiets' and 'Uber' took off in the Netherlands and around the world. However, these developments are highly uncertain and difficult to understand because they can involve new unknown actors and the transition requires behavioural change.

Transitioning to service models which decrease the ownership of vehicles appears to have a significant effect on the material demand. The reduction in material demand is proportional to the extent to which the effect can be implemented, and how fast the transition takes place. This pathway represents more effective utilisation of vehicles, through alternative servitization business models reducing the fleet of passenger cars by 50%, and bicycles by 25%. Two-way transportation similarly aims to optimise freight transportation by reducing the number of empty freight trips to reduce the fleet size by 25%.

Because this pathway explores how fewer vehicles can be used, it shows the strongest decrease in in-stock level: 19% by 2050 compared to REF (table 4.8 & figure 12). Note that no changes were modelled in this scenario for sea vessels because only a small share of ships ac-

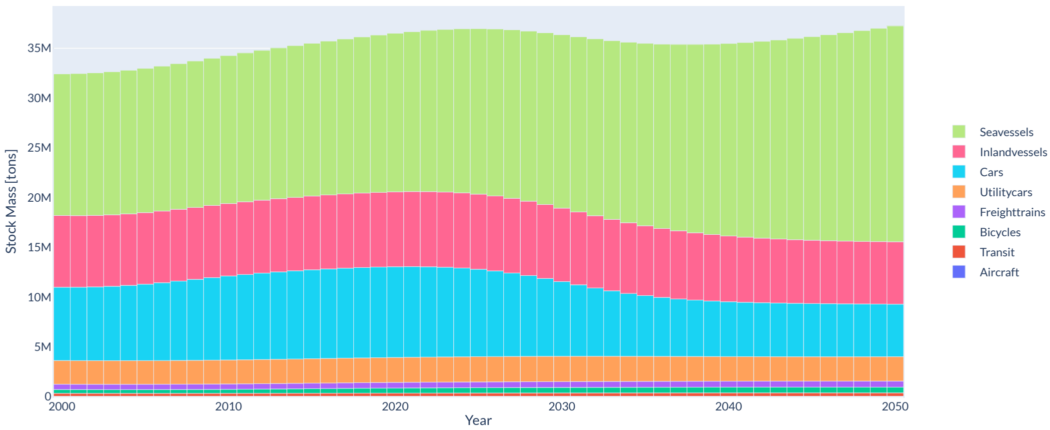


Figure 4.25: Stock of materials in vehicles under the De- and Realignment (RA) pathway. Data Appendix C.3.

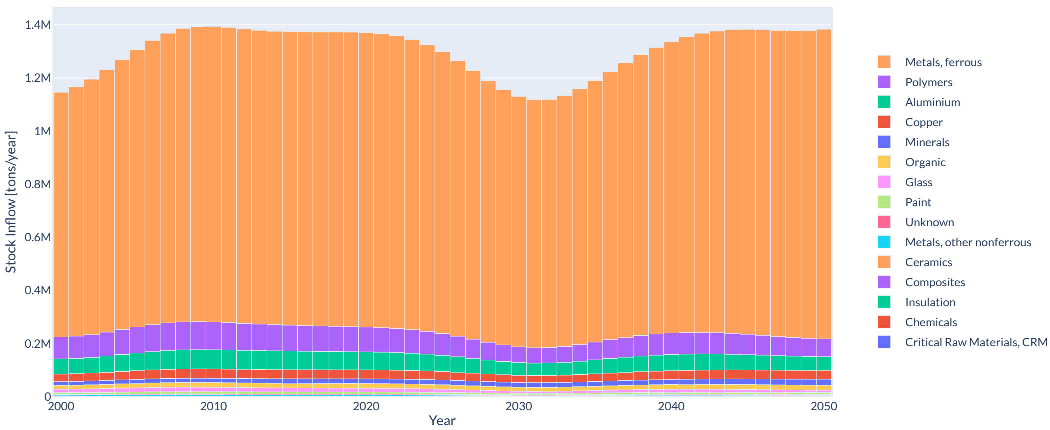


Figure 4.26: Inflow of materials in vehicles under the De- and Realignment (RA) pathway. Data Appendix C.3.

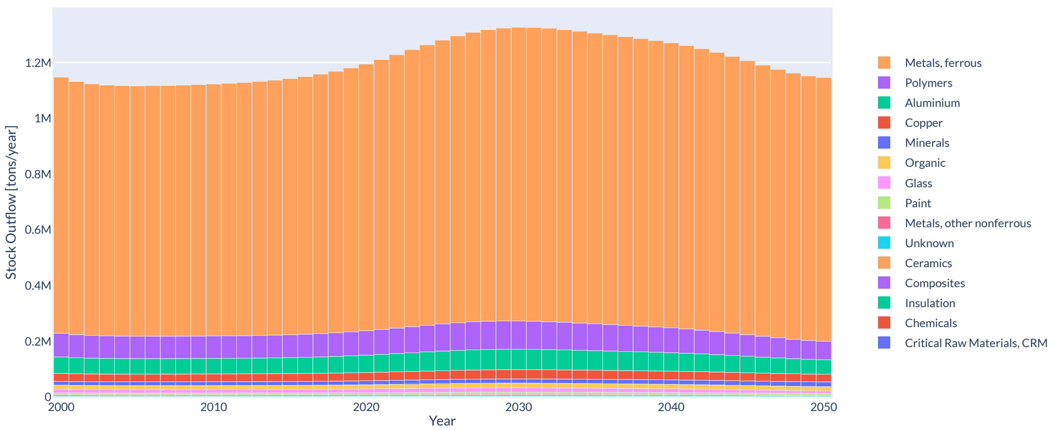


Figure 4.27: Outflow of materials in vehicles under the De- and Realignment (RA) pathway. Data Appendix C.3.

Table 4.9: Material stocks and flows for vehicles in the Reconfiguration (RC) pathway. Data Appendix C.3.

	absolute			*increase relative to REF*		
	Inflow [t/y]	Outflow [t/y]	Stock [t]	Inflow	Outflow	Stock
2020	1 434 000	1 186 000	36 810 000	-1%	-1%	0%
2030	1 303 000	1 048 000	39 350 000	-18%	-22%	0%
2040	1 224 000	975 500	41 860 000	-25%	-30%	0%
2050	1 177 000	916 900	44 380 000	-33%	-39%	0%

tually transport freight, most supply (offshore) marine services.

The increase in the utilisation of personal vehicles and bicycles through transport-as-a-service business models is projected to have a strong effect on the material demand, allowing material stock for vehicles to remain constant even as an increase in delivered service was modelled.

Valuable materials like CRM, Copper, and Aluminium show lower requirement in this pathway. Cumulative material demand for the period 2020-2050 shows a significant decrease of 20% compared to Reference. Cumulative outflows are higher than inflows for most material groups, opening opportunities for material reuse. (Table C.3)

4.4.4 Reconfiguration pathway

This pathway is characterised by incumbent actors like transportation companies gradually reconfiguring their practices by e.g. refurbishing, including better components in their products or adopting reverse supply chains. Transitions take a long time but having a big and lasting impact. This pathway does potentially conflict with other more disruptive transitions, for example, if you want to replace ICE cars with electric cars, you necessarily give up a longer lifetime. This pathway represents all vehicles increasing their lifespan linearly by a factor 1.5 of 2017 levels by 2050, which is a regression of a trend found in cars going back at least 20 years (Appendix, figure B.4).

The stock in the reconfiguration pathway by total remains relatively similar to the Reference pathway. However, due to increased lifetimes, the yearly in- and outflow rates are significantly lower, up to 45% less than in the REF (table 4.9). Because lifespan was assumed to be constant and a sudden linear increase is started in 2020, a peak can be seen in the in- and outflows around 2020 (fig. 4.29-4.30). This was done to allow for a fair comparison with the reference pathway.

The in- and outflows, however, are strongly different from REF in the sense that the reduction in material inflow into cars and inland ships more than makes up for the increase in material inflow for seagoing vessels. An increase in lifespan for vehicles does, however, result in that outflows are lower than inflows, because newly introduced vehicles have a longer life expectancy.

Material cumulative inflow shows an immense decrease of 40% in material inflows compared

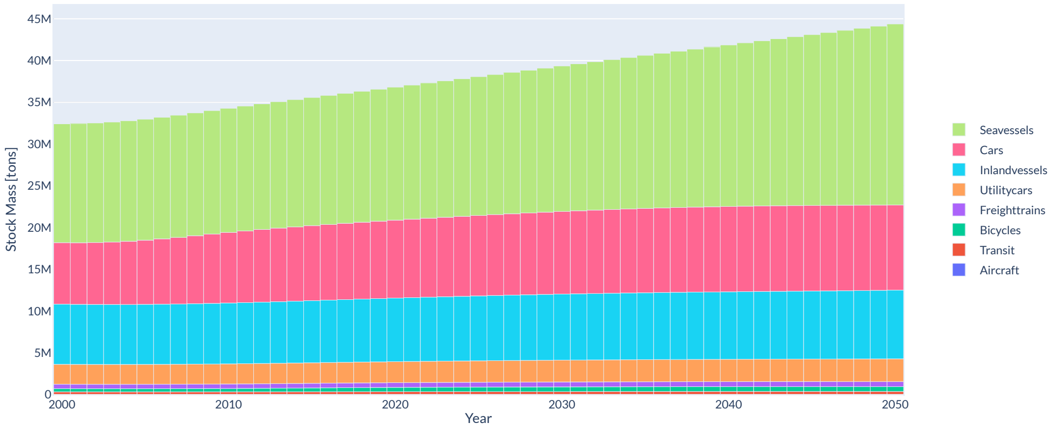


Figure 4.28: Stock of materials in vehicles under the Reconfiguration (RC) pathway. Data Appendix C.3.

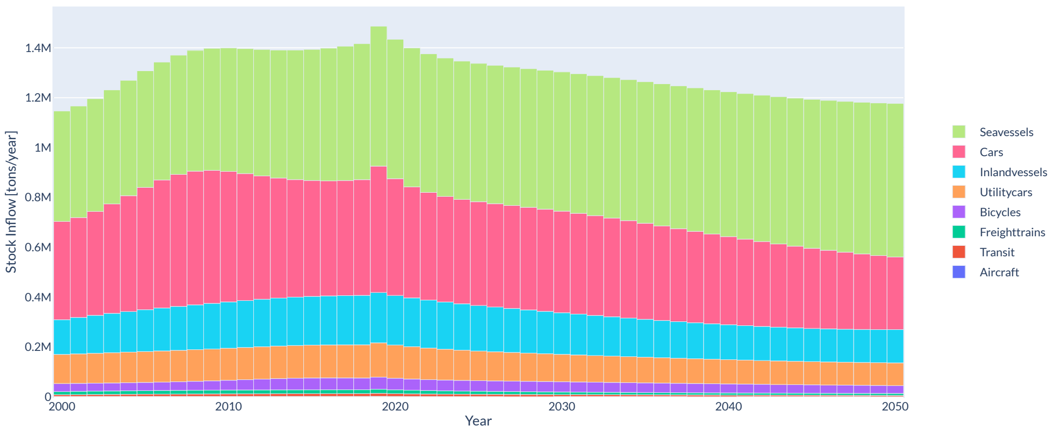


Figure 4.29: Inflow of materials in vehicles under the Reconfiguration (RC) pathway. Data Appendix C.3.

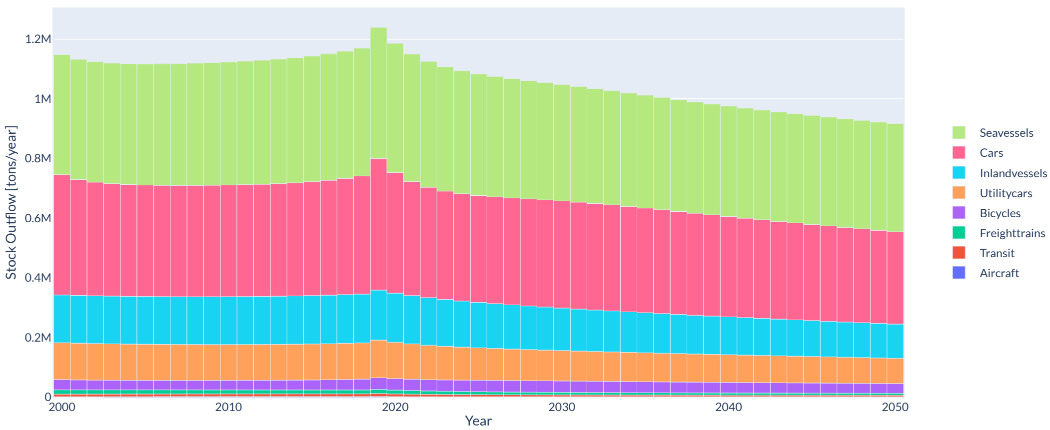


Figure 4.30: Outflow of materials in vehicles under the Reconfiguration (RC) pathway. Data Appendix C.3.

Table 4.10: Material stocks and flows for vehicles in the Transformation (TF) pathway. Data Appendix C.3

	absolute			*increase relative to REF*		
	Inflow [t/y]	Outflow [t/y]	Stock [t]	Inflow	Outflow	Stock
2020	1 441 000	1 196 000	36 820 000	0%	0%	0%
2030	1 485 000	1 335 000	38 940 000	-7%	0%	-1%
2040	1 459 000	1 334 000	39 830 000	-11%	-4%	-5%
2050	1 503 000	1 218 000	42 110 000	-15%	-19%	-5%

to REF (table C.4). This is interesting, especially for vehicles with a high material impact like the introduction of electric cars in the substitution pathway. One aspect that was not considered in this study is that refurbishment often requires an 'investment' of material to elongate the lifespan, but this is almost certainly less than the material required for whole new vehicles.

4.4.5 Transformation pathway

This pathway represents Modal Shift, for passenger transportation, this means a shift from cars to mass transit and for freight, it means a shift from road freight to rail and shipping freight. It represents radical and disruptive societal change, triggered by important actors including outsider groups criticising the existing system, actors who have the power to change institutional rules, and incumbent actors not able to solve the criticism.

The endpoints for this transition are a modal split of 12% driving, 63% mass transit, 20% s cycling, and 5% walking for passenger transport and 36% road, 27% rail, and 39% inland freight transportation. No modal shift was modelled for sea vessels because most Dutch ships are not freight vessels but (offshore) service ships.

The material stock required for this pathway is set to slightly grow (table 4.10), but remains 10% lower than in the Reference pathway. Especially passenger transportation vehicles require a dramatically lower material stock (53% less than REF pathway, figure 14a), whilst the transition from road freight to inland freight surprisingly represents a material stock increase of 13% (figure 14b). This does make sense as the required stock for inland vessels is larger than for trucks, but because of the longer lifespan of vessels in the long term, the material turnover could eventually be lower.

The decrease in the number of personal cars is so extreme in this pathway that inflow halts entirely over a 7 year period (fig. 14c), and extra cars are deprecated before end of life (fig. 14d). This seems unlikely to happen in the real world so the assumed rate of transition under this pathway is likely to be overestimated.

This extreme transition, however, does not have a marked effect on the material turnover,

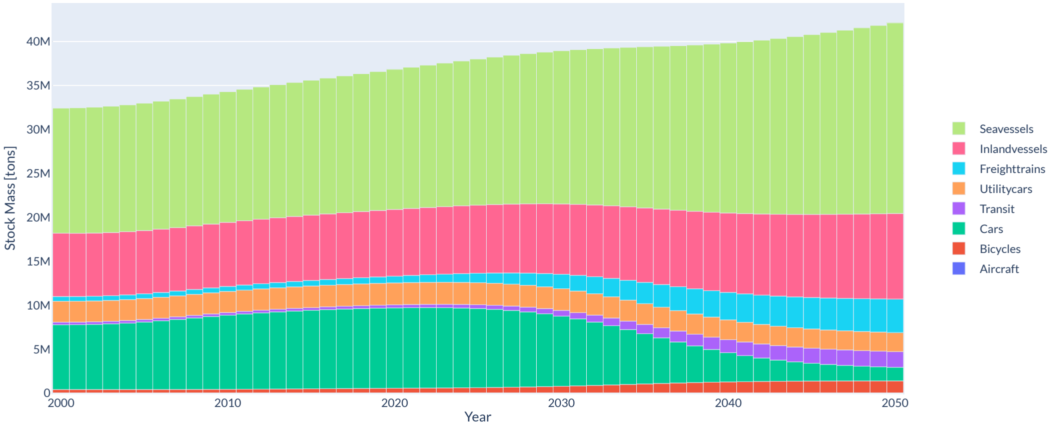


Figure 4.31: Stock of materials in vehicles under the Transformation (TF) pathway.

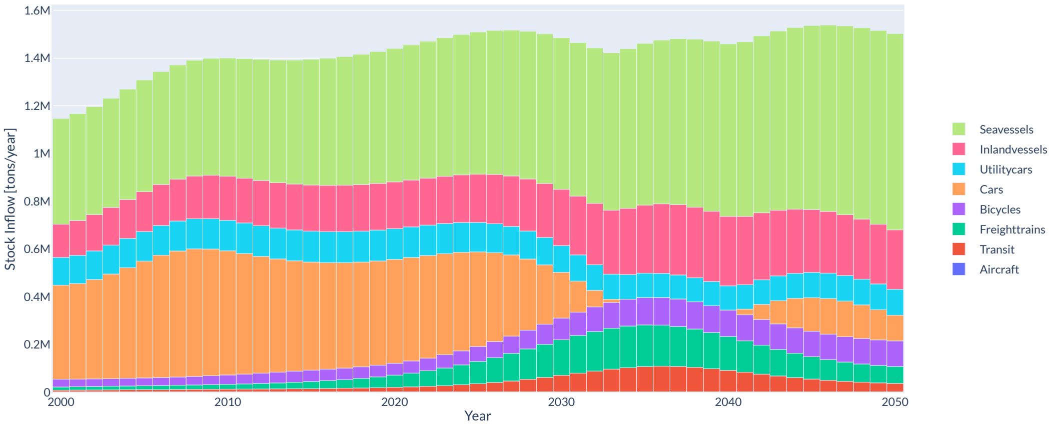


Figure 4.32: Inflow of materials in vehicles under the Transformation (TF) pathway. Note that the colors do not all match figure 4.31

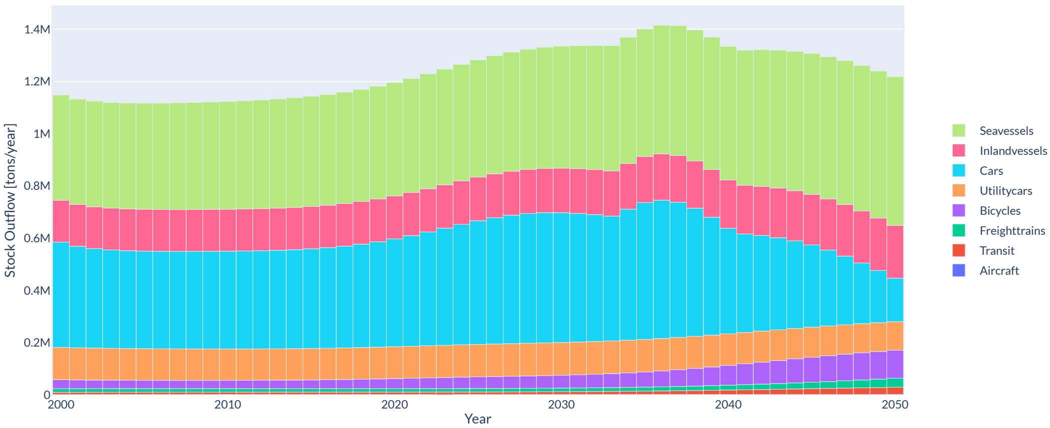


Figure 4.33: Outflow of materials in vehicles under the Transformation (TF) pathway. Note that the colors do not all match figure 4.31.

with the cumulative material in- and outflows remaining relatively unchanged compared to the REF pathway for the bulk materials (steel, polymers, aluminium, copper), but show a marked decrease for the materials used in electric vehicles (table C.5).

4.5 Transition pathways in quantitative modelling

Where conventionally, quantitative modelling studies design pathways according to certain end-points (e.g. the 1.5^oC pathway by the IPCC (*Allen et al.*, 2019)), fewer studies have designed pathways that reflect and compare the material impact of different policy choices or developments (*Wiedenhofer et al.*, 2019). This thesis aims to do just that, and take it a step further by placing the studied developments into a socio-technical context according to the typologies developed by (*Geels and Schot*, 2007).

Eight developments identified in the literature review are categorised by four transition pathway typologies introduced by (*Geels and Schot*, 2007). This helps to interpret the results by identifying the roles of influential and powerful actors, provides insight into the disruptive or symbiotic nature of developments, and provides insight into the timing rate of transition.

For comparison next to the material stock, the *cumulative in- and outflow* are compared. The cumulative inflow describes the total quantity of materials flowing in to of a system in a certain time range, which is essentially the dependence on primary raw materials. Of course, a certain percentage of metals are already recycled, but this is not covered in this thesis because of time limitations. The cumulative outflow represents the amount of material available from the Urban Mine. Between 2020 and 2050, different developments have different effects on the cumulative in- and outflows. For example, the Reconfiguration pathway which describes lifespan elongation has the same material stock but requires significantly fewer materials to maintain this level (table 4.11).

The quantified transitions can be compared with the socio-technical framework in mind. Electrification (the substitution pathway) represents minimal behavioural change, but comes at a significant material cost (table 4.11), especially when looking at valuable and supply critical materials. In comparison, lifespan elongation (the reconfiguration pathway) promises the strongest reduction in material requirement (table 4.11), but requires high levels of coordination and behavioural change.

Modal shift (the transformation pathway) requires immense social change but shows considerable material benefits, especially for passenger transportation, but not so much for freight transportation because few opportunities were identified with regards to modal shift. This pathway represents the one with most potential benefits to emission reduction from transportation because there is a shift from high emission (e.g. cars) to low emission vehicles (e.g. trains).

Transport servitisation for passenger transport and two-way freight trade (the realignment

Table 4.11: Comparison of stocks and flows for the different pathways. Data Appendix C.3.

developments:	*stagnation of the current situation*	*Introduction of low emissions passenger vehicles; Enlargement of freight vehicles*	*Passenger transportation as a service; Introduction of two-way trade in freight transportation*	*Lifespan elongation, refurbishment and modernisation in freight and passenger transportation*	*Modal shift in passenger and freight transportation*
pathways: .	**REF: Stagnation**	**Substitution**	**Realignment**	**Reconfiguration**	**Transformation**
Vehicle stock in 2050 [t]	44.4M	49.5M	37.2M	44.4M	42.1M
Cumulative inflows 2020-2050 [t]	49.9M	69.8M	40.0M	32.3M	46.2M
Cumulative outflows 2020-2050 [t]	42.1M	57.0M	39.0M	24.5M	40.6M
Steel inflow compared to REF	-	13%	-18%	-34%	-6%
Steel outflow compared to REF	-	16%	-7%	-42%	-4%
Aluminium inflow compared to REF	-	105%	-27%	-41%	-3%
Aluminium outflow compared to REF	-	76%	-10%	-43%	2%
Copper inflow compared to REF	-	153%	-21%	-35%	-13%
Copper outflow compared to REF	-	110%	-8%	-42%	-6%
CRM inflow compared to REF	-	114781%	-24%	-42%	-33%
CRM outflow compared to REF	-	66428%	-9%	-44%	-6%

pathway) transition represents the strongest decrease in vehicle material stock. This transition, however, is characterised by game-changing actors with innovative solutions (like Swapfiets or uber) challenging and disrupting incumbent actors with their innovations, and the development of these kinds of innovations are notoriously hard to predict.

5

Conclusions and discussion

THIS THESIS DEVELOPS AND APPLIES prospective material flow analysis models to explore long-term stocks and flows for virtually all vehicles in the Netherlands in order to develop knowledge for the urban mine. This knowledge allows for better planning of the circular economy because it gives insight into the material requirements and the potential for urban mining. The method used in this thesis extends the current practice by systematically comparing the material impact for five transition pathways, which represent different sustainable transportation developments and places them into a socio-technical context. Empirical demographic data for vehicles are used to inform lifespan distributions and model in- and outflows. Driving forces are based on passenger and freight transportation performance projections.

The conclusion (5.1) answers the research questions and presents novel insights. The discussion (5.2) interprets the results and places them in an academic context. The recommendations (5.3) address academics, decision-makers, and the general public with lessons from this thesis.

5.1 Conclusions

In order to develop knowledge about the urban mine for vehicles, and to analyse what the potential impact is of sustainable transportation options on circular economy policy in the Netherlands, a prospective material flow analysis was conducted. The method was used as a comparative tool to analyse the material impacts of different developments for sustainable transportation, and the concept of transition pathways was used to systematically compare the different developments in a socio-technical context. Two interpretations of transition pathways were encountered during this research and were found to be complementary in combination with prospective MFA. The quantitative modelling interpretation allows for comparison of the material impact of different pathways, and the socio-technical transition analysis interpretation allows to place the results in a socio-technical context which allows the identification of important actors and their roles, and the nature of the interactions of these actors. Empirical data for vehicle demographics were used to model lifespan with Weibull distribution functions, which provides significant improvements regarding a more realistic dampening effect for the dynamic response of in- and outflows to changes in stock, compared to conventional methods (without distributions) of modelling with a constant lifespan.

The material stock in vehicles in the Netherlands has increased over the past two decades, from an estimated 28 Megatons to 36.3 Mt in 2017. Of the 2017 stocks, most of the mass (66%) consists of inland and seagoing ships, followed by passenger cars (26%), utility road vehicles (5%), Bicycles (1.8%), Mass transit (0.7%), and Aircraft (0.06%). Steel is the largest material group in most vehicles, and overall accounts for the highest proportion of the total mass (82%), followed by Polymers (5.6%), Copper (3.4%), and Aluminium (3.4%). Another important contribution is Critical Raw Materials (CRM), which only contribute 0.2% but this equals a significant stock of 74 thousand tons of valuable and supply critical materials. Two causes were found for the observed increase in material stock: (a) the number of vehicles has grown, (b) virtually all vehicle types are becoming heavier over time and car electrification accelerates this growth. One other trend implies a decrease in vehicle stock: that higher capacity vehicles are taking over lower capacity vehicles, but the growth in the number of vehicles more than cancels out this reduction.

A reference pathway was chosen to represent a situation where our transportation systems do not change from the current situation, and was based upon the WLO projections for transportation in the Netherlands. The stocks are expected to grow in the next three decades to some 44.2 Mt in 2050. Between 2020 and 2050 dynamic prospective MFA was used to show that a cumulative inflow of materials or primary material demand will be 48.9 million tons, and 44.1 million tons will be released from vehicles at end-of-life for the urban mine. This situation represents the *reference* (REF) pathway, and is compared to four pathways which describe a range of different developments.

After literature review and an expert interview, several current and expected sustainable transportation developments were chosen to analyse their potential material impact on both passenger and freight transport vehicles. (i) electrification of the vehicle fleet, (ii) servitisation and more efficient utilisation of the vehicle fleet, (iii) lifespan elongation of vehicles, and (iv) modal shift towards low emission modes of transportation. These developments were categorised into four socio-technical transitions typologies for comparison.

The *substitution* pathway explores electrification and freight vehicle capacity enlargement. These developments reduce emissions, but comes at a significant material cost, requiring a vehicle stock of 50 Mt in 2050 (factor 1.12x reference) and a cumulative inflow of 70 megatons (1.4x reference, 2020-2050) for the transition. Several valuable materials related to electric drivetrains will require a disproportionate increase in demand: valuable materials like Copper (2.53x reference), Aluminium (2.1x reference) and Critical Raw Materials (1100x reference). This also means that a significant amount of material is available from the urban mine after a certain delay- during the same period, 57 Megatons of material is released, of which 39 Mt ferrous metals, 5.6 Mt polymers, 4 Mt Aluminium, 3.2 Mt CRM, and 2.2 Mt copper. Under the assumptions of this scenario, the model would force existing vehicles to deprecate before end of life, which reduces the effective lifetime and is detrimental for material efficiency. Using more valuable materials however incentivises reuse, but a significant delay is expected between when materials are required and when they are released.

The *realignment* pathway assumes the rollout of passenger transportation-as-a-service solutions and freight two-way trade practices to utilise vehicles more efficiently. In this pathway, the material stock in vehicles is reduced the most, simply because fewer vehicles are required. The stock is reduced by 14% by 2050, the cumulative materials required during 2020-2050 would be reduced by 20%, and the materials available for the urban mine are also reduced by 10% compared to the reference scenario.

The *reconfiguration* pathway explores the increasing the lifespan of vehicles through better engineering and increased refurbishing. This hardly affects the size of the vehicle stock, but the cumulative material requirement and the materials available for the urban mine are significantly lower, showing a reduction of around 40% for most materials.

The transformation pathway explores a radical systemic change: a modal shift that favours low emission modes of transport. The effects of passenger transportation are different from those on freight transportation. For *freight transportation*, a modal shift from road freight to inland shipping and rail freight would increase the material stock for freight by 13% because inland ships are significantly heavier than the trucks they replace. They do, however, have a longer lifespan, so the increase in material demand is seen as an upfront material investment. For *passenger transportation*, a modal shift from driving to mass transit and cycling would reduce the passenger vehicle material stock by up to 53% because trains and buses are significantly lighter than the cars they replace. A large number of materials currently used in cars will be released from the stock.

5.2 Discussion

The first section (5.2.1) will focus on interpretation of the results, and the second section (5.2.2) places these results into a wider academic context.

5.2.1 Interpretation of results

Premise

This study explores different pathways which were informed by existing trends, however, the pathways do not aim to predict the future. The Netherlands is currently undergoing several transitions which are complex, interrelated, and difficult to predict (e.g. the rapid adoption of electric vehicles). Various transitions for the future were identified and are separated as much as possible, in order to be able to identify individual effects and avoid missing insights because of interference.

This approach was chosen because it allows contrasting the impacts of different options and transitions. The philosophy underlying this approach is that there is no correct way to model the future, and the only reason to still attempt to do so is if the assumptions are clear and the insights that are gained are useful. The comparative approach to MFA was found to be useful in the sense that the material impact of transitions was able to be quantified and using the transition pathways framework allowed to place these impacts in a socio-technical context.

The five pathways discussed in this thesis are separated by design. However, the future is likely to contain combinations of these transitions. Where the different developments or pathways do obviously interact or seem to be incompatible or complementary, clear analyses were given. However, it is up to the readers to use their own insight and expertise to make a final judgement on how these possible developments might interact with each other, and what the future of transportation should look like.

On using the WLO-low background scenario

The WLO scenarios (*CPB/PBL*, 2015) were used to inform the driving factors for different modes of passenger transportation, different modes of freight transportation and air traffic. These projections are based on expected developments for population and economic growth.

The low scenario was selected because this represents a minimum in terms of material consumption, as material use increases with both population growth and economic growth (*Krausmann et al.*, 2017). The results of this thesis should, therefore, be interpreted as a minimum regarding the amount of material needed in the future and the minimum amount of materials expected to be released from vehicles.

Because it is likely that the actual economic and population growth are going to be higher than the low-scenario, the material demand is likely to be higher than modelled in this thesis. The WLO-high scenario projects a 10% higher passenger transportation demand, a 33% higher freight transport demand, and a 130% higher flying demand in 2050 compared to WLO-low. If the goal would be to explore the likely material demand and urban mine, different assumptions should be considered.

On prospective modelling

The projections in this study do not aim to be predictions, instead, an analysis of the future are done based on what falls within reasonable assumptions for technology and behaviour. 'Reasonable' is understood as following: if there is evidence that a certain development is currently feasible at a national scale, then it is valid for this thesis. This means that existing, small-scale alternative fuel technologies are not considered if the evidence supporting large scale adoption is missing, even though the potential impact for emission reduction is large. This implies that results from this study do not account for potentially game-changing technologies or radical transformations like a new battery concept or adoption of a new mode of transportation like a Hyperloop.

Data and uncertainty

The Netherlands is a well-suited country for a study of this scope, as national accounts of many vehicles are detailed. A few exceptions are in place: no usable data was found for metros and trams (which were excluded from this study) and for trains (which were included because of their important contribution to mobility, but with data of questionable reliability).

In contrast, material content data for vehicles are extremely difficult to find, and the quality of this data varies wildly, ranging from acceptable quality for (e-) cars, (e-) bicycles, trucks, and buses to exceptionally bad for aircraft (which represent an aircraft as a homogeneous block of aluminium and polyethylene). Even with good quality data, the results remain uncertain as there are many different types of cars using very different types of materials. It is up to producing companies, and regulators to choose to force reporting on this information, which is essential in enabling a circular economy.

Because of this unavailability of data for many vehicles, it is impossible to achieve a similarly high level of detail between the different types of vehicles that are analysed, simply because data does not exist. Averages of vehicle types are assumed, meaning that the results are valid at a national scale and cannot be used to assert performance at the individual level. If one would require more granularity (e.g. the use of more lightweight materials in cars over time), it makes more sense to focus on a smaller subset of vehicles.

Similarly, because not a single material but many are included, the quality of the results are affected, as it is impossible to use a similar level of quality control for all the materials required in this thesis, but aiming to include an exhaustive bill of materials for all vehicles would allow for the identification of material hot spots and development of end-of-life strategies for not only valuable or significant materials but all materials for which data can be found.

This study assumes that current technologies and practices regarding vehicle production will stay roughly the same in the future. This is not a very reliable assumption, but holding this assumption does give an indication of where the current practices should change if a similar transition would be attempted. Also, data limitations regarding the material content of different types of (more modern) vehicles are absent, if these data become available it could be possible to represent the future in a more dynamic and realistic way.

Another uncertain factor is the lifespan of electric vehicles, as most electric cars and bicycles that have been sold are yet to outlive their own warranty period. Anecdotal evidence shows that electric bicycles are reported to have been deprecated due to battery failure much earlier than their nonelectric counterparts, but quantitative (average) data is essential to answer this question. Especially as this study shows how large the material impact is for an electric vehicle transition, it is essential to elongate their lifespan as long as possible to keep material impact within manageable levels.

Comparing models with the present situation

If one would relate the pathways that were explored in this thesis to the current state of transportation in the Netherlands, and the direction of current transitions we are undergoing, several things stand out.

The rate of electrification of cars is already strong, and might even overtake the projections shown in this thesis if one looks at the historical growth of stocks. This thesis does underline the fact that this transition will come at a material cost, and recent studies have suggested that a full transition would not be equitable from a fair resource use perspective (*Bosch et al.*, 2019).

Another pathway that seems compatible to the current situation to a certain extent is that of reconfiguration and lifespan elongation, as certain vehicles like cars show this trend, but others like buses and trucks show the opposite, which is in part to blame on environmental regulations requiring newer lower emission vehicles which hurt the lifespan and material efficiency.

The realignment pathway explores how we collectively could use fewer vehicles to deliver the same amount of service, whilst data suggests the opposite: that the vehicle fleet is growing even as the use of these vehicles is declining. It seems as if a change of mindset is required to if we would want to explore this pathway, as the nature of this transition requires a behavioural change of end-users.

The transformation pathway explored in this thesis represents massive changes to transportation systems, but this option has by far the most potential to reduce reliance on fossil fuels and comes closest to complying with climate goals. The material cost of this tradition is unremarkable, even compared to doing nothing, however, a transformation of the scale explored in this thesis is unlikely because of the immense changes required in all levels of the socio-technical landscape.

All in all, the future is expected to be a combination of the pathways explored in this thesis and then some that were not foreseen or could have been foreseen by the author. Hopefully the results from this thesis aid in the understanding of the material implications of current choices regarding the circular economy.

5.2.2 The wider academic context of this thesis

Prospective Material Flow Analysis

Studies applying prospective MFA were found to focus mainly on the built environment in Europe and East Asia. The material scope often includes a select subset of materials like concrete or steel. Recently, more studies have aimed to consider other parts of society, like consumer electronics and passenger cars (*Huisman et al.*, 2016; *Deetman et al.*, 2018), and this thesis aims to contribute by including all other road vehicles like company/utility vehicles and two-wheeled vehicles. Aircraft, rail transportation, inland shipping, and sea shipping were also considered. Using the bottom-up approach, as many materials were considered as available data would allow.

Using the Weibull distribution in stock and flow modelling

This thesis confirms that lifespan of materials remains a crucial and uncertain factor required to model material flows (*Müller et al.*, 2014). Whilst it has been shown that the choice of lifespan distribution does not have significant effects on the results (*Kleijn et al.*, 2000), this thesis provides evidence that using a fixed lifespan (compared to of a lifespan distribution) strongly overestimates the dynamic response of in- and outflows.

Assuming a fixed lifespan is especially problematic for subjects where there is evidence that lifespan shows stochastic behaviour, as was found with most vehicle types in this study. Using a lifespan distribution dampens the delayed impulses that result from changes of stock over time, and does so in a manner that seems to be consistent with the behaviour observed in empirical data. This is considered to be favourable to assuming a fixed lifespan, where noise resulting from changes in stock levels persist throughout the modelling period instead of being dampened. This does not influence the total amount of available or required materials, but if one would aim to identify when peaks of material demand or availability would arise, it becomes very important.

Where studies use the Weibull distribution, often the method was not explicitly described, which made it difficult to replicate. This thesis aims to contribute by explicitly reporting on the method used, and by validating the parameters used with demographic data for vehicles.

Using transition pathways in comparative prospective MFA

This thesis identifies that there remains confusion in the field of MFA about the use of concepts like *scenarios* and *pathways* which are sometimes used interchangeably. Some studies will report to consider different *scenarios* and interpret this as conducting a sensitivity analysis on key assumptions. Other studies will report the use of *scenarios* to consider distinct paradigms e.g. *circularity scenario* or *dematerialisation scenario*.

Literature review uncovered potential compatibility between the interpretations of *transition pathways* used in quantitative modelling (*Turnheim et al.*, 2015) and *transition pathways* used in the multi-level perspective of transitions in society.

Combining these two concepts allowed for both the comparison of material impact of distinct transitions, and with interpreting these impacts from a socio-technical context. It was valuable in the sense that it allows the identification of important actors in particular transitions, and importantly giving indications of the possible speed of transitions.

Whether to account for in-use materials

This thesis focuses only on the materials residing in vehicles, according to the state of the art methods used in Material Flow Analysis (*Müller et al.*, 2014). MFA focus on these materials because from a waste management perspective they are the secondary raw materials that will be released at the end of life.

This means that the materials used in the production of the vehicles, the materials leached into the environment during use, and e.g. fuels required for operation, are not considered. To combine these materials used during other life cycle stages with MFA, is an experimental field that combines material flow analysis with life cycle assessment. However interesting, this field is still far from developed (*Van der Voet*, 2011).

5.3 Recommendations

Recommendations are split into three relevant audiences: academics in the field of Industrial Ecology and Material Flow Analysis (5.3.1), decision makers in both public and private sectors (5.3.2), and the general public who might wonder what they might learn from the results from this thesis (5.3.3).

5.3.1 Recommendations for academics in the field of Industrial Ecology

Further research on the urban mine for vehicles

When planning for a circular economy, the first step is to account for materials in a system, the second to quantify the in- and outflows, the third step to quantify which proportion is reusable as an urban mine, and the last is to actually do it. This study aims to give a head start by completing the first two steps for a wide range of vehicles. The recommendation for future research about the urban mine and circular economy for vehicles is to further analyse the in- and outflows at a more detailed level and to quantify how much materials are actually accessible for reuse, and how much of the primary material inflow can be reduced by replacing them with secondary materials.

This is especially interesting because this thesis shows that ships contribute most to the material stock and flows, but very few materials are expected to be available at end of life due to the fact that most ships are exported at end of use (*Boers*, 2019). A similar trend was found for cars, where an increasing number of cars are exported internationally instead of dismantling within the Netherlands (*BOVAG-RAI*, 2019a). For other vehicle groups, it remains difficult to find data describing what happens to vehicles at the end of life, and how many are exported, as the photograph in figure 5.1 illustrates.

Figure 5.1: *"At shift-change time at the numerous tourist hotels at Guardalavaca a fleet of former Dutch buses carries workers in and out. Most show Dutch destinations!"* (*Flett*, 2008, Cuba)

Material content data

One major limitation to the analysis in this thesis is the quality and variety of data describing material content in vehicles. To be able to make reliable assertions is entirely dependent on reliable data regarding material content. This thesis shows where the gaps in data lie, and it is up to academics to publish, review, and improve material content data for future use. As it stands, the development of methodology seems to be far ahead of the quality of data for vehicles.

On using MFA as a comparative tool

Achieving a more sustainable society depends on large transitions, and like similar studies, for example, the energy transition, this thesis underlines that some transitions come with significant material impacts. To understand where bottlenecks lie, systematically quantifying and comparing the material impact of different options for the future is strongly recommended if the underlying assumptions are clearly communicated (*Turnheim et al.*, 2015).

The Transition Pathways framework (*Geels and Schot*, 2007) was found to be compatible with quantitative approaches, and helps to interpret of the socio-technical context of these options, and gives valuable insight into the role of key actors in transitions and the rate of transition. But to find out which framework is most useful to answer these kind of questions, a comprehensive literature review is recommended where different options are considered.

On combining life cycle assessment and material flow analysis

Next to analysing the end-of-life materials in vehicles like is done in MFA, many other material flows are associated with the use of vehicles, like fuels and waste from production and repair. Combining the analysis of the end-of-life materials and of the materials used in other life cycle stages is extremely interesting, but this is an experimental field which is far from developed (*Van der Voet*, 2011). This is a topic that is expected to contribute greatly to a more comprehensive understanding of materials used in society. Even though this thesis does not cover this subject, its data and findings could be an interesting contribution to future research that would aim to do this.

On using lifespan distributions in stock and flow modelling

Developing the stock- and flow model using Weibull distributions, it became clear that most studies do not clearly report on how they implement these distributions which makes it difficult for practitioners to replicate results. It is recommended that reporting on the use of statistical methods with regards to lifespan is improved to maintain transparency. Also, using a fixed lifespan tends to exaggerate the dynamic response of in- and outflow to changes in stock. This thesis examined stock demographics, and suggests that the stochastic behaviour of lifespan strongly dampens the dynamic response of in- and outflow to changes in stock levels.

5.3.2 Recommendations for decision-makers

Vehicle electrification contributes to sustainability by reducing emissions and reducing dependence on fossil fuels for transportation service and is growing rapidly. However, this research shows that electrification has a significant material demand, and that replacing existing cars with electric ones will not contribute to circular economy policies which aim to reduce primary material extraction. Embracing electrification is essential to reduce emissions and so it should be accompanied with initiatives that reduce reliance on driving and improve the effective utilisation of vehicles to indeed continue to reduce primary material demand.

Public mass transit systems are a keystone for sustainable mobility which power some of the largest and most productive cities in the world. To reduce material impact, the role of this mode of transportation should only grow by replacing driving, but this would also require large investments in infrastructure.

Some vehicles, like cars, show a hopeful trend where lifespan is increasing, which improves resource efficiency, but for other vehicles, this trend does not hold. Some older utility vehicles are even forced deprecate early to comply with environmental regulations. Implementing reverse supply chain solutions like modernisation and refurbishing to elongate the lifespan of vehicles is a time-consuming reconfiguration of current practice. However, many great examples exist (fig. 5.2) and this is an option that has to be considered by manufacturers.

Adopting alternative business models which supply service instead of selling as many products as possible should incentivize more efficient use of fewer vehicles. Policymakers should be aware of such initiatives and allow for experimentation, but only if they deliver what they promise, and do so in an equitable way that works for all.

One of the main limitations of this study is the availability of data describing the material content of vehicles. If manufacturers were to include reporting on materials used, planning for end-of-life scenarios of individual vehicles would become easier, and analysis of vehicles at the aggregated level would improve.

(a) SGM passenger train in original 1972 paintjob. (b) SGM after modernisation in 2015.

Figure 5.2: SGM passenger trains that were built in 1972 are only expected to leave service starting in 2020. (*Van Vulpen*, 1995; *Berkelaar*, 2015)

5.3.3 Recommendations for the general public

From a circular economy perspective, the results of this thesis underline that large material efficiency gains can be had with a relatively noninvasive action: elongating the lifespan of products. If a transition is necessary to lower emissions, retrofitting and modernisation are potentially cheap and low material requirement alternatives for which great examples exist, and which have to be considered.

A modal shift can strongly reduce the emissions of transportation, but this means embracing low emission modes of transportation like mass transit, and use driving only as a niche solution. This transition provides the strongest reduction in emissions at a relatively low material cost, but it relies heavily on behavioural change. Such a transformative transition relies on criticism of the status quo and leading examples showing how things can be done differently.

Figure 5.3: A 1972 (48-year old) Citroen DS retrofitted with an electric drivetrain (*Reins*, 2019).

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A

Appendices to the Literature Review chapter

A.1 On the concepts of Industrial Ecology and Circular Economy

The term *Industrial Ecology* draws a parallel between natural ecosystems and industry, which juxtaposes current industry in society as inefficient ecosystems with ever-accumulating waste and pollution in contrast to natural ecosystems where waste flows are rather by-products which are never lost but are indefinitely used as resources by a network of actors in a cyclical chain of interdependent organisms (*Lifset and Graedel*, 2002). However appealing, this biological analogy has limitations (*Boons and Baas*, 1997; *Erkman*, 1997), in the sense that biological systems tend to local equilibrium and are driven by evolutionary mechanisms as opposed to industries which are driven by (local and non-local) socioeconomic drivers. Also, biological system boundaries are entirely separate from system boundaries for industrial or society. Arguably, the value of the biological analogy lies in the emphasis on the inter-relatedness of actors in systems, and reframing waste instead as a by-product with an inherent value.

Also, *Van der Voet* (2011) calls for hybrid approaches to the traditional Industrial Ecology tools by integrating methods to be able to explore both the micro and macro levels. The integration of these inherently very different tools show that the scope of Industrial Ecology tasks is becoming wider; instead of analysing just the life cycle of a single service, or the flow of a single substance in a limited geographical boundary, it seems that IE analyses are growing to include ever larger parts of what has been called the socio-economic metabolism (SEM) by *Pauliuk et al.* (2015).

Another modern and important concept associated with the implementation of Industrial Ecology practices is the concept of Circular Economy (CE). This concept can be traced back to the *Boulding* (1966) conceptualisation of *spaceship earth* but only emerged into policy in the 1980s (*Pearce and Turner*, 1990) which since evolved as a paradigm to improve resource efficiency and reduce environmental impact by closing material and energy loops (*MacArthur*, 2013).

The *Ghisellini et al.* (2016) review describes that the ultimate goal of a CE appears to be to decouple environmental pressure from economic growth. So far, CE has proved to be a prominent and effective conceptualisation in the efforts of many countries around the world to develop environmental policies that improve resource efficiency (*Ghisellini et al.*, 2016; *McDowall et al.*, 2017).

However, several studies have substantiated criticisms of these conceptualisations. *Prieto-Sandoval et al.* (2018); *Homrich et al.* (2018) admit that definitions of CE vary significantly between practitioners, which could impair the coordination of activities (*Jiao and Boons*, 2014). Furthermore, *Ward et al.* (2016) argue that absolute decoupling is neither possible nor desirable especially in developing countries because affluence and GDP are poor proxies for societal well being, instead new frameworks for assessing societal wellbeing should be developed.

The value of *Ciruclar Economy* as a concept is similar to the biological analogies of Industrial *Ecology* and Industrial *Symbiosis*: the concept carries a widespread understanding that materials in society can be used in a cyclical fashion instead of being discarded as waste (*Homrich et al.*, 2018).

A.2 Literature review of Prospective MFA: Scenarios and sensitivity

The various different methods for prospective dynamic MFA will be discussed in the next paragraphs. The studies will be (loosely) ordered by increasing complexity in prospective studies. For example, the first study might only describe a single scenario without sensitivity analyses, whereas the last study might include several policy scenarios and sensitivity analyses for both lifetime and use cases. This is not meant to reflect on the quality of the discussed studies, nor to be an exhaustive list of prospective modelling methods, only to illustrate the variety in scope for different prospective studies. The studies in this section were selected to show a variety of different approaches. Three aspects are of interest for review: (a) the exploration of different (policy) scenarios, (b) the exploration of the sensitivity of driving factors, and (c) the modelling principles: use of time series input for stocks and flows. The main insights are shown in table A.1

Table A.1: Comparison of selected studies on the basis of scenarios and the variation of parameters used for sensitivity analysis.

- *Elshkaki et al.* (2005) use top-down stock modelling methods to describe a single reasonable future scenario driven by historic regression analysis and projections of several socio-economic driving forces. Linear regression for a single time step is used for accounting for stocks. No sensitivity analysis is conducted for any of the driving factors. This approach gives the reader a reasonable reader insight into the future for lead in cathode ray tubes in the European Union, but no insight into the contribution of certain factors.

- *Kleijn et al.* (2000) also analyse a single scenario and a single time step for the existing material stocks (1995), explore the effects of different assumptions for lifetime and input distribution with six different modelling assumptions, and find that the shape of input distribution has the strongest effect on results. They recommend using a historical time-series as input.

- *Zhang et al.* (2011) also use a single time step (2009) for the account of existing material stocks, but compare two assumptions for a lifetime (a complex Weibull distribution function for the lifetimes of various household appliances, and the same but with a gradually shortening lifetime due to increased standard of living). A sensitivity analysis is done for one assumption: the peak of deprecated household appliance generation baseline case is advanced by 10 years and then delayed by 10 years to analyse the effects of this development.

- *Sandberg et al.* (2016) only looks at a single scenario, and use a single lifetime assumption (a complex Weibull distribution function for the lifetimes of buildings in various countries). But the input is more complex than in previously described studies. A time series is used with lifetime composition of buildings for each country. This allows assertions about the changing composition of buildings in the future scenario.

- *Müller* (2006) explores a single scenario and conducts extended sensitivity analysis by varying three driving factors floor area per capita, concrete intensity, and lifetime for high, medium and low scenarios. Time series data for population, historical stocks, material intensity, new dwellings, cement use, and concrete per UFA are used as input for the stock driven model. This approach results in bandwidth for the stocks and flows of concrete in the future and informs the reader of the implications of certain developments. *Hu et al.* (2010) uses a similar method.

- *Hou et al.* (2015) explores two distinct scenarios (recycling versus no recycling) and explore the sensitivity for high and natural levels of water use, high and medium levels of

Publication	Inflow	Stock	Outflow	Year
Kleijn2000Dynamic	Several	-	LifetimeSeveral	2000
Elshkaki2005Dynamic	ScenarioGDP, ScenarioPop, Substitution, Reuse	-	LifetimeWeibull, LeachingRate	2005
Muller2006Stock	MaterialPerUnit,	ScenarioPop, UnitPerCap	LifetimeNormal	2006
Hu2010Iron	MaterialPerUnit,	ScenarioPop, UnitPerCap, Urbanisation	LifetimeNormal	2010
Zhang2011Predicting	HAperHH	HouseHoldPrediction	LifetimeWeibull	2011
Sandberg2016Dynamic	Modernisation	ScenarioPop, Cap/Dwelling	LifetimeWeibull	2016
Wiedenhofer2019Integrating	PrimaryMaterials, Remanufacturing, Construction	-	LifetimeWeibull, ProcessingLosses	2019

Table A.2: Description of ***exogenous*** driving factors used in selected studies. Driving factors are categorised with their relation to either *inflow, stock* or *outflow*.

recycling, and short, medium, and long lifetime. This approach provides insight into questions like what the impact is of recycling versus not doing so. The sensitivity analysis provides bounds for the results.

- *Wiedenhofer et al.* (2019) conducts an extensive prospective study on economy-wide materials. All driving factors are extensively analysed using Monte Carlo Sampling and Global Sensitivity Analysis. Two distinct future scenarios are discussed (Resource use stabilisation and Sustainable circularity) which both describe completely different interpretations of driving factors. This approach allows for the interpretation of e.g. the effect of different policy pathways on material demand.

A.3 Literature review of Prospective MFA: Driving Forces

From the review of the selected publications (see table A.2) the first conclusion is that most studies are not explicit enough to easily discern which factors are exogenous and which are endogenous, and which relate to inflows, stocks, or outflows. From the review by *Augiseau and Barles* (2017) it becomes clear that many studies replicate the method described by *Müller* (2006). This study is also the most explicit about the driving factors and other modelling choices. The reason for this might be because there was no standardised method for reporting modelling choices or drawing system flowcharts before the ODD-MFA protocol by *Müller et al.* (2014). Few studies since hold to this protocol, which shows that there is still room for improvement to increase the transparency for modelling methods in MFA.

However, from the review, it seems as if there is a consensus that the outflows are driven by the lifetime of products, regardless of the case. The studies agree that a Weibull cumulative distribution function (CDF) is the preferred method for modelling the lifetime of materials in a system, provided that demographic information is available. If this is not the case, a normal distribution function is chosen. A minority of studies also include a form of unintended losses through leaching or manufacturing (processing losses) as an outflow.

Four of the studies explicitly document that they are stock driven (*Müller*, 2006; *Hu et al.*, 2010; *Zhang et al.*, 2011; *Sandberg et al.*, 2016). In other studies, stocks are endogenous factors in the model which are driven by inflows. The effect of different inflow shapes on the stocks is found to be one of the most important factors determining stock levels; this behaviour is best described by *Kleijn et al.* (2000). For the prospecting of stocks, often the population is used as a driving force coupled with a material intensity factor which expresses the amount of material used per person, e.g. floor area per capita with the material per floor area. *Zhang et al.* (2011) is an exception, which uses a complex regression model to estimate the number of households in the future which is coupled with an urbanisation projection which gives a stock estimation for urban and rural households in the future.

(*Elshkaki et al.*, 2005) argue that the dynamics of stocks in society are dependant on in- and outflow. Inflows are characterised by socioeconomic factors like import and demand, and outflows are characterised by leaching and delay. This proposal would argue that exports should be considered as an important factor. Following this concept, the outflows of both lead in cathodes and materials in vehicles are driven by product lifetime. Additionally, the export of (second hand) vehicles needs to be considered as an outflow. Because this is a largely unregulated market, it is expected that finding reasonable data for export as outflows will be difficult. Leaching in the case of vehicles could be represented by spare parts like tires being lost during use. However, the scope of this proposal is limited to the material stocks present in the vehicle, and materials like fuels and the loss of spare parts during use are not considered because of time limitation. This means that a difference should be expected between the number of materials flowing in and out. Furthermore, *Elshkaki et al.* (2005) study the case of lead in the EU. They discuss the relationship between substances which are contained in materials which are contained in the products. Their scope is to cover materials, and not to refine this to the level of substances. Finally, *Elshkaki et al.* (2005) defines certain driving factors for dynamic analysis. These are (a) availability of substitute materials, (b) GDP, and (c) the size of the population. Their driving force 'availability of substitute materials' describes a change of paradigm for the lead used in cathodes. In comparison, this proposal discusses a paradigm shift in modes of transportation. An example of this for vehicles could be the energy transition (share of electric cars), sustainable mobility (share of public transport), or government policy (prohibition or subsidising of certain vehicles). GDP and population size are considered to be relevant as macro-scale drivers for the proposed research project.

The methods for modelling inflows is understandably very different. Different case studies require different system boundaries and are governed by driving factors unique to the case at hand. One type of study uses the demand for material as a driving force (e.g. with many metals like lead in *Elshkaki et al.* (2004)). In these cases, proxy data like GDP projections govern the demand.

The review in sections 2.2.1 and 2.2.1 confirms the findings by (*Müller et al.*, 2014; *Augiseau and Barles*, 2017), that prospecting models vary considerably between studies. Most focused on sensitivity analysis and providing bandwidth for their results importantly, but very few studies were found that considered distinct scenarios in their analysis. It is striking that few MFA studies consider different (policy) scenarios, or a paradigm shift. The importance of integrating MFA with factors relevant for societal transition are discussed in (*Hodson et al.*, 2012), which describes how visioning can influence transitions of socio-technical systems.

Studying such *paradigm shift* could give insight into the effect of policy choices. For example, *Hu et al.* (2010) gives insight into how material stocks will behave in scenarios with high and lower affluence. This is something which is difficult to project, and something that have only limited power over. However, if one studies the effects of a scenario where recycling is enforced, like the study by *Hou et al.* (2015), one can compare the potential impact of such an intervention and use that to inform policy which gives decision-makers control over outcomes related to environmental impact.

A.4 The future of transportation, as understood by the IPCC scenarios

The *IPCC scenarios* provide extensive climate change scenario work at a global level and are provided by the assessment reports by International Panel on Climate Change (IPCC) (*Allen et al.*, 2019). The scenario data exploration tool developed by *Huppmann et al.* (2019) is used for this analysis and can be accessed via: `https://data.ene.iiasa.ac.at/iamc-1.5c-explorer` and `https://dev.climatescenarios.org/finder/`. The scenarios can best be understood as an integration of socioeconomic scenarios and climate scenarios. Socioeconomic scenarios are based upon *shared socioeconomic pathways* described in *Riahi et al.* (2017) and shown in figure A.1. Climate scenarios are based upon *Relative Concentration Pathways* from (*Porter et al.*, 2014) described in figure A.2. An integration of these two concepts in e.g. the IPCC climate models show for example what the potential abatement costs are of different scenarios (*Van Vuuren et al.*, 2014; *Riahi et al.*, 2017).

The disadvantage of the global climate scenarios is that the determinants in the model are not detailed enough to describe what happens in a particular country. The models focus on several factors at a global scale which is relevant to a mobility study like GDP-PPP and population. The IMAGE 3.0.1 model with the IAM15 scenario is a below 1.5-degree scenario described by *Van Vuuren et al.* (2018). This is the only scenario found to include projections for passenger and freight transport (ton-kilometres and passenger-kilometres) by road, train, and air *Huppmann et al.* (2019). This is important because this can be used to describe a shift between transport modes, or *modal shift*, for the future.

However interesting these scenarios, the relation between the global development of transportation and the development of transportation in the Netherlands is not evident. Most of the global growth in urbanisation, population, and affluence in the coming decades will happen outside of Europe, so global data seems to be a bad proxy data for a country like the Netherlands *United Nations* (2019); *Ritchie and Roser* (2018); *OECD* (2014).

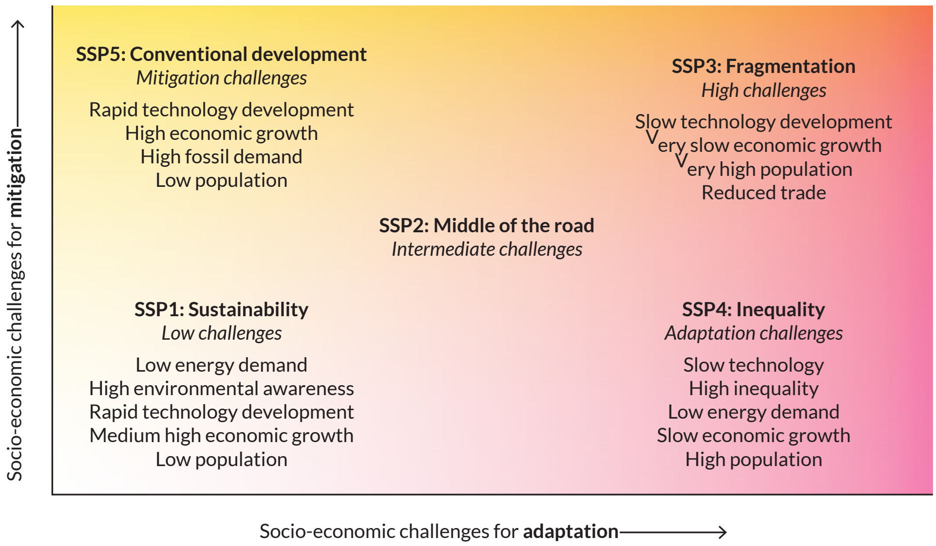


Figure A.1: Shared Socioeconomic Pathways (SSPs) based on: *Riahi et al.* (2017)

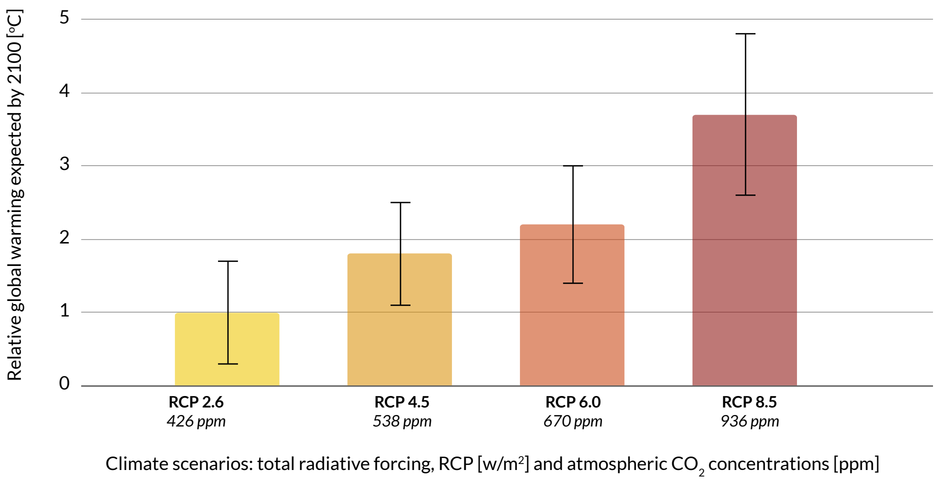


Figure A.2: Relative Concentration Pathways (RCPs) and their radiative forcing, CO_2 concentrations, and expected warming, based on: *Porter et al.* (2014)

A.5 The future of transportation, as understood by the WLO scenarios

The Dutch *WLO Scenarios* (*CPB/PBL*, 2015) were developed to better understand the implications of the Paris climate agreement at a national level. Two government agencies (PBL and CPB; the environmental assessment and central planning bodies of the Dutch government) worked together to create two scenarios to explore the development of the environment in the future. For the two scenarios, two main assumptions are used: high demographic growth and high economic growth for a *high scenario*, and limited demographic growth and low economic growth for a *low scenario*. Together, these provide bandwidth for the development of various aspects of Dutch society, and aim to inform the public and policy makers about the future. The mobility section of these scenarios will serve as a basis for this thesis.

The WLO scenarios discuss four themes in the living environment: regional development and urbanisation, mobility, climate and energy, and agriculture. The underlying driving factors which are used for analysis are an interaction between population and macroeconomics. The sections most important to this thesis are the mobility and climate and energy sections, and the underlying assumptions for population and macroeconomics. The projection of important driving forces in the WLO scenarios provide very interesting input for studying passenger and freight and transport, which both scenarios agree upon are an assumed increase over time in GDP, productivity, oil and CO_2 prices, urbanisation, road mobility, train freight and mobility, aeroplane freight and mobility, railway freight and mobility. Both scenarios agree on a decrease in emissions and energy use. The two scenarios disagree on several aspects and show a relative decrease for factors like urbanisation, population growth, and public transport.

A disconnect is identified between the WLO scenarios and resolutions later passed by the Dutch government. As an example, climate commitments stipulate that emissions reduction should take place compared to 1990, with 49% by 2030 and 95% by 2050 (*Rijksoverheid*, 2019).

However, the WLO scenarios (*CPB/PBL*, 2015) describe that by 2050, the number of cars will increase by between 10-33%, but that the share of entirely fossil dependent Internal Combustion Engine Vehicles (ICEV) will only decrease by 15-30%. Furthermore, car sharing is expected to decrease, and car usage is expected to increase even more than use of trains. The prognosis for freight transportation shows even less opportunity for lower emissions, with an expected increase of 80% for transported mass, and virtually no modal shift towards low emissions modes (trains, shipping). None of these important developments indicate that the transport and mobility sector will comply with the climate goals. The magnitude of the transportation sector is expected to grow, and the transport modes which are most polluting are projected to grow the most.

From comparing these selected scenarios, it seems that the existing prospects for mobility were conducted at different temporal and spatial scales. The focus of the projections vary, some focusing on safety and others on future visions, and others on macroeconomic metrics. It remains unclear whether they agree or disagree with another and how compatible they are. This might be because the development of these works was probably done concurrently and that all heavily refer to and rely on work done by the IPCC. To answer the research questions, the most important data are the projections for passenger-kilometers, ton-kilometers which can be provided by the WLO scenarios; GDP and Population, which can be provided by both the WLO and IMA15 scenarios. The IMAGE/IMA15 scenario provides a projection which could be used to describe a modal shift for transportation, but this is global data which is not necessarily a useful proxy to describe transportation in the Netherlands. Data analysis and regression models could also provide a baseline for modal composition through time. Also, the choice of interesting scenarios to answer the research question could rely on different assumptions for modal shifts in the future (e.g. increased autonomous transport, increased electric vehicles, increased public transport)

A.6 Literature review for Prospective Material Flow Analysis for vehicles

Two titles by the same author which both conduct an MFA and account for stocks show how difficult it can be to find a harmonised search strategy which finds relevant articles. *"Dynamic stock modelling: A method for the identification and estimation of future waste streams and emissions based on past production and product stock characteristics."* and *"The environmental and economic consequences of the developments of lead stocks in the Dutch economic system."*

The search strategy (listing 1) starts by including publications with topics related to MFA, urban mining, and stock modelling. The search is then filtered by including a case topic (e.g. building or waste) combined with an MFA methodology (e.g. MFA or stock modelling). The title filters were added and changed to include or exclude certain results (e.g. car AND cars instead of car* which would return many results including carbon). Finally, several irrelevant Web of Science categories were excluded (e.g. *energy fuels* which returned many building energy efficiency publications).

```
TS=(material flow analysis OR mfa OR stock model* OR stock
↪  dynamics OR urban mine OR urban mining OR urban mines) AND
↪  TI=(building OR vehicl* OR urban OR city OR cities OR car OR
↪  cars OR train OR infra* OR waste OR ship OR airplane OR
↪  aeroplane OR food OR constr* OR metal*) AND TI=(material
↪  flow analysis OR mfa OR stock model* OR stocks OR stock OR
↪  stock dynamics OR urban mine OR urban mining OR urban mines)
```

Listing 1: Search strategy with Web of Science.

The final search strategy returns 481 records, which were filtered by the keywords in the title search. These were manually mapped to the categories: *urban*, *waste*, *metal*, *mobility*, and *food*. The 10 main journals of the returned publications can be seen in figure A.4, which are mainly journals focused on resource conservation which validates the results. Results can be seen in

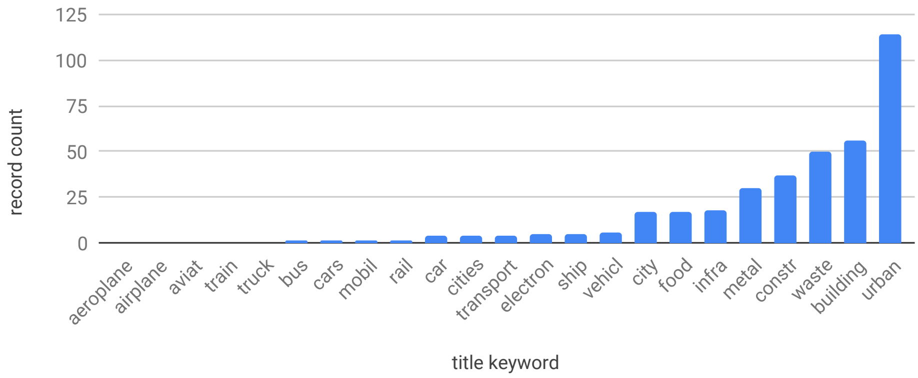


Figure A.3: Count of publications with keywords in title from the search strategy shown in listing 1.

figure 2.3.

The main topic of dynamic MFA and stock models from this search strategy is *urban* which counts 246 publications which include the following keywords from titles: building*, city, cities, infra*, constr*, and urban. Significantly fewer publications were found for the *mobility* category which only scores 18 records which include the keywords from titles: aeroplane, airplane, aviat*, train, cars, rail, car, cities, ship, vehicl*, mobil*, truck, bus*, transport.

Of the records categorised into mobility, the keyword in the title which returned most relevant articles for this study was *vehicle*. Only 10 had topics relevant to dynamic MFA of which 5 were relevant to this study. These will now be discussed.

a. Material Stock Demographics: Cars in Great Britain (*Cabrera Serrenho and Allwood*, 2016). This publication studies the age composition of cars in the UK in 2002, 2007, and 2012 and compares the age with the vehicle performance and steel- and aluminium content of vehicles. One conclusion is that resource efficiency is declining because the material intensity of cars in increasing over time, even though car mileage and utilisation are decreasing. This provides interesting input for driving factors for a study of the Netherlands and allows for comparison of vehicle mass between countries. Another conclusion is that using stock demographics allows for more accurate assertions about things like lifetime which could be relevant for dynamic analyses.

b. UPIOM: A New Tool of MFA and Its Application to the Flow of Iron and Steel Associated with Car Production (*Nakamura et al.*, 2010). This study describes a novel method for visualising MFA data as an alternative to the classic Sankey diagram. The most relevant information to this research is their data and methods for collecting the mass of iron in a car which can be used for validation of results.

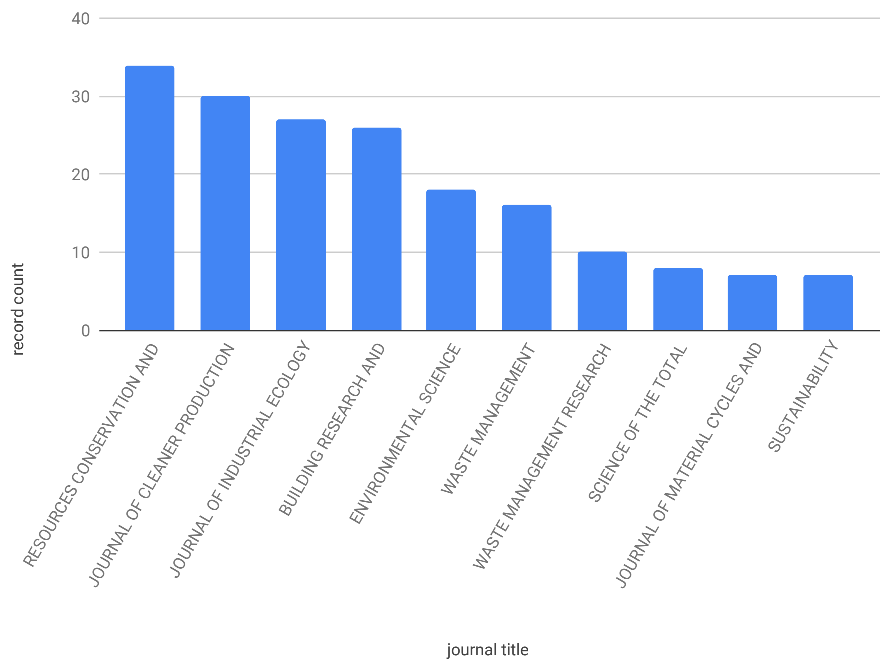


Figure A.4: Record count for the first ten source titles (from listing 1 search strategy).

c. End-of-life product-specific material flow analysis. Application to aluminium coming from end-of-life commercial vehicles in Europe (*Mathieux and Brissaud*, 2010). This study is the first to consider product specific (static) MFA for road vehicles above 3,5 tons and considers aluminium at the scale of the EU. This study can be used to validate and compare results for aluminium stocks.

d. *Restrepo et al.* (2017) provides an extensive in-depth analysis of critical metals in all embedded electronics for passenger cars. Whether this is usable for this study remains to be seen because there is a large data gap for CRM content of other vehicle types.

e. ProSUM: Prospecting Secondary raw materials in the Urban mine and Mining wastes (*Huisman et al.*, 2016). The European PROSUM project achieves a very extensive analysis of the urban mine for four categories: batteries, electrical and electronic equipment (EEE), vehicles and mining waste. The vehicle types in this study are limited to motorised road vehicles up to 3.5 tonnes, which are mostly passenger cars. Not all road vehicles are considered. Material content estimation was based on a few electronic components only (catalytic converters, EV motor magnets, battery cells, and other electronics). The chassis, which is a structural element which contains a lot of valuable materials like aluminium and steel, are not considered. The focus of materials for this study are 28 elements from the periodic table, of which most are from the list of critical raw materials. CRM are not considered in this study because there is a large data gap for CRM for vehicles other than (passenger) cars. Materials like plastics are not considered in the PROSUM study, but it is important to also account for these to understand a more comprehensive material composition of vehicles. One very important result which is unique to this study is that a 15-year time series for a share of electric vehicles (EV) can be inferred from the results.

B

Appendices to the Methodology chapter

B.1 Data collection and material stock accounts

To be able to conduct this prospective stock-driven MFA, two datasets are required to provide a historical account of materials in the Netherlands: a list of relevant vehicle categories, and the material composition of these vehicles. These datasets are then harmonised.

The starting point for data collection is a material stocks account for all vehicles in the Netherlands. This seems like a rather tall order, but this country is unique in the sense that a lot of data that would allow one to answer this question is readily available. In academia, none have yet attempted to make such an account. To better understand the different types of vehicles, in the Netherlands, transportation is categorised into four important domains: *road*, *rail*, *air*, and *water*. Two purposes of transportation are identified: *freight* and *mobility*.

First, data will be gathered for the number of vehicles in the Netherlands. With estimations for mass, an indication can be made regarding the contribution of a vehicle type to the total. The goal is to provide an insight into the mass of all vehicles in the Netherlands, but if no data is available, proxy data will be used. To illustrate:

> *The mass of drones is less than a thousandth of that of all Aircraft, but they are categorised as the same vehicle type. Aircraft by category are only a thousandth of the total mass of vehicles, so in this case the mass of Aircraft is approximated as if the total mass (including mass of drones) is made up of 2- and 4- engine jet airplanes. In this*

case, the total mass is exactly the same, and the aggregated composition is only very slightly different from reality. This assumption is deemed to be valid, unless one uses the results to assess the material performance of drones, which would be nonsensical and the assumption would obviously be invalid (data from appendix B.1 and B.2)

The next step is to find material compositions for all vehicles. Priority is given to vehicle types which contribute most to total mass, or if data can be found easily.

Material stock for road vehicles

Count and gross mass data for registered road vehicles is provided by CBS (*CBS*, 2019a,b,d,e). Count data for bicycles is provided by *BOVAG-RAI* (2019b). Eurostat (*Eurostat*, 2019) provides time-series data for passenger and freight performance data in ton-kilometres and passenger-kilometres per vehicle type. This is used in combination with projections for passenger and freight transportation projections provided by the WLO scenarios (*CPB/PBL*, 2015).

Material composition for road vehicles is one of the most important data for this thesis, two sources are compared: Ecoinvent 3.5 (*Wernet et al.*, 2016) and (*Hawkins et al.*, 2013). The (*Hawkins et al.*, 2013) data was eventually chosen over ecoinvent because the method for estimation of battery and drivetrain mass was more transparent. The data was extended by disaggregating materials referred to as *electronics* or *circuitboards* according to ecoinvent flow *electronics production, for control units[RER]* which includes average lengths of certain cables and circuitry for control units. Material composition for cars was used as proxy for vans, by scaling the mass to match that of average vans.

The best available material composition for bicycles was found from EcoInvent (*Wernet et al.*, 2016). Two types of bicycle were chosen, conventional bicycles and ebicycles. mass of these datasets (bike: 16.3kg, ebike: 23.5kg) agree with (grey) literature describing average mass of bicycles.

For *road* transportation, detailed stock accounts for various vehicle types classified by mass are available starting from 2000, through CBS. BOVAG/RAI provides import, export and internal trade counts for passenger cars, but Eurostat provides import counts and stocks for all vehicle types. If export and internal trade counts are required for vehicle types other than passenger cars, the passenger car dataset could be used as a proxy by scaling it for other types.

Material stock for aircraft

Count data for aircraft are provided by (*CBS*, 2019c). To assess the mass of the entire aircraft fleet, raw data for 2018 was retrieved from (*ILENT*, 2019). Manual mapping of entries was required to harmonise the two databases. More than 1000 aircraft brand and model combinations were explored, and reported empty mass was recorded via online search. This allowed for a

Table B.1: Aircraft model contribution to total by mass

Type	Model	Mass, cml [tons]	Contribution [%]	Model count
2x jet engine	737-800	2 899	16.31%	70
2x jet engine	777-300ER	2 234	12.57%	14
4x jet engine	747-400	2 202	12.39%	12
2x jet engine	777-200	2 022	11.37%	15
2x jet engine	787-9	1 439	8.09%	13
2x jet engine	A330-203	965	5.43%	8
2x jet engine	737-700	904	5.08%	24
2x jet engine	ERJ 190-100 STD	899	5.05%	32
2x jet engine	A330-303	875	4.92%	5
4x jet engine	747-400F	551	3.10%	3
2x jet engine	ERJ 170-200 STD	371	2.09%	17
2x jet engine	787-8	312	1.76%	3
2x jet engine	737-900	206	1.16%	5
2x jet engine	737-8	124	0.70%	3
2x jet engine	787-10	124	0.70%	1
2x jet engine	767-300	88	0.50%	1
2x jet engine	Falcon 2000EX	47	0.26%	5

rather accurate average mass per aircraft category. Only two aircraft categories contributed 92% of total aircraft mass of 17.81 million kilograms: 2- and 4- engine jet planes, with an average mass of 57 103.55 kg and 183 500 kg, respectively. Tables describing all models and types can be found in Appendix B.1 & B.2. Interestingly, recent registrations are dominated by drone aircraft. No time series data were found for drones, but a static analysis shows that the proportion of mass that this category represents is extremely low, 0.0003%.

Yearly in- and outflows of aircraft data was not found. Possibly, interviews with ILENT or an aviation company like KLM could provide more insight into these flows. For a stock driven approach, the data seems to be sufficient to answer the research questions.

Material composition data for aircraft are difficult to come by. For 2-engine jet airplanes, proxy data for a Boeing A330-200 was used from (*Lopes*, 2010) which has high resolution at a component level, but limited resolution with regards to types of materials (Aluminium, Composites, Ferrous alloys, Iron, Nickel, Niobium and tantalum, Steel, Titanium). *Warren* (2004) provides material composition for the five most important Boeing Aircrafts (Aluminium, Steel, Titanium, Composite, Unknown). Also, no indication was found to the mass of onboard electronics, which would allow disaggregation via EcoInvent.

For *air vehicles*, detailed current stock accounts with vehicle type information exist through the Dutch air traffic register, *luchtvaartregister*, (*ILENT*, 2019). A time series for this stock exists through CBS, but harmonisation would require manual mapping of categories.

Material stock for sea- and inland vessels

Nederland Maritiem Land (2019) provides detailed historical stock accounts categorised by ship type and Gross Tonnage (GT) for 2012-2016. *Jain et al.* (2016) provides one of the only reviews of estimations for the Lightweight Dead Tonnage (LDT) from literature, and provides a novel method for creating a bill of materials for a ship according to their onboard documentation. The most detailed material breakdown is provided for a handymax bulk carrier ship (11 000 LDT),

Table B.2: Aircraft type contribution to total by mass

Type	Mass, cml [tons]	Contribution [%]	Average mass [kg]	Type count
2x jet engine	13 705	77.1%	57 103.55	240
4x jet engine	2 753	15.5%	183 500.00	15
1x piston engine	403	2.3%	644.32	626
Hot air balloons	250	1.4%	590.85	423
Unpowered gliders	126	0.7%	262.16	481
2x propeller engine	112	0.6%	5 595.94	20
2x helicopters	80	0.5%	2 215.14	36
3x jet engine	72	0.4%	12 010.00	6
2x piston engine	71	0.4%	1 686.38	42
Ultra Lights MLA	60	0.3%	118.05	511
1x propeller engines	52	0.3%	2 177.17	24
Powered gliders	52	0.3%	355.17	147
1x helicopters	27	0.2%	690.47	39
Ultra Lights VLA	10	0.1%	391.78	26
Drone	5	0.0%	2.23	2 264
Total	17 778	100%	-	4 900

and more basic breakdowns for general cargo and tankers. The level of detail for the materials is not very high, as only six material categories are discussed, amoung which are 'electronics' and 'machinery'. These categories are then linked to Ecoinvent which allows for a more detailed material breakdowns.

Interestingly, count, mass, and material composition data was found for pleasure craft, thanks to Ester van der Voet. The data only described the year 2014, and no indications were found describing these factors for other years. For the year 2014It remains to be seen what proportion of mass and materials this category represents, and if it is significant enough to contribute to answering the research question. Yearly in- and outflows were not found, so for a stock driven approach, the data seems to be sufficient to answer the research questions. For material content, vehicle types from stock accounts can be mapped to vehicle types in the Ecoinvent LCI database.

Material stock for rail vehicles

With no official data describing a time series for the number of train vehicles in the Netherlands, alternative data sources were selected. The Dutch Wikipedia pages (*Wikipedia contributors*, 2019) provided very detailed information about each train type, their mass, and their span of service. Certain train types. This information found matched other websites like (*SOMDA*, 2019) and (*Treinenweb.nl*, 2019).

With no data from reputable online sources available, the Human Environment and Transport Inspectorate of the Dutch ministry of Infrastructure and Water Management was approached. They could only provide a list of rolling stock registered after 2010 (*ILENT*, 2019). This list was cross checked with the data gathered from the previously described sources, but the data is very messy. It was possible to retrace the FLIRT3 train which was introduced after 2016, and the numbers did match, but for the V250 model, the numbers did not match. The data could therefore not be validated, and the numbers are classified as highly uncertain.

Conclusions from data collection

Finding usable data for historical stocks of vehicles and future data for driving forces, to cover all vehicles across modes, is challenging because various different parties manage and control these data. Luckily, reporting practices in the EU and the Netherlands allows for vehicle stock time series spanning almost 20 years for road and air vehicle categories. Alternative sources were found for Railroad and Water transportation.

Material composition data was found for a small selection of all counted vehicles. For each vehicle class (road, air, water, and rail) at least one vehicle composition was found. There is a large variability in the quality of the datasets that were found, with the highest quality being cars, and the lowest quality being airplanes and ships. In most cases, the vehicle types with no composition data were linked to the closest available vehicle type, scaling the total mass to match the average mass of the vehicle type.

All data has been published on the Urmive GitHub repository (*Van der Zaag*, 2019), but in the Appendices C.1 - C.2 excel sheets can be found which summarize the most important data.

To assess how the use of these vehicles and their materials will develop over time, scenarios and transition pathways are discussed.

B.2 End-points for transition pathways

To aid in finding interesting end points for each transition pathways, aa storyline is made for each pathway. The following storylines and end points have been chosen according to the topics found to be relevant for vehicles from the literature review: (a) lower emissions, and (b) better material efficiency. These pathways will be be contrasted with the WLO scenario reference future, to allow comparison of the likely consequences for materials for the different pathways.

Note that none of the described pathways even potentially allow compatibility with the commitment to net zero emissions from transportation. Arguably, no transportation technology has the potential to achieve net zero life cycle emissions, but with green fuel/electricity, in-use emissions can be eliminated.

Haghshenas and Vaziri (2012) provides an extensive literature review discussing STI, Sustaintable Transport Indicators, and show that private vehicle ownership and private modal split both negatively correlate with environmental performance. *Litman* (2003) describes that large scale environmental benefits are to be gained from from shift to public transport, but that a paradigm shift is required to garner acceptance of public transport in America.

One of the few modes of transport which already exist and can already provide services at a large scale at a fraction of emissions compared to cars is railroad transport: train, metro and trams. See figure 2.2 for emission factors per mode of transport, for mobility and freight trans-

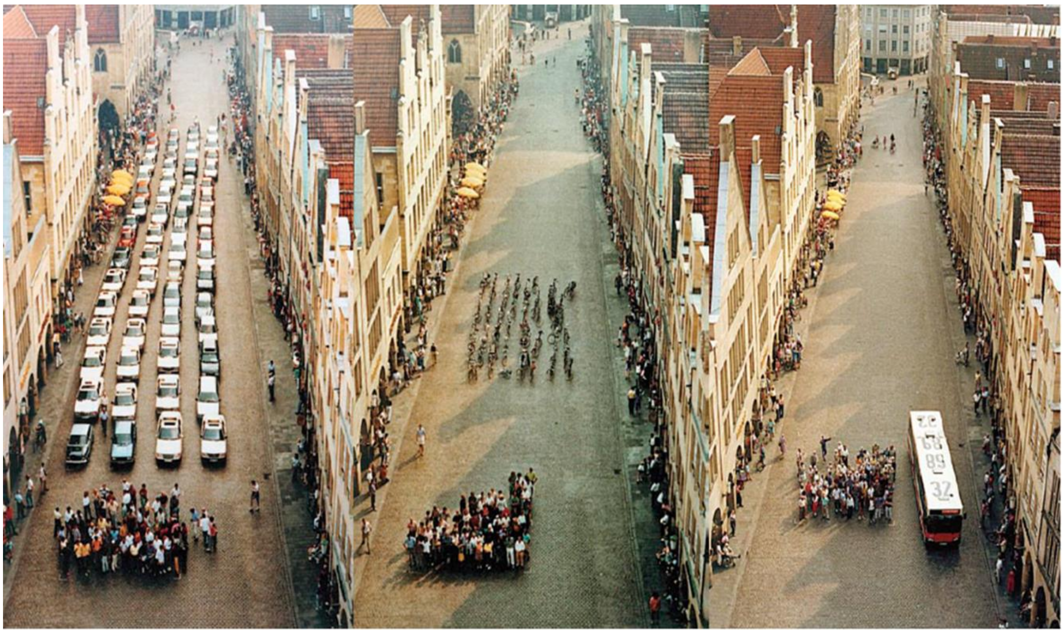


Figure B.1: Three photos showing the impact of modal shift between car, bikes and a bus for 72 people commissioned by the City of Münster Planning Office in 1991. Image: public domain.

port. The Netherlands, or the Randstad metropolitan area is a relatively car-centric region compared to for example Tokyo or New York which rely far more on (underground) trains to provide mobility service. Also, making use of the existing high quality infrastructure in the Netherlands, expanding the use of bicycles by promoting bicycle sharing could potentially reduce emissions by replacing bus-, moped- or car use, which is a fast growing trend around the world which even brings proven health benefits (*Midgley*, 2011; *Woodcock et al.*, 2014).

Modal shift towards mass transit

The backdrop for this storyline is that the transportation system of the Netherlands is overhauled because the increasing growth of road infrastructure cannot keep up with increasing demand for transport, especially in the rapid metropolisation of the Randstad. The photo in figure B.1 illustrates the potential effects on material use for modal shift in personal transportation.

Mobility systems in other regions are analysed and are taken as a model for a radical reinvention of the Dutch mobility system from the perspective of a modal shift. The possibilities for modal shift to contribute to lower emissions from transportation is illustrated by examining different situations around the world according to their share of modality, see figure B.2. Where at a national level, the Netherlands has a high share of car usage even compared to Germany (a country where the use and production of cars is a national pride), the Amsterdam region shows

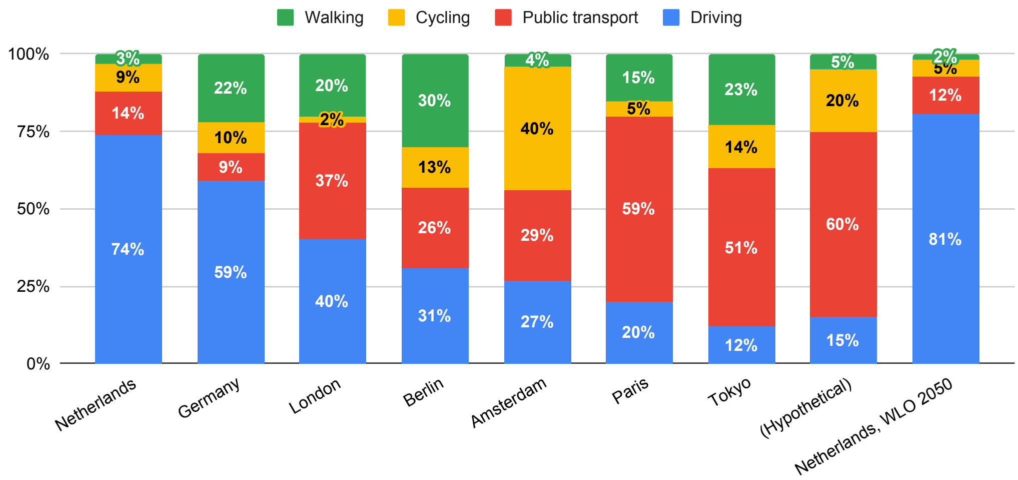


Figure B.2: Modal split by person-kilometre for various regions, ordered by decreasing car share and increasing share of public transport (*EPOMM*, 2019). *'Hypothetical'* refers to the hypothetical modal split described in this paragraph, B.2. *'Netherlands, WLO'* describes the current situation extrapolated according to the WLO-2050 Hoog scenario.
Data from (*CPB/PBL*, 2015).

a much better example of low emission mobility. Looking around the world, especially Tokyo shows a promising example. The region has an area 1.7x the size of the Randstad and 2.7x the population, but shows much lower car usage compared to most regions in the world, with relatively high use of public transport and cycling.

A hypothetical modal share is constructed by doubling the share of emission free slow transport (cycling and walking) from 12% to 25 % to approximate that of other regions with better public transport shares. Of slow transport, 80% is reserved for cycling and 20% for walking. This represents an expansion of cycling infrastructure in the Netherlands, from 14% to 20%. This is a substantial increase but still only half of the current cycling share for Amsterdam. This also represents an increase for walking, from 3% to 5%. The share for driving is radically reduced from 74% to 10%, lower than that of current Tokyo.

The **end-point for modal shift towards mass transit** proposes shares of 65% public transport, 20% cycling, 5% walking, and 10% driving, by to person-kilometers in 2050, and is shown as the *Hypothetical* entry in figure B.2.

Using emission factors supplied by (*Ministerie EZK*, 2019) (listing. 2), one can make a very rough estimation of the potential impact reduction for emissions. This method does not assume improved fuel efficiency. Combining the modal split (km/passenger) for the hypothetical situation and emission factors (g CO_2/passenger/km), one can can assume a 66% reduction in emissions compared to the current Dutch national modal split. If one would also assume transition to elec-

$$
\begin{aligned}
Driving &= 161\ g\ CO_2 \cdot passenger^{-1} \cdot km^{-1} \\
Mass\ transit,\ average &= 36\ g\ CO_2 \cdot passenger^{-1} \cdot km^{-1} \\
Cycling &= 0\ g\ CO_2 \cdot passenger^{-1} \cdot km^{-1}\ (electric : 7\ g) \\
Walking &= 0\ g\ CO_2 \cdot passenger^{-1} \cdot km^{-1}
\end{aligned}
$$

Listing 2: Emission factors describing modal split for mobility.
Data from (*Ministerie EZK*, 2019).

tric cars, the potential reduction rises to 75%. If one would also assume a clean electricity grid, the potential emissions reduction could be even more.

Modal shift in freight transport

The backdrop for this storyline is that few alternatives exist for sea transportation, and to reduce emissions and to reduce congestion on roads, a shift towards inland and railroad shipping is achieved.

For freight transport a shift towards non-fossil fuels has has been shown to be feasible. Ships powered by hydrogen has been shown to be feasible and would potentially reduce emissions by >95% (*DNV-GL*, 2018; *Rajasekhar et al.*, 2015). Road freight could potentially transition towards hydrogen fuel cells, which supplies similar ranges to conventional lorries, or electric drivetrains, which currently have relatively short range. These options are however not considered because none of the proposals have been demonstrated at meaningful scale yet. Modal shift of sea vessels is not considered, because no alternatives have been demonstrated yet at scale.

Another solution which already has ready technology and could provide emission reductions, is a modal shift from road freight to rail freight (>90% emissions reduction) or road freight to inland shipping (>75% emissions reduction), see emission factors in fig. 2.2. The WLO scenarios describe a modal split being very similar to the current situation, with an overall increase in transported kilometers, and a relative increase in share for road and rail vehicles, see figure B.3.

An alternative for the modality of freight could be informed by redistributing 50% of road capacity towards inland shipping (one third) and towards freight trains (two thirds). This is however problematic because the modes have very different infrastructure and it is unclear whether the same service can be provided with a radical modal shift like this. A potential story line is that the majority of international inland transportation is taken over by inland shipping and rail transport. Road transportation by truck would be used for inter regional transportation where rail or shipping infrastructure is impossible. It is very difficult to assign numbers for the potential for such a transition because it requires infrastructure very different from the current situation. But

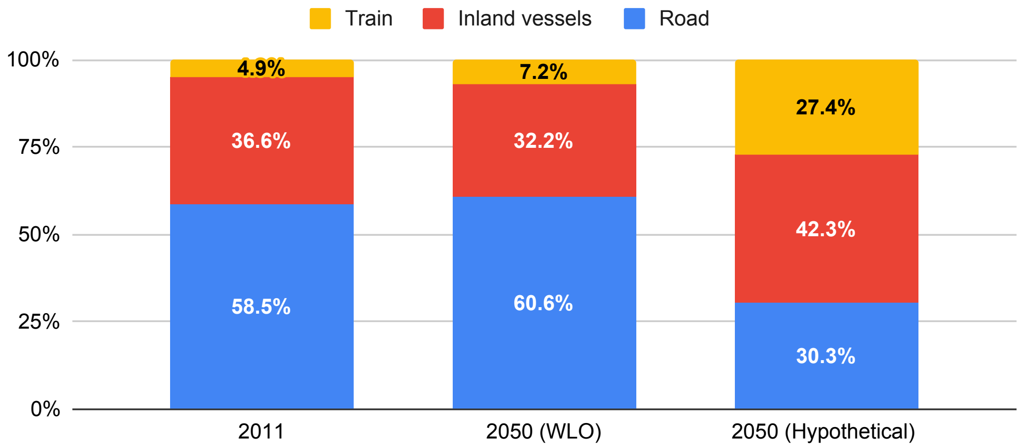


Figure B.3: Modal split by ton-kilometer for the Netherlands in 2011 compared to WLO scenarios, and a hypothetical scenario. Data from (*CPB/PBL*, 2015).

$$\begin{aligned} Lorry &= 359\ g\ CO_2 \cdot ton^{-1} \cdot km^{-1} \\ Inland\ shipping &= 36\ g\ CO_2 \cdot ton^{-1} \cdot km^{-1} \\ Train,\ gray\ electricity &= 10\ g\ CO_2 \cdot ton^{-1} \cdot km^{-1} \end{aligned}$$

Listing 3: Emission factors describing modal split for freight, from (*Ministerie EZK*, 2019).

because the purpose of this thesis is to explore the potential implications of an interesting end-point and not whether this is feasible, the following is proposed.

The potential emissions reduction are informed by the emission factors in listing 3. This method does not assume improved fuel efficiency. Where the WLO reference indicates an emissions increase of 56% by 2050, the modal shift pathway indicates an emission reduction of 12%.

Roll out of electric vehicles

The backdrop for this storyline is that one of the few replacements for current vehicles that allow independence from fossil fuels are hydrogen Fuel Cell Vehicles (FCV) and Electric Vehicles (EV). FCV are not considered because at this point the feasibility of large scale green hydrogen production at competitive market prices is very uncertain (*Mulder*, 2019) and less than 30 fuel cell vehicles have actually driven in the Netherlands over the last ten years (*BOVAG-RAI*, 2019a).

Hybrid-electric Vehicles (HV) and their relatives (plug-in, etc.) have celebrated some popularity but are in most cases incapable of reducing life-cycle emissions (*Helms et al.*, 2010) and perpetuate reliance on fossil fuels. EV perform relatively better and reduce life cycle CO2 emissions by around 15% on the current electricity grid, but potentially 75% with a green grid (*Hawkins et al.*, 2013). Assuming that the Dutch grid transforms to a fully green grid, a radical adoption of EV is needed to significantly reduce emissions. A promising sign is that EV are the only category of car to have increased sales year to year for the last ten years, and amount to 2% of sales even though the car fleet has only 0.2% EV share (*BOVAG-RAI*, 2019a).

Electric bicycles do have higher emissions than conventional bicycles, which have no (in use) emissions because they do not use fuel. However, they do provide an option

From the current perspective, the closest one can get to an emission free transportation sector in 2050 would be if the vast majority of cars were electric, and powered by clean renewable energy. The **end-point for the roll out of lower emissions cars** proposes a replacement of 90% of internal combustion engine vehicles on the road with electric vehicles, and 20% of bicycles with electric bicycles.

A downside to this transition is that there is a higher material requirement for the production of EV, so an increase in share indicates an increase in required resources. To compensate for this, improving car utilisation and occupancy through ride sharing and autonomous transport could be a solution.

Ride sharing and autonomous transport

Ride sharing and autonomous transport; which are in essence very different topics but from the perspective of this thesis both represent the same end point which is to improve the effective utilisation of cars. *Hannon et al.* (2016) considers the development and possible role of autonomous driving, and where it is likely to roll out. They describe public transport as the backbone of mobility, ride sharing and (electric) autonomous vehicles as first- and last-mile solutions.

The backdrop for this storyline is that both autonomous transport and ride sharing achieve a higher occupancy and utilisation of vehicles, which in turn reduces the resources needed for production of vehicles.

One aspect which was found to be described a lot in literature, is the developments surrounding autonomous transport (*Hannon et al.*, 2016). This development is expected to have a lot of impact on the global economic situation because it promises to be one of the first big Artificial Intelligence business cases. From the perspective of materials and emissions in this thesis, however, the main factor is that the number of cars per capita could go down if cars are used more than the current 2% of the time (*CBS*, 2019f). To be clear, this assumes that individual ownership would become redundant. Also, the occupancy of vehicles can go up in a similar way to ride sharing and carpooling. Current car occupancy is 1.39 (*Ministerie EZK*, 2019). These developments indicate a possible emissions reduction (*Wadud et al.*, 2016).

On the other hand, this new situation could introduce unforeseen changes in usage patterns, which according to system dynamic analyses, might actually rebound and increase emissions (*Gruel and Stanford*, 2016). Whether the introduction of autonomous vehicles would increase or reduce emission is uncertain (*Alexander-Kearns et al.*, 2016).

More certain is the effect of ride sharing and autonomous transport on the material demand of mobility. Reduction in the absolute number of cars means a reduction in the resources needed to maintain the vehicle fleet, and an absolute reduction in the upstream resources needed. An indication of the theoretical amount of cars actually needed comes from looking at a situation where the roads are most busy. During peak traffic, at most 2.6m out of 7.7m cars were on the road, indicating that theoretically only 33% of cars were actually needed (*CBS*, 2011).

The **end-point for ride sharing and autonomous transport** proposes an effective utilisation of cars by 50% through smarter sharing of resources and services, would allow the vehicle fleet to shrink by half, requiring fewer resources for production whilst maintaining its ability to provide the services.

Generic developments

Separate from radical and paradigm shifting changes as described in above paragraphs, are more gradual macro scale developments. These will be described for *road*, *water*, *air*, and *rail* vehicles.

For *road vehicles*, certain developments have been identified: a gradual increase in lifespan for cars (*BOVAG-RAI*, 2019a), an overall increase in mass of cars (see fig. B.4, B.6) (*CBS*, 2019e). The increase in proportions for lightweight materials in cars is also apparent, but this is at a level of detail which is not possible within the time and scope for this thesis.

For *air* vessels, a decrease in lifespan has been identified. This has a negative impact on resource use for the production of vehicles, but assuming each generation of aircraft showing significantly lower in-use emissions, this might have overall benefits (*Timmis et al.*, 2015).

For *rail* and *water* transport, technology has been around for a very long time, and no significant developments in material use were identified. There are certain developments like the higher use of specialty steels in e.g. shipping, but this is at a level of detail which is not possible within the time and scope for this thesis.

Conclusions from scenario and transition pathways

The WLO Scenarios developed to inform the public and policy makers are not compatible with *policy and climate commitments* which were since adopted. To explore future pathways which are compatible with these recent commitments, four end points for transition pathways are proposed

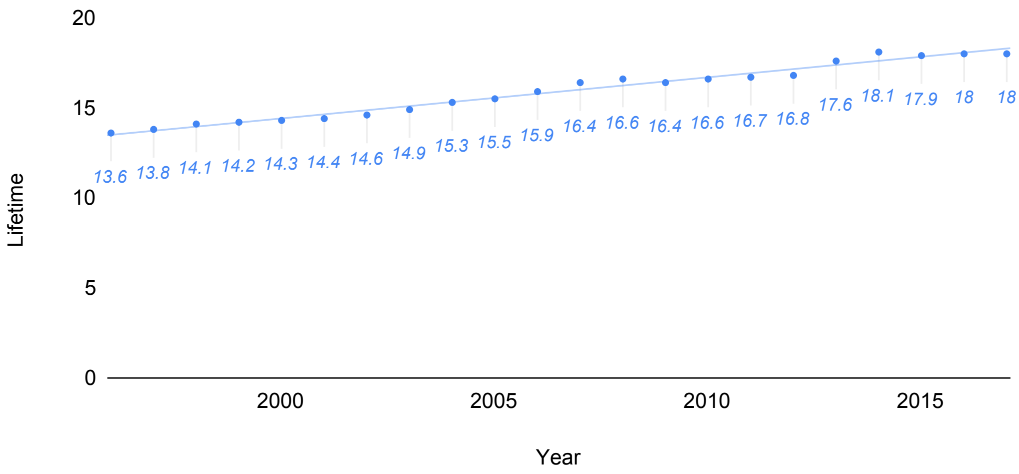


Figure B.4: Average age of cars in the Netherlands over time.
Data from (*BOVAG-RAI*, 2019a).

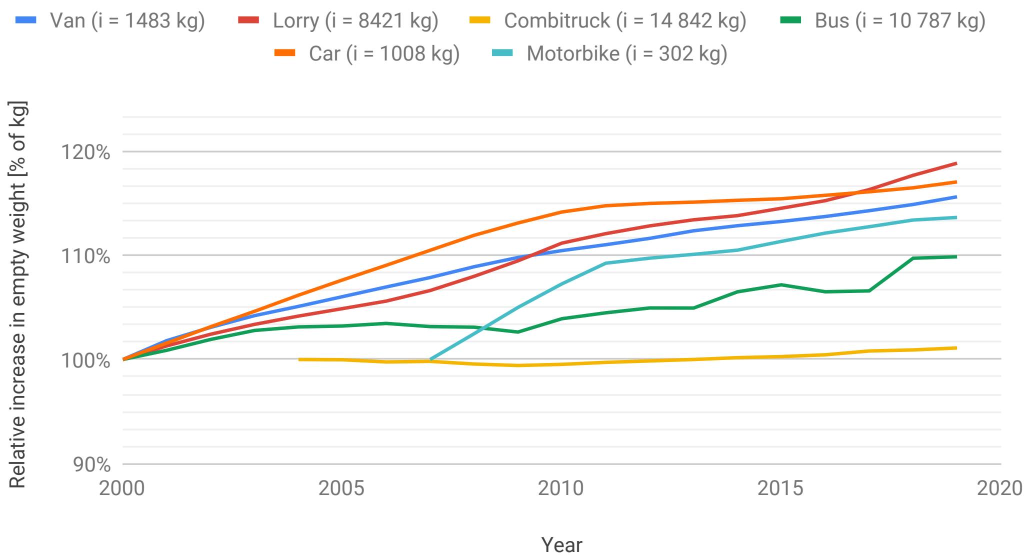
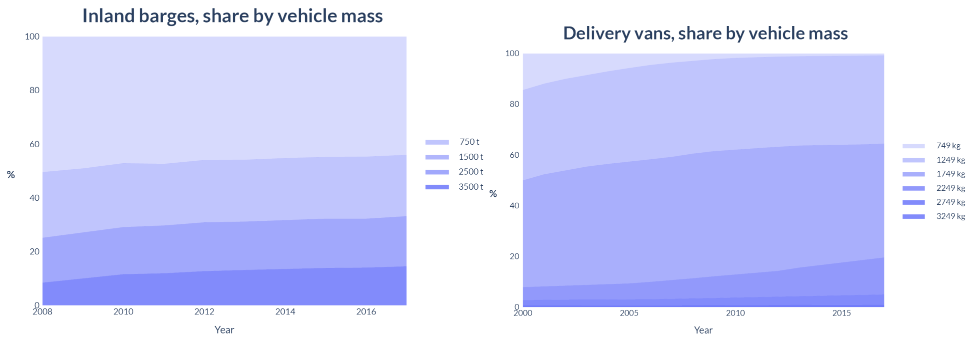


Figure B.5: The empty mass of vehicles seems to increase over time, with the exception of Combitrucks. The index i=100% is given for each vehicle in kilograms.
Data from (*CBS*, 2019a,e).



(a) Share of inland ships by mass over time.

(b) Share of delivery vans by mass over time.

Figure B.6: Share of vehicles over time, darker color represents heavier vehicles. Data from (*Nederland Maritiem Land*, 2019; *CBS*, 2019a)

which aim to reduce emissions and resource use in the future. These end points are to serve as driving factors to influence the system-dynamic material flow model discussed in the following chapter B.3. The baseline, or *reference future*, are the WLO scenarios (*CPB/PBL*, 2015).

- *Modal shift for mobility* provides many opportunities to significantly reduce in-use emissions and resource intensity of vehicles.
- The benefits of a *modal shift for freight transport* is less apparent, but a modal shift could theoretically reduce emissions and reduce resource intensity of especially for non-sea freight transport.
- *Low emissions vehicle roll-out* provide opportunities to eliminate dependency on fossil fuels, but have an inherent demand for valuable materials like cobalt, copper and lithium.
- *Ride sharing and autonomous transport* is something which is expected to be a big part of the transport economy in the future, but whether this will reduce or increase emissions is uncertain. It does seem likely that these factors will increase utilisation and occupation of vehicles, and by extension, reduce the amount of vehicles and required resources.

B.3 Implementation of transition pathways.

Currently, the service of passenger transport in the Netherlands is supplied mostly by cars, and very few changes can be seen in the last 10 years except for a very slight overall decline in personal transportation (fig. B.7). Interestingly, the correlation between the amount of cars in the Netherlands, and the level of service they provide, is weak (R^2 = 0.72) (*CBS*, 2019e; *KIM*, 2019). This can be explained by assuming the ownership of cars increases with population instead,

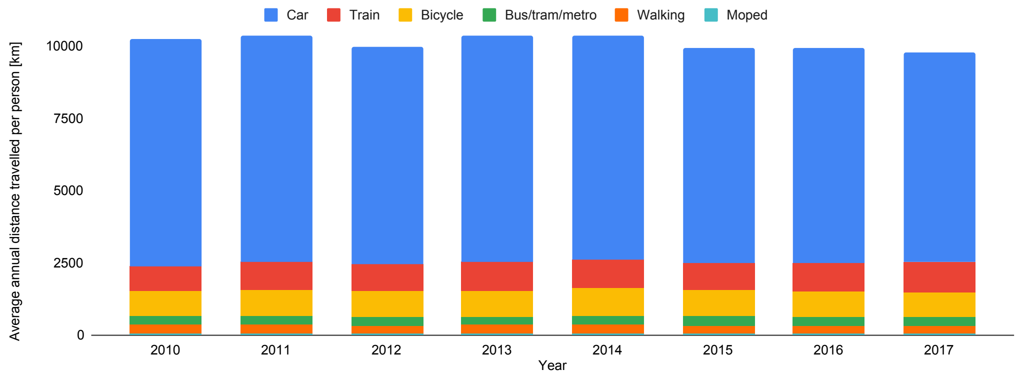


Figure B.7: Passenger-kilometers over time by vehicle. The share stays relatively constant, but an overall decrease in total passenger-kilometers is identified (*KIM*, 2019).

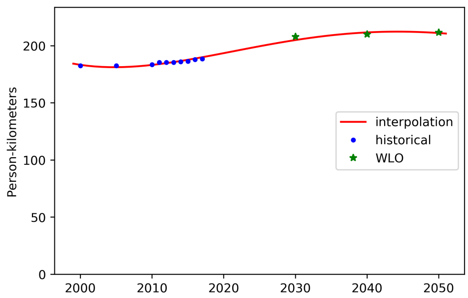


Figure B.8: Passenger transportation. WLO-low scenario (green stars: 2030, 2040, 2050) and historical data (blue points) fitted with a fourth order polynomial (red line). Data from (*CPB/PBL*, 2015) and (*KIM*, 2019).

which is more strongly correlated (R^2 = 0.98) (*CBS*, 2019e). Exploring alternative pathways requires to assume that the ownership of vehicles is indeed coupled with the delivery of an actual service, and not with ownership. The problem with ownership of such immense numbers of vehicles which are only used 4% of the time (*CBS*, 2019e) is that they require large amounts of valuable and rare materials which produce environmental impacts which can not comply with future climate goals.

Projections have been made by the WLO to describe passenger transport in the future. Historical data for personal transport is plotted along with the WLO projections, and a fourth order polynomial is fitted to interpolate for the years in between.

Alternative pathways will be explored for delivering this increase in passenger transport service as described by the WLO scenarios in figure 3. The main variables in this exercise are the shares of different modes of transport which can deliver passenger transport service. Changing

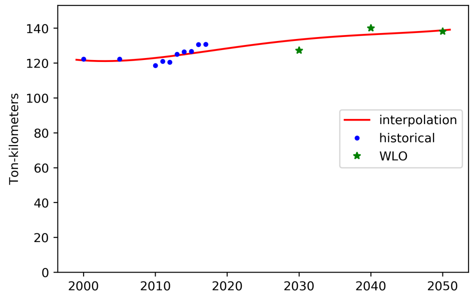


Figure B.9: Freight transportation. WLO-low scenario (green stars: 2030, 2040, 2050) and historical data (blue points) fitted with a fourth order polynomial (red line). Data from (CPB/PBL, 2015) and (KIM, 2019).

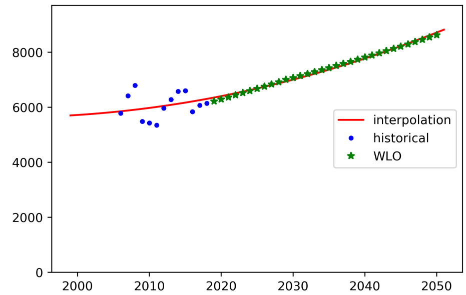


Figure B.10: Service delivered by seagoing ships. WLO-low scenario (green stars) and historical data (blue points) fitted with a second order polynomial (red line) . Data from (CPB/PBL, 2015) and (KIM, 2019).

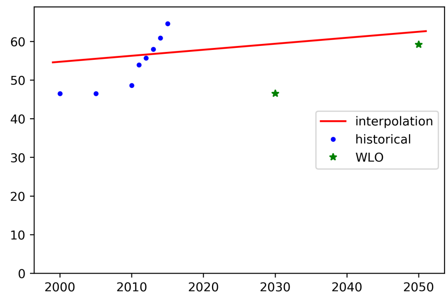


Figure B.11: Service delivered by airplanes. WLO-low scenario (green stars: 2030, 2040, 2050) and historical data (blue points) fitted with a linear regression (red line) . Data from (CPB/PBL, 2015) and (KIM, 2019).

the share of these mode of transports are described as transitions. The transitions that will be explored are hypothetical, and do not reflect particular predictions of the future. Rather, they aim to explore extreme end points of transitions, which would allow to compare the ultimate effects on material demand.

The transitions will be described from the theory of diffusion of innovations (*Loorbach and Rotmans*, 2006). This theory argues that certain transitions follow a characteristic S-shaped curve instead of e.g. a linear transition. A common function used to describe such an S-shaped transition is the logistic curve. A logistic curve can be interpreted as the cumulative distribution function of an adoption with a particular probability density. This curve incorporates the passage of time required to adopt innovations, and a steepness which reflects the quickness of adoption. Input can be the expected transition midpoint, and the curve steepness or growth rate, as seen in the following equation, with x = time, L = endpoint value, x_0 = midpoint time, k = steepness.

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}} \tag{B.1}$$

In order to describe three of the eight developments mentioned earlier in this report, the modal share is split into ten vehicle categories. These vehicle categories are accompanied by nine binary shifts which follow the logistic curve. The combination of these nine binary shifts describe the full 'modal shift' of passenger transportation described in this thesis. Each transition is modular, so it can be switched on or off which allows to compare each transition with reference pathway.

The shifts for all transition pathways were achieved by subdividing into nine different binary shifts, and parameters were adjusted to achieve the desired final characteristics for each transition pathways, for example modal split in 2050 for thre transformation pathway. Each of the shifts can be switched on or off, to enable isolation of a single pathway for calculation.

The shift for the binary driving/non-driving in the TF pathway is expected to be the toughest, so the far midpoint (2035) and low steepness (0.2) reflect that. The binary electric-car/hybrid-car transition is expected to happen earlier and faster than others, so that is reflected in the early midpoint (2025) and high steepness (0.3). The proportion of train vs. metro/bus transportation will be kept the same, and the proportion of cycling vs. walking is also kept the same, because no evidence was found to suggest that these might change.

The nine binary shifts are combined, giving the modal split over time in figure 6. This is then combined with the service demand of figure 3 to give the final hypothetical modal split in figure 7. This is then translated to the number of vehicles needed to deliver this service, shown in figure 8. Note that the different binary shifts are modular, and can be switched on- or off according to the question that needs to be answered.

The next step is to translate the transportation service to number of vehicles. For most vehicles, a relationship was found between fleet size and service delivered. This relationship is

Table B.3: Input values for logistic functions describing nine binary shifts for passenger transportation

A	B	start value	end value	midpoint	steepness	pathway
Driving	non-driving	0.74	0.1	2035	0.2	TF
ICE car	non-ICE car	0.99	0.15	2030	0.3	ST
Electric car	Hybrid car	0.01	0.99	2025	0.3	ST
Mass transit	Walk/Cycle	0.5	0.72	2030	0.2	TF
Train	*Metro/bus*	*0.77*	*0.77*	*2035*	*1*	-
Cycle	*Walk*	*0.75*	*0.75*	*2035*	*1*	-
Bicycle	Moped	0.93	0.85	2030	0.3	TF
Bike	Ebike	0.99	0.66	2030	0.3	ST
Moped	Emoped	0.99	0.01	2030	0.3	ST

Table B.4: Input values for logistic functions describing nine binary shifts for freight transportation

A	B	start value	end value	midpoint	steepness	pathway
Van	non-van	0.0797	0.0797	-	1	ST
E-van	IVE-van	0.01	0.85	2035	0.2	ST
Road	non-road	0.6	0.29	2035	0.2	TF
16t lorry	larger lorries	0.06	0.1	2030	0.2	ST
40t lorry	28t lorry	0.22	0.4	2030	0.2	ST
Rail	inland shipping	0.11	0.4	2030	0.2	TF
Small inland	M/L/XL inland	0.47	0.2	2030	0.1	ST
Medium inland	L/XL inland	0.45	0.2	2030	0.1	ST
Large inland	XL inland	0.6	0.4	2030	0.1	ST

assumed to be constant over time, except for the de- and realignment pathway. Note that for cars and bicycles the relationship between fleet size and delivered service is weak, the following paragraph describes how this is dealt with.

When modelling a a reduction of fleet size according to service delivered by vehicles, a problem arises because these two vehicle categories do not show a relationship with the delivered service and the number of vehicles (rather, the number of vehicles grow with the population, as shown earlier in this paragraph). Following, if one assumes a relationship between the number of vehicles and the service delivered, the number of vehicles currently observed will be much higher than the model would show, therefore, a correction is introduced to the number of vehicles per delivered service to show accurate historical numbers of vehicles for the period 2000-2018.

This correction would not be necessary if one would consider to model the number of cars and bicycles by the number of vehicles per population instead of the number of vehicles per amount of service they deliver. However, as the main assumption of this thesis is that vehicles exist to deliver a service, the choice was made to hold this assumption. However, applying this correction does imply that a change in behaviour is assumed- where currently it is clear that ownership of cars and bicycles are unrelated to the service they provide it was chosen to assume that this will decline in the future. Finally, with data describing the number of vehicles needed to deliver a certain amount of service, a projection for the number of passenger transportation vehicles could be constructed.

Both airplanes and sea vessels are not considered separately, because with the current assumptions they do not interact with other modes of transport. This is potentially problematic because there could potentially be an interaction between air travel and train travel, especially for short travelling distances. However, not enough time was available to consider travel data for each airline company in the Netherlands, but this could be potentially interesting to consider a modal shift between (short) air travel and train travel. A separate projection is constructed for both air travel and sea freight transport. These projections follow the WLO-low scenario projections. Including these vehicles serves mainly to identify the material impact of their use, and no alternative pathways are considered for these vehicles.

The following figures show the shift relevant to several transition pathways.

B.4 Stock flow modelling using the Weibull distribution

Dynamic stock modelling: flow modelling

To construct a model describing the in- and outflow from stock, a hypothetical scenario is constructed where a stock of 5000 vehicles is kept constant for the period 2000-2050. For a lifespan of 50 years, the expected in- and outflow rate would be 100 per year. For convenience sake, this chapter will describe the inflow of vehicles into the stock as 'births' and the outflow as 'deaths' which makes it easier to describe the behaviour.

For dynamic behaviour, the a discretized weibull function with shape factor=(k) and lifespan=λ_d is subtracted from demographic histogram of the previous time step. This is then shifted using a lower shift matrix ($\mathbf{L}$). Depending on whether the stock change (external factor) is negative or positive: either births are added to the first age cohort using queue vector q, otherwise the entire histogram is scaled according to the magnitude of deaths.

$$\mathbf{s}_{(v,z,k,m,\lambda_d)}(t,i) = \begin{cases} \mathbf{L}_i \times \left(\mathbf{s}_{(t-1)} - m \cdot \left(e^{-\left(\frac{i}{\lambda_d}\right)^k} - e^{-\left(\frac{i-1}{\lambda_d}\right)^k} \right) \right) + \delta s_t \times \mathbf{q} & \text{if } \delta s_t \geq 0 \\ \mathbf{L}_i \times \left(\mathbf{s}_{(t-1)} - m \cdot \left(e^{-\left(\frac{i}{\lambda_d}\right)^k} - e^{-\left(\frac{i-1}{\lambda_d}\right)^k} \right) \right) \cdot \frac{|\mathbf{s}| - \delta s_t}{|\mathbf{s}|} & \text{if } \delta s_t < 0 \end{cases} \tag{B.2}$$

With a lower shift matrix $\mathbf{L}_i$ defined as a matrix with ones on the subdiagonal, as described by *Beauregard* (1973): a 4×4 example is shown in B.3. The queue vector q is defined in eq. B.4

$$\mathbf{L} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \tag{B.3}$$

$$q = \begin{bmatrix} 1 & 0 & 0 & 0 & \dots & i \end{bmatrix} \tag{B.4}$$

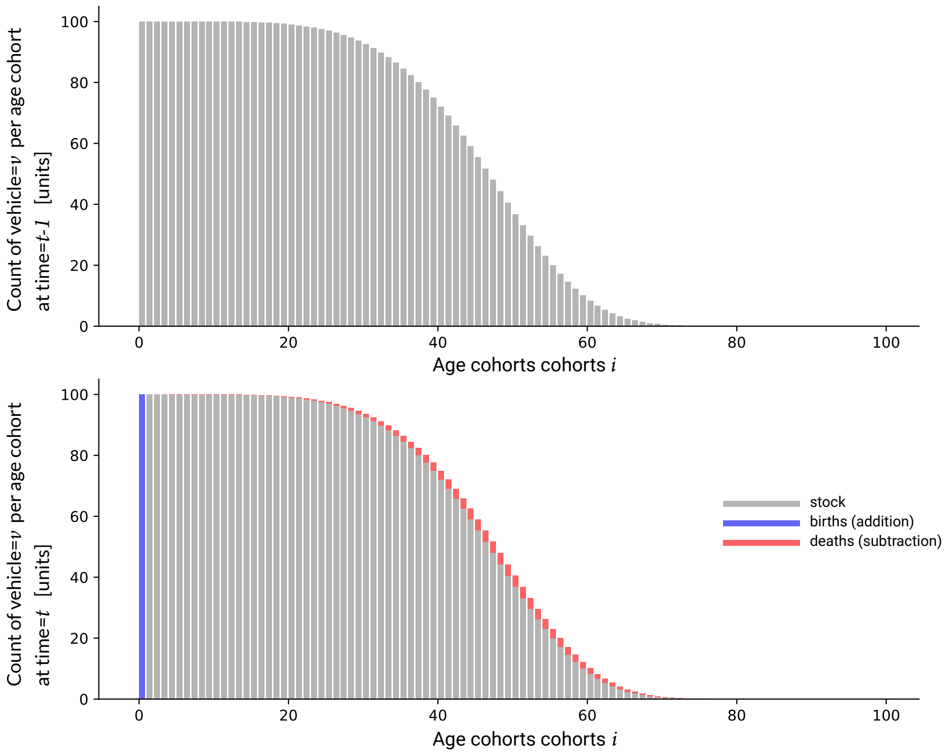


Figure B.12: Demographic histogram at time t, which shows new births in blue and deaths in red compared to previous timestep $t-1$ for a hypothetical vehicle v, with lifespan $\lambda = 50$, and shape factor $k = 5$.

To track the age of individual vehicles, and to model their outflow according to their lifespan using a Weibull distribution, a demographic histogram is constructed for the first year. This demographic histogram will be described as a vector or array, which allows it to be algebraically manipulated. In this notation, the magnitude of the histogram (sum of all cohorts) is equal to the scalar value of the stock at a certain time step.

In this hypothetical scenario where there is no net stock change, for each time step, a proportion of the stock dies (in effect a subtraction of a certain magnitude and distribution), and an equal number of units are born (in effect all age cohorts are shifted to a year older and the new youngest age cohort slot is added with the magnitude equal to the number of deaths). Because there is no net stock change, and we assume stochastic (randomly distributed according to lifespan) behaviour, the histogram at t=1 should be identical to the histogram at t=0. When we allow stock change, either additional deaths occur next to the lifespan-related deaths, or additional births occur. This is shown in figure B.12.

The lower shift matrix L is in effect an identity matrix with 1's on the subdiagonal instead of the diagonal. It is used to shift the demographic histogram for the next timestep. The queue vector Q fills the now-empty first age cohort with the number of births in that timestep.

Note that there is an assumption here that when negative stock change is larger than the number of age-related deaths, that the negative stock change is distributed according to the same Weibull distribution as that of age-related deaths because it is unknown what the distribution is of this behaviour is. It might be the case that for example younger cars are discarded in this situation, and the expected effects of this would be to dampen the dynamic response instead of aggravating it.

This section describes the process of estimating the parameters for a Weibull probability distribution function which satisfies the following requirements:

- For a constant stock level, the demographic histogram does not change over time.
- Parameters should be resilient to a range of different demographic histogram shapes, as described in the previous section (cars, figure 3).
    - 1 < Shape factor < 7
    - 1 < Lifespan < 50

The parameters are estimated manually, as opposed to via analytical methods like the log- or maximum- likelihood method because the manual method was found to show good results with just a tiny amount of tweaking. It is recommended to use the analytical method if one would aim to explore shape factors and scale factors outside of the ranges described in this paragraph.

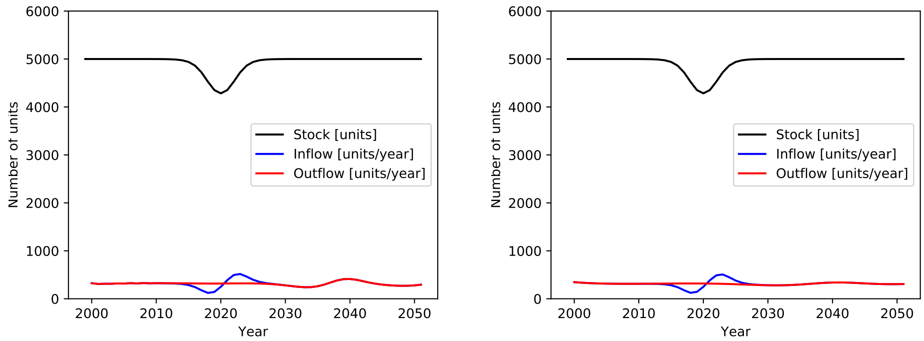
The aim is to use the parameters for the initial histogram value as a starting point, which would allow the model to run in as many possible situations as possible. Starting with estimations identical to the parameters of the starting histogram, one can see a very bad performance.

The calibrated model is scaled for the outflow to match the expected outflow, and the performance is found to be acceptable, as can be seen in figure 11 for lifespan=5 and shape=5. Table 1 shows the relative performance for a range of lifespans and shapes.

The model is tested for dynamic performance by adding changes in stock levels and is found to work as expected, with inflow and outflow intersecting where the stock peaks, as shown in figure 12. Importantly, when the inflow hits 0 because of a steep decline in the stock, the outflow experiences a sharp peak. Also, around 2040, the expected peak in outflow and inflow is visible where the surge in vehicles introduced around 2020 is deprecated. Comparing the high- and low-resolution graphs show that the influence of resolution is not significant, and for the vehicle data set the model will be run at low resolution to conserve computing time.

The dynamic behaviour of the model is explored for different shape factors. For a relatively high shape factor like that of cars (shape $k = 5$), which reflects a steep and narrow lifetime distribution, the long term response is clearly visible. On the other hand for lower shape factors like that of company vehicles (shape $k = 2$) the long term effects on the dynamic response are strongly dampened, as visible comparing figure B.13(a) and B.13(b).

This test setup can be run using dynamic_test.py which calls the stockflow.py class which can be found via the github page `https://github.com/grimelda/urmive`. (*Van der Zaag*, 2019)



(a) Weibull stock-flow model response to impulse with shape factor $k = 6$.

(b) Weibull stock-flow model response to impulse with shape factor $k = 3$.

Figure B.13: The response to in- and outflows after a change in stock level

The values of m and λ_d are unknown, and parameter estimation should find the proper input for the discretized weibull distribution that describes the deaths during a timestep. A full description of this method is given in Appendix B.4, but the conclusions are shown in figure 3.1. Good results are found for all lifespan values, and shape factors between 1.4 and 6.5.

$$m(k) = 3.41 \cdot k + 4.92 \tag{B.5}$$

$$ls(k) = 5.887 \cdot k^{-1.562} \cdot e^{-k/3.553E13} + 1.322 \tag{B.6}$$

The accuracy of the model was tested under static circumstances for various lifespans and shape factors. The results show acceptable performance, as shown in the following table:

Dynamic stock modelling: Stock demography

The existing stock of vehicles will be modelled in this thesis as having certain demography with characteristic lifespans, where the outflow is governed by the age of individual units in the stock. To be able to do this, detailed data is needed to describe the demography of the stock.

Empirical data were only found for several road vehicles and is shown for cars in figure 1 for 2017. In this year, the average stock age was found to be 10.9 years, and in the same year,

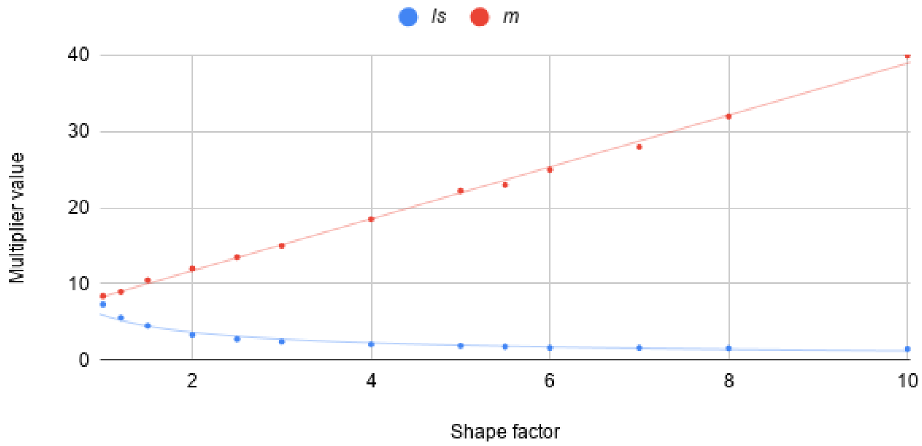


Figure B.14: Values of m and $ls = \frac{\lambda_d}{\lambda}$ after calibration

Table B.5: Accuracy of stock-flow model under static circumstances for different lifespans and shape factors.

shape \ *exp. lifespan*	2	4	7	10	20	30	50
1.2	96%	98%	99%	99%	99%	100%	100%
1.4	98%	100%	101%	101%	101%	101%	101%
1.8	99%	101%	101%	102%	102%	102%	102%
2	99%	100%	101%	101%	102%	102%	102%
3	97%	98%	99%	99%	100%	100%	101%
4	96%	98%	99%	99%	100%	100%	100%
5.5	97%	99%	100%	100%	101%	101%	101%
6	98%	99%	100%	100%	101%	101%	101%
8	96%	98%	98%	99%	99%	99%	99%
10	92%	98%	98%	99%	99%	99%	98%

BOVAG-RAI described cars to deprecate after an average of 18 years, figure 2 (*BOVAG-RAI*, 2019a).

As of yet, studies that have applied dynamic material flow analysis are limited to passenger cars. Whilst this is an important contributor to material demand, other vehicles used in Dutch society are expected to have large stocks of valuable materials which have yet to be quantified.

The chosen approach is "retrospective and prospective bottom-up", as characterised by *Müller et al.* (2014). This method for dynamic analysis requires extensive amounts of data, and specific stock models for different product groups, which makes it prohibitively time-consuming. In the case of the Netherlands, however, the relative abundance and quality of data regarding vehicles provide a unique case for conducting this method as the results can inform studies which use a top-down approach which would be the method of choice in a situation where fewer data are available.

Whilst this method seems to work to a satisfying degree for the vehicles above, it seemed to be less applicable for other vehicle types like trains and aeroplanes. One reason might be that these vehicles are managed in different ways- where cars and motorcycles are often owned by private individuals, whilst aeroplanes and trains are managed as assets at a large scale by companies. Vehicles are custom ordered in batches to the specification of the company, and their lifespan is influenced by maintenance and obsolescence planning (*Wilkinson*, 2015). Another explanation could also be that there are simply far fewer rail and air vehicles compared to road vehicles, so the sample size is insufficient to be used for descriptive statistics.

Because the practice of planned obsolescence is so usual for aircraft and trains, it might make more sense to use a static and constant lifetime for vehicles to describe their deprecation. However, the variance of the lifespan of different aircraft models are high- with Boeing 747's famously flying on average 27 years (*Lyte*, 2016) which is far longer than their flight cycle goal, whilst other aircraft have shown to not achieve their flight cycle goal with an age of just 15 years (*Zhou*, 2019). For this reason, it was chosen to describe the deprecation with a Weibull curve instead of by batches with constant lifetime, but with a high shape factor to describe the effect of planned obsolescence- 95% of aircraft will survive by age 16, yet fewer than 7% will survive age 23 with a steep shape factor of 10. If one would aim to predict when exactly vehicles would be replaced, using batches would be recommended, but in this case, the average material in and outflows are of importance, so the average distribution method is chosen.

No data regarding demographics or lifespan were found for two important vehicles: bicycles and e-bicycles. For the sake of including them in the analysis, lifespans are assumed of 10 years for normal bicycles and 5 years for e-bicycles, based on anecdotal evidence that electric bicycles lose their value very quickly because batteries quickly lose their capacity (from the website `Electrischefietsenkiezen.nl`, 2019). A low shape factor of 2 chosen as the variance in lifespans of bicycles is expected to be large. The same trend is expected for electric mopeds. For electric cars, the lifespan is similarly chosen to be half that of conventional cars, but this is highly uncertain as many electric cars are yet to reach their warranty lifespan (which is 8 years for the most common Tesla model, from anecdotal evidence from Roberson 2019). Including the lifespan in a sensitivity analysis would be especially interesting for these electric vehicles because of the uncertainty of this data. A full table B.6 with chosen values for all vehicles considered in this thesis is shown. Figures with demographic data and fitted weibull curves are shown in figures B.15 through B.23.

Vehicle demography and Weibull distributions: Discussion

When detailed and high quality data is available describing the demographics of a vehicle stock, the vehicle stock is relatively constant over time, and there is reason to believe that inflow and outflow would follow stochastic (randomly distributed according to lifespan) behaviour, a weibull

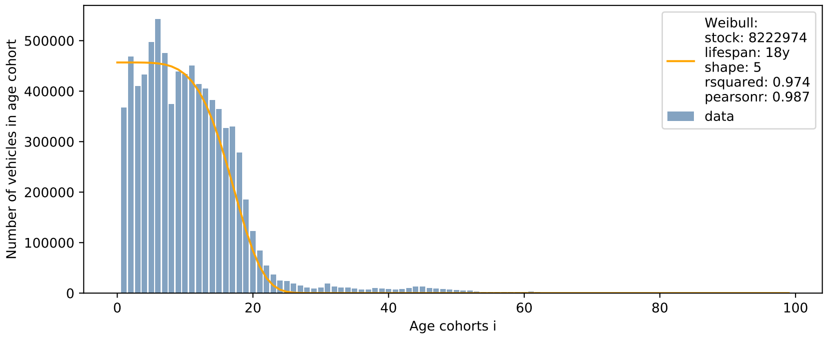


Figure B.15: Cars: demographic data fitted with weibull scaled survival function

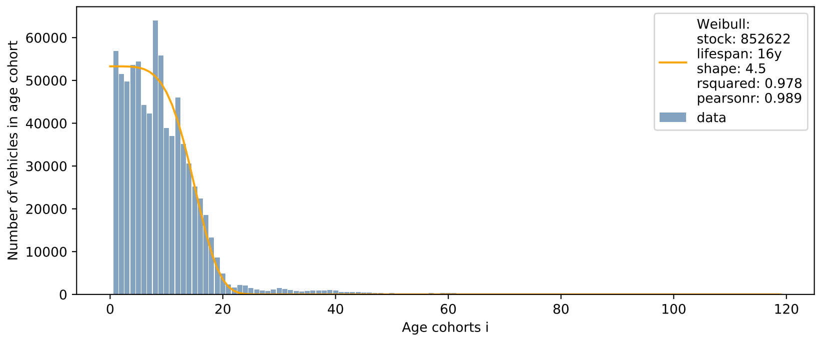


Figure B.16: Delivery vans: demographic data fitted with weibull scaled survival function

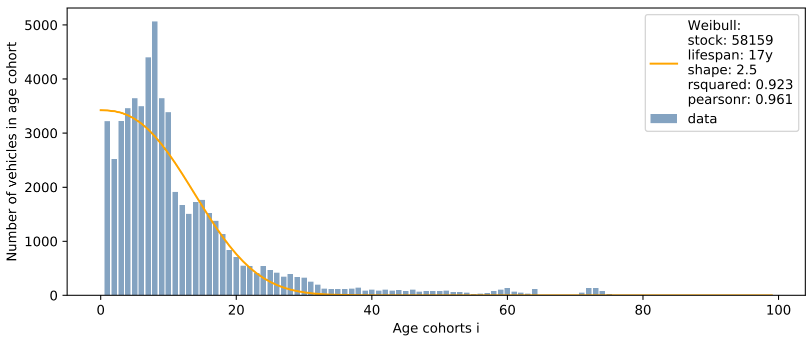


Figure B.17: Trucks: demographic data fitted with weibull scaled survival function

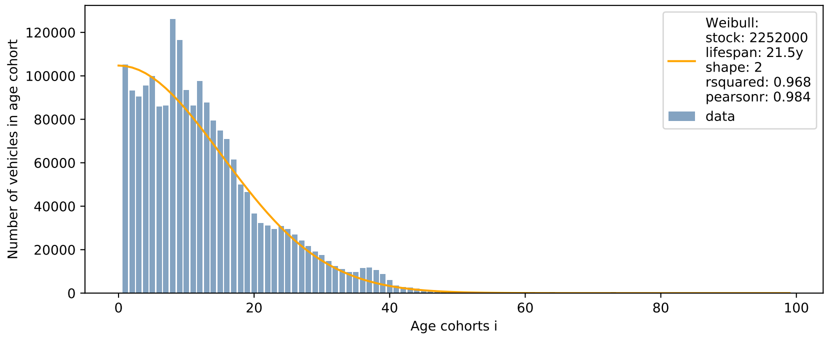


Figure B.18: Utility cars: demographic data fitted with weibull scaled survival function

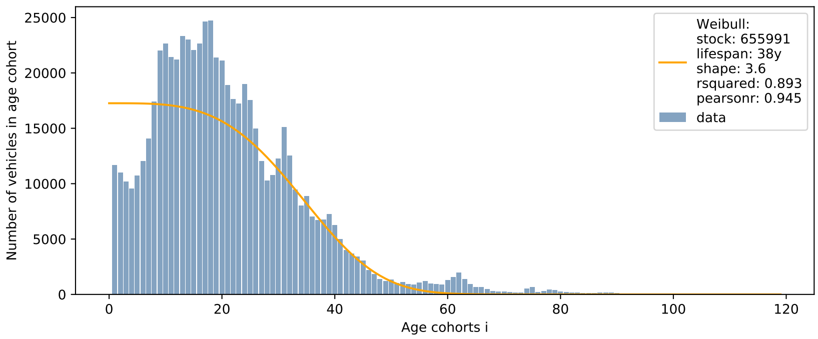


Figure B.19: Motorbikes: demographic data fitted with weibull scaled survival function

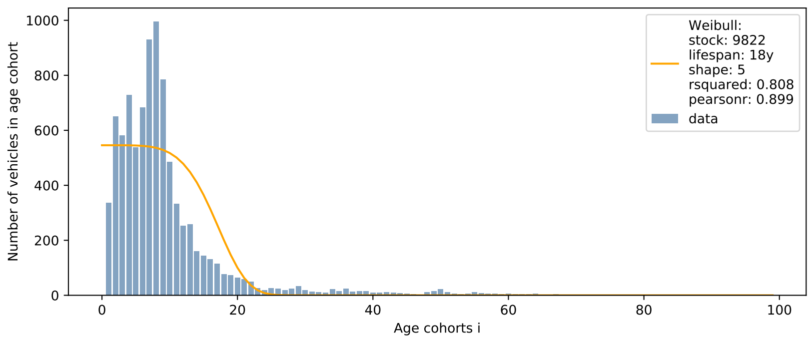


Figure B.20: Bus: demographic data fitted with weibull scaled survival function

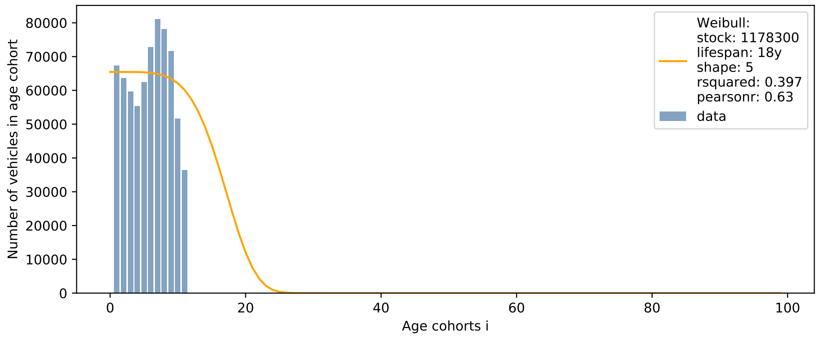


Figure B.21: Mopeds: demographic data fitted with weibull scaled survival function

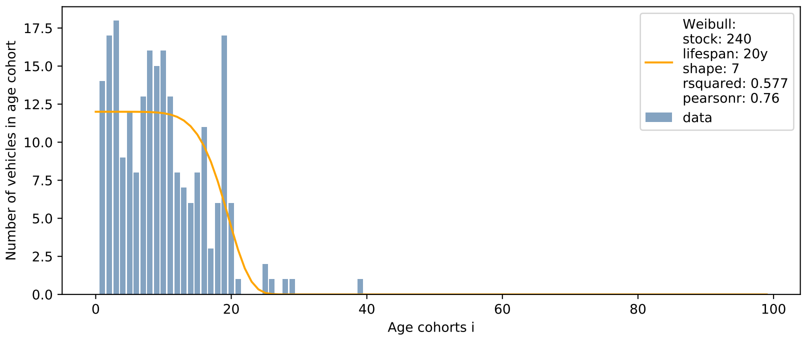


Figure B.22: Jets: demographic data fitted with weibull scaled survival function

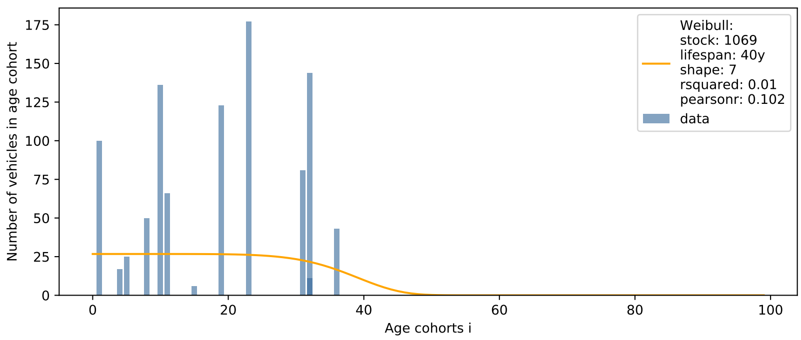


Figure B.23: Trains: demographic data fitted with weibull scaled survival function

Table B.6: Table with the chosen values for vehicles considered in the projections for this thesis

Domain	Class	lifespan	shape	lifespan source	Vmass	Vehicle	Vehiclename
Mobility	Aircraft	20	8	demographic data	181840	A330	A330
Mobility	Aircraft	20	8	demographic data	161000	B787	B787
Mobility	Bicycles	10	3	guess	16	bike	bike
Mobility	Bicycles	5	3	guess	25	ebike	ebike
Mobility	Bicycles	9	3	guess	100	emoped	emoped
Mobility	Bicycles	18	3	demographic data	100	moped	moped
Mobility	Cars	9.5	5.5	demographic data	1776	ev	ev
Mobility	Cars	19	5.5	demographic data	1211	hev	hev
Mobility	Cars	19	5.5	demographic data	1121	icev	icev
Mobility	Transit	22.5	1.8	demographic data	10787	bus	bus
Mobility	Transit	40	8	informed guess	155000	ptrain	ptrain
Mobility	Walking	1	1	-		walk	walk
Freight	Inlandvessels	45	1.4	demographic data	1041700	hmaxin	lbarge
Freight	Inlandvessels	45	1.4	demographic data	625000	hmaxin	mbarge
Freight	Inlandvessels	45	1.4	demographic data	312500	hmaxin	sbarge
Freight	Inlandvessels	45	1.4	demographic data	1458300	hmaxin	xlbarge
Freight	Utilitycars	21.5	2	demographic data	1694	icevan	icevan
Freight	Utilitycars	21.5	2	demographic data	2684	evan	evan
Freight	Utilitycars	17	2.5	demographic data	8275	lorry16t	16tlorry
Freight	Utilitycars	17	2.5	demographic data	14842	lorry28t	28tlorry
Freight	Utilitycars	17	2.5	demographic data	21203	lorry40t	40tlorry
Freight	Seavessels	35	1.4	demographic data	6893840	hmax	Bagger schip
Freight	Seavessels	35	1.4	demographic data	157714	hmax	Bergings schip
Freight	Seavessels	35	1.4	demographic data	3988160	hmax	Bevoorradings schip
Freight	Seavessels	35	1.4	demographic data	8430080	hmax	Boorvaartuig
Freight	Seavessels	35	1.4	demographic data	15200512	bulker	Bulk Carrier
Freight	Seavessels	35	1.4	demographic data	25822745	hmax	Container schip
Freight	Seavessels	35	1.4	demographic data	50521512	hmax	Cruise schip
Freight	Seavessels	35	1.4	demographic data	10860882	tanker	Gas tanker
Freight	Seavessels	35	1.4	demographic data	22681383	hmax	Koel schip
Freight	Seavessels	35	1.4	demographic data	1191696	hmax	Kust en zeesleepboot
Freight	Seavessels	35	1.4	demographic data	390720	hmax	Meet- en peil vaartuig
Freight	Seavessels	35	1.4	demographic data	11472098	hmax	Multi purpose vessel
Freight	Seavessels	35	1.4	demographic data	7314752	hmax	Offshore support vessel
Freight	Seavessels	35	1.4	demographic data	15714330	tanker	Olie-chemicalien tanker
Freight	Seavessels	35	1.4	demographic data	3260956	hmax	Overig
Freight	Seavessels	35	1.4	demographic data	40004800	hmax	Ro-Ro Vessel
Freight	Seavessels	35	1.4	demographic data	18308784	hmax	Sleephopper zuiger
Freight	Seavessels	35	1.4	demographic data	6112104	hmax	Snijkop zuiger
Freight	Seavessels	35	1.4	demographic data	2588672	hmax	Splijtbak - Omnibarge
Freight	Seavessels	35	1.4	demographic data	39362672	hmax	Steen storter schip
Freight	Seavessels	35	1.4	demographic data	3789056	hmax	Transport ponton
Freight	Seavessels	35	1.4	demographic data	128216640	hmax	Veer schip
Freight	Seavessels	35	1.4	demographic data	1062400	hmax	Werk schip
Freight	Seavessels	35	1.4	demographic data	2284528	hmax	Zuiger schip
Freight	Seavessels	35	1.4	demographic data	32497905	hmax	Zware lading schip
Freight	Freighttrains	40	4	informed guess	590000	ftrain	ftrain

survival function scaled to the expected outflow (stock over expected lifespan) shows a convincing proxy for demographic data.

In this case, if the lifespan is known or assumed, the shape value can be optimized to show the best fit, and if the results are unsatisfying this indicates that other factors have a high influence on the demographics of the vehicle. Three examples of factors that can influence: (a) foreign import/export of second-hand vehicles, (b) that stock is not constant over time, and (c) evidence of non-stochastic behaviour of inflow and outflow e.g. when vehicles are managed as assets.

Influence from import and export is expected to have an influence on the shape of the demographic distribution, but for cars (the only vehicles with export data available) the expected lifespan produced a good fit for the demographic data. The most likely explanation is that the expected lifespan was derived from the stock demographics instead of the average age of dismantling.

If the stock is not constant, a recent stagnation of stock growth would be visible as a dip in recent age cohorts, and recent growth of stock would be visible as a peak in recent age cohorts, as can be seen in the example of motorcycles (figure 4c).

For vehicles that are managed as assets, e.g. trains and aircraft, demographic data shows evidence of vehicles being bought in batches. If different models of the same type of vehicle have similar lifespans, it makes sense to assume a constant lifespan, however, if different models within the same vehicle category have a wide range of lifespans, it makes sense to use a lifespan distribution.

In most cases, only demographic data was available and data describing the expected lifespan of vehicles was absent. In these cases, both the lifespan and the shape were varied to find the best fit. This does mean that there is no way to discern which part of the outflow comprises of exports and which of the dismantling of vehicles, which would be possible if lifespan data was available.

C
Appendices to the Results Chapter

C.1 Historical data and Sources

The most important data and results for the historical stocks are published in an excel sheet, *NL_vehicle_counts_historical.xlsx*, accompanying this thesis. It can be found on the TU Delft repository via the following url: https://repository.tudelft.nl/islandora/search/jochem%20van%20der%20zaag?collection=education

C.2 Material composition data and Sources

The most important material composition data and results are published in an excel sheet, *NL_vehicle_future_pathways* accompanying this thesis. It can be found on the TU Delft repository via the following url: https://repository.tudelft.nl/islandora/search/jochem%20van%20der%20zaag?collection=education

C.3 Projections data

The most important data and results for the projections for different pathways are summarized in the spreadsheet *NL_vehicle_future_pathways.xlsx* available via the TU Delft repository: https://repository.tudelft.nl/islandora/search/jochem%20van%20der%20zaag?

collection=education but can also be explored via the online ipython notebook published in the GitHub repository (*Van der Zaag*, 2019), and available via https://colab.research.google.com/github/grimelda/urmive/blob/master/Pathways_comparison.ipynb

C.4 Cumulative in- and outflows for five transition pathways

Table C.1: Material turnover in tons (cumulative in- and outflows of material groups) in the period 2020-2050 for the Stagnation (REF) reference pathway.

Material	Cumulative inflow	Cumulative outflow
Total	**49 890 130**	**42 143 240**
Metals, ferrous	40 400 000	33 600 000
Polymers	3 400 000	3 150 000
Aluminium	2 400 000	2 270 000
Copper	1 240 000	1 050 000
Minerals	646 000	492 000
Organic	644 000	529 000
Glass	525 000	495 000
Paint	288 000	249 000
Metals, other nonferrous	165 000	156 000
Unknown	114 000	87 600
Ceramics	24 800	23 400
Chemicals	16 100	15 200
Composites	12 900	12 500
Insulation	9 290	8 730
Critical Raw Materials, CRM	5 040	4 810

Table C.2: Material turnover in tons (cumulative in- and outflows of material groups) in the period 2020-2050 for the Substitution (ST) pathway.

Material	Cum. inflow	Cum. outflow	inflow ST/REF	outflow ST/REF
Total	**69 817 700**	**56 952 400**	**1.40**	**1.35**
Metals, ferrous	45 500 000	39 000 000	1.1	1.2
Polymers	6 830 000	5 560 000	2.0	1.8
Critical Raw Materials, CRM	5 790 000	3 200 000	1148.8	665.3
Aluminium	4 920 000	3 990 000	2.1	1.8
Copper	3 140 000	2 210 000	2.5	2.1
Glass	922 000	808 000	1.8	1.6
Organic	889 000	706 000	1.4	1.3
Minerals	777 000	570 000	1.2	1.2
Paint	402 000	341 000	1.4	1.4
Ceramics	252 000	216 000	10.2	9.2
Metals, other nonferrous	190 000	196 000	1.2	1.3
Unknown	115 000	89 200	1.0	1.0
Insulation	44 000	27 900	4.7	3.2
Composites	27 700	18 600	2.1	1.5
Chemicals	19 000	19 700	1.2	1.3

Table C.3: Material turnover in tons (cumulative in- and outflows of material groups) in the period 2020-2050 for the De- and Realignment (RA) pathway.

Material group	Cum. inflow	Cum. outflow	inflow ST/REF	outflow ST/REF
Total	**39 964 850**	**38 999 310**	**0.80**	**0.93**
Metals, ferrous	33 000 000	31 300 000	0.8	0.9
Polymers	2 310 000	2 780 000	0.7	0.9
Aluminium	1 760 000	2 050 000	0.7	0.9
Copper	974 000	963 000	0.8	0.9
Minerals	589 000	482 000	0.9	1.0
Organic	532 000	494 000	0.8	0.9
Glass	325 000	425 000	0.6	0.9
Paint	216 000	226 000	0.8	0.9
Metals, other nonferrous	107 000	136 000	0.6	0.9
Unknown	103 000	85 400	0.9	1.0
Ceramics	15 400	20 100	0.6	0.9
Composites	11 200	11 900	0.9	1.0
Chemicals	9 750	13 000	0.6	0.9
Insulation	8 680	8 530	0.9	1.0
Critical Raw Materials, CRM	3 820	4 380	0.8	0.9

Table C.4: Material turnover in tons (cumulative in- and outflows of material groups) in the period 2020-2050 for the Reconfiguration (RC) pathway.

Material group	Cum. inflow	Cum. outflow	inflow ST/REF	outflow ST/REF
Total	**32 319 440**	**24 474 440**	**0.65**	**0.58**
Metals, ferrous	26 500 000	19 600 000	0.7	0.6
Polymers	2 020 000	1 780 000	0.6	0.6
Aluminium	1 420 000	1 290 000	0.6	0.6
Copper	802 000	606 000	0.6	0.6
Minerals	452 000	298 000	0.7	0.6
Organic	423 000	307 000	0.7	0.6
Glass	305 000	274 000	0.6	0.6
Paint	182 000	143 000	0.6	0.6
Metals, other nonferrous	96 200	87 200	0.6	0.6
Unknown	79 400	52 900	0.7	0.6
Ceramics	14 500	13 100	0.6	0.6
Chemicals	9 340	8 420	0.6	0.6
Composites	7 350	6 960	0.6	0.6
Insulation	5 710	5 150	0.6	0.6
Critical Raw Materials, CRM	2 940	2 710	0.6	0.6

Table C.5: Material turnover in tons (cumulative in- and outflows of material groups) in the period 2020-2050 for the Transformation (TF) pathway.

Material group	Cum. inflow	Cum. outflow	inflow ST/REF	outflow ST/REF
Total	**46 169 410**	**40 610 400**	**0.93**	**0.96**
Metals, ferrous	38 100 000	32 400 000	0.9	1.0
Polymers	2 460 000	2 930 000	0.7	0.9
Aluminium	2 320 000	2 320 000	1.0	1.0
Copper	1 080 000	988 000	0.9	0.9
Organic	703 000	512 000	1.1	1.0
Minerals	689 000	497 000	1.1	1.0
Glass	296 000	438 000	0.6	0.9
Paint	243 000	232 000	0.8	0.9
Unknown	120 000	88 000	1.1	1.0
Metals, other nonferrous	90 900	140 000	0.6	0.9
Insulation	35 400	15 000	3.8	1.7
Ceramics	11 500	20 800	0.5	0.9
Composites	10 300	11 900	0.8	1.0
Chemicals	6 940	13 200	0.4	0.9
Critical Raw Materials, CRM	3 370	4 500	0.7	0.9