AVOID, SHIFT OR IMPROVE PASSENGER TRANSPORT?

MODELLING OF SUFFICIENCY SCENARIOS FOR THE CASE OF GERMANY

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Abstract

Passenger transport is responsible for a large share of greenhouse gas emissions. Its decarbonisation requires improved vehicle technologies and renewable energy supply, which, however, put the electricity system decarbonisation under additional pressure. Besides, passenger transport shows the most significant social inequalities across all consumption sectors and serious externalities that negatively impact human life and well-being. Hence, corresponding solution approaches must go beyond "technofixes" and should take into account sufficiency strategies. The German passenger transport system is the case study of this dissertation because those issues are particularly pronounced here.

This work provides the open source transport model quetzal_germany as a tool to simulate the impacts of such strategies on the transport system. It first shows the need for sufficiency measures when pursuing ambitious climate mitigation targets. Then, it connects measures of traffic avoidance and mode shifts to sufficiency transitions, which can capture the full complexity of large-scale system transformations towards human life between planetary boundaries and satisfaction of basic needs. The identification and classification of corresponding drivers of change allows for constructing three storylines, which describe feasible sufficiency futures in German passenger transport: unalloyed traffic avoidance, unalloyed mode shifts, and the combination of both, in addition to push measures against private cars. The latter describes a maximum sufficiency threshold.

Modelling these storylines in quetzal_germany shows that sufficiency strategies can reduce passenger kilometres by half and shift mode shares up to 46 % from private cars to public and active modes, compared to a reference. Beyond transport system indicators, the sufficiency transitions qualitatively show co-benefits in health, equity, and communal life. Furthermore, modelling these transport demand scenarios in an energy system model reveals savings of up to one quarter of Germany's final energy demand. In a 100 % renewable energy system, this translates into capacity and cost reductions of the same magnitude. The Improve strategy (100 % battery-electric vehicles) shows similar reduction potentials. However, public infrastructure cost in the transportation and housing domain are much lower than in the sufficiency scenarios. Instead, individuals with cars bear the transformation cost.

As such, sufficiency and efficiency strategies show similar impacts, but the former supports a steady social foundation, while the latter promotes individual responsibility. Still, Germany must pursue all strategies simultaneously. One strategy alone is highly improbable to succeed, and the window towards reaching the climate targets is closing swiftly.

Keywords: Mobility transformation, sufficiency, demand-side mitigation, transport modelling, energy system modelling, socio-technical transitions, storylines, transport decarbonisation, discrete choice theory

Zusammenfassung

Der Personenverkehr ist für einen großen Teil der Treibhausgasemissionen verantwortlich. Seine Dekarbonisierung erfordert verbesserte Fahrzeugtechnologien und eine erneuerbare Energieversorgung, was wiederum zusätzlichen Druck auf die Energiewende ausübt. Außerdem zeigt der Personenverkehr die größten sozialen Ungleichheiten aller Konsumsektoren und ernsthafte Externalitäten, welche die Lebensqualität negativ beeinflussen. Entsprechende Lösungsansätze müssen über "Technofixes" hinausgehen und sollten Suffizienzstrategien beinhalten. Der deutsche Personenverkehr ist das Fallbeispiel dieser Dissertation, weil diese Probleme hier besonders sichtbar sind.

Diese Arbeit stellt mit dem Open-Source-Verkehrsmodell quetzal_germany ein Werkzeug zur Verfügung, um die Auswirkungen solcher Strategien auf das Verkehrssystem zu simulieren. Zuerst zeigt sie, dass Suffizienzstrategien notwendig sind, um ambitionierte Klimaziele zu erreichen. Daraufhin verbindet sie Maßnahmen der Verkehrsvermeidung und -verlagerung mit Suffizienz-Wenden, welche die volle Komplexität tiefgreifender Systemtransformationen in Richtung planetare Grenzen und Befriedigung menschlicher Grundbedürfnisse erfassen können. Die Identifikation und Klassifizierung entsprechender Transformationstreiber erlaubt die Erstellung dreier Narrative: die reine Verkehrsvermeidung, die reine Verkehrsverlagerung und die Kombination aus beidem inklusive Push-Maßnahmen gegen den Individualverkehr. Letzteres beschreibt eine Messlatte für maximale Suffizienz.

Die Modellierung dieser Narrative in quetzal_germany zeigt, dass Suffizienzstrategien die Personenkilometer um die Hälfte reduzieren und die Verkehrsträgerverteilung um bis zu 46 % vom privaten Pkw auf öffentliche und aktive Verkehrsmittel verlagern können. Darüber hinaus zeigen die Suffizienznarrative positive Effekte für Gesundheit, soziale Gerechtigkeit und das lokale Zusammenleben. Die darauffolgende Modellierung in einem Energiesystemmodell zeigt Einsparungen von bis zu einem Viertel des deutschen Endenergiebedarfs. In einem 100 % erneuerbaren Energiesystem führt dies zu Kapazitäts- und Kostenreduktionen in der gleichen Größenordnung. Die vollständige Antriebswende (100 % batterieelektrische Fahrzeuge) zeigt ähnliche Einsparpotenziale. Dabei sind die Kosten für öffentliche Infrastruktur im Verkehrs- und Bausektor deutlich geringer als in den Suffizienzszenarien. Stattdessen werden die Transformationskosten von Privatpersonen beim Autokauf getragen.

Suffizienz- und Effizienzstrategien zeigen also ähnliche Auswirkungen, aber erstere fördern eine stabile soziale Gesellschaft, während letztere die individuelle Verantwortung hervorheben. Dennoch muss Deutschland alle Strategien gleichzeitig verfolgen. Der Erfolg einer einzelnen ist sehr unwahrscheinlich und das Zeitfenster zur Erreichung der Klimaziele schließt sich schnell.

Schlüsselwörter: Mobilitätswende, Suffizienz, Nachfrageveränderungen, Transportmodellierung, Energiesystemmodellierung, sozio-technische Transformationen, Narrative, Verkehrswende

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At the beginning of this dissertation, I had no peers in the field I wanted to work in. Thus, I am pleased to have found comrades along the way. Thank you, Johannes Thema, for all our online discussions about sufficiency and transport policy, methods and models, politics and the future. Thank you for jointly supervising our exceedingly competent master students Johanna and Kikan. Your motivation for the topic helped me throughout the last three years. I also want to thank Quentin Chasserieau for introducing me to Quetzal and, basically the art of transport modelling. How would this work look like if I had not found you? I am also very thankful for all the master students and young researchers who had to go through my transport modelling courses or developed new transport models based on quetzal_germany. You contributed to opening up macroscopic transport modelling, even though you might not have felt like it.

Further, I feel blessed to have such marvellous colleagues at the Graduate School *EnergieSystemWende*. Thank you for the supportive atmosphere, the heaps of interesting discussions, and those joyful activities throughout the last few years. I hope to keep you as friends. That atmosphere is not least due to Philipp and his impressive leadership style, as well as his passion and devotion to our graduate school. This would not have been possible without the stable infrastructure of the Reiner Lemoine Institut, especially when my modelling efforts grew far beyond what laptops could handle. But more than the servers, this institute's beauty lies in its wonderful people – an extraordinary place. And what could I have possibly achieved without Karlo, my guide through the jungle of WIP-specific rules, infrastructures, and conventions. Thank you for being so supportive in every possible situation. Not least, I want to thank Jens for making me slide into all of this after supervising my master thesis.

I also want to thank my parents and entire family for giving me the feeling that all I would do would eventually succeed. As the first of us with any academic degree, I felt morally supported without the slightest strain. You built the foundation on which I could thrive as I pleased.

Thank you!

Rechtliche Erklärung

Hiermit versichere ich, dass ich die vorliegende Dissertation selbstständig und ohne unzulässige Hilfsmittel verfasst habe. Die verwendeten Quellen sind vollständig im Literaturverzeichnis angegeben. Die Arbeit wurde noch keiner Prüfungsbehörde in gleicher oder ähnlicher Form vorgelegt.

Marlin Arnz
Berlin, December 20, 2023

Overview

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List of abbreviations

ASC	Alternative-specific Constant
EV	electric vehicle
GHG	greenhouse gas
LoS	level-of-service
MiD2017	"Mobility in Germany 2017"
MIT	motorised individual transport
NDCs	nationally determined contributions
OD	origin destination
pkm	passenger kilometres
PT	public transport
RES	renewable energy sources
ViZ	"Transport in figures"
VP2030	"Forecast of transport interconnectivity 2030"

Chapter 1

Introduction

1.1 Motivation

"Infrastructure Policy in the 21st Century" was the title of the 25th-anniversary celebration of the Workgroup for Economic and Infrastructure Policy (WIP) at the Technical University Berlin in 2022. It suggested that dominant economic debates of the 20th century need to be reconciled to cope with 21st-century challenges. The central discourse should cease from "free versus social market economy" and face new substantial questions that require global solution approaches. Only in this way can we shape a livable future for humanity. Recent research supports this notion and demonstrates the need for deep transformations across all parts of society to stir towards a "good anthropocene" (Spangenberg 2014; Sluisveld et al. 2015; Turnheim et al. 2015; De Neve and Sachs 2020; McPhearson et al. 2021; Fanning et al. 2021).

These 21st-century economics promote a "safe and just space" for humanity within limits (Raworth 2012, 2017). The upper limit is set by the ecological sealing, i.e. planetary boundaries (Steffen et al. 2015), and the lower limit is the satisfaction of human needs, defined as the social foundation (O'Neill et al. 2018). The objective is to fulfil all human needs without transgressing planetary boundaries (the green space in figure 1.1). Currently, no country in the world achieves this goal.

1.1.1 Climate change mitigation strategies

One of the nine planetary boundaries already transgressed is greenhouse gas (GHG) emissions. With global average temperatures already risen by 1.1 degrees Celsius in 2022 compared to pre-industrial levels, the issue of climate change led to international action. The Paris Agreement (UNFCCC 2015) formulated the goal of "limiting global warming to well below 2 degrees Celsius and pursuing efforts to limit it to 1.5 degrees Celsius" in order to limit the risk of triggering large-scale ecological tipping points that would impact life on earth noticeably (Armstrong McKay et al. 2022). One hundred seventy-five nations signed the treaty and formulated nationally determined contributions (NDCs) to pursue this goal, revising them every five years. However, the IPCC Sixth Assessment Report shows that current NDCs do not suffice to stay within the Paris Agreement's temperature range (IPCC 2022).

The largest cause for anthropogenic GHG emissions is the energy system. Fossil fuel combustion and industrial activities are responsible for 64 % of the global carbon footprint (IPCC 2022).

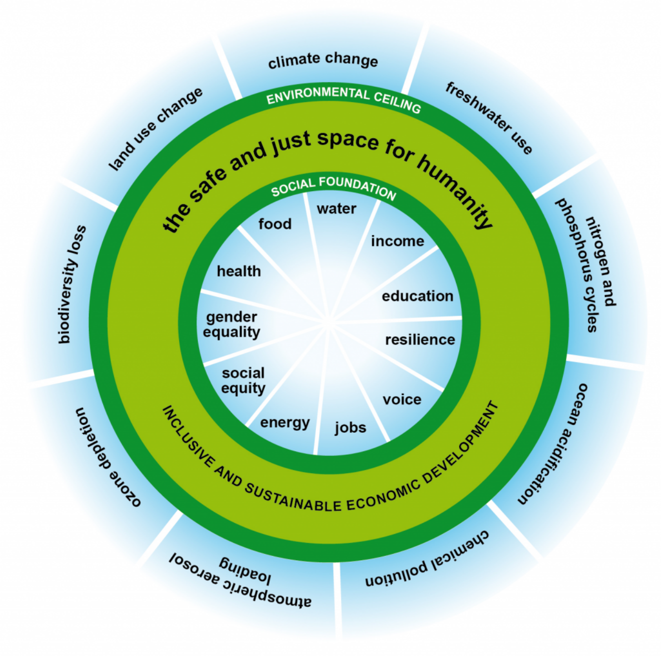

Figure 1.1: The framework of "Doughnut Economics". Inclusive and sustainable economic development should target the safe and just space for humanity between planetary boundaries as the environmental ceiling and social sustainability indicators as the social foundation. Source: Raworth (2012).

As a consequence, decarbonisation of energy supply has been the focus of energy research in the past decades. Therein, a large body of literature considers energy systems with 100 % renewable energy sources (RES) (Khalili and Breyer 2022). These studies highlight technological and economic feasibility of 100 % RES on global scales (Diesendorf and Elliston 2018) and its potential limit global warming to 1.5 degrees, if the energy system transformation happens swiftly (Breyer et al. 2022). Thereby, such systems do not rely on geoengineering and carbon dioxide removal, which are connected to substantial uncertainties and risks (Lawrence et al. 2018; Grant et al. 2021). It is evident that full energy supply decarbonisation is necessary for climate change mitigation, but it is not the only strategy to pursue.

So-called demand-side mitigation strategies concern the reduction of final energy demand by avoiding the need for energy use, shifting it to more energy efficient modes, and improving energy demand technologies (see Creutzig et al. 2018). These *Avoid, Shift,* and *Improve* strategies are applicable to all energy demand sectors and have received special attention from the Workgroup III of the IPCC Sixth Assessment Report (IPCC 2022). Avoid and Shift strategies are often framed as behavioural measures, while Improve strategies concern more efficient technologies and their adoption. Here too, techno-economic strategies have seen much more attention in research (e.g. Gota et al. 2019), as well as in the political and public debate.

Jenny Stephens calls this techno-economic focus “climate isolationism”, arguing that climate change is framed “as an isolated, discrete, scientific problem in need of technological solutions” (Stephens 2022). As introduced above, we know that transformations must be substantial and beyond this isolationism to move towards the safe and just space for humanity (Spangenberg 2014). Spengler (2016) connects this space to sufficiency[1], by defining the space’s limits as levels of “enoughness”; enough in the sense of limiting consumption to the upper end and enough as a matter of distributional justice to the lower end. Lage (2022) shows that sufficiency can be understood as the final objective (i.e. the safe and just space for humanity) or as a means to reach the objective, which is commonly described as sufficiency transitions (Sandberg 2021). In general, sufficiency measures show synergies between them (Lage 2022) and towards reaching the Sustainable Development Goals (Roy et al. 2021), even though some are connected to rebound effects (Sorrell, Gatersleben, and Druckman 2020). They are urgently needed to achieve the climate targets, as other strategies alone will likely fail (Haberl et al. 2020; Hickel and Kallis 2020).

1.1.2 Passenger transport and sufficiency

The transport sector is responsible for 27 % of the global final energy consumption (IPCC 2022). In high-income regions, roughly two thirds account for passenger (IEA 2022). As such, personal mobility in high-income regions is responsible for more than 7 % of global final energy consumption, currently fuelled mainly by oil derivatives (IEA 2022). 100 % renewable energy supply for passenger transport would put the electricity system transition towards 100 % RES under additional stress, as these sectors have been largely decoupled by today (Hainsch 2023). Past research on transport decarbonisation has focused on Improve measures, i.e. technological change to more efficient propulsion technologies, such as battery-electric vehicles (Gota et al. 2019). This strategy increases the stress for the renewable energy system, but would be able to fully decarbonise passenger (land) transport.

Sufficiency strategies, on the other hand, would follow an approach that considers carbon footprints and their distribution. The wealthiest 10 % of the European population spend the largest share of their carbon footprint on transport. At the same time, the “poorest” 40 % of the population would travel more if they could afford it (Ivanova and Wood 2020). There is a highly unequal distribution of mobility access across income groups, which has been described as mobility poverty at the lower end (Lucas et al. 2016; Mattioli, Lucas, and Marsden 2017; King,

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[1] Sufficiency is one of the three complementary sustainability categories, next to efficiency and consistency (also known as renewable energy in energy research).

Smart, and Manville 2022). A sufficiency-oriented transport system would target the upper and lower levels of “enoughness”: reduce those carbon and material footprints that overshoot planetary boundaries by restructuring provisioning systems, and eradicate mobility poverty to facilitate decent mobility standards for all. However, it remains unclear what sufficiency transitions in mobility look like and how they are connected to Avoid and Shift measures.

1.1.3 Currently in Germany

Germany is a high-income country with over five times above limits overshoot in GHG emissions (Fanning et al. 2021). Passenger transport (without freight transport and international aviation) is responsible for 11 % or $89\,\mathrm{MtCO_{2eq}/a}$, dominated by road transport with 98 % (BMWK 2022). The transport sector has seen the least reduction of GHG emissions since 1990 (-9 %) and the current trend will fail Germany’s pledge to reduce emissions to net zero by the year 2045[2]. The Federal Transport Ministry should initiate immediate action, but in 2023, the government instead channelled efforts into a different direction: ditching the intermediate emissions reduction goals for 2030 and accommodating synthetic fuel-driven internal combustion engines into the European Union’s definition of zero-emission vehicles. German transport politics is not on the path towards acknowledging the ecological sealing.

The situation is also difficult for the social foundation. Fanning et al. (2021) find that equality has just passed the minimum threshold in Germany, taking the Gini coefficient as an evaluation measure. However, this is probably not the case for private mobility, which shows significantly larger inequities within countries than other sectors (Oswald, Owen, and Steinberger 2020). As an example, the German National Mobility Survey ("Mobilität in Deutschland 2017"; infas et al. 2017) shows that people without cars make 26 % fewer trips for education purposes, and one-third of these comes from low-income households (own calculation). A range of factors influences individuals’ education and socio-economic status, which cannot be assessed thoroughly with this dataset. However, the great difference supports the existence of social exclusion through mobility poverty.

Especially in rural German regions, car ownership is "forced" and bears a heavy financial burden on low-income households (Mattioli 2017). In general, the German mobility provisioning system shows strong car dependency, following the definition of Giulio Mattioli (2016): “high levels of car use have become a key satisfier of human needs, largely displacing less carbon-intensive alternatives”. This is systemically embedded in the political economy, as the transport system, culture, and built environment (i.e. buildings and settlement structures) have been shaped

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[2] This target is compatible with the 2 degrees Celsius target of the Paris Agreement, but Germany’s emissions budget for the 1.5 degree target (50 % probability) would be depleted in the year 2031, already, when assuming linear emissions reduction (SRU 2022).

towards high use of car driving for decades (Mattioli et al. 2020). Adverse effects of this system design are considerable: Road accidents cause 2,800 deaths and 361,000 injured persons per year; 61 % caused by car drivers (DESTATIS 2023). Air pollution from traffic is responsible for 13,000 premature deaths, which is roughly 50 % above levels of other European Union states (icct 2019).

There is a clear need to transition German passenger transport towards less GHG emissions, less car dependency, less inequality, and less traffic externalities. Sufficiency might be a suitable problem solving strategy.

1.2 Demand-side mitigation in passenger transport

Summing up the approaches to adhere to the ecological sealing from section 1.1, transport decarbonisation resides on four pillars (figure 1.2): Avoiding the need for traffic, shifting traffic to public and active modes, improving transport technologies, and defossilising transport's energy supply. The first three are energy demand-side mitigation strategies, and the latter belongs to the supply side. Together, they address the entire effect chain of transport emissions. As described above, techno-economic analysis has seen much more attention in research than behavioural aspects and the sufficiency realm. This section briefly narrows the research gap and derives research questions for this dissertation.

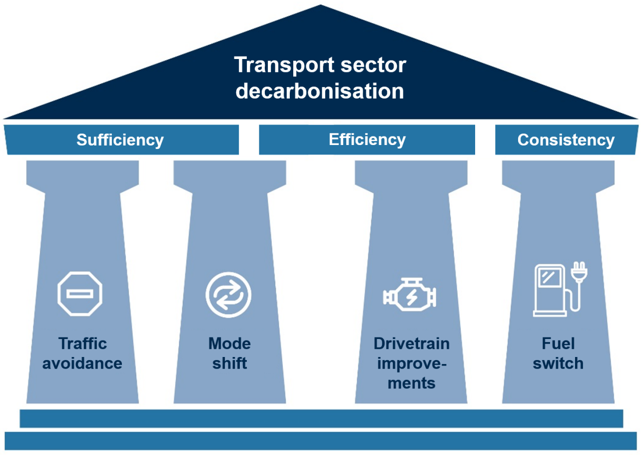

Figure 1.2: Decarbonisation of passenger transport encompasses three demand-side strategies (left pillars) and supply-side strategies to the right. They are connected to the three sustainability dimensions. Source: adapted from Reiner Lemoine Stiftung (2020).

1.2.1 Assessment of behavioural aspects in passenger transport

Various disciplines show different approaches towards the analysis of mobility behaviour. Psychological studies tend to highlight the individual and the determinants of their mobility choices. Sociological studies employ a more systemic perspective by analysing individuals within a societal context. Those fields, however, have difficulties estimating the impact of behavioural change on the energy system transformation because they rarely quantify those impacts.

In the quantitative realm, energy research has shown ambitions towards analysis of behavioural aspects in passenger transport in recent years. Venturini et al. (2018) review integrated modelling techniques from energy and transport domains, finding 14 studies that incorporate mobility behaviour into energy modelling. Methods used in these studies are well-established in economic research. However, they primarily project behaviour into a techno-economic realm that neglects the multitude of features usually incorporated in human behaviour (Schwanen, Banister, and Anable 2011). In a more recent review, Luh et al. (2022) compare energy modelling ambitions with endogenised mobility behaviour against model coupling exercises. They conclude that model coupling is more suitable for analysis of different perspectives in more complex transformation processes. Hence, energy modelling should be complemented by transport modelling to assess demand-side mitigation options in depth.

The discipline of transport modelling exists since the 1950s and has developed well accepted methods to simulate mobility choices and their impacts on the transport system (Boyce and Williams 2015). Due to large development efforts for a geographically explicit transport model, the field is dominated by spatially restricted research projects that use proprietary software and closed source models (Lovelace, Parkin, and Cohen 2020). This hampers their application in other fields, even though its methods would allow for the analysis of long-term future scenarios with large-scale system change (Banister and Hickman 2013). To the best of the author's knowledge, transport models have never been utilised for comprehensive sufficiency transition scenarios - neither in depth (the multitude of drivers of change) nor width (the stretch of the study region). There is a clear research gap in connecting transport decarbonisation to the substantial provisioning systems changes needed to reach the safe and just space for humanity. Sufficiency transitions are a reasonable pathway, but they have never been assessed in their entire socio-economic complexity.

1.2.2 Research questions

Section 1.1.1 shows that demand-side mitigation and sufficiency strategies are an under-researched but potentially effective approach to support the timely decarbonisation of the energy system and, consequently, climate change mitigation. Sections 1.1.2 and 1.1.3 demonstrate that passenger transport in Germany is especially interesting for this analysis, and the previous section derives the research gap: comprehensive analysis of sufficiency transitions. This dissertation addresses this gap with the following research questions:

1. How to model the impact of Avoid and Shift measures in passenger transport?
2. How do Avoid and Shift measures relate to sufficiency and how to achieve sufficiency transitions in passenger transport?
3. What is the impact of different sufficiency scenarios on the transport system?
4. How can sufficiency and efficiency in passenger transport support the energy system transformation?

1.3 A useful tool: quetzal_germany

The macroscopic transport model quetzal_germany has been developed as an open source tool to assess these research questions. It covers inner-German passenger transport and orients towards the classical four-step methodology (Ortúzar and Willumsen 2011). Its structure is broadly divided into a network model and a demand model, as shown in figure 1.3. The network model represents land and air transport networks realistically (i.e. geographically explicit). The demand model simulates mobility decisions concerning trip frequency, trip distance class, trip destination, and mode choice based on route characteristics from the network model and other socio-economic variables. It is calibrated with the German National Travel Survey (infas et al. 2017). Detailed methodological and mathematical backgrounds can be found in the methods of this dissertation's first paper (section 2.3) and the appendix of the second paper (A.3). The supplemental material of the third paper summarises the model design in its updated release, which enhanced the first representation of mode choice and made the results more accurate compared to national statistics (appendix B.1). Mode shares now deviate less than one percent from validation data (except for aviation).

quetzal_germany is developed in Python using the open source modelling framework Quetzal (Chasserieau and Goix 2019) and can be accessed on github (Arnz 2023). As such, it is the first open source transport model on a national level. Open source models are common in regional studies with activity-based frameworks like MATSim (Horni, Nagel, and Axhausen 2016), but national models use aggregated designs. Here, modelling frameworks are developed by large companies, selling them as their business concept (except for Quetzal, which is rather new in the field). Moreover, national models require high investments in build-up and maintenance, which is why large research institutions or government departments usually develop them. This lack of openly available tools and knowledge for national-scale transport behaviour analysis might be

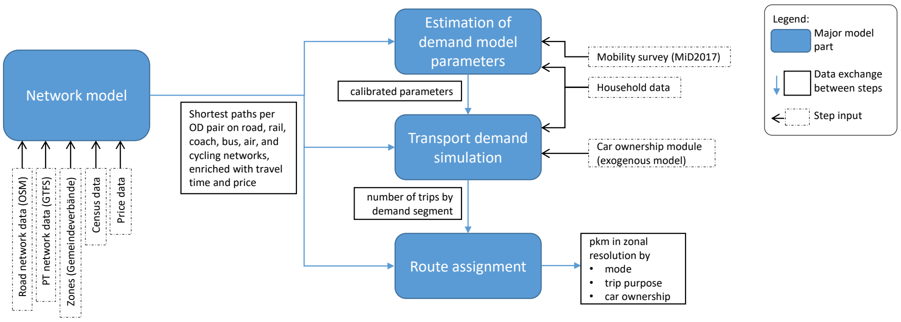

Figure 1.3: Simplified structure of the transport model quetzal_germany. Transport networks connect origin-destination (OD) pairs on routes with different mode combinations and performance attributes. These feed into the demand models (generation, distribution and mode choice) and their calibration. Mobility demand is then assigned to the network model for the final results in passenger kilometres (pkm).

one reason for the large research gap in Avoid and Shift measures. quetzal_germany aims at providing opportunities for new research by closing the corresponding application gap.

1.4 Outline of this dissertation

This dissertation consists of three consecutive papers, which are briefly described below. Figure 1.4 puts the contributions of each paper into the context of passenger transport decarbonisation. Table 1.1 lists the chapter origins and paper contributions.

1.4.1 The demand-side mitigation gap in German passenger transport

The first paper of this dissertation focuses on the development and discussion of the open source transport model quetzal_germany. It derives the best-fit mode choice model, develops a detailed network model, and validates the base year results. Further, it provides background information on transport system analysis, corresponding model requirements, other national transport models, and existing open source approaches, leading towards an insightful reflection on quetzal_germany's method, design, and use case. The model is then applied to a technology improvement scenario for German passenger transport in the year 2035 to analyse the compatibility of this pathway with ambitious climate targets. The scenario includes high market penetration of battery-electric vehicles and 100 % RES, but no Avoid or Shift measures. The results clearly show that this Improve strategy does not sufficiently contribute to the 1.5 degrees target. It would require further technological substitution or the implementation of Avoid and Shift measures on the transport demand side. However, their impact remains unclear.

1.4.2 Sufficiency in passenger transport and its potential for lowering energy demand

The second paper develops an inter-disciplinary, participatory research design to analyse comprehensive sufficiency transitions in German passenger transport. It incorporates a data basis of 133 diverse drivers for traffic avoidance and mode shifts that was collected in an expert workshop. These drivers are used first, to construct three sufficiency storylines, using methods from socio-technical transitions research; then, to quantify their impact through an expert survey; and finally to build three sufficiency scenarios that are simulated in quetzal_germany. The results are a blend of qualitative insights about transition dynamics and quantitative impacts on transport system indicators. As such, the paper contributes to demand-side mitigation research by exploring a benchmark for sufficiency and quantifying its impact on the final energy demand of passenger transport. The latter can be reduced by nearly three quarters. Thereby, this paper answers the open question of the first paper: What is the maximum impact of Avoid and Shift measures? Additionally, it advances the understanding of transport sufficiency between equitable mobility access and energy demand reduction.

1.4.3 Avoid, shift or improve passenger transport? Impacts on the energy system

The third paper, finally, connects transport demand-side mitigation to transport supply-side and energy supply-side mitigation, addressing all four pillars in figure 1.2. It uses the sufficiency scenarios from the second paper and couples quetzal_germany to the energy system optimisation model EuSys/AnyMOD.jl (Göke 2021a). Scenario analysis allows the comparison of Avoid, Shift, and Improve strategies with an energy supply of 100 % RES. The results show different energy system designs and corresponding capacity reduction potentials. The sufficiency scenarios can reduce energy demand to a similar degree as the Improve scenario does, but the potential of sufficiency decreases as the private vehicle fleet becomes more energy efficient. Those energy savings translate into cost reduction potentials in the energy system, but require investments in public infrastructure and the private vehicle stock. These insights frame the concepts of sufficiency and efficiency and raise major societal questions. Does the responsibility for demand-side mitigation lie with individuals when buying a car privately or with governmental actors who plan the public infrastructure?

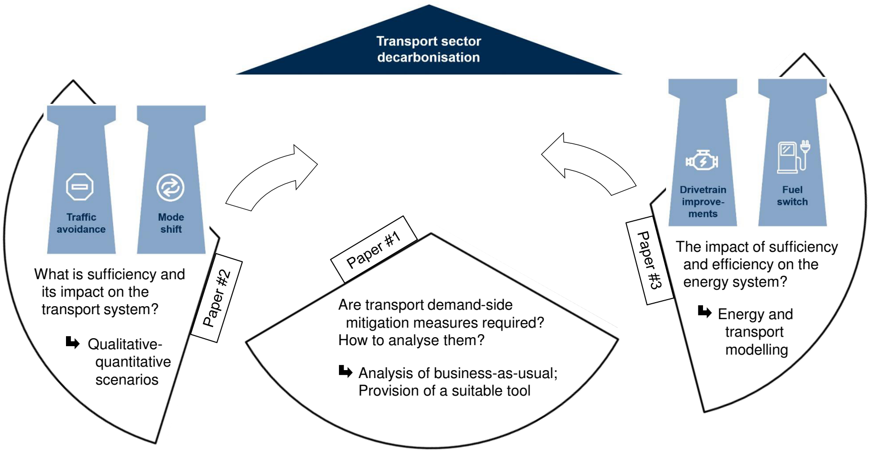

Figure 1.4: Each paper provides a wedge with its research questions and solutions. The full circle encompasses all dimensions of passenger transport decarbonisation with a focus on sufficiency.

Table 1.1: Chapter origins and own contributions

Chapter	Pre-publications & Own Contribution
2	**The demand-side mitigation gap in German passenger transport**
	This chapter is based on the accepted manuscript under the same title in *European Transport Research Review* 14 (1), 2022
	Single author original research article.
3	**Sufficiency in passenger transport and its potential for lowering energy demand**
	This chapter is based on the accepted manuscript under the same title in *Environmental Research Letters* 18 (9), 2023
	Joint work with Alexandra Krumm. Conceptualisation, development of methodology, participation of experts, and validation of results was carried out jointly by both authors; M. A. curated data, developed software, generated and visualised results, and wrote the paper; A. K. reviewed the paper.
4	**Avoid, shift or improve passenger transport? Impacts on the energy system**
	This chapter is based on a preprint under the same title, which is under review in *Energy Strategy Reviews*
	Joint work with Leonard Göke, Johannes Thema, Frauke Wiese, Niklas Wulff, Mario Kendziorski, Philipp Blechinger, and Karlo Hainsch. M.A., L.G., J.T., F.W., N.W., K.H., M.K. conceptualised the study; M.A. and L.G. were responsible for the formal analysis, methodology, and software; M.A. wrote the original draft; M.A., L.G., F.W., J.T., N.W., M.K., P.B. validated the results and edited the paper.

Chapter 2

The demand-side mitigation gap in German passenger transport

Abstract

Deep transport decarbonisation requires not only technological measures, but also large-scale changes towards sustainable mobility behaviour. Researchers and decision-makers need suitable tools for corresponding strategy development on a macroscopic scale. Aiming at broad accessibility to such methods, this paper presents an open source passenger transport model for policy analysis in German medium- to long-distance transport. It discusses model design and data, limitations, alternative approaches, and its base year results and concludes, that macroscopic transport modelling is very suitable for policy analysis on national scales. Alternative approaches promise more insight on smaller scales. As an exemplary case study, the model is applied to ambitious technology projections for the year 2035, showing the ambition gap towards reaching the 1.5 degree-target of the Paris Agreement. Results indicate that 66 million tCO_{2eq} per year must be mitigated through further technological substitution or demand-side mitigation strategies.

2.1 Introduction

Fast transport sector decarbonisation is deemed difficult yet crucial for climate change mitigation in alignment with the Paris Agreement (Creutzig et al. 2015). Since time until reaching an average global temperature increase of 1.5 degree Celsius is limited, unleashing full transport mitigation potential requires not only technological measures, like fuel switches and new propulsion technologies, but also large-scale behavioural changes towards sustainable mobility (Sims et al. 2014). These different mitigation strategies are often referred to as *Avoid*, *Shift*, *Improve*: Avoiding the need for traffic, shifting traffic to more environmentally friendly modes, and improving vehicle technologies (IEA 2013). Avoid and Shift measures are especially effective and low-cost in the long term (Creutzig et al. 2015) and promise high increases of well-being as co-benefits to GHG emissions reduction (Creutzig et al. 2022).

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Yet, quantitative analysis of Avoid and Shift strategies in swift transport mitigation is comparably rare: Only one third of the measures analysed in national transport mitigation studies address mobility demand perspectives, which makes policy strategy comparison uncertain (Gota et al. 2019). The same picture occurs for measures included into national climate action plans in nationally determined contributions (Gota et al. 2016), which highlights policy relevance of this research field. On a global scale, some integrated assessment studies advanced methods for the depiction of demand-side action (see reviews from Edelenbosch et al. 2017; Yeh et al. 2017). On local scales, Creutzig (2015) finds that transport modelling yields the most realistic representation of behaviour. Transport modellers increasingly use their tools for long-term scenarios towards emissions mitigation and sustainability (Banister and Hickman 2013). However, large-scale models are usually proprietary, making it difficult for new ideas to enter the field (Lovelace, Parkin, and Cohen 2020).

This paper presents quetzal_germany, an open source, macroscopic passenger transport model for Germany. It explores the suitability of macroscopic transport modelling for nation-wide analysis of demand-side mitigation pathways. I define demand-side mitigation from the transport system perspective, as described in section 2.2. That section gives a brief overview of transport system analysis, corresponding methodological requirements, national transport modelling in practice, and starting points for open source approaches. Section 2.3 presents quetzal_germany's structure and method. Its base year results are discussed in section 2.4, followed by a critical review of its capabilities and normative assumptions. Section 2.5 gives an exemplary outlook into the year 2035 to quantify the ambition gap towards reaching the 1.5 degree-target of the Paris Agreement. Section 2.6 concludes.

2.2 Background on transport system analysis

2.2.1 Classification and requirements of models

Transport system analysis is naturally complex because it involves a large number of heterogeneous decision-makers with difficult to predict behaviour on the demand side, as well as different temporal layers at the supply side and the built environment. Figure 2.1 outlines short-term interactions between the supply and demand side, as well as long-term impacts of external effects on decision making, land use, and transport supply. Allsop (2008) defines two main purposes of transport analysis: estimating features and use of existing transport systems that are difficult to observe; and estimating them in circumstances that do not yet exist. The first purpose describes the work of classic transport economists, while the second is particularly interesting for comprehensive emissions mitigation scenarios.

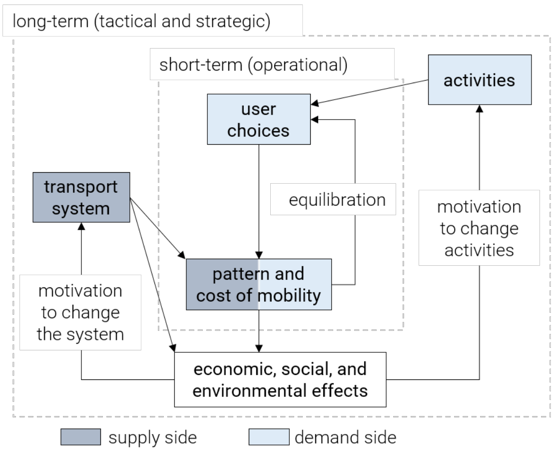

Figure 2.1: A multi-perspective framework for transport analysis (own illustration based on Allsop 2008; Ortúzar and Willumsen 2011)

Transport analysis applications must meet a number of requirements: On the demand side they need i) a probabilistic distribution of travel demand over space and time, ii) variation of demand depending on perceived travel cost or its benefit, and iii) differences among travellers in perception of cost or benefit and its variation over time. Supply-side requirements comprise iv) different classes of vehicles or modes in the network (private and public), v) flow-dependent link cost, and vi) options for traffic management (Allsop 2008). Accurate depiction of the transport sector in an energy system context further requires vii) choice of not making a trip (physically), viii) vehicle ownership and drive train technologies, ix) private vehicle use patterns, and x) infrastructure investment decisions (Schäfer 2012; Anable et al. 2012; Dodds and McDowall 2014; McCollum et al. 2017; Yeh et al. 2017; Venturini et al. 2018).

While techno-economic energy models usually fail to represent behavioural aspects of above (Krumm, Süsser, and Blechinger 2022), transport modelling has been a central tool for simulation of mobility behaviour since the late 1950s (Boyce and Williams 2015). There are two major approaches: activity-based (micro-) and aggregated (macro-) modelling. Micro-modelling is the younger field of research and utilises agent-based modelling techniques with rich sets of dependent variables and usually involves high spatial and temporal resolutions (Axhausen and Gärling 1992; Vovsha et al. 2011). Macro-modelling, on the other hand, follows the classical four steps of transport modelling (figure 2.2) and simulates travel between aggregated demand zones for aggregated demand segments (e.g. trip purposes or population groups) at the desired level of detail.

Transport models with national scope are particularly interesting for the analysis of large-scale policies within the transport sector and beyond. Even though publications concerning design of large-scale transport models are rare in scientific literature, they shed light on many

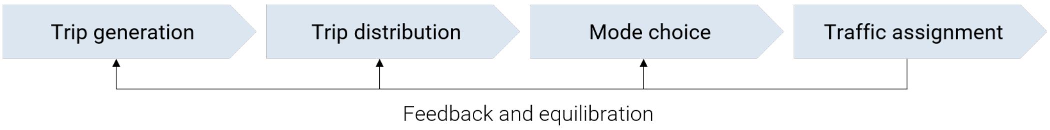

Figure 2.2: Classical four steps of macroscopic transport modelling

non-trivial considerations. The Danish (Rich and Overgaard Hansen 2016), Italian (Beria et al. 2019), Norwegian (Rekdal 2006), Swedish (Beser and Algers 2002), UK (DfT 2020), and Dutch (Joksimovic and Grol 2016) national transport models have aggregated designs with inter-connected demand and supply modules. All of them are logit models, based on discrete choice theory. The four latter models have separate modules for short- and long-distance travel to ensure high levels of detail and high computational performance. This differentiation further helps to accurately depict the impact of few, but long trips on the overall traffic system (Rohr et al. 2013). Similarly, the German national *DEMO* model divides passenger travel into distances at a threshold of 100 km, which allows simulation of mobility choices at a resolution of 6,561 zones (Winkler and Mocanu 2017).

2.2.2 Open source modelling

Availability of models and corresponding data is crucial in order to support – and often enable – quantitative analysis of Avoid and Shift measures in transport. Open source modelling and open data is desirable as it promotes barrier-free co-development of new perspectives and approaches of complex problem solving. It helps reducing parallel efforts in maintaining large code bases and data sets, allowing researchers to collaborate efficiently on shared problems (Pfenninger et al. 2018). Additionally, closed source modelling often lacks options to integrate into other simulation or optimisation tools, which is deemed important for thorough decarbonisation pathway analysis (Krumm, Süsser, and Blechinger 2022).

Still, there are no open source transport models on national scales to the author's knowledge. In many countries, an underlying reason can be lack of required data sources (that are openly licensed). For many practicioners however, required open source software has high entry barriers, such as a poor overview of appropriate solutions, steep learning curves, and lack of an established community. Until today, proprietary software largely dominates transport modelling (Lovelace, Parkin, and Cohen 2020). While there are many frameworks for micro-modelling approaches, the only open source software for macroscopic transport modelling is Quetzal (Chasserieau and Goix 2019). It implements methods of the classical four-step model and beyond, allows full demand-supply interaction, realistic network representation, full flexibility in demand group segmentation, and is highly modular due to its implementation in Python.

2.3 Introduction of quetzal_germany

quetzal_germany is an aggregated transport model (see figure 2.2) for medium- and long-distance passenger travel within the area of Germany. It is divided into 2,225 zones, simulating traffic in between them. They are defined by clustering 4,605 municipality unions to similar zone sizes. If computational power is limited, the model zones can easily be reduced to 401 NUTS3-level zones. Inner-zonal traffic is computed from other data sources, making local and urban mobility an exogenous element (see sub-section 2.3.3). The model is developed in Python under use of the Quetzal open source transport modelling suite (Chasserieau and Goix 2019). It is openly available on github.

Trip generation and distribution (steps one and two in figure 2.2) are currently covered by an exogenous origin destination (OD) matrix from the Federal Transport Infrastructure Plan 2030 "Forecast of transport interconnectivity 2030" (VP2030) (Schubert et al. 2014). Transport demand of the whole population, linearly interpolated between 2010 and 2030 to the base year 2017, is divided into twelve demand segments, corresponding to the national mobility survey "Mobility in Germany 2017" (MiD2017): commuting, business, education, grocery shopping or medical executions, leisure, and accompanying trips; each trip purpose further divided into car availability in the household. Mode choice is designed as a Multinomial Logit model for each of these segments with land and air transport alternatives. Logit models and random utility maximisation are by far the most common and best understood applications in discrete choice analysis (Ben-Akiva and Lerman 1985; Cascetta 2001; Ortúzar and Willumsen 2011). Sub-section 2.3.2 describes the choice model specification and its variables in detail.

The network model for Germany with measurable level-of-service (LoS) attributes is described in sub-section 2.3.1. Both road and public transport use the Dijkstra algorithm to find shortest paths in terms of travel time. Demand-supply equilibration is implemented as iterative convergence between the equilibrium road traffic assignment, using the Frank-Wolfe algorithm (Frank and Wolfe 1956), and the logit modelling step. In a subsequent step, quetzal_germany calculates emissions from transport activities as described in sub-section 2.3.4.

2.3.1 Network model and level-of-service attributes

quetzal_germany includes a highly detailed network model based on OpenStreetMap data for motorised individual transport (MIT) and GTFS feeds for public transport (PT). The latter is aggregated to the most relevant services for inter-zonal travel, using agglomerative clustering and filtering methods, in order to increase computational performance for the German-wide model. As a blueprint for regional studies however, the whole network graph can be selected. There are seven different network layers for corresponding transport modes:

1. Long-distance rail transport: ICE, IC and EC rail services
2. Short/medium-distance rail transport: Local and regional rail services
3. Local public transport: Bus, ferry, tram and underground services
4. Coach transport: Connections based on FlixBus' network coverage
5. Air transport: Connections between 22 major airports
6. Road: Motorways, A and B roads, as well as interconnecting links
7. Non-motorised transport: Straight-line connections between zone centroids with distances up to 40 km

All relevant PT interconnections are realised through footpaths between stops of different layers. Network access/egress links connect each layer to sources and sinks of transport demand in the population centroid of each zone. As measures of LoS, every network link is equipped with two attributes: travel time (eq. (2.1)) and monetary travel cost (eq. (2.5); table 2.2).

$$TT = T^{\text{iv}} + T^{\text{wait}} + T^{\text{ae}} + T^{\text{walk}} \tag{2.1}$$

In-vehicle time T^{iv} results from the network graphs. Road network average speeds are calculated from OpenStreetMap speed limits and conversion factors from Lange, Hendzlik, and Schmied (2020). PT link duration stems from real GTFS schedule data. Waiting time T^{wait} applies as zero for car transport and as the average waiting time at PT stops based on vehicle headways of the respective route. Entering an airplane costs 45 minutes including security checks, luggage handling, boarding, and longer walking distances within airports. Delay times of any kind are currently neglected. Walking time T^{walk} accrues for PT intermodal transfers (at 5 km/h) or cycling connections between centroids (at 17km/h). T^{ae} is the average access/egress time and represents a measure of accessibility. It is constant five minutes for MIT, depicting access, starting, and parking, while PT accessibility depends on the corresponding zone's and network's characteristics. Expression (2.2) calculates PT $T^{\text{ae}}_{z,j}$ for mode j and zone z, inspired by a two-step floating catchment technique presented in Langford, Fry, and Higgs (2012):

$$T^{\text{ae}}_{z,j} = \sum_{m \in M} \eta_{m,u_z} \cdot \overline{d_{m,n}} \cdot \alpha_m \quad \forall n \in N_{z,j} \tag{2.2}$$

The mean of weighted distance $d_{m,n}$ over all PT stops (i.e. nodes) n in $N_{z,j}$ is again, weighted by share η_{m,u_z} of PT access/egress mode m in $M = \{\text{walk, bicycle, car}\}$. Values for η_{m,u_z} depend on the zone's urbanisation degree u_z and can be found together with speed variable α_m in table 2.1.

$$d_{m,n} = \sum_{c \in z} \frac{\sum_{n' \in N_{z,j}} s_{n'} \cdot D_{n',c}}{\sum_{n'' \in N_{z,j}} s_{n''}} w^P_{m,n} \tag{2.3}$$

Table 2.1: Values for access/egress link parametrisation. η values are derived from the calibration data set.

Variable		walk	bicycle	car
	$u_z = 1$	0.948	0.017	0.035
η	$u_z = 2$	0.899	0.034	0.067
	$u_z = 3$	0.883	0.026	0.091
α in km/h		5	17	30
d_{max} in km		0.4	10	30

Distance measure $d_{m,n}$ is based on the geodesic distance $D_{n,c}$ from node n to population cell c (at a resolution of 100x100m). $d_{m,n}$ is weighted by the number of PT vehicles that depart from this stop between 6 a.m. and 6 p.m. during the week s_n and by the population weight measure $w^P_{m,n}$.

$$w^P_{m,n} = \frac{\sum_c D_{n,c} \cdot P_c \cdot \left(\frac{D_{n,c}}{d_{\max,m}}\right)}{\sum_c P_c \cdot \left(\frac{D_{n,c}}{d_{\max,m}}\right)} \quad \forall c \in D_{n,c} \leq d_{\max,m} \tag{2.4}$$

Each access/egress mode has a catchment area defined by $d_{\max,m}$, wherein the cell population P_c is counted and linearly weighted by its distance to node n. This double weighting makes population counts close to a node more relevant than distant ones, or, from the perspective of PT users, closer nodes more attractive. It also reduces the impact of distance thresholds choice for access/egress modes. As a result, $\overline{d_{m,n}}$ yields realistic average distances relative to population density and service frequency of stops. Access/egress mode parameters can be varied in scenario settings as an approximation to inner-zonal mobility choices.

$$TC = \frac{D \cdot c_{\mathrm{d}} + T^{\mathrm{iv}} \cdot c_{\mathrm{t}} + c_{\mathrm{fix}}}{f} \tag{2.5}$$

Travel cost TC is composed of distance-specific cost c_{d} in EUR/km, in-vehicle time specific cost c_{t} in EUR/h, fix cost c_{fix} in EUR per trip, and a split factor f, used for car occupancy rates or average shares of PT subscriptions in the population. Sunk costs, like car ownership cost or PT subscriptions, are not included. Empirical evidence frequently shows, that individuals usually do not account them in daily mode choice (e.g. Andor et al. 2020). Table 2.2 summarises all cost function parameters for the base year except for local PT. Pricing schemes are very diverse within Germany so that the following assumptions apply: Unimodal bus trips cost 7 EUR. They reduce to 5 EUR, if origin or destination is a city, because cities are centers of price zoning systems and there is a higher share of subscriptions in the population. If bus transport occurs on the first or last leg of a multimodal trip, half these cost accrue, respectively.

Travellers decide upon their route and mode based on a set of shortest paths between their origin and destination. The Dijkstra algorithm computes shortest paths for car and bicycle transport,

Table 2.2: Monetary cost function components by mode of transport in 2017

Mode	c_d	c_t	c_fix	f	min	max
Rail short	0.233	0	1.47	2	5	50
	Linear regression of DB price list 2nd class; subscription shares from calibration data set					
Rail long	0.053	7.33	15.56	1	19	139
	Linear regression with 56 OD-specific prices from DB website in Jan. 2021); 30 % savings tariff					
Coach	0.057	0	0	1	5	60
	Average coach prices in Germany					
Airplane	0	0	OD-specific	1	50	-
	Economy prices from Sept. 2020 where available; 50 EUR elsewhere					
MIT	0.114	0	0	1.5	-	-
	Average fuel cost for 2017's new car models with mileage of 15,000 km/a; average car occupancy in Germany					
Non-motorised	0	0	0	1	-	-

and for every PT mode combination available. The main leg's transport mode represents the path's main mode, which is the decision variable in the mode choice model.

2.3.2 Mode choice model specification and calibration

Scope, explanatory power, and policy analysis suitability of the demand-side model depend on the attributes included and how they apply for different demand groups. Witte et al. (2013a) show that travel time and price are the most frequently used LoS attributes across multiple disciplines, while others, such as car availability or income, have a higher significance. All national transport models shown in section 2.2 use time and price as mode choice variables, and so does quetzal_germany. Moreover, PT mode accessibility and frequency is included through T^{ae} in TT, while demand segmentation includes car availability. Other individual or social attributes are neglected due to limited data availability.

For distance-dependent cost factors, many transport studies find non-linear marginal utilities, i.e. decreasing cost sensitivity over time (Daly 2010). Modellers commonly encounter this issue by so-called *cost-damping* mechanisms like the Box-Cox transformation (Box and Cox 1964) to generate realistic elasticities of demand (Rich and Mabit 2015). It is also common practice to aggregate time and price into a generalised cost term GC, using exogenous value of time (retrieved by mode, purpose and distance from Axhausen et al. (2015)), in order to decrease model complexity (Ortúzar and Willumsen 2011). Given the available mode choice variables, four different utility formulations V for alternative j, with Alternative-specific Constants (ASCs) and marginal utility parameters β, were tested:

1. Box-Cox transformation of GC with $\hat{\tau}$ fitted to the calibration data: $V_j = \mathrm{ASC}_j + \beta \frac{GC_j^{\hat{\tau}}-1}{\hat{\tau}}$
2. log-power transformation of GC: $V_j = \mathrm{ASC}_j + \beta \cdot log\left(GC_j\right)^3$
3. log-power spline of GC from Rich (2020) with knot points corresponding to a mean GC at distances of 20km and 60km: $V_j = \mathrm{ASC}_j + \mathcal{F}\left(\beta, GC_j\right)$
4. log-power spline of TT with knot points at 1h and 3h plus linear perception of TC: $V_j = \mathrm{ASC}_j + \mathcal{F}\left(\beta_t, TT_j\right) + \beta_c \cdot TC_j$

The German mobility survey MiD2017 is a revealed preference, repeated, and cross-sectional survey with the same zonal resolution as quetzal_germany. Out of 417,094 inner-German trips with observed origin, destination, mode, and purpose, 134,637 inter-zonal trips serve as calibration data set. Prices are calculated using the same assumptions as described in sub-section 2.3.1, because MiD2017 does not report them. OD distance comes from the network model's shortest paths, because 17 % of stated distances don't fit the survey's routed distances. Travel times from the shortest paths are mapped to the observations so that the mode combination and route with a travel time closest to the stated time applies. The choice set is defined as $M = \{\text{rail, road PT, air, MIT, non-motorised}\}$. Corresponding modes of the network model are aggregated because responds in MiD2017 do not differentiate among short-distance and long-distance rail or road PT accurately.

All of above's models can be estimated with this data set using Maximum Likelihood Estimation in the Biogeme software (Bierlaire 2020). Due to the aggregation of the choice set, a hierarchical model always collapses into a Multinomial Logit model. In terms of final log-Likelihood, the Box-Cox transformation performs worst, followed with similar log-Likelihoods by the log-power transformation and the GC-log-power spline. The log-power spline of TT with linear perception of TC performs best with a difference in final log-Likelihood of 65 (which is reasonable). The linear-in-the-parameters model does not produce significant results at all. These results imply, that the difference in perception of time and price cannot be captured by exogenous values of time sufficiently. Hence, the mode choice model is specified as

$$V_j^i = \mathrm{ASC}_j^i + \mathcal{F}\left(\beta_t^i, TT_j\right) + \beta_c^i \cdot TC_j \tag{2.6}$$

for demand segment i with a log-power spline function as proposed in Rich (2020):

$$\mathcal{F}\left(\beta, x\right) = \beta \sum_{q=1}^{Q} \lambda_q\left(x\right) \left[\theta_q ln\left(x\right)^{Q-q+1} + \alpha_q\left(\beta\right)\right] \tag{2.7}$$

$$\theta_q = \frac{Q}{Q-q+1} \prod_{r=2}^{q} ln\left(c_{r-1}\right) \quad \forall q = 2, \ldots, Q$$

$$\alpha_q(\beta) = \alpha_{q-1}(\beta) + \frac{(q-1)!\beta}{Q-1} ln\left(c_{q-1}\right)^{Q-q+2} \prod_{r=1}^{q-2} ln\left(c_r\right)$$

where λ_q is a binary parameter such that $\lambda_q(x) = 1 \Leftrightarrow x \in [c_{q-1}, c_q]$ and zero elsewhere. The spline has a number of $Q = 3$ knot points c_q with $c_0 = 0$ and $c_Q = \infty$, defining the cost intervals at which different log-power expressions operate. The Rich spline function conforms with random utility theory for $\beta < 0$ (see Rich (2020) for proof). Iterative adjustment of knot points c_1 and c_2 yields approximated optimal knot points for each segment's model

All β values were found significant on a 1 % confidence interval. Estimation results show that travel price has no impact on mode decisions for business trips, whereas price sensitivity for commuting trips is double the average. Moreover, commuting and business trips have a larger time sensitivity on longer distances (higher knot points), while education and shopping trips become less sensitive earlier.

2.3.3 Inner-zonal travel

Aggregated transport models cannot depict inner-zonal travel by design. quetzal_germany's zoning system explains 86.7 % of total traffic endogenously, while local mobility is approached as follows: Inner-zonal trip volumes come from VP2030, segmented by the same demand segments as above. MiD2017 data yields trip distances as means by segment, mode, and the zone's urbanisation degree, which are relevant for passenger kilometres (pkm) calculation. Travel time and prices are calculated with the same formulas and assumptions as for inter-zonal travel in order to allow subsequent transport system evaluations.

2.3.4 Emissions calculation

GHG emissions are a relevant indicator for transport system sustainability. Direct and indirect driving emissions (well-to-wheel) can be calculated in a post-processing step, whereas a full life-cycle analysis goes beyond the scope of transport modelling. Calculation methods differ between private and public transport: MIT emissions directly depend on transport demand (formula 2.8); PT emissions depend on transport supply, which reacts to transport demand only with delay.

$$\mathrm{Em}_{\mathrm{MIT}} = \sum_i \mathrm{pkm}_i o_i \cdot \sum_d \gamma_d \mathrm{em}_d \tag{2.8}$$

Total MIT emissions are the product of vehicle kilometres - as demand segment i-specific pkm times occupation rates o from MiD2017 - and distance-specific emission factors. The latter is the weighted mean over drive-train technologies d. In 2017, diesel cars have the largest share

($\gamma_{\text{diesel}} =$) 0.66 with real driving emissions of 173.6 $\text{gCO}_{2\text{eq}}$/km; gasoline cars have a share of 0.33 and $\text{em}_{\text{gasoline}}$ =187.6 $\text{gCO}_{2\text{eq}}$/km; the rest is dominated by natural gas, which has emissions of 104 $\text{gCO}_{2\text{eq}}$/km (data from TREMOD based on HBEFA; see Allekotte et al. (2020)).

Classic PT modes (i.e. no shared or pooled systems) are scheduled services corresponding to prior demand analysis or political decisions. Small mode share changes might lead to increased vehicle loads under constant emissions, whereas large-scale changes require adaptation in the supply system. Most transport models do not consider vehicle loads endogenously and assume proportional increase of capacities (Hellekes and Winkler 2021). So does quetzal_germany, as it is designed for long-term scenarios. Hence, it calculates GHG emissions using 2017 pkm-specific values from TREMOD (well-to-wheel; see Allekotte et al. (2020)). This method diverts from official numbers in rail transport, where supply-chain emissions of electrified rail transport are omitted to prevent double counting.

2.4 Base year results and discussion

2.4.1 Validation of inter-zonal mode shares

All the described modelling ambitions aim at a realistic depiction of German passenger transport in the base year 2017. But there is no data set available for validation of absolute inter-zonal model results except VP2030, which is already used as input data. Hence, quetzal_germany's mode shares can be validated with relative figures from MiD2017 by demand segments or all together (figure 2.3). In this context, mode shares always refer to the trip's main mode. Summed over all demand segments, quetzal_germany's modal splits vary only slightly from MiD2017 data with the exception of rail transport (table 2.3).

Table 2.3: Modal shares by main mode, segmented by trip purpose in percent. The upper value represents quetzal_germany's results, the lower is the survey average from MiD2017

Main mode	commuting	education	buy/execute	business	leisure	accompany	all
MIT	84.6	43.9	91.8	90.2	86.5	96.8	86.1
	88.0	*40.4*	*94.2*	*91.5*	*90.1*	*98.2*	*89.2*
rail	11.8	26.8	5.3	7.5	9.0	2.3	9.3
	8.2	*21.4*	*3.1*	*6.4*	*5.8*	*1.0*	*6.0*
road PT	3.5	28.4	2.4	2.0	3.8	0.8	4.2
	3.5	*36.9*	*2.1*	*1.6*	*3.2*	*0.6*	*4.1*
air	0.00	0.00	0.00	0.10	0.02	0.00	0.02
	0.00	*0.00*	*0.01*	*0.26*	*0.05*	*0.00*	*0.03*
non-motor.	0.1	0.9	0.5	0.2	0.7	0.1	0.4
	0.3	*1.3*	*0.5*	*0.2*	*0.9*	*0.1*	*0.6*
Segment share	26.6	4.3	25.7	5.7	31.4	6.3	100.0

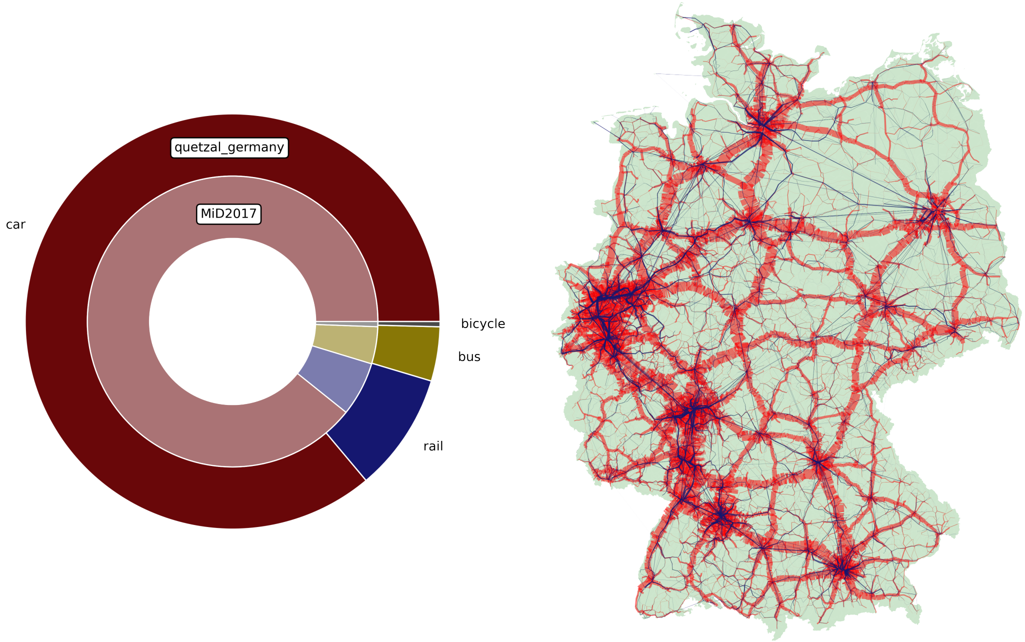

Figure 2.3: Modal splits for inter-zonal travel without air transport (left) and traffic distribution of car (red) and public transport (blue) (right)

In quetzal_germany's results, air travel is underestimated even though it accounts only for a very small share of inner-German traffic. In the education segment, rail transport takes over a big share from road PT; in all other segments a small share of MIT. These inaccuracies largely stem from unrealistic depiction of pricing systems in rail transport. In quetzal_germany, prices mostly rely on linear regression and crude assumptions (see table 2.2), while real pricing mechanisms are fairly complex. Again, a major barrier is the lack of open data for PT and air prices. Another reason for higher rail shares lies in the network connection: Travellers can choose freely any major rail stop within origin or destination zone, respectively, all having the same accessibility. The result is lower average trip cost. Non-motorised travel, on the other hand, is slightly underestimated, because trips are assumed to happen between zone's geometric centroids. In reality however, people who are located close to the destination zone's border set out for most of these trips.

Except these inaccuracies, the mode choice model performs well. Since there is no measured data for the entire German medium- to long-distance passenger transport system, above figures cannot validate quetzal_germany's results with certainty. Still, they suggest a realistic representation of the 2017 transport system.

2.4.2 Total traffic and emissions

quetzal_germany accounts for inter-zonal traffic through endogenous simulation (86.7 % of total pkm), as well as inner-zonal traffic through exogenous calculations (see section 2.3.3). This allows subsequent computation of indicators for policy effects, such as total pkm and GHG emissions.

A relevant indicator for validity of results is the yearly mileage of an average private vehicle: quetzal_germany yields 15,618 km, which comes close to the official 14,290 km (Allekotte et al. 2020). Table 2.4 compares pkm results to figures from "Transport in figures" (ViZ). Total pkm of MIT might be overestimated in quetzal_germany for three reasons: travellers are assumed to start and end their journey at the zone's geometric centroid, which might not represent residential structures in reality; inadequate representation of air travel (see above); and inner-zonal travel is overestimated. This mainly explains higher total pkm, too. Rail pkm divide between long- and short-distance services. quetzal_germany yields 13 and 76 bn. pkm respectively, while the German national transport emissions model calculates 40 and 55 bn. pkm, respectively (Allekotte et al. (2020); figures are more reliable than those of ViZ). Besides aforementioned pricing inaccuracies in long-distance rail transport, the difference in pkm is explained by inaccurate network distances: quetzal_germany uses air-distances between stations, while real distances depend on the rail network's curvature.

Table 2.4: Total traffic (billion pkm) by mode for ViZ and quetzal_germany results (the upper value shows modelled results, the lower value shows data generated from VP2030 and MiD2017). Column NM comprises non-motorised trips

		MIT	rail	road PT	air	NM	all
quetzal_germany	inter-zonal	985.3	75.8	37.1	1.5	0.0	1,100
	inner-zonal	92.6	13.2	34.3	0.0	28.6	169
ViZ	total	950.4	95.7	81.4	10.4	55.3	1195

Table 2.5 shows, that MIT's emissions are overestimated to roughly the same extend as its pkm. While air transport results are not adequately modelled in quetzal_germany, road PT is. The difference of rail transport emissions is caused by different accounting methods, as described in section 2.3.4.

2.4.3 Evaluation of transport system analysis requirements

Requirements for transport system analysis, as collected in section 2.2, make a tool more or less suitable for its purpose. On the demand-side, a major limitation to endogenous explanatory power of quetzal_germany is the outplacement of choices related to physical mobility and trip

Table 2.5: Driving emissions (million tCO_{2eq}) by mode from quetzal_germany results (the upper value shows modelled results, the lower value shows data from VP2030 and MiD2017) and values retrieved from BMU (2019)

		MIT	rail	road PT	air	all
quetzal_germany	inter-zonal	116.5	3.8	2.7	0.3	119.2
	inner-zonal	10.9	0.7	2.5	0.0	18.3
BMU	total	98.2	1.0	NaN	1.9	NaN

destination. Currently, this is covered by results from the German national modelling study, which also covers inner-zonal travel volumes. Hence, variation of demand on trip cost is limited to mode choice between zones. Here, quetzal_germany differentiates between travellers by trip purpose and car availability, which allows more detailed policy analysis and evaluation of traffic flows on specific routes or means of transport. However, trip cost is limited to travel time and monetary cost. These are, in a macroscopic setting, the most significant influence levers, while other LoS attributes like service frequency and reliability translate easily into time or willingness-to-pay. Still, further research should look into utility formulations with more LoS or idividual attributes.

The supply-side, i.e. the network model, has great spatial detail and covers all modes of transport realistically. The reduction of temporal complexity by using a PT headway model instead of minutely resolved itineraries increases computational performance and allows analysis of comprehensive PT-supply policies, which do not have to be specified in regional detail. It makes the implementation of a time-of-day choice redundant, which is a common element of demand models and their reaction to traffic. However, reduced temporal complexity also diminishes the impact of traffic situations on transport demand (i.e. supply-demand equilibration): Road link capacities, which are usually critical during rush hours, are rescaled and applied to yearly aggregates. Further research should investigate time-expanded demand modelling or appropriate computation of aggregate road capacities based on OpenStreetMap data.

Depiction of passenger transport in an energy system context requires more features than quetzal_germany - and transport modelling in general - offers. Vehicle ownership, drive train technologies, and infrastructure investment are exogenous assumptions, that require thorough consideration. quetzal_germany depicts individual every-day mobility choices, which are influenced by above's factors. A feature not represented are individual car driving styles. Agent-based modelling approaches can depict corresponding energy demand of MIT more advanced, even though its applicability and data availability on national scales are uncertain.

What is more, the open source model quetzal_germany serves as a blueprint for other regions, where administrative borders, population density, and PT schedules are openly available (applies for all EU countries). The demand model further requires a mobility survey, which is available in sufficient detail in most high-income countries. At least in Europe, demand model structure adaption is not required because of the implemented cost damping mechanism and similar mobility behaviour across countries (Fiorello et al. 2016). Due to its open design and full documentation, quetzal_germany may contribute towards opening up macroscopic transport modelling and the investigation of demand-side mitigation strategies in passenger transport across Germany and beyond.

2.4.4 Discussion of alternative methods

In general, micro-simulation is an attractive alternative approach, because it can better capture population heterogeneity and other externalities of transport than GHG emissions. Moreover, it would endogenise quetzal_germany's workaround for inner-zonal travel. However, data requirements and computing times of these models tend to be enormous, which drastically reduces their applicability to large scales (Wegener 2011).

Yet, both approaches rest upon the same method: Discrete choice modelling. It is based on random utility theory, which draws from micro-economic utility maximisation and rational choice, adding a probabilistic error component. Random utility theory is the most elaborate theoretical basis for analysis of discrete choice problems (Ortúzar and Willumsen 2011). It shows great flexibility with a simple mathematical formulation at low computational complexity. Yet, it has normative assumptions and limitations, which modellers must reflect on.

In high-income countries, it is obvious and well-researched, that mobility behaviour often deviates from rational choice. An extensive review of reviews by Javaid, Creutzig, and Bamberg (2020) supports that argument, finding strong correlations between non-rational factors and low-carbon mode adoption in urban contexts. Empirical evidence shows, that the Theory of Planned Behaviour (Ajzen 1991) or the Norm Activation Model (Schwartz 1977) perform well in describing patterns of more sustainable mode choice (Hoffmann et al. 2017). Moreover, behavioural economics exhibit concepts, which can enhance our understanding of mobility decisions and corresponding sustainability-directed policies (Mattauch, Ridgway, and Creutzig 2016; Avineri 2012). Witte et al. (2013b) argue that Kaufmann's mobility concept (Kaufmann 2002) is the most promising framework for bridging economic, social, cultural, and political aspects in mobility research and build upon their own multi-disciplinary framework. Finally, Creutzig (2020) argues, that the liberal world view connected to utility maximisation theory is ill-suited to cope with global challenges we face today.

Logit modelling, however, has advanced in recent decades. Mixed Logit models are state-of-the-art (Train 2002; Cherchi and Ortúzar 2007), acknowledging taste variations within aggregated demand groups and allowing for the inclusion of individual and social attributes. Another advancement are latent choice models, capable of including individual attitudes of mobility choices. Bahamonde-Birke et al. (2015) extend this further by differentiating between perceptions and attitudes in order to “represent the decision making process and the way in which the different variables take part in it as accurately as possible”. However, Vij and Walker (2016) show, that most latent choice models have the same explanatory power as the corresponding multinomial logit model formulation. And still, they are based on rational choice theory.

In practice, demand model formulations crucially depend on data availability (surveys and socio-economic details), while the price for data gathering strongly increases with the size of the model region and its heterogeneity. Hence, large model regions often come with rather simple logit model specifications. This can well be sufficient, when the level of detail in simulated decarbonisation strategy measures fits. As an example: While for small model regions, individual perceptions within a neighborhood might contribute great insight for policy advise, national-level policies, like fuel taxation, do not require more advanced model attributes than monetary cost. Within the limitations of data availability, quetzal_germany can depict a broad set of transport policies through price mechanisms and transport supply system changes (travel time and network accessibility), segmented by useful demand groups.

2.5 German passenger transport towards the Paris Agreement

Germany can contribute to limiting global temperature increase to 1.5 degree Celsius by becoming climate neutral by 2035 across all sectors (see SRU 2020). With current policy and technology pathways, transport emissions would not be lower than 154 million tCO_{2eq} in 2030 (Hendzlik et al. 2019). This projection clearly fails the climate neutrality goal, even though projections become more optimistic over time due to the implementation of new policies and faster technology deployment than expected. In quetzal_germany’s base year 2017, passenger transport had a share of 65 % of the transport sector’s GHG emissions (BMU 2019). This section’s outlook shows the GHG emissions gap that would appear in 2035 without demand-side strategies for passenger transport, i.e. no behavioural change in transport demand except its linear increase proportional to population growth.

2.5.1 Supply-side development

In general and across all modes, transport supply remains constant relative to transport demand: Capacities get expanded proportional to traffic volume increase so that congestion remains at 2017 levels. Future pricing follows assumptions from VP2030 in order to be consistent with trip generation and distribution, which is consistent with Allekotte et al. (2020) (see table 2.6). According to the authors, these projections exhibit a clear political intention to make transport more environmentally friendly. Only aviation ticket prices increase due to higher cost of synthetic fuels (see Cabrera and Sousa 2022).

Table 2.6: Yearly user cost increase between 2017 and 2035, following assumptions from Allekotte et al. (2020) and Schubert et al. (2014)

	Price development [% p.a.]
MIT, combustion engines	0.5
MIT parking cost	2.0
Road PT	1.0
Rail	0.5
Air	0.5

2.5.2 Technological development

Private vehicle technology development is heavily discussed in German society, industry, science, and politics. Will Germany continue to be diesel-driven or switch to electric vehicles (EVs)? Common techno-economic approaches to this question (such as Grube et al. 2021) neglect socio-technical aspects like co-evolution, niche-regime interactions, and behavioural change (see Köhler, Turnheim, and Hodson 2020). In a thorough robustness and uncertainty analysis, Wanitschke (2021) shows that battery EVs are likely to claim a significant share of vehicle sales in the medium term. However, production capacities will cap their market penetration at least until 2030. After dialogues with automobile manufacturers, Windt and Arnhold (2020) calculate a maximum stock of 14.8 million EVs in 2030 (corresponding to 32 % of 2017's private vehicle stock; including plug-in hybrid EVs). Drees et al. (2021) project 15.1 million EVs in their progressive scenario for 2035, which is in line with production capacities and assumptions of this outlook. Future EV charging cost are highly controversial, yet crucial for its competitiveness (Wanitschke 2021). For sake of simplicity, all EVs are assumed to be operated at cost of battery-driven vehicles with today's home charging price of 0.3 EUR/kWh. The remaining vehicles are assumed to have the same drive train shares and operating cost as in 2017, while efficiencies of combustion engines continue to increase with 1.5 % p.a. as a mean across fuel types (Schubert et al. 2014). Car ownership rates of households are assumed to stay at 2017 levels for sake of simplicity.

A deep-decarbonisation scenario as ambitious as this, requires fossil-free electricity generation by 2035, which yields zero driving emissions for all electric drivetrains. The German rail operator "Deutsche Bahn" already announced climate neutrality in 2038, even earlier in passenger transport. Hence, rail transport is assumed emissions free, here. The same assumption applies to road PT, though mainly driven by the European Union's clean vehicle directive. Air transport technology displays the least robust pathways and faces high technological barriers towards full decarbonisation. Hence, 50 % of its fuels are assumed to be climate neutral (i.e. biofuels or synthetic fuels), while technologies remain unchanged.

2.5.3 Emissions in 2035

Above's assumptions yield modal shares very similar to those of 2017. Higher vehicle efficiencies of private cars decrease driving cost per kilometre, which produces a mode shift of 0.5 % towards MIT on medium to long distances, taking equally from rail and road PT. Total traffic increases to 1,407 billion pkm (7 % more than in 2017). Through technological development, passenger transport emissions decrease to 65.5 mio. tCO_{2eq}, which is a reduction of 45 % compared to 2017, but still far from climate neutrality.

Several national research projects have investigated pathways for (passenger) transport decarbonisation in the past: *Transport and Environment* analyses three explorative bottom-up scenarios until 2040, of which the reference scenario yields 45 % emissions reduction compared to 2010, mainly through improve strategies (Ehrenberger et al. 2021; Winkler and Mocanu 2020). With similar assumptions and within the same time horizon, the *GreenLate* scenario in the *RESCUE* study achieves a 46 % emissions reduction (Purr et al. 2019). The technology pathway report of the *Ariadne* study concludes that a technology shift alone does not contribute enough to short-term (2030) decarbonisation goals and further demand-side mitigation measures are needed (Koller et al. 2021).

Full decarbonisation of the German energy system by 2035 is challenging (see Kobiela et al. 2020) and this exemplary scenario already includes progressive technological assumptions. There are natural barriers towards technology deployment, which are usually considered in energy system modelling (e.g. Purr et al. 2019). Avoid and Shift strategies would support decarbonisation without challenging technological boundary conditions such as renewable fuel imports, electricity generation capacities, production chain ramp-up, or resource availability.

2.6 Conclusion and outlook

Unleashing full transport decarbonisation potential is crucial for reaching the 1.5 degree-target of the Paris Agreement. This paper's outlook for Germany's passenger transport emissions shows that even in an ambitious technology scenario, there remains a large emissions gap. It can be bridged by further technological ambition, i.e. improve strategies, within uncertain boundary conditions. Avoid and Shift strategies, on the other hand, do not violate these boundary conditions, but affect society's well-being. How much they can contribute, and which effect they would have, remains open.

quetzal_germany, as presented here, can be used to analyse strategies to fill this knowledge gap. It realistically depicts mode choice behaviour on medium- to long-distance travel in Germany and exhibits suitable levers for national policy analysis. Future development ambition should direct towards endogenous depiction of trip generation and distribution to make it standalone and aid as an open source blueprint for other countries or regions. The discussion of quetzal_germany's properties shows: Macroscopic transport modelling is a suitable tool for large-scale transport demand-side analysis and should be used to support deep decarbonisation scenarios in techno-economic modelling.

Chapter 3

Sufficiency in passenger transport and its potential for lowering energy demand

Abstract

Prior research suggests that energy demand-side interventions have a large potential in climate change mitigation, connected to co-benefits in human well-being and several Sustainable Development Goals. However, it is challenging to translate such strategies into local and sectoral realities. We explore sufficiency futures for German passenger transport, a sector that is assumed to further grow in most studies, to analyse demand reduction potentials. In an interdisciplinary research design, we collect 133 diverse drivers of change of which we construct three sufficiency storylines. We translate them into parameters of the aggregated transport model quetzal_germany and quantify it through an expert survey. Results indicate that passenger transport energy demand can be lowered by up to 73 %, while pointing at the various cultural, political, economic, technological, and organisational developments that are responsible for this change and show co-benefits for well-being. The comparison to global low energy demand studies suggests that our results lie between two boundaries: the absolute minimum for decent living standards and the most ambitious illustrative modelling pathway in the IPCC Sixth Assessment Report. This work bridges the gap between ambitious climate targets from a global perspective and corresponding system design requirements in the local context.

3.1 Introduction

Transport systems around the world are moving people and goods faster than ever before, reaching new performance peaks every year (OECD 2023; Mattioli and Adeel 2021). This growth poses several sustainability threads: Particulate matter pollution from traffic causes autoimmune diseases and generates high costs in healthcare systems (BAFU 2020; Levy, Buonocore, and Stackelberg 2010), traffic accidents account for the greatest proportion of deaths among young people (Peden et al. 2022), and transport infrastructure destroys local ecosystems in rural regions

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(Sovacool, Kim, and Yang 2021) or is socially inequitable in urban regions (Creutzig et al. 2020). The Paris Agreement's climate change mitigation targets further put the shift towards sustainable mobility under serious time pressure. North America's and Europe's transport activities alone consume 30 % of global final transport energy demand (IEA 2022), which is disproportional to their population share. Thereof, passenger transport consumes 68 % (European Commission 2021; BTS 2022). Today, this causes over-proportionally high greenhouse gas (GHG) emissions. By extrapolating this trend, most long-term decarbonisation studies still assume increasing transport activity levels and energy demands for high-income countries, even those considering the 1.5 degree target (C1 and C2 scenarios in the IPCC AR6 (Byers et al. 2022)). However, recent studies show that lowering final energy demand is crucial for achieving this goal (Keyßer and Lenzen 2021; Grubler et al. 2018). Still, this field stays under-researched, especially for high-income countries, where future demand assumptions spread wide between unconstrained growth and radical decline.

A common term addressing these challenges in passenger transport is sustainable mobility. There are different definitions from various research fields, which allow for rather flexible interpretation of this concept (Gallo and Marinelli 2020; Berger et al. 2014). Generally, and especially in the context of climate change mitigation, the vague goal of sustainable mobility commonly translates into three more tangible strategies (see Berger et al. 2014; Banister 2008; Nykvist and Whitmarsh 2008): *Avoid* the need for traffic, *Shift* traffic to more sustainable modes, and *Improve* transport technologies. In long-term decarbonisation studies, technologically dominated Improve measures, such as high market penetration of electric vehicles, have already seen a lot of attention, while Avoid and Shift measures remain underrepresented (Gota et al. 2019). However, the rigid time limitation for limiting global warming to 1.5 degrees requires unleashing full transport decarbonisation potential (Mundaca, Ürge-Vorsatz, and Wilson 2019).

Hence, we focus on Avoid and Shift measures and frame them as demand-side mitigation strategies, contributing to the ongoing debate in scientific literature (Creutzig et al. 2022; Sorrell, Gatersleben, and Druckman 2020). We exclude Improve measures that require behavioural adoption towards new technologies by end users, but do not affect the service provided (e.g. electric vehicles provide the same *service* as combustion engine vehicles, even though they differ in *energy service*). On this basis, we draw on definitions of energy sufficiency (Zell-Ziegler et al. 2021) and sustainable consumption corridors, framing Avoid and Shift measures as sufficiency measures (as derived in A.1). We focus on passenger transport not only because of its high energy demand, but also due to its complex cultural embedding (Mattioli 2016), which has not been analysed thoroughly in the context of sufficiency transitions. Freight transport would require a different approach, as it is a secondary effect of consumption patterns, industry facilities, and transportation cost.

How can sufficiency look like in passenger transport? Which influence do sufficiency futures have on the transport system? Some modelling exercises tried to answer parts of these questions (e.g. Anable et al. 2012; Replogle and Fulton 2014; Pomponi et al. 2021), but there is no reference of sufficiency in mobility describing a comprehensive transition process to the best of our knowledge. We choose an interdisciplinary, participatory research design to analyse a sufficiency-directed transport system design in Germany (section 3.2). We consider the spatial restriction important for a detailed examination of sufficiency transitions, as they are context-specific (Sandberg 2021). Germany is particularly interesting as a high-income country with strong car-dependency and growing transport activity while population is declining (BMDV 2021).

3.2 Research design

Answering these research questions about sufficiency futures requires a normative approach, as it implies countering currently observable trends (Banister and Hickman 2013). We employ a backcasting scenario technique, where we start from a desirable end-point and examine the means by which this future can be attained (Robinson 1982). Transport modellers commonly use this technique to analyse policy pathways. However, sufficiency transitions – the process of advancing sufficiency practices – are multidimensional processes (Sandberg 2021), which require methods of analysis that go beyond common policy analysis and (techno-)economic modelling practices. Schwanen, Banister, and Anable (2011) argue that the qualitative basis which ensures valid quantitative outcomes should receive more attention in transport research. Additionally, a participatory perspective is deemed important to explore energy demand perspectives in its full complexity (Nikas et al. 2020; Hirt et al. 2020).

Some studies addressed these points for passenger transport decarbonisation in the past: Köhler, Turnheim, and Hodson (2020) combine qualitative mobility narratives, derived with the Multi-Level Perspective (Grin, Rotmans, and Schot 2010), and an agent-based model in order to describe the Dutch low-carbon mobility transformation. A Danish study of transport and energy system decarbonisation uses a participatory and narrative-based research design, following the Story and Simulation approach (Alcamo 2008), in order to model long-time policy scenarios (Venturini, Hansen, and Andersen 2019). Anable et al. (2012) constructed a lifestyle storyline and quantified its transport demand in a spreadsheet model. Several other approaches exist in the domain of transport modelling (e.g. Banister and Hickman 2013; Varho and Tapio 2013; Hickman et al. 2012), where participation of stakeholders is very common, but use of transition theory is rare. Building upon this work, we use methods from socio-technical transition theory together with aggregated transport modelling, wrapped into a participatory research design. It divides in two main phases: development of storylines as a qualitative basis and scenario modelling yielding the quantification of storylines (see figure 3.1). We do not consider a temporal

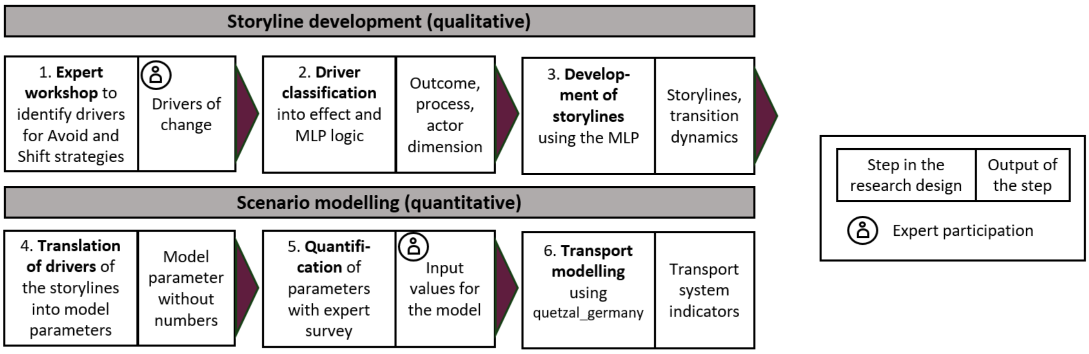

Figure 3.1: Research design divided into a qualitative and quantitative phase. Steps 1 and 5 involve mobility and sufficiency experts.

dimension, as our quantitative method simulates only one year with the desired transport system configuration and our qualitative method does not allow for exact identification of a temporal scope. In the end, the time frame depends on the level of ambition, but is restricted by realism.

3.2.1 Storyline development

The first phase starts by collecting drivers of change towards sufficiency for the German passenger transport system. We asked 15 transport and sufficiency experts from different disciplines[1] to collect concise drivers for traffic avoidance and/or modal shift in an online workshop. Due to our normative approach, we neglected barriers or driver uncertainties. We guided the brainstorming process to yield distinct results that are more detailed than just the driver outcome, but also less detailed than the precise implementation. None of them contradicts realism, even though they come at different levels of ambition. It was designed as a World Café around four topic fields: infrastructure and spatial planning, social factors, individual factors, and systemic factors (derived from the conceptional decision making model in Javaid, Creutzig, and Bamberg (2020)). The result comprises 133 sufficiency drivers, which cover a wide range between infrastructural measures (e.g. constructing cycling highways) and cultural factors (e.g. increased awareness of road fatalities). They consist of 60 % policy interventions, 21 % individual mindset changes, 14 % corporate action, and 5 % consumption changes. A full list of drivers can be found in the supplementary material. It comprises most of the 35 Avoid and Shift measures found in the global review by Roy et al. (2021).

We use these drivers to construct three storylines: One with drivers that have a traffic avoidance effect only, one with drivers that cause mode shifts exclusively, and one that comprises all drivers

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[1] Expert backgrounds: research (9), lobbying (2), consulting (2), planning (2); from disciplines: sufficiency policy (1), mobility concepts (2), sustainability transitions in mobility (3), mobility transitions on small islands (1), transport modelling (1), society in mobility transformations (3), strategy (3), spatial planning (1); 73 % males

of change. The latter can be understood as the benchmark for potentially achievable levels of sufficiency in German passenger transport. The effect classification of drivers (i.e. Avoid, Shift or both) is done with expert knowledge, following Roy et al. (2021) and Creutzig et al. (2018). Each storyline answers three fundamental questions of storyline studies: Where does the future lead and what is the solution to the underlying problem? (outcome dimension); Why are certain developments to be expected and what are their drivers? (process dimension); Which actors are responsible for change or stability? (actor dimension). A detailed written out version of the storylines can be found in A.2.

We use the Multi-Level Perspective (MLP), an established method in transition research (Geels 2012, 2002), for construction of the inner workings in each storyline. The MLP frames socio-technical transitions as a process where innovations (social or technical) affect incumbent regimes within a slowly changing landscape. Niche momentum, (de)stabilising regime forces, landscape pressures, and inter-linkages are the principles of change. Yet, not all innovations that effect transport system regimes must come from the transport system (e.g. remote work). Rosenbloom (2020) calls this multi-system interactions. We classify each driver as niche, regime or landscape effect of the corresponding system and determine its interactions with other elements of this storyline. This allows us to analyse transition dynamics, which is a central feature in the MLP framework (Geels and Schot 2007). It describes the constellation of change mechanisms in a system that cause a transition and represents a valuable resource for explaining the corresponding process. Following our backcasting technique, we deduce the transition dynamics from the outcome, process, and actor dimensions, instead of constructing them bottom-up. Table 3.1 summarises the storylines.

3.2.2 Translation and quantification

The translation of storylines into modelling scenarios requires quantification of suitable model parameters. Hence, the first exercise is distinguishing between model-affecting sufficiency drivers and corresponding preconditions that do not have to be quantified. The remaining 64 drivers translate into distinct model parameters each (see supplementary material). Naturally, the process of parameter quantification for economic models is opaque and depends on the knowledge and personal beliefs of the modeller (e.g. Royston et al. 2023). We use a survey method to inform the directions of future developments of the drivers as suggested in Alcamo (2008). The aim is enhancing transparency and reproducibility in the quantification process (Mallampalli et al. 2016).

The survey contains the affected model parameters and we distribute it amongst participants of the sufficiency driver workshop, as well as additional experts who were invited to the workshop initially, but did not participate (29 invites in total). This selection was made to ensure that

Table 3.1: Summary of sufficiency storyline outcomes.

	Avoid	Shift	Avoid+Shift
outcome dimension	High availability of goods, services, amenities, and social activities in local environment; digitisation in work relations and distant social contacts	Minimum car dependency; efficient, attractive, interconnected PT; safe and comfortable cycling infrastructure; increased public health	Main aspects in addition to Avoid and Shift: New core principles of integrated transport and spatial planning; private cars as anti-status symbol
transition dynamics	Several digitalisation niche developments with large momentum reduce the need for traffic; local and shared economies (niches) build up momentum, while landscape developments put the economic growth imperative under large pressure; the welfare state regime stabilises	Strong niches advance diverse mobility offers, helping public and non-motorised transport regimes stabilise and grow (enabled by a large number of landscape developments)	In conjunction with Avoid and Shift dynamics: Radical landscape changes exert large pressure on the automobile regime, which becomes subaltern; further landscape pressures and formerly small niches lead to regime breakdown of materialism
driver classification	moderate policy intervention (56 %) and large cultural shifts from equal shares of mindset and consumption changes, as well as corporate action	largely driven by policy intervention (73 %) and corporate action (17 %) with minor mindset shifts (7 %)	60 % policy interventions, 21 % individual mindset changes, 14 % corporate action, 5 % consumption changes

participants have a profound knowledge of transport sector transitions to make statements about future developments. The survey is structurally divided into five action fields (cycling, PT, regulation, spatial planning, culture and economy), first summarising all corresponding drivers that were classified as precondition in form of an introductory text and then stating slider questions to quantify model parameters. Overall, the survey consists of 59 questions. These, together with the background information given to the participants, are available in the supplementary material. We use all twelve complete responds (41 % response rate) to generate average values for the corresponding model parameter, yielding a single value with the least arbitrariness (equivalent to fuzzy set theory; see Alcamo 2008).

These quantitative values turn the sufficiency storylines into three modelling scenarios. Additionally, we define a *reference* scenario that serves as relative comparison for the others. It does not account for any transport demand-side developments, neither in direction of Avoid or Shift, nor in direction of historic trends (i.e. more car ownership and use). It assumes equal population development and household compositions as in the other scenarios and in the Federal Spatial Development Forecast (Maretzke et al. 2021).

On the transport supply side, all scenarios assume full electrification of PT modes, 100 % synfuels in aviation, 100 % battery-electric private cars, and energy supply that comes from 100 % renewable energy sources. Energy intensities for transport technologies come from Robinius et al. (2020). These assumptions do not affect the transport model structure, nor the storylines, because the transport service satisfies basic human needs independent of the propulsion technology. Most German energy system studies suggest that these assumptions are unrealistic within the next two decades because of limited industry capacities, high resource demands, and limited renewable energy sources build-up capacities – domestic and internationally (e.g. Ehrenberger et al. 2021; Luderer, Kost, and Sörgel 2021; Purr et al. 2019). Still, they are useful for comparison to other long-term energy scenario studies, which is why we use them for post-processing of results.

3.2.3 Transport modelling

We use the open source aggregated transport model quetzal_germany (Arnz 2022) to quantify each of the three sufficiency scenarios and the reference scenario. It features six land transport modes with detailed networks and domestic aviation for the region of Germany, twelve demand segments (six trip purposes divided into car availability), and a zoning system of 2,225 traffic zones. Its flexible and openly accessible structure allows high degrees of customisation and integration of various levers for sufficiency measures. The full list of drivers and brief descriptions of their implementation can be found in the supplementary material. Our refinements of the transport model's demand module, to endogenously account for all storyline effects, are described in A.3.

3.2.4 Reflection on methods

The choice of scientific methods for scenario studies is usually connected to normative assumptions that must be reflected on to prevent invalid interpretations of results. First, our participatory steps include transport experts that we chose ourselves in a nonrandom selection process (see Creswell 2014). We acknowledge that providing generalisation and representation are important aspects in conducting quantitative social science (Creswell 2014). This selection type might have implicitly biased the results. However, it does not corrupt the backcasting scenario technique connected to the normative approach to our research questions, it is rather necessary to provide a comprehensive picture of sufficiency from different disciplines.

Second, Whitmarsh (2012) questions the suitability of the MLP framework for analysis of substantial mobility transformations. Moreover, the MLP was developed primarily for the analysis of growth-dependent pathways, not in the context of "less". We address both points with multi-system interactions (Rosenbloom 2020). They allow us to allocate drivers that cause less mobility to other systems, as well as radical developments that go beyond the transport system's niche-regime interactions.

Third, a common critique of long-term transport modelling studies is their notion of static mobility preferences, even though they might change in future (Mattauch, Ridgway, and Creutzig 2016). We try to overcome these limitations with our translation and quantification process: It enables us not only to change transport system characteristics, but also mobility preferences. This is an innovative approach that needs further research and validation. A limitation we inherit through transport modelling is its reliance on individual utility maximisation. This method performs well in macroscopic analysis today, but might be ill-suited for solving climate change issues, which are largely driven by the liberal concept of utility maximisation (Creutzig 2020).

3.3 Effects of sufficiency drivers on the transport system

The Avoid and Avoid+Shift scenarios show the strongest total decline in commuting and business trips due to remote work and remote meetings throughout industries (figure 3.2). Non-compulsory trip purposes are less prone to decrease, but still decline due to increasing digitisation of social events and shopping/execution trips. Here, particularly trips in rural and suburban areas, that go beyond the municipality borders (i.e. inter-zonal trips), decline because of spatial planning processes that increase the diversity and livelihood in the local environment. Local economies,

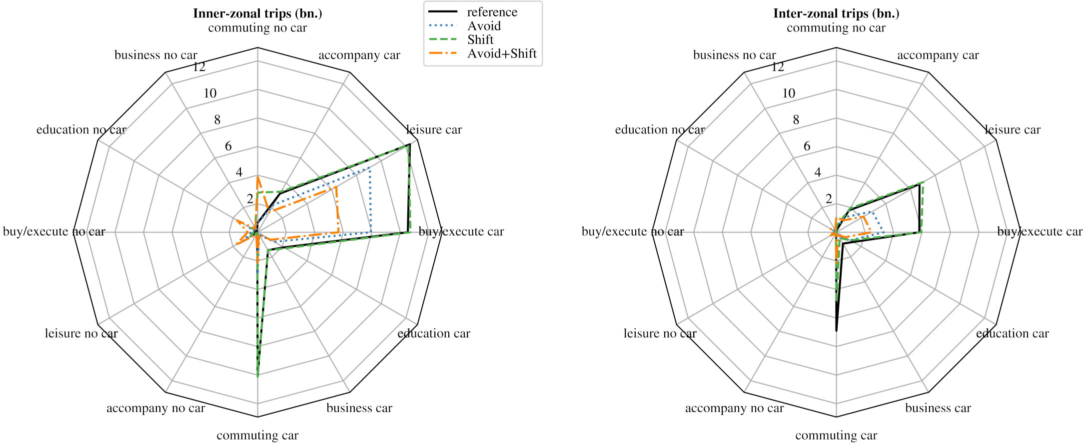

Figure 3.2: Inner- and inter-zonal trip frequencies by scenario and demand segment. To the left, there are trip purposes from households without car(s) available and trips with car available to the opposite. Non-car owners have better mobility access in Shift scenarios and mobility demand drops starkly in Avoid scenarios, as compared to the reference.

Table 3.2: Characteristics of car use (private and shared).

	reference	Avoid	Shift	Avoid+Shift
Average annual mileage [vehicle km]	12700	6500	8200	3500
Private cars owned (mio.)	46.0	37.1	44.9	29.5
Share of trips by car [%]	86.0	80.0	52.9	40.0

moreover, boost the availability of goods, services, and amenities. The decline in inter-zonal trips is especially interesting, as they produce the gross of total passenger kilometre (pkm; 86 %), although being responsible for only 36 % of total trips in the reference scenario. The Shift scenario exhibits a slight increase in non-compulsory trip purposes, which are sensitive to lower travel cost (time and price). Compulsory trips, however, do not see an absolute increase, but a shift from car-owning households to non-car owners: Car dependency declines to a minimum and everybody gets full access to the labour market and education system[2] (likewise in the Avoid+Shift scenario).

Car ownership (defined as households with at least one car available) and underlying drivers vary largely between scenarios (see table 3.2). The Shift scenario features a highly interconnected PT system, but reduces car ownership only by 2 % through more attractive transport services and ticket offers for older generations. Hence, the social status of cars prevails, even though

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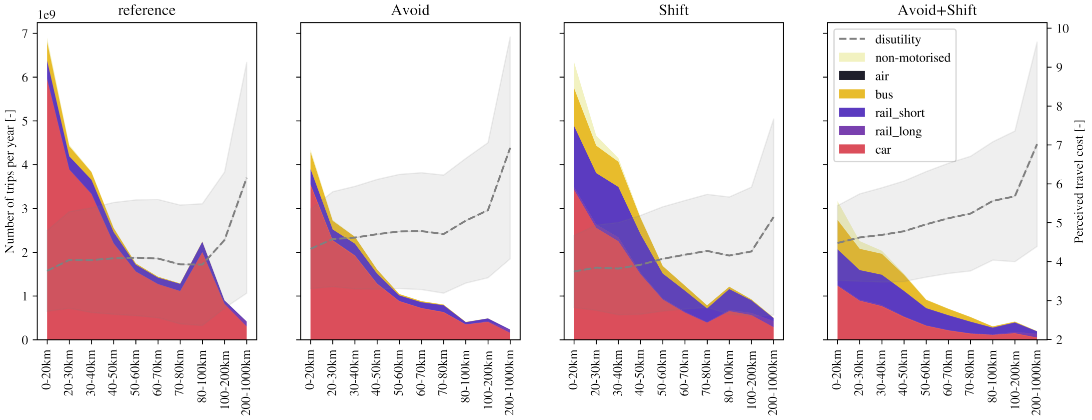
[2] In the reference scenario, non-car owners undertake one third less educational trips and 63 % less commuting trips than car owners


reference

Avoid

Shift

Avoid+Shift

Figure 3.3: Modal split by number of inter-zonal trips and main mode of transport. The average disutility of a distance class (volume-weighted) and its standard deviation across demand segments (grey area) quantify perceived travel cost. Large transport demand shifts are possible in sufficiency scenarios. The combined scenario shows synergies between Avoid and Shift measures, as well as Push and Pull measures. The trip distribution is shaped, among other factors, by perceived cost, which decreases for long distances in the Shift scenario and increases in the Avoid+Shift scenario.

its use decreases. In contrast, the Avoid scenario reduces mileage and car ownership through a trend “from ownership to access”. It features widespread opportunities for car sharing on the one hand and increased local cohesion on the other hand (e.g. through mixed neighbourhoods, revival of hitchhiking, and local economies), reducing the need for private cars. Adding stringent tax policy and multiple other car-disincentivising policies, the Avoid+Shift scenario exhibits an average car availability of 52 % (only 29 % in cities). It entirely shifts the perception of cars towards an anti-status symbol, drastically reducing use and ownership.

Scenario trends in car ownership reflect themselves in modal shares, too. Figure 3.3 shows that modal shares of rail and bus transport can increase by 30 % when PT supply drivers of the Shift scenario interact to make it as attractive as possible. There is also a notable increase in cycling, mainly driven by significant investments into cycling infrastructure and safety, as well as cultural shifts towards tranquility and appreciation of the landscape. Especially car owners use the bicycle more for leisure and execution trips. Vice versa, car sharing – as introduced in the Avoid scenario nationwide – is used only by non-car owners, as the private car is still cheaper in operation. Car sharing helps reducing car ownership, providing the feeling of flexibility, even though it is used only occasionally.

The Avoid+Shift scenario reduces car transport by 46 % in total, compared to the reference. This is due to drivers pulling users towards PT (as in the Shift scenario), drivers pushing users away from cars (e.g. car-free inner cities or tax policy), and drivers that affect mobility culture (e.g. ban of car advertisement or trends of post-materialism). Still, the private car persists as an important pillar of the transport system and is used for all trip purposes, especially on short distances. Where Shift drivers apply, medium to long distances are dominated by PT, as it offers overly attractive connections and tariffs (see figure 3.3). The degree of urbanisation reduces the importance of the car, but even a fraction of city inhabitants keeps using it for daily short-distance trips. In fact, the average distance slightly decreases in the Avoid and Avoid+Shift scenarios for private cars, while car sharing's average distance pertains at the reference level, as shared cars are used for holiday trips, too.

Figure 3.3 also depicts the trip distance distribution. The Avoid and Avoid+Shift scenarios decrease total trip frequency and shift short-distance trips to the local environment, where availability of daily demands increases. On the other hand, the Shift scenario shifts medium-distance traffic to shorter distance classes. This is due to local on-demand services which replace scheduled bus services outside of cities and make short-distance travel overly attractive: They reduce the average access, egress and waiting time significantly and increase PT flexibility by offering efficient ride-pooling schemes. They dominate road PT with a 90 % share of trips.

The perceived travel cost, which consists of transport system prices, travel times, and mobility attitudes of the corresponding demand segment, is an economic measure from transport research. It shapes the choice of trip destinations, i.e. the distance distribution, as can be seen in figure 3.3. The Shift scenario exhibits a smoother ascent than the reference due to lower PT fares and better connectivity. In contrast, the Avoid+Shift scenario imposes high cost on car travel, yielding a steeper curve. Here, the curve is smoother for the rural population and steeper for urban inhabitants, as rural environments become more accessible and cars are pushed out of cities, respectively. In general, scenarios with Avoid character shift attitudes from appreciating inter-zonal travel towards local cohesion.

Resulting passenger kilometres are similar to mode shares (see figure 3.4). In general, urban-rural mobility differences decrease in the sufficiency scenarios. Still, urban regions are better connected by long-distance train services and cycling highways in the Shift scenarios, leading to less car travel. Compared to the final energy demand, road and air transport stand out, as they are less energy efficient than rail modes. These figures imply a technology mix that is 100 % electrified, as described in section 3.2.2. Hence, carbon emissions depend on the carbon intensity of the electricity mix and go beyond the scope of this study.

3.4 Discussion and conclusions

The three sufficiency scenarios are the product of qualitative storylines and the quantification of their drivers of change. All corresponding modelling results support key features of the

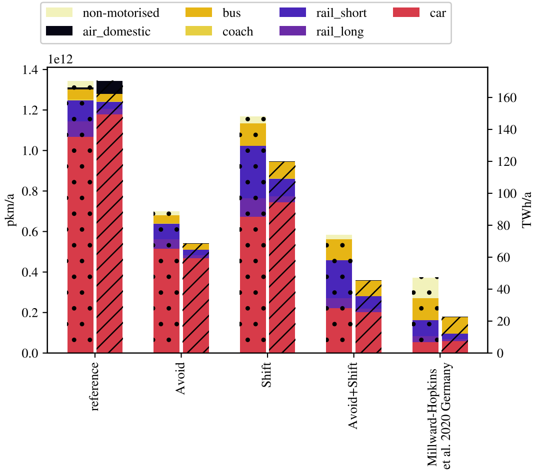


Figure 3.4: Passenger kilometres (dotted) and final energy demand (hatched) by mode and scenario. The car remains an important transport mode, but rail transport is more energy efficient. Millward-Hopkins et al. (2020) show the lower bound of sufficiency with even lower travel demand and very high shares of non-motorised transport, further reducing the energy demand (assuming the same technology mix as in the sufficiency scenarios for consistency).

storylines (see A.2 and table 3.1). The Avoid scenario makes 38 % of motorised trips obsolete through sufficiency-directed spatial planning, digitisation of work relations, and cultural, as well as economic trends forming a "new localism". 6 % more trips can be avoided in the Avoid+Shift scenario by dis-incentivising car travel; especially on long distances through high taxation and in cities through regulation. The new perception of cars as anti-status symbol and corresponding policy measures also reduce their mode share by 13 % more than the Shift scenario can achieve. The latter represents a classical pull strategy[3] with a highly attractive PT system and growing PT culture, but no shift in economic principles.

It is questionable, whether the Shift scenario is a sufficiency scenario after all. There is no consistent definition of sufficiency in mobility, but in general, sufficiency transitions are a fundamental change towards "enoughness" (Jungell-Michelsson and Heikkurinen 2022), while some connect it to degrowth (Lage 2022). The Shift scenario shows no such change, as for individual consumption, and even produces more trips than the reference. It follows liberal principles of increasing transport connectivity that used to dominate transport planning of the last century (Marvin and Guy 1999). Still, the Shift scenario fits our notion of transport sufficiency from an energy demand perspective, as it shows a 30 % reduction while using the same propulsion technologies. Further research on sufficiency should gain a deeper understanding of

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[3] Pull and push strategies are common terms in transport policy, aiming at attracting users towards sustainable travel or dis-incentivising the use of unsustainable travel, respectively.

fundamental systemic change that facilitates sufficiency transitions to define this concept more precisely.

Nevertheless, the Avoid+Shift scenario satisfies all sufficiency requirements. On the one hand, it reduces mobility consumption, on the other hand, it dis-incentivises car travel and stimulates PT use – pull and push. It establishes a new mobility culture by setting new fundamental principles of mobility: equity, health, and diversity (see A.2). This is highly effective, as can be seen in mode shares and trip frequencies. These indicators are malleable through diverse political, economical, technological, and social interventions, as well as their interplay (see table 3.1). More precisely, we observe synergies. Single policy measures like road charges show a lower impact on the modal split as when combined with PT investments. Vice versa, infrastructural measures should be accompanied by regulatory interventions to yield the maximum outcome: Mobility hubs at city borders show no effect, unless accompanied by car-free inner cities; cycling highways are not as attractive without the ban of car advertisement. All developments in these comprehensive sufficiency scenarios show higher effects than the sum of its single measures, as decision processes are non-linear. Hence, the combination of pull and push measures, as well as political, economical, technological, and social drivers is crucial for promoting sufficiency. There is no “silver bullet” in transport policy (see Givoni et al. 2013).

Still, our scenarios show two measures with especially high impact. An important pull measure is full coverage of remote regions with on-demand ride pooling services. Such services have seen much attention in recent research (Maas 2022). If they are managed highly convenient, they will help fostering a public transport culture. Rail transport can profit from this culture, but has to become reliable and operated at higher frequency. Moreover, high-density living blocks in agglomeration areas show large reduction potentials in motorised transport – especially private car use –, if they replace (newly built) single-family home settlements to counter current trends. High-density living comes with lower resource use, which supports sustainability ambitions in the building sector.

Another important discussion regarding sufficiency transitions is quality of human life. Here, we draw on eudaimonic notions of well-being, as it is founded on universal, objective, and structural conditions that facilitate a good life (Lamb and Steinberger 2017). Rao and Min (2018) utilise this concept to quantify decent material living standards, which Millward-Hopkins et al. (2020) use to quantify decent energy needs. Its comparison in figure 3.4 shows that all German sufficiency scenarios are well above the minimum energy demand necessary to provide decent levels of mobility. But well-being also accounts for other indicators that see improvements in our scenarios: Public health, social equity, accessibility to need satisfiers, and social cohesion in the local environment. This is consistent with global-level findings from Creutzig et al. (2022), who underline synergies between sufficiency measures and well-being, and Roy et al. (2021), who find positive effects of sustainable mobility on several Sustainable Development Goals.

Further research should define and quantify impacts on well-being indicators in mobility (Zhao et al. 2020), which are, to this date, not clearly defined (Virág et al. 2022). However, we show that well-being at high levels of personal mobility does not depend on growth in pkm.

The final aim of this study is to explore the energy demand reduction potential of sufficiency futures, which makes the realisation of ambitious climate targets more likely. All scenarios reduce energy demand – up to 73 % in the Avoid+Shift scenario. These 2.0 GJ of final energy per capita are also 72 % lower as the Global North's land transport final energy demand per capita in the Low Energy Demand (LED) scenario in 2050 (Grubler et al. 2018), which is the IPCC Sixth Assessment Report's most ambitious Illustrative Mitigation Pathway. It shows 29 % increase of transport activity in global north countries (20 % reduction against historic trends) and moderate shifts from car to rail and air transport. Mode shifts are mainly driven by developments towards teleworking and more livable and healthier cities. The LED scenario halves the vehicle stock through car sharing and digitisation of mobility supply, which is a relevant lever for transport's total energy demand.

Our Avoid+Shift scenario reduces the private vehicle fleet by 36 %, although the low average mileage suggests that car ownership could drop even further in the long run. Put together, the LED scenario's narrative differs from our sufficiency storylines. We do not have the same focus on digitalisation, even though it is a major driver for traffic avoidance in work relations and a crucial enabler of new technologies that resolve car dependency and corresponding inequity. The LED narrative breaks with fewer conventions than the Avoid+Shift storylines, yet it is difficult to assess which storyline is more likely. The transition dynamics and driver classes in table 3.1 suggest that our storylines rely to relatively large degrees on target-oriented policy intervention. Individual mindset shifts are largely enabling these actions, but also resulting from them. Corporate action is mostly a result of the new system configuration. Consumption changes towards local products and services are an enabler of local economies, even though economic system shifts require more profound drivers.

Results of this paper contrast common transport demand-side assumptions in long-term energy modelling (see Byers et al. 2022). They suggest that more ambition in reducing energy demand through demand-side interventions is possible and show a promising future for both, climate change mitigation and human well-being. These results can incentivise global energy modelling studies to consider behavioural change more thoroughly, as it is often overlooked today (Samadi et al. 2017). That might go beyond current economic principles and challenge the economic growth dependency, a topic that should receive more attention in the IPCC Seventh Assessment Report (Keyßer and Lenzen 2021). However, this is just a national, sectoral study. More research should direct towards its connection with the energy system, the freight transport system, and towards exploring comprehensive sufficiency transitions for the whole economy in other regions of the world.

Chapter 4

Avoid, shift or improve passenger transport? Impacts on the energy system

Abstract

Demand-side mitigation strategies have been gaining momentum in climate change mitigation research. Still, the impact of different approaches in passenger transport, one of the largest energy demand sectors, remains unclear. We couple a transport simulation model to an energy system optimisation model, both highly disintegrated in order to compare those impacts. Our scenarios are created for the case of Germany in an interdisciplinary, qualitative-quantitative research design, going beyond techno-economic assumptions, and cover Avoid, Shift, and Improve strategies, as well as their combination. The results show that sufficiency – Avoid and Shift strategies – have the same impact as the improvement of propulsion technologies (i.e. efficiency), which is 25 % reduction in generation capacities. This lowers energy system transformation cost accordingly, but requires different kinds of investments: Avoid and Shift measures require public investment for high-quality public services, while Improve measures require individuals to purchase more expensive vehicles at their own cost. These results raise socio-political questions of system design and well-being. However, we must pursue all strategies to unleash the full potential of climate change mitigation.

4.1 Introduction

High-income regions like Europe and the United States consume 18 and 24 % of their final energy demand for passenger transport, respectively (European Commission 2022; EIA 2023). This demand is currently fuelled with fossil oil derivatives that are shipped around the world and impose complex geopolitical inter-dependencies. Their combustion translates into a relevant share of greenhouse gas emissions, which must be fully mitigated by mid-century in order to contribute to the climate targets of the Paris Agreement (Rogelj et al. 2015). In general, there are two directions for emissions mitigation: Decarbonising energy supply and reducing energy

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This chapter is based on the joint work with Leonard Göke, Johannes Thema, Frauke Wiese, Niklas Wulff, Mario Kendziorski, Philipp Blechinger, and Karlo Hainsch. The preprint with the same title is under review in *Energy Strategy Reviews*.

demand. Many long-term energy system transformation studies have investigated technological pathways towards full decarbonisation and 100 % renewable energy sources (RES) (Khalili and Breyer 2022; García-Olivares, Solé, and Osychenko 2018; Wiese, Thema, and Cordroch 2022). However, these studies usually simplify energy demand in passenger transport to the technologies that consume energy, neglecting other demand-side dimensions that go beyond techno-economic analysis. We address this research gap through comprehensive analysis from both perspectives; the energy and transport system.

From a transport perspective, demand and supply have different notions than in energy system research: Human activities within the built environment produce a physical mobility demand that is satisfied (i.e. supplied) by use of transport technologies (and non-motorised transport). This results in three prominent energy demand mitigation strategies: Avoiding unnecessary traffic, shifting traffic to more energy-efficient modes, and improving transport technologies (Creutzig et al. 2018). While technological improvements have seen much attention in international research and policy, the role of *Avoid* and *Shift* measures remains under-represented (Gota et al. 2019). However, these two strategies are not only relevant for demand-side mitigation (Mundaca, Ürge-Vorsatz, and Wilson 2019; Creutzig et al. 2015; Girod, Vuuren, and Vries 2013), but also create significant co-benefits that increase human well-being (Creutzig et al. 2022) and support the Sustainable Development Goals (Roy et al. 2021). We formulate two research questions: What is the potential impact of Avoid, Shift, and Improve measures in passenger transport? Is there a preferable strategy?

As such, we analyse the impact of comprehensive demand-side mitigation strategies on an optimised, fully defossilised energy system. Germany is selected as case study because it is a high-income country with strong car-dependency, where Avoid and Shift strategies play a minor role in past and current transport policy. We model fine-granular Avoid and Shift scenarios in the transport simulation model quetzal_germany (Arnz 2022) and couple them to the EuSys/AnyMOD.jl model. It optimises technological capacities and respective dispatch for the European energy system towards 100 % RES in 2040 (see figure 4.1; further details in appendix B). All transport demand scenarios are combined with a scenario representing a propulsion technology mix and an Improve scenario, respectively (table 4.1). We compare resulting energy supply capacities, flexibility indicators, and system cost across all scenario combinations.

Our approach is innovative in two ways. First, the impact of applying comprehensive Avoid, Shift, and Improve strategies in passenger transport on the energy system has never been compared on a national scale, and in such detail (similar approaches found in Anable et al. (2012), Brand, Anable, and Morton (2019), Venturini, Karlsson, and Münster (2019), and Köhler, Turnheim, and Hodson (2020)). Second, our research design aims at overcoming common critique in energy and transport modelling: We couple highly specialised models, which is found beneficial to gain

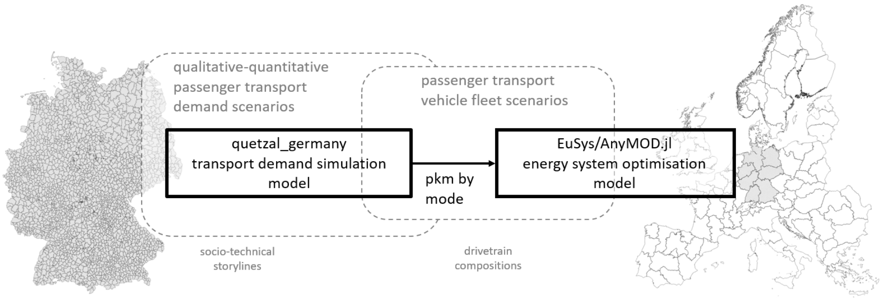


Figure 4.1: Research design: The aggregated transport model quetzal_germany (Arnz 2022) simulates German transport demand based on a multitude of technological, economic, organisational, cultural, and political drivers that affect the number, distance, and mode of trips. Resulting passenger-kilometres (pkm) are fed into the EuSys/AnyMOD.jl energy system model to analyse the effect of energy demand scenarios with 100 % renewable energy supply. Transport demand scenarios are created in a qualitative-quantitative research design (Arnz and Krumm 2023), whereas transport supply scenarios contain different drivetrain technology compositions. Both model's geographical resolutions are sketched to the left and right.

Table 4.1: Scenarios of this model coupling exercise. Four different transport demand characteristics (rows) are further elaborated in the supplemental information and include no measures (reference), Shift measures only, Avoid measures only, and a combination (Avoid+Shift). Supply characteristics (columns) contain a technology mix with battery-electric vehicles (BEVs), plug-in hybrids (PHEVs), and internal combustion engine vehicles (ICEVs) (Luderer, Kost, and Sörgel 2021), as well as the Improve case 100 % BEVs. Public transport vehicles are 100 % electrified in all scenarios.

	Mix: 56 % BEV, 14 % PHEV, 30 % ICEV	Improve: 100 % BEV
reference	Ref+Mix	Ref+Improve
Shift	Shift+Mix	Shift+Improve
Avoid	Avoid+Mix	Avoid+Improve
Avoid+Shift	Avoid+Shift+Mix	Avoid+Shift+Improve

deeper insights from different perspectives in complex transformation processes (Luh et al. 2022) and to not under-estimate the decarbonisation potential (Creutzig 2015); we consider drivers outside the techno-economic realm to include further social aspects in transport modelling (Schwanen, Banister, and Anable 2011), energy modelling (Krumm, Süsser, and Blechinger 2022), and corresponding policy conclusions (Royston et al. 2023).

4.2 Results

4.2.1 Transport demand changes

The proposed transport demand scenarios (i.e. Avoid, Shift, Avoid+Shift) are connected to a paradigm shift in German passenger transport. They comprise 133 infrastructural, socio-cultural, organisational, and regulatory drivers of change, which were collected, translated, and quantified in a participatory, interdisciplinary research design (further information found in appendix B). On the qualitative side, this process resulted in socio-technical storylines, which show co-benefits of sufficiency-oriented system design on human well-being (Arnz and Krumm 2023). The Shift scenario decreases car dependency to a minimum through strong initiative towards rail transport reliability and capacity, as well as safe and fast cycling networks, and attractive on-demand ride pooling systems. The Avoid scenario, on the other hand, depicts sufficiency-oriented lifestyles that feature strong local economies, social cohesion, and supply structures, combined with remote work across sectors. The Avoid+Shift scenario combines both of the previous scenarios, and adds strong push measures against private car driving. Here, industry policy and regulatory frameworks are fully tailored towards sustainable transport and equity.

Figure 4.2 shows quantitative results of these storylines, generated with quetzal_germany. The reference case is dominated by car transport over all distance classes and involves an increase of total passenger-kilometres (pkm) against 2020 due to increased household incomes. The Shift scenario is able to replace 33 % of the car trips by other modes with only slight decreases in car ownership. The total number of trips slightly increases, even though total pkm decrease by 9 %. This is due to disruptive mobility concepts that make short and medium distance travel overly attractive. The Avoid scenario shows a different transport system with 42 % less pkm, especially on long-distance segments that were previously dominated by car travel. The combined scenario shows even fewer trips, especially by car due to strong push measures, but more pkm in total, as the public transport system becomes more connected and attractive.

The Improve scenarios on the transport supply side show similar results as the Mix scenarios, despite higher shares of car travel. This is due to reduced operation cost of private vehicles, as the share of electric driving increases to 100 %. This rebound effect accounts for less than 1 % in

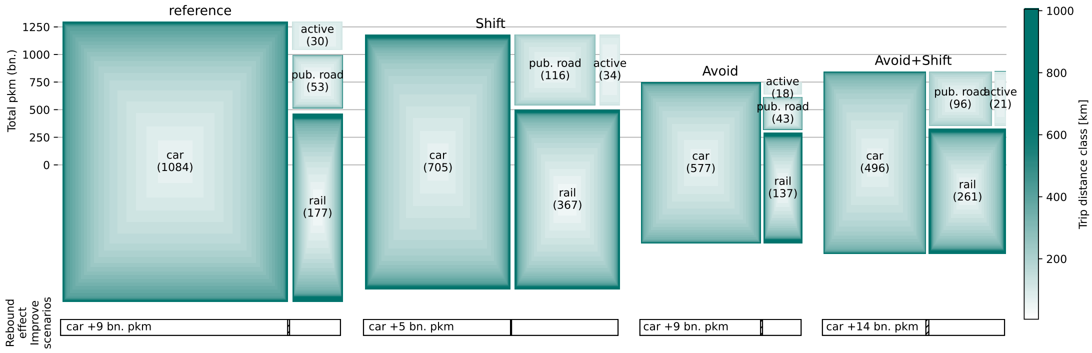
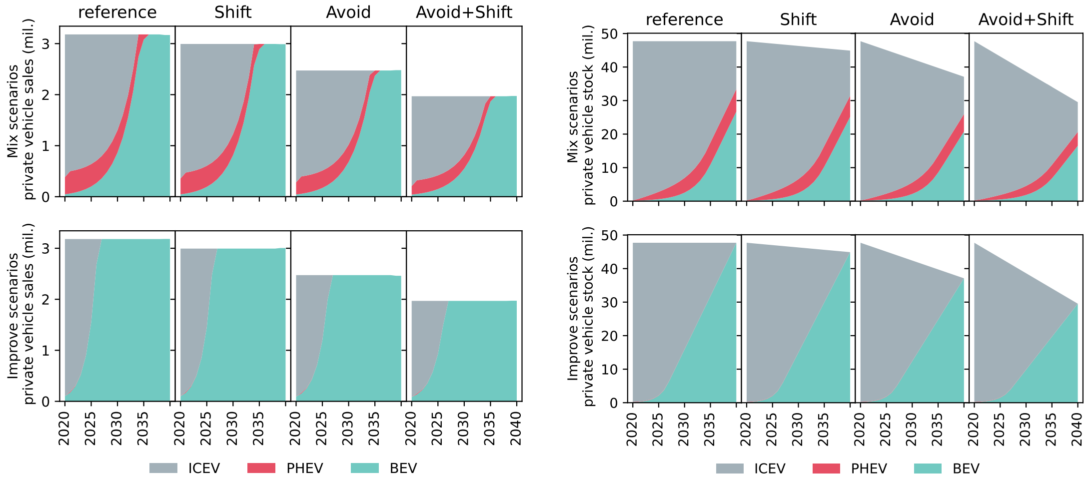


Figure 4.2: Results of the transport demand scenarios. Passenger-kilometres (pkm; in parentheses) can shift to public and non-motorised modes or decrease starkly in the Shift and Avoid scenarios, respectively. Trip distance distributions (indicated by the colour scale) shift to shorter distances in the Avoid scenarios. The private vehicle drivetrain change in the Improve scenarios causes more kilometres driven by car, as operation cost decrease, a phenomenon known as the rebound effect (depicted in the lower bars).

the reference case, but 2.6 % in the Avoid+Shift scenario, where car driving is heavily taxed and, thus, the marginal utility of lower operation cost increases. The private car stock development differs strongly between transport supply scenarios. While Mix scenarios show a moderate uptake of electric vehicle sales, Improve scenarios show a radical increase of battery-electric vehicle (BEV) sales in order to match the scenario targets. Sales reach 100 % BEV share in the mid-2020s, which takes a decade longer in the Mix scenarios. Figure 4.3 depicts the radical shift in private car technologies, deduced with a simplified car stock model (see appendix B). It also shows car ownership development as outcome of the transport demand scenarios. The car stock declines as low as 29.5 mil. vehicles in the Avoid+Shift scenarios, interpolated linearly over the scenario period for sake of simplicity. In this study, we neglect possible energy demand implications from changes in industry capacities.

4.2.2 Impact on the energy system

Changes in transport demand correspond with a reduction of energy supply. Two different effects can be distinguished here: First, changes in technology adaption between the Mix and Improve scenario, specifically the switch from internal combustion engine vehicles to BEVs, greatly reduce the demand for synthetic fuels by 83 % in the reference scenario. The remaining share is used primarily for international aviation and shipping, which uses biomass as primary input. In turn, the additional demand for hydrogen to produce these synfuels in the Mix scenarios is reduced, and ultimately also electricity generation, the input for hydrogen production. As a result, the



(a) Private car sales

(b) Private car stock

Figure 4.3: Private vehicle sales (a) and corresponding stocks (b) over the scenario period. Reproduced vehicle stock compositions of the Mix scenarios in 2040 come from the Ariadne research project (Luderer, Kost, and Sörgel 2021).

required wind and solar capacities decrease by 25 % in the Improve scenarios. Furthermore, the electrical capacity of electrolysers drops from 153 to 63 GW in the reference case. Since the creation of synfuels requires carbon filtered from the atmosphere as well, finally, capacities for direct air capture are reduced from 12 GW to zero. Figure 4.4 depicts aggregated capacities across scenarios.

The second effect does not relate to technology adaption but the utilisation of these technologies. In the Avoid+Shift case, the reduction of transport demand and the shift towards more efficient public transportation reduces the overall energy demand as well. The total effects differ for the Improve and Mix scenario. In the Improve scenario, the total effect is smaller, amounting to 92 TWh/a, since comparatively efficient BEVs already dominate in the reference case. In the Mix scenario, a greater effect of 318 TWh can be observed since traffic reduction and public transport replace inefficient private combustion vehicles. Figure 4.5 demonstrates changes in energy flows across scenarios showing the most pronounced differences. The full set of sankey diagrams can be found in appendix B.

Changes in the transport sector already affect the provision of flexibility in the power system, which is a critical feature of energy systems reliant on fluctuating wind and solar power. Flexible charging of electricity contributes to the system's flexibility and must be substituted, if the share of BEVs is reduced. Furthermore, the level of hydrogen demand affects the flexibility provision starkly since electrolysers in combination with hydrogen storage add flexible demand. The

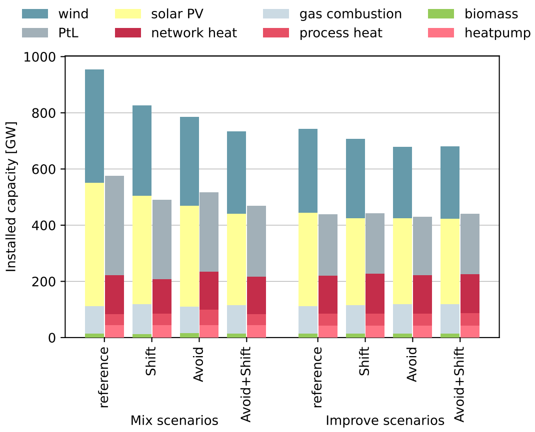
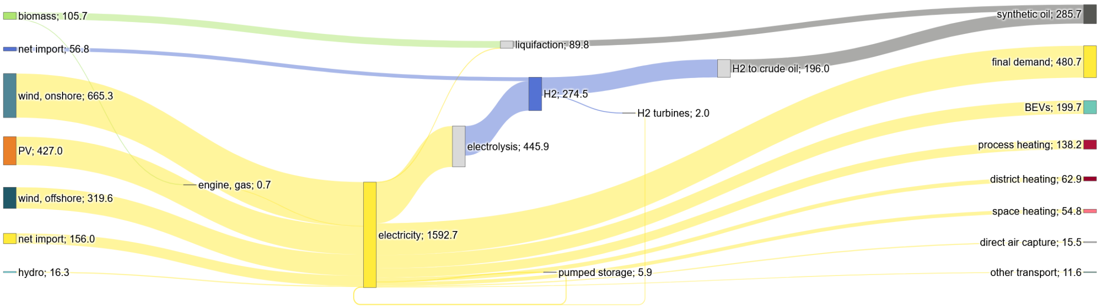


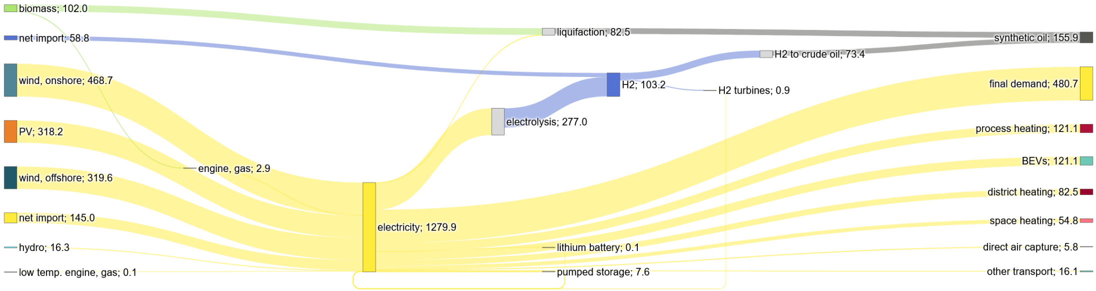
Figure 4.4: Installed capacities in a 100 % RES-based German energy system, separated by generation (left bar) and conversion (right bar) technologies. Transport demand and supply strategies show similar capacity reductions that decrease when strategies are combined.

Improve scenarios show large shifts of flexibility from synfuels (facilities and demand) to methane storage. Correspondingly, gas use increases from 0.7 to 8.2 TWh/a in the reference+Improve scenario (figure 4.5c), but it is mainly used for flexibility provision through higher gas engine capacities. Since the scenarios with Avoid character show significantly smaller stocks of electric vehicles, they result in more stationary batteries and gas storage vice versa (figure 4.6). Similarly, the larger public vehicle stock compensates flexibility demand in the Shift+Mix scenario. It should be noted that stationary batteries are a comparatively expensive flexibility option, which is why the model does not expand them to large scales, but makes use of sector coupling opportunities.

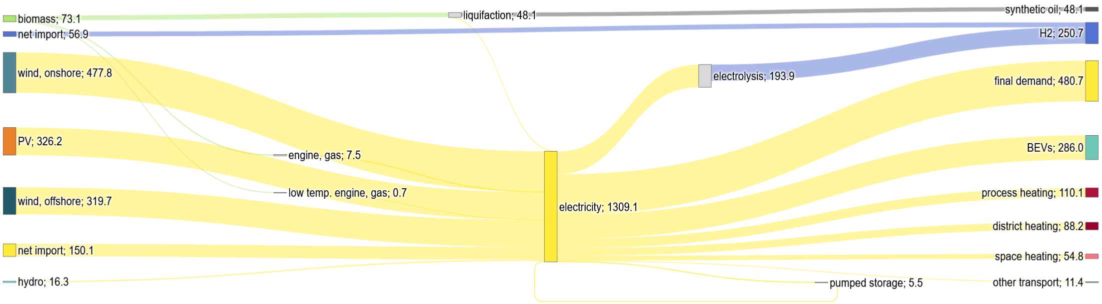
Gas and batteries alone cannot compensate for all flexibility from synfuels, as they provide the largest share of flexibility in the Mix scenarios. Thermal storage more than doubles on average for the Improve scenarios, as the heat sector adapts to the new energy system configuration and thermal storage is comparably cheap. In the Avoid+Shift+Mix scenario, combined heat and power plants are replaced with gas engines to provide flexibility, whereas the opposite is the case in the Avoid+Shift+Improve scenario. Here, both capacities increase due to the largest deficit of flexibility in our scenarios. Changes in storage capacity are roughly equivalent to changes in stored energy.



(a) reference+Mix



(b) Avoid+Shift+Mix



(c) reference+Improve

Figure 4.5: Energy flows of the German energy system compared between the reference+Mix scenario (a) and its counterpart on the transport demand (b) and supply (c) side, respectively. Primary (left side) and final (right side) energy demands vary starkly, as well as demand for synthetic fuels and electricity for BEVs. Sankey diagrams for all scenarios can be found in appendix B.

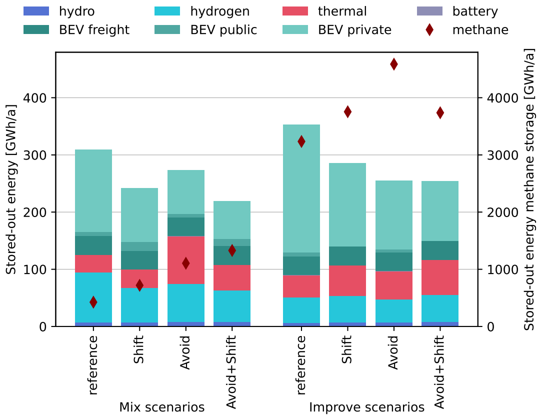


Figure 4.6: Stored-out energy by storage technology, cumulative for the target year. Avoid and Avoid+Shift scenarios reduce the private vehicle stock drastically so that some flexibility is shifted to the heat sector, some to methane storage (secondary axis). The loss of synfuel facilities in the Improve scenarios increases methane storage starkly.

4.2.3 Energy and transport system cost

As an addition to the energy system model's output of component cost, we carried out a cost analysis for every infrastructure- or vehicle stock-related driver of the transport scenarios after their setup. Hence, we did not select Avoid and Shift drivers or their intensity based on a cost-benefit analysis, which is common in transport economics, but included every possible measure, following the rationale of the original study (Arnz and Krumm 2023). We use annualised cost with static interest rates of 5 % and 15 or 50 years for vehicles or infrastructure, respectively. Specific assumptions for each transport system driver can be found in the supplemental material. Put coarsely, reductions in final energy demand translate in cost reductions for the energy system, but demand-side measures add other types of cost (figure 4.7).

Energy savings through lower transport demand have a higher impact on cost of generation and conversion capacities in the Mix scenarios than in the Improve scenarios, where vehicle technologies are less energy-intensive. The Improve scenarios require additional capacities in energy storage in order to compensate for flexibility that is provisioned by synfuel facilities in the Mix scenarios, but the impact on total cost is small (less than 1 bn. EUR/a). Shifting traffic to public modes has a smaller energy system cost reduction potential as avoiding traffic – 14 bn. EUR/a versus 15 bn. EUR/a less than the reference in the Mix case –, though at comparably high transport infrastructure cost (32 bn. EUR/a). The Avoid case, on the other hand, saves some expenditures for road infrastructure in new settlements and adds cost for living infrastructure, which includes buildings for living and provisioning systems with corresponding

Figure 4.7: Scenario cost by component. Private vehicle stocks make up the largest share and increase in Improve scenarios. Shift and Avoid scenarios add infrastructure cost for public transport and living (multiplex buildings, provisioning), making cost without private vehicles exceed the reference. Energy system cost decrease stronger on the transport supply axis (vertically) than on the transport demand axis (horizontally) due to less Power-to-Liquid (PtL) facilities and corresponding renewable energy generation.

technical infrastructure (13 bn. EUR/a). With a drivetrain technology mix, this is the option with least system cost and starkly reduced private vehicle cost. The Avoid+Shift scenarios reduce energy system cost the most, but add both, transport and living infrastructure investment. The most significant factor, whatsoever, is private vehicle cost. These are direct results from vehicle sales in the car stock model, and – as can be seen in figure 4.3 – decline drastically in the Avoid and Shift scenarios.

4.3 Discussion

Our results show that inner-German passenger transport's final energy demand can be reduced from 381 TWh/a to 152 TWh/a through Avoid, Shift, and Improve measures. The reference compared against already breaks the historic trend of increasing car ownership, keeping it on 2020 levels, and promotes BEV adoption in line with production capacities and realistic consumer-oriented vehicle sales (Luderer, Kost, and Sörgel 2021). That means, our scenarios imply ambitious levels of change on the transport demand- and supply-side. As such, the transport energy demand of 1.8 MWh/a/cap lies under the level for the Global North in the IPCC Sixth Assessment Report's most ambitious illustrative modelling pathway (Grubler et al. 2018). This Low Energy Demand scenario highlights the crucial role of energy demand-side mitigation measures for keeping global warming below 1.5 degrees Celsius without reliance on carbon dioxide removal. At the same time, our per capita energy demand lies nearly four times above the absolute minimum needed to satisfy basic human needs in mobility with maximum technological efficiency (Millward-Hopkins et al. 2020). However, these studies are highly stylised, while our study examines the German context in ample detail.

National studies in Germany compute passenger transport final energy demands between 1.2 MWh/a/cap with strong assumptions for sufficiency and efficiency (Purr et al. 2019) and 2.1 MWh/a/cap with moderate behavioural change and moderate adoption of BEVs (Gnann et al. 2022). Assumptions for transport demand and reported pkm differ from ours, but these studies do not employ transport models as detailed as quetzal_germany. More importantly, vehicle efficiency is lower in our input data (Robinius et al. 2020). This conservative approach nuances the differences between scenario results, as it stresses the energy supply system.

The same applies for energy imports. Our results contain more RES generation and synthetic fuel capacities than other German studies because we restrict energy imports from Europe and put imports from non-European countries at prohibitive prices. This setting makes changes in German transport energy demand visible in the German energy system. Otherwise, reduced passenger transport demand could have difficult-to-observe effects across the pan-European energy system. Non-European hydrogen imports account for 2 TWh/a for all of Europe, less than 0.1 %. Future prices are highly uncertain (Peterssen et al. 2022) and there are ethical implications, too (Müller, Tunn, and Kalt 2022). Currently, energy imports from non-European countries come with large uncertainties regarding social and environmental sustainability (Cremonese, Mbungu, and Quitzow 2023).

In general, sustainability concerns three complementary strategies: sufficiency, efficiency, and consistency. This study addresses consistency by targeting 100 % RES and efficiency through 100 % directly electrified drivetrains, even though further techno-economic measures like lightweight design or technological efficiency improvements would be possible. Sufficiency is not clearly defined in transport literature, but it corresponds to Avoid and Shift strategies in the context of energy sufficiency (Zell-Ziegler et al. 2021; Bobinaite et al. 2023). The Avoid+Shift scenario describes a maximum sufficiency threshold by employing a systemic perspective that goes beyond individual lifestyle changes. It thereby alters the mobility system towards new targets: a fairer distribution of mobility options by reducing car dependency; positive effects in public health and well-being through increased use of active modes (Barros dos Santos and Lima 2023; Smith 2017); reducing traffic externalities like pollutants, noise (Tobollik et al. 2016), and road fatalities (Rojas-Rueda et al. 2012); strengthening social cohesion in the local habitat through local economies and changes in the built environment (Arundel and Ronald 2017). As such, sufficiency appears as multi-objective solving strategy. Globally, these co-benefits help achieving the Sustainable Development Goals (Roy et al. 2021).

The energy demands for the efficiency and sufficiency pathways are similar: Germany can save one fourth of the total required RES generation capacity by either, incentivising private car owners to purchase BEVs or, by transforming the transport system towards sufficiency. The efficiency route involves least investment from and in public domains, but therefore in private vehicles, whereas the sufficiency route requires public investment into public services and infrastructure. Specifically, this amounts to annualised cost of 168 bn. EUR/a for individuals who want or need a car and 11 bn. EUR/a in public infrastructure versus 78 bn. EUR/a for cars and 44 bn. EUR/a for infrastructure.

This is an efficiency-biased estimate in two aspects. On the BEV-side, we do not account for charging infrastructure. This could be either private or public, but BEV diffusion as large as in our scenarios would require additional investments into low-voltage grids (Rahman et al. 2022). This becomes evident, as the annual peak load from flexible BEV charging rises from 73 in reference+Mix to 105 GW in the reference+Improve scenario. Currently, however, the extent of this retrofit is unclear, as it depends on dominant charging strategies and pricing schemes (Hartvigsson et al. 2022). Moreover, the impact of sufficiency on low-voltage grids should be subject to further research. As the second bias in our cost analysis, we do not select measures based on their cost-benefit ratio, but include everything. As a result, some drivers might contribute under-proportionally utility for their cost. For example, 66 % of the transport infrastructure investments are spent on the high-speed rail network, which is only relevant for long-distance travel. Further research should pursue cost-benefit analysis, taking into account the various types of cost and actors for infrastructural, educational, regulatory, economic, and socio-cultural drivers.

Under these limitations, the sufficiency route comes with private vehicle cost less than a half of the efficiency route, but four times the infrastructure cost. This is a dilemma of cost allocation – private or public. There are different economic principles to judge this dilemma and we cannot find a definite answer within this study. However, we want to highlight a concept that emerged only recently – the safe and just space for humanity (Raworth 2012, 2017). It promotes provisioning systems that satisfy human needs and well-being without transgressing planetary boundaries. Currently, no country achieves these goals and provisioning systems need substantial transformations to do so (Fanning et al. 2021). In this context, international evidence across income classes shows that public service quality acts beneficial for high levels of well-being with low energy use (Vogel et al. 2021), while private car use is the single most significant factor for intra- and international inequity (Oswald, Owen, and Steinberger 2020).

This study is designed to compare different demand-side mitigation options in passenger transport in terms of energy demand and cost. Avoid and Shift measures show synergies, while Improve measures are connected to rebound effects and moderate the impact of sufficiency measures (figure 4.4). The assessment of the "best" option goes beyond our analysis, as it depends on answers to large societal questions. However, we highlight that every scenario is connected to unprecedented levels of ambition and change, making it improbable (though feasible) within the limited time frame of two decades. Increasing the probability of large-scale energy demand reduction requires employing all strategies simultaneously. We do not account for greenhouse gas emissions, but it is certain that high-income countries like Germany cannot leave any demand-side mitigation options unexploited in order to contribute limiting global warming to 1.5 degrees Celsius.

Chapter 5

Conclusion and outlook

5.1 Key findings and conclusions

Each of the previous chapters answered their research questions and summarised their findings. This question connects them with each other and with the super-ordinate questions from section 1.2.

How to model the impact of Avoid and Shift measures in passenger transport? Aggregated transport models like quetzal_germany are the most suitable tools for modelling Avoid and Shift measures, given current data availability and the scope of analysis (see section 2.4.4). Their methodological grounding shows one crucial benefit compared to aggregated economic methods (see Venturini et al. 2018): in-depth explicability of human behaviour. Derived parameters are well interpretable, and their variety offers more elaborated levers to analyse change in future scenarios. However, as demonstrated in paper two, it requires further methods to comprehend the full complexity of socio-cultural and socio-technical transitions. The conjunction of these research strains is important but very new (section 5.2.1 discusses further research).

How do Avoid and Shift measures relate to sufficiency and how to achieve sufficiency transitions in passenger transport? Paper two describes possible sufficiency futures in German passenger transport and shows how to achieve them. Still, there is no consistent definition of “transport sufficiency”. Zell-Ziegler et al. (2021) include Avoid and Shift measures, drawing upon energy sufficiency. However, the discussion of the second paper shows that mode shifts alone and better transport system connectivity do not match definitions of sufficiency from other domains. Waygood, Sun, and Schmöcker (2019) suggest a definition of “to achieve the best quality of life given global constraints”. This definition is vague but corresponds to the concept of the save and just space for humanity. It thereby underlines the importance of well-being, even though they include only Avoid measures through urban planning. This however, does not suffice to cease car dependency and guarantee equal mobility access, which is needed for the lower boundary condition of sufficiency. In an attempt to conclude for a high-income country; sufficiency transitions in passenger transport are substantial changes in the transport system that include Avoid and Shift measures.

What is the impact of different sufficiency scenarios on the transport system? Substantial changes are feasible; in terms of mode shift away from private cars, as well as avoidance of a large share of trips and long-distance travel (see paper two). Though, the impact of sufficiency transitions goes beyond transport system indicators that are measurable with transport models. Social life, personal time spending, and resilient living environments are only some “soft” indicators that are impacted positively. Impact quantification is a strategy often used for higher policy relevance (e.g. Royston et al. 2023), but more research is required to quantify sufficiency transitions fully (see section 5.2.2).

How can sufficiency and efficiency in passenger transport support the energy system transformation? Paper three shows that Avoid and Shift measures show large energy system capacity and cost reductions of roughly one quarter compared to the reference. The same applies to efficiency measures (i.e. electric cars). Already seven years ago, the Federal Environmental Agency calculated the same figures in a large research project (Bergk et al. 2016), even though they did not employ a detailed transport demand model. Since then, German transport politics have spent much more ambition on supporting electric vehicles. Will sufficiency always be the well-performing but untapped option to support rapid decarbonisation? For transport sufficiency to really support the energy system transformation, it requires mindset shifts across the population. Narratives, like the storylines from paper two, might help achieve large-scale shifts because narratives are the root of all societal transformation processes if they are sufficiently compelling (Leeuw 2020).

Overall, this dissertation contributes in three ways to rapid passenger transport decarbonisation. First, it fills an application gap for macroscopic transport behaviour analysis in Germany by developing and validating quetzal_germany. As has been demonstrated, it can be utilised to inform energy modelling, and it has already been used in other research projects. Second, this dissertation fills a “vision gap” by providing quantified narratives of possible sufficiency futures, including their drivers of change and corresponding transition dynamics. This vision and its measures database can aid other scenario projects and inform policy-making. Third, and in an academic sense, this dissertation fills the research gap of comprehensive sufficiency transitions in passenger transport and how to assess them. It develops a reasonable research design that negotiates limitations from different methods and links disciplines. This is a multi-faceted work suitable for finding solutions for (German) passenger transport in light of 21st-century economics.

Finally: *Avoid, Shift or Improve Passenger Transport?* All of it! The Avoid strategy shows high mitigation potential connected to high levels of cultural and economic change; a mode Shift strategy ceases car dependency and reduces transport intensity while keeping pressure on mobility culture low; a push against private car driving accompanies both of these and is highly effective; and the Improve strategy shows great mitigation potentials without further impacts on mobility culture. We do not have the time to leave any of these options untapped.

5.2 Limitations and research outlook

5.2.1 From normative to explorative scenarios

Transport models (more specifically, discrete choice models) are no "crystal balls". In fact, they perform terribly at forecasting the distant future because they are calibrated to a unique mobility culture given by a travel survey from a specific year. In turn, they cannot depict mobility culture changes endogenously and assume static preferences, values, attitudes, and norms over time (Mattauch, Ridgway, and Creutzig 2016). Static preferences do not pose a problem if the mobility system does not change, except for infrastructure capacity adjustments. However, long-term scenarios with substantial changes are likely to create a different mobility culture. Mattauch et al. (2022) show that low-carbon policies *do* change preferences, and this effect should be accounted for in order not to underestimate them[1].

According to Banister and Hickman (2013), three basic distinguishable scenario types in transport research are forecasting, exploratory, and backcasting approaches. Forecasting mostly extrapolates current trends on shorter time frames, exploratory approaches are trend-breaking, opening up possible developments along specified indicators, and backcasting starts from a normative goal in the future, deducing the pathway back to the present. The normative approach is required for sufficiency transitions because they are trend-breaking and evolve along multiple dimensions. Preference changes are obvious here, but they lack any measure of probability and feasibility without use of additional methods.

There needs to be more methodological research to endogenise preferences in discrete choice modelling. Such methods would allow for exploratory approaches towards sufficiency or any other system transformation. Reul et al. (2023) recently proposed a solution for this problem by coupling a mobility framework from social sciences – the mobility cultures framework – to a discrete choice model that captures the choice heterogeneity currently observed. Such blends of qualitative and quantitative methods seem promising, but further research and validation with historical data should define consistent methods for endogenising preferences. Such advances might help other fields, too, where demand-side forecasting has a shorter tradition than in transportation.

5.2.2 Quantifying well-being

Repeating this study for other regions or sectors is possible with today's state of research, given enough resources. Thus, quantifying the benefits of sufficiency for climate change mitigation is

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[1] In transport modelling, preferences operate like a multiplier for indicator changes through, e.g. infrastructure measures. Without them changing, the results are much less nuanced for large-scale system changes.

well-advanced compared to quantifying well-being impacts. There is a multitude of indicators for human well-being that are quantifiable (e.g. Rosling and Zhang 2011; Fanning et al. 2021), but they do not necessarily align with indicators of the social foundation of the safe and just space for humanity (figure 1.1). However, a measure of these indicators is desirable to evaluate transformations towards this goal.

While economic growth and the gross domestic product dominated economic research of the last decades, current research shows ambitions to decouple prosperity from these indicators (Wiedmann et al. 2020). Actually, growth has been found counter-productive for reaching the safe and just space (Meran 2023; Vogel et al. 2021), while first studies find increased well-being in post-growth economies (Komatsu, Rappleye, and Uchida 2022). A compiled set of alternative measures is not enough, whatsoever. In order to make use of them, the research community needs consistent quantification methods, too. There are well-established methods and tools for health assessment in transport research (Barros dos Santos and Lima 2023), but it lacks evaluation methods for e.g. equity or resilience. This dissertation shows qualitatively that reduced car dependency contributes to equitable access to jobs and education and the positive impacts of mixed-use neighbourhoods on resilience. However, more research is needed to quantify such relationships. The results would add reason to pursue sufficiency pathways in national politics.

5.2.3 Global scales

An obvious limitation of this dissertation is its scope. While limiting the focus to one country is necessary for an in-depth assessment of multi-dimensional transformations, this is only a case study to the global research community. Quantitative and qualitative results might differ for other high-income regionsmaking up-scaling difficult. Still, such results are in high demand for informing global modelling ambitions (Yeh et al. 2022). They can help Integrated Assessment Models (IAMs) become independent of economic growth by providing well-informed transition dynamics with corresponding pkm and energy demands. IAMs are the biggest contributor to the IPCC Assessment Reports and should become less growth-focused to better assess those pathways compatible with the 1.5 degrees target (Keyßer and Lenzen 2021).

5.2.4 Policy effectiveness

Research itself does not help mitigate climate change. It must be applied. Bridging the implementation gap between research and policy is a difficult task that requires metrics relevant to policy-makers. Reducing uncertainty of GHG emissions impacts, economic impacts, and individual social life is crucial for policy-relevant transitions research. This work performs poorly in these uncertainty reductions. It does not account for GHG emissions reductions because the chosen time frame allows for the assumption of 100 % renewable energy supply. This time frame itself is difficult for informing policy decisions, which consider much shorter periods and effect chains.

Much more research is needed to assess the impacts of sufficiency transitions on the economic system. Many sufficiency studies are connected to degrowth (Lage 2022), but the interdependencies with the economic system remain unclear. Powerful industries, like the automobile industry, are likely to lose financial benefits through large-scale transformations, which makes them likely to oppose. They have exerted large political influence in the past (Michaelowa, Allen, and Sha 2018) and will do so in the future, if policy-makers cannot deliver a compelling vision for the whole economy, or if they do not experience pressure from other powerful actors.

In the transportation domain, it is widely known that the mobility transformation happens “on the ground”. It must consider local peculiarities and engage with the local population for its support. This work misses out on describing *local* sufficiency futures. Its aggregation level is too high for such analysis, even though the modelling would allow it. More research should consider impacts on realities of individual life in order to build a better communication basis to policy-makers and communities (as in Rauber et al. 2022).

Moreover, local analysis can consider the impact of activist bottom-up movements. Their contribution to transition dynamics must not be under-estimated, as “radical change will not come into being without active resistance, protests, and solidary movements that rise up against unacceptable modes of living and politics” (Pirgmaier and Steinberger 2019). As noted above, policy effectiveness is a game of power. We, as researchers, too, must engage in activism to channel public efforts towards a better life for all – in the words of Gardner et al. (2021): “from publications to public actions”.

Appendix A

Appendix for chapter 3

Resource availability

The transport model used for this study is openly available on github: Arnz (2023). The repository contains all data relevant for this study. The supplementary material contains further information used to create the sufficiency storylines and scenarios.

A.1 Transport sufficiency

In 2022, the Working Group III "Mitigation of Climate Change" of the IPCC Sixth Assessment Report for the first time dedicated special attention to demand-side mitigation measures, i.e. climate change mitigation measures aiming at changes in energy and material consumption patterns. This is due to a growing body of literature concerning demand-focused interventions and sufficiency (as a complement to the sustainability categories efficiency and consistency). Despite this evolving research, the definition of sufficiency is context-dependent and remains unclear when looking into a sub-system such as passenger transport.

Generally in scientific literature, sufficiency concerns the question of "how much is enough?". Spengler (2016) connects two kinds of "enoughness" as lower and upper boundary conditions of sustainable human life and thereby connects sufficiency to the common concept of sustainable consumption corridors (see Raworth 2017): The lower limit refers to human needs and a minimum approach to distributive justice, while the upper limit concerns not exceeding planetary boundaries. The political challenge is governing in between these boundary conditions (Spangenberg 2014) to foster a good life for all (O'Neill et al. 2018).

In transport literature, there is no uniform definition of sufficiency, even though there are overlaps with Avoid and Shift strategies of sustainable mobility. A growing body of literature treats sufficiency as an individual attitude to mobility behaviour that helps reducing GHG emissions (e.g. Loy et al. 2021; Verfuerth, Henn, and Becker 2019; Vita et al. 2019). Zell-Ziegler et al. (2021) draw on the concept of energy sufficiency and define sufficiency in transport as a change in service quality yielding lower energy demand, facilitated mainly through Avoid and Shift measures. Waygood, Sun, and Schmöcker (2019) define transport sufficiency from an urban planning perspective as "to achieve the best quality of life given global constraints". Here, quality of life does not only refer to benefits of carrying out human activities, which require physical mobility, but also negative impacts of transportation and large potential co-benefits of their mitigation (see Creutzig et al. 2022).

We build upon these notions of sufficiency from a systemic energy demand perspective. We treat transport sufficiency as a system design strategy to support a swift reduction of energy demand and GHG emissions. This concerns the upper boundary condition of sufficiency. The lower boundary, basic human needs, is more fuzzy because mobility serves as an indirect need-satisfier. We define basic needs as independent of the mobility culture, which is relative, contextual and historical (Mattioli 2016). Hence, the immediate action, like car driving, is no need on its own. Virág et al. (2022) try to define "decent mobility standards", which describes decent levels of physical mobility connected to decent levels of well-being across different cultural and spatial contexts. Even though they cannot find a definite threshold, we adopt this idea as lower boundary of transport sufficiency. We can compare our results to the absolute lower bound of sufficiency as calculated in Millward-Hopkins et al. (2020), who are not taking into account the cultural context and the current built environment.

A.2 Sufficiency storylines

The *first storyline* describes a radical pull strategy that reduces car dependency to the absolute minimum. Drivers of this process mainly concern strengthening of PT and cycling, transport planning, and digitised mobility services. Rapidly increasing the reliability and capacity of the rail network is of particularly high priority, as well as the establishment of comprehensive on-demand ride-pooling systems. The necessary money comes from the expansion stop of roads and airports, comprehensive parking pricing in public urban and suburban spaces, and the reduction of climate-damaging or car-friendly subsidies. Transport planning and the corresponding budget is fully directed towards PT. As juridical underpinning, road traffic regulations give cycling and PT priority in the traffic flow. Moreover, wide and secure cycling highways between urban and suburban regions incite more active mobility.

Technological and organisational innovations, such as mobility hubs in metropolitan areas, free bicycle entrainment, or bike sharing hubs at train stations, enable comfortable multi-modality. E-bikes and cargo bikes support the shift to active mobility additionally. Digital mobility services are emerging that are easy to understand, include all transport services and can be used nationwide. In any case, all PT schedules are well coordinated and a uniform tariff system throughout Germany facilitates easy use and reduces prices in remote regions. There, too, and at off-peak times, autonomous on-demand shuttles provide high service quality and flexibility.

This completely new prioritisation also involves a lot of education work among the population. The most important actor here is the federal government in cooperation with local transport planning. Besides these strong top-down initiatives, innovative business models are also driving the process. Society plays a minor role and adjusts its mobility culture to the new transport system with a temporal delay.

The *second storyline* describes cultural and economic change resulting in traffic avoidance - eliminating the need for long and many trips. The initiative comes from two different directions: Top-down and bottom-up. Urban and spatial planning focuses exclusively on densification of existing settlement areas instead of new development, as well as improvements in quality of life and diversity in the local habitat. In this way, many journeys by motorised vehicles become unnecessary, because the environment in walking distance offers shopping, errands and recreational opportunities, as well as space for social activities.

At the same time, various new bottom-up initiatives establish local economies and restorative, local lifestyles. The former strengthen local coherence and make the decentralised offer of products, services, and amenities economically attractive. The prerequisite for this is a less growth-oriented economic policy and rejection of materialism throughout a critical mass in society. Car sharing systems, which emerge throughout the country, support this trend: Following the slogan “from ownership to access”, they lead to reduced car dependence and ownership. The new lifestyles are characterised by local cohesion, while social contacts and work relationships that lie outside the local area are primarily cultivated in digital space. To this end, structures and rights for remote work are comprehensively created and their conditions favoured. This goes beyond office work and comprises remote control of industrial sites.

The *third storyline* combines three elements: the radical pull strategy of a reliable and interconnected public transport system (as in the first storyline), resilient local lifestyles (as in the second storyline), and a fundamental restructuring of transport planning and economic activity. While the first storyline minimised car dependency, the fundamental restructuring aims at maximum human-centred mobility planning and minimum car ownership (as a main driver of transport externalities), facilitated through strong top-down initiatives and large-scale shifts in individual mindsets.

The regulatory framework is subject to particularly strong adaptation. Interdepartmental mobility policy bans cars from cities, leads industrial policy to the necessary shift towards PT, bans car advertising (because of the severe consequences for health and life) and reforms the tax system to incentivise PT use and disincentivise car ownership. Hence, ousting of the automobile lobby from party politics is necessary. At the same time, transport planning becomes more people-centred, more diverse, better staffed and better integrated with urban and spatial planning. Its guiding principles are equity (in terms of reducing car dependency), health (fostering active mobility and lowering transport externalities), and diversity (including all perspectives of society into transport planning).

On a cultural level, climate protection, social justice and health - corresponding to the new mobility planning principles - are becoming more important in the consciousness of the population, while economic growth and materialism are losing relevance. Comprehensive criticism of consumption manifests itself in sufficiency-oriented lifestyles, which is demonstrated by role models from the rich and influential classes and slowly spreads through all layers of society. Socially, the car is not only losing its status, but is becoming an anti-status symbol for a critical mass of the population. This is made possible by an ongoing global restructuring of the economic system with the aim of decoupling prosperity from growth, as the neo-liberal economic system is coming under strong pressure due to the consequences of climate change.

A.3 Transport model refinements

We refined the demand model structure, as initially described in Arnz (2022), in order to endogenously depict generation and distribution of trips for each demand segment. Compulsory trips (i.e. commuting, education, and business trips) are computed using a doubly constrained distribution with the logsum of mode choice utility building the deterrence matrix. Trips for other purposes (utilities, leisure, and accompany) utilise multinomial logit models to depict trip generation and destination choice, respectively. The generation model's utility function looks as follows:

$$\begin{aligned} V_j^i = & ASC_j + log\left(\text{pop}_z\right) * \alpha_j^i + \text{hh\_size}_z * \beta_j^i \\ & + \text{hh\_income}_z * \gamma_j^i + \text{is\_working}_z * \delta_j^i \\ & + \text{is\_learning}_z * \epsilon_j^i + \text{is\_caring}_z * \zeta_j^i \\ & + \text{acc}_z * \eta_j^i \end{aligned} \tag{A.1}$$

Applied to zones z for each demand segment i: with and without car availability for each non-compulsory trip purpose. Choice alternatives $j \in 0, 1, ..., 5$ describe the number of trips per day. Except for $j = 0$, all alternative-specific constants ASC are fixed to zero. Zone population pop, average household size hh_size, household income hh_income, and the population share of a certain occupation (is_working, is_learning, is_caring; not for buy/execute trips) influence the decision. Moreover, the trip frequency depends on the accessibility acc (calculated as the average cost of mobility to other zones), linking the generation of trips to the transport system design. Marginal utility parameters α to η for every alternative and demand segment are calibrated using the same mobility survey as the mode choice model (the German National Mobility Survey)

- here and in all following choice models. Building upon this, a binary logit model formulates the choice between executing a trip within or beyond the origin zone's boundaries:

$$\begin{aligned} V^i_{inner} &= log\left(\text{pop\_dens}_z\right) * \alpha^i + log\left(1 + \sum_{a_n \in A^i} a_{n,z}\right) * \beta^i \\ V^i_{inter} &= ASC + \text{acc}_z * \gamma^i \end{aligned} \tag{A.2}$$

with

$$\begin{aligned} A^i \in A = \{&\text{childcare, school, higher education, medical,} \\ &\text{daily leisure, occasional leisure, shop, special shop}\} \end{aligned}$$

While inter-zonal choice utility depends on the zone's accessibility and an ASC, inner-zonal utility consists of the zone's population density pop_dens and the number of attractions a_n of the attraction categories A^i that are relevant to this demand segment. Corresponding points of interest data for these categories was fetched from OpenStreetMap in 2022. For the choice between inter-zonal trip destinations, a third-level logit choice model is applied. Its utility function concerns the same demand segments and zones, while choice alternatives d comprise the full set of model zones:

$$\begin{aligned} V^i_d =& log\left(\text{pop\_dens}_d\right) * \alpha^i \\ &+ log\left(1 + \sum_{a_n \in A^i} a_{n,z} * exp\left(\beta^i_n\right)\right) * \gamma^i \\ &+ D_{z,d} * \delta^i + D^2_{z,d} * \epsilon^i + CC_{z,d} * \zeta^i \end{aligned} \tag{A.3}$$

with $\beta_0 = 0$, following the formulation for destination choice models with attraction variables from Daly (1982). Additionally, the distance $D_{z,d}$ between origin and destination and the squared distance $D^2_{z,d}$ are significant choice variables. Here too, cost of mobility CC (i.e. the mode choice composite cost) influence the distance distribution of trips. Resulting trip volumes are calibrated towards distance distributions from the national German mobility survey and total volumes of the Federal Ministry of Transport (BMDV 2021). Additionally, we implement interfaces for drivers that affect model parameters, as described above. The full list of drivers and brief descriptions of their implementation can be found in the supplementary material.

Appendix B

Appendix for chapter 4

Resource Availability

Transport modelling code and data is openly available and fully documented on github (Arnz 2023). The AnyMOD.jl energy system modelling framework is available and fully documented on github (Göke 2020) and the model data is available upon request to the authors. The supplemental material, which includes all material relevant for this study, is available upon request to the authors, as long as this article is not published.

B.1 Transport model quetzal_germany

quetzal_germany simulates transport demand as individual decisions of trip frequency, trip destination, and mode of transport. This demand is routed on spatially explicit transport networks, yielding passenger kilometres (pkm). The model is developed in Python under use of the Quetzal open source transport modelling suite (Chasserieau and Goix 2019) and is openly available on github (Arnz 2023).

It follows the method of aggregated transport modelling, having 2,225 zones, defined by clustering 4,605 municipality unions to similar zone sizes. Aggregated transport models simulate traffic between zones, whereas inner-zonal traffic, accounting for 13 % of total traffic, is computed exogenously based on the German National Travel Survey (infas et al. 2017).

B.1.1 Network model and level-of-service attributes

quetzal_germany incorporates a highly intricate network model that utilises OpenStreetMap data for the road network and GTFS feeds for public transportation (PT) in Germany. It consists of seven distinct network layers, each corresponding to different modes of transportation: Long-distance rail transport: Includes ICE, IC, and EC rail services; short/medium-distance rail transport: Encompasses local and regional rail services; local public transport: Comprises bus, ferry, tram, and underground services; coach transport: Represents connections based on the network coverage of FlixBus; air transport: Includes connections between 22 major German airports; road: Consists of motorways, A and B roads, as well as interconnecting links; non-motorised transport: Involves straight-line connections between zone centroids, with distances of up to 40 km.

Footpaths are established between PT stops to facilitate seamless connections between different layers. Furthermore, network access/egress links connect each layer to the sources and sinks of transport demand located at the population centroid of each zone. Two attributes, travel time (eq. (B.1)) and monetary travel cost (eq. (B.2)), are assigned to every network link as indicators of the level of service.

$$TT = T^{\mathrm{iv}} + T^{\mathrm{wait}} + T^{\mathrm{ae}} + T^{\mathrm{walk}} \tag{B.1}$$

$$TC = \frac{D \cdot c_{\mathrm{d}} + T^{\mathrm{iv}} \cdot c_{\mathrm{t}} + c_{\mathrm{fix}}}{f} \tag{B.2}$$

In-vehicle time T^{iv} is the result of link speed and length in the network graph. Additionally for PT, there is waiting and walking time, T^{wait} and T^{walk}, respectively, that applies at PT stops during transfer. Access/egress-time T^{ae} depends on the number of parking lots in the origin and destination zone for car transport and on the PT stop density of the corresponding PT mode, respectively. Travel cost TC is composed of distance-specific cost c_{d}, variable in-vehicle time specific cost c_{t}, fix cost c_{fix}, and a split factor f, used for car occupancy rates or average shares of PT subscriptions in the population. Further details can be found in Arnz (2022).

B.1.2 Transport demand model

Classical aggregated transport models simulate demand in three mobility choices: trip frequency, trip destination, and mode of transport. The following paragraphs briefly describe all of these models, while further information can be found in Arnz (2022) and Arnz and Krumm (2023). The German National Travel Survey (infas et al. 2017) serves as calibration dataset for all forthcoming models. Their calibration parameters are given in Greek letters.

The first step in the mobility demand choice tree is the number and destination of trips. Compulsory trips (i.e. commuting, education, and business trips) are computed using a doubly constrained distribution with the logsum of mode choice utility building the deterrence matrix. Trips for other purposes (utilities, leisure, and accompany) utilise multinomial logit models to depict trip generation and destination choice, respectively. The generation model's utility function looks as follows:

$$\begin{aligned} V_j^i = & ASC_j + log\left(\text{pop}_z\right) * \alpha_j^i + \text{hh\_size}_z * \beta_j^i \\ & + \text{hh\_income}_z * \gamma_j^i + \text{is\_working}_z * \delta_j^i \\ & + \text{is\_learning}_z * \epsilon_j^i + \text{is\_caring}_z * \zeta_j^i \\ & + \text{acc}_z * \eta_j^i \end{aligned} \tag{B.3}$$

For all zones z and for each demand segment i: with and without car availability for each non-compulsory trip purpose. Choice alternatives $j \in 0, 1, ..., 5$ describe the number of trips per day with alternative-specific constants ASC being fixed to zero for $j! = 0$. Zone population pop, average household size hh_size, household income hh_income, and the population share of a certain occupation (is_working, is_learning, is_caring; not for buy/execute trips) influence the decision. Moreover, the trip frequency depends on the accessibility acc (calculated as the average cost of mobility to other zones), linking the generation of trips to the transport system design. Building upon the trip frequency for non-compulsory trips, a binary logit model formulates the choice between executing a trip within or beyond the origin zone's boundaries:

$$\begin{aligned} V_{inner}^i &= log\left(\text{pop\_dens}_z\right) * \alpha^i + log\left(1 + \sum_{a_n \in A^i} a_{n,z}\right) * \beta^i \\ V_{inter}^i &= ASC + \text{acc}_z * \gamma^i \end{aligned} \tag{B.4}$$

with

$$\begin{aligned} A^i \in A = \{ & \text{childcare, school, higher education, medical,} \\ & \text{daily leisure, occasional leisure, shop, special shop} \} \end{aligned}$$

Inter-zonal choice utility depends on the zone's accessibility and an ASC, while inner-zonal utility consists of the zone's population density pop_dens and the number of attractions a_n of the attraction categories A^i that are relevant to this demand segment. Corresponding points of interest data for these categories are sourced from OpenStreetMap in 2022.

Another multinomial logit model applies for the choice between inter-zonal trip destinations. Its utility function concerns the same demand segments and zones, while choice alternatives d comprise the full set of model zones:

$$\begin{aligned} V_d^i = & log\left(\text{pop\_dens}_d\right) * \alpha^i \\ & + log\left(1 + \sum_{a_n \in A^i} a_{n,z} * exp\left(\beta_n^i\right)\right) * \gamma^i \\ & + D_{z,d} * \delta^i + D_{z,d}^2 * \epsilon^i + CC_{z,d} * \zeta^i \end{aligned} \tag{B.5}$$

with $\beta_0 = 0$. The distance $D_{z,d}$ between origin and destination and the squared distance $D^2_{z,d}$ are significant choice variables. Here too, cost of mobility CC influence the distance distribution of trips. It entails the composite cost of the nested logit mode choice model, depending on the route's level-of-service attributes described above. The choice tree contains all modes of the network model, as listed in subsection B.1.1, with one nest for rail transport and another nest for use of private car and car sharing. The mode choice model is specified as

$$V^i_j = \mathrm{ASC}^i_j + \mathcal{F}\left(\beta^i_t, TT_j\right) + \beta^i_c \cdot TC_j \tag{B.6}$$

for each demand segment i with a log-power spline function as proposed in Rich (2020):

$$\mathcal{F}\left(\beta, x\right) = \beta \sum_{q=1}^{Q} \lambda_q\left(x\right)\left[\theta_q ln\left(x\right)^{Q-q+1} + \alpha_q\left(\beta\right)\right] \tag{B.7}$$

$$\theta_q = \frac{Q}{Q-q+1} \prod_{r=2}^{q} ln\left(c_{r-1}\right) \quad \forall q = 2, \ldots, Q$$

$$\alpha_q\left(\beta\right) = \alpha_{q-1}\left(\beta\right) + \frac{(q-1)!\beta}{Q-1} ln\left(c_{q-1}\right)^{Q-q+2} \prod_{r=1}^{q-2} ln\left(c_r\right)$$

B.2 Energy system model EuSys/AnyMOD.jl

For the analysis of renewable energy systems, we employ a linear optimisation model that determines the expansion and operation of technologies to meet final energy demand. The model's objective is to minimise the total system cost, which includes annualised expansion cost, operation cost of technologies, and costs associated with energy imports from external sources. The expansion and operation aspects in the model encompass two components: technologies for energy generation, conversion, or storage, and grid infrastructure for energy exchange between different regions.

To handle high shares of fluctuating renewables and sector integration, the model utilises a graph-based formulation specifically designed for this purpose, allowing for varying temporal and spatial resolutions within a single model (Göke 2021b). This feature enables the application of high resolutions where the system is sensitive to small imbalances of supply and demand, such as in the power sector, while modelling more inert parts, like gas or hydrogen transmission, at a coarser resolution. This approach reduces computational complexity and captures the inherent flexibility in the energy system. Göke (2021a) elaborates this approach in greater detail and Göke, Weibezahn, and Kendziorski (2023) present a case study including mathematical formulations.

The potential of battery-electric vehicles (BEVs) in future energy systems remains uncertain and relies on technological and regulatory advancements. On the one hand, we anticipate charging flexibility within certain limits and adaptability to supply, although this does not currently align with regulations in all European countries and does not necessitate additional infrastructure (Strobel, Schlund, and Pruckner 2022). On the other hand, we do not assume that BEVs can supply electricity back to the grid, which is also known as bidirectional charging or vehicle-to-grid, as it requires the use of bidirectional chargers (Hannan et al. 2022). It is important to note that BEV technologies are not restricted to passenger cars but are also applicable to all forms of road and rail transport.

The model implements flexible charging based on a driving and charging pattern. First, an hourly profile restricts the charging of BEVs to reflect the capacity of vehicles currently connected to the grid. A second hourly profile provides the actual driving patterns that determine when electricity is being consumed. To supply this electricity, the vehicle batteries must be charged sufficiently while they are plugged in. As such, BEVs are effectively modelled like storage systems with a predefined discharging pattern and a temporal profile restricting vehicle charging. The assumed maximum charging capacity amounts to 10 kW and the battery capacity to 50 kWh for private vehicles. BEVs for public passenger and heavy road transport have maximum charging rates of 150 kW (ENTSO-E and ENTSO-G 2022). By applying a safety margin, all charging profiles are reduced by 75%.

The AnyMOD.jl framework is applied to the region of Europe, covering all countries of the European Union, along with the United Kingdom, Switzerland, and the Balkans. The model's time frame encompasses a single year. It takes a brownfield approach, utilising the available transmission infrastructure and hydro power plants without any expansion. The model encompasses a comprehensive set of 22 distinct energy carriers, which can be stored and converted among each other using 120 different technologies. These technologies cover various sectors such as heating, transportation, industry, and the production of synthetic fuels. The full documentation of the case study model can be accessed in Göke, Weibezahn, and Kendziorski (2023). Figure B.1 depicts available transport technologies and their energy carriers. Vertices in the graph either represent energy carriers, depicted as coloured squares, or technologies, depicted as grey circles. Entering edges of technologies refer to input carriers; outgoing edges refer to outputs. Green squares are the mobility demand of each mode. Air transport is exogenously defined as a static demand for liquid fuels, depending on scenario assumptions on domestic and international aviation. Efficiencies, cost, and reference case load factors for transport technologies come from Robinius et al. (2020).

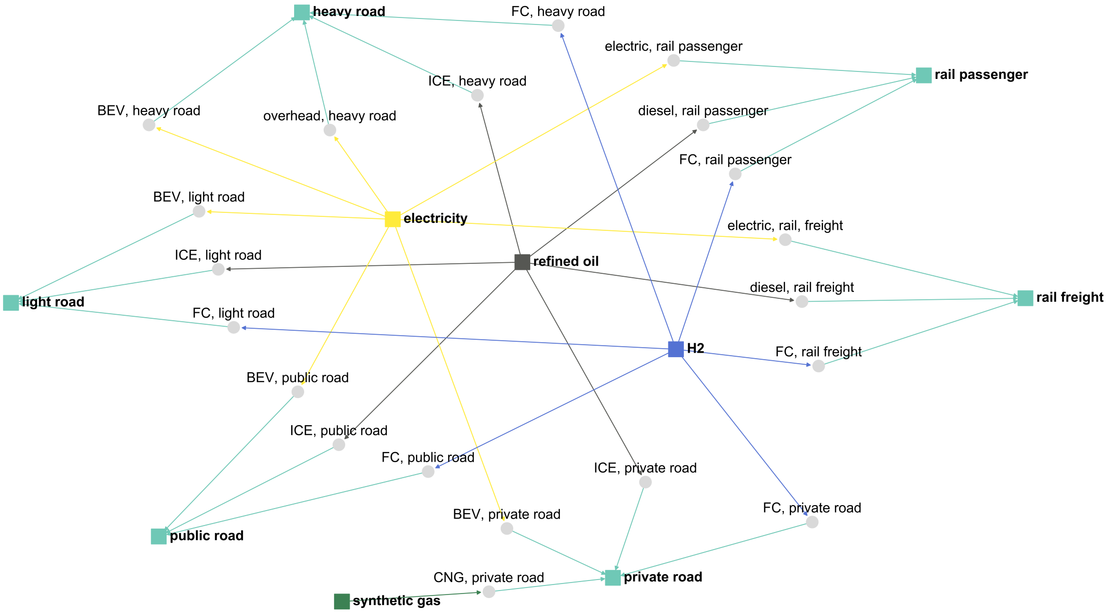


Figure B.1: Sub-graph of transport technologies and corresponding energy carriers.

B.3 Model coupling process and assumptions

The coupling process of the two models is one-directional: Passenger travel demand feeds into the energy system model by mode of transport and region within Germany. We refrain from iterative hard-linking by implementing an interchange of energy prices for two reasons: First, transport demand is relatively inelastic to fuel price changes (not so for public transport fares), which makes an iterative coupling disproportional to its computational cost. Second, the definition of prices differ between both models. The energy system model calculates marginal prices, while the transport model uses consumer prices including taxes and supply revenues. Making assumptions about the latter factors is as good as assuming consumer prices in total.

In general, we assume a yearly inflation rate of 1.5 % applying to all fuel prices and public transport fares. The average charging cost for electric vehicles amount to 0.4 EUR/kWh, based on 2022 prices. The double applies for trips that use public charging, approximated as half of all shopping and execution trips. Plug-in hybrid electric vehicles are assumed to have an electric driving range of 80 km, which is fully utilised before switching to synthetic fuels because these are more expensive (i.e. the same as inflation-adjusted petrol prices in 2022).

Extending the transport demand scenarios to other countries would require other national transport models, which are very resource-intensive and inaccessible (Arnz 2020). Assuming the same macroscopic transport demand changes as in Germany for other countries is problematic because the socio-cultural and infrastructural conditions vary widely. Our approach to corresponding scenarios relies on fine-granular drivers of change (see sec. B.4) that most probably differ from country to country. Hence, we focus our study to the region of Germany. Still, comprehensive passenger transport demand-side mitigation scenarios have never been studies for a region as large and populated.

However, the energy system model optimises the full European energy system, as described in sec. B.2. We fix other countries to a reference case in order to coarsen the energy system analysis to Germany, too. Specifically, we run the optimisation problem for the reference+Improve scenario for all of Europe, yielding the cost-optimal energy system. Non-German capacities are then fixed to this solution for all other scenario runs. This allows us to study impacts of German passenger transport demand only on German energy capacities. Other countries cannot trade more energy with Germany, as in the reference+Improve case. Fixing Europe to the reference+Mix scenario would generate large generation capacities for synthetic fuels in southern Europe, which is then available in all other scenarios, omitting the impacts of transport demand changes.

International air travel is not affected by our scenarios, as we can only model inner-German transport. We do not make assumptions about medium- and long-distance flight reductions because they are not covered by our qualitative-quantitative research design and would outweigh other levers of change. Air travel is expected to account for more than half of German passenger transport's energy demand in the future (Gnann et al. 2022). On the technological side of air transport, we do not assume large changes, except slight efficiency gains and adoption of 100 % synthetic fuels.

Public transport vehicles, on the contrary, are assumed to be fully electrified in all scenarios by 2040. The German rail operator already announced full climate neutrality by 2038 and the European Union's clean vehicles directive is a strong driver for electrified drivetrains in public road transport.

Finally, the assumptions for vehicle occupancy are as follows. No changes apply for air transport. Car occupancy rates differ by scenario, as defined in its quantification process (sec. B.4): 1.5 applies for the reference and Shift scenarios, 1.8237 for the Avoid and Avoid+Shift scenarios. For public transport, the relative increase in road and rail use per pkm is calculated, and this increase is multiplied by the corresponding average occupancies found in the energy system model's input data set (Robinius et al. 2020). We ensure no overcrowding of transport carriers by setting a cap of 70 % occupancy, under which all scenarios stay below. The Shift scenarios introduce on-demand ride pooling services, which account for 90 % of road PT traffic. Zech et al. (2022) suggest high ride pooling system efficiencies with average loads of 6 persons in 8-person vehicles. However, due to the spatial and temporal periphery of these services, the average occupancy is set to 3, which is still a progressive assumption.

B.4 Transport demand scenarios description

The qualitative-quantitative transport demand scenarios are a crucial element for the novelty and extent of this study because they allow analysis beyond techno-economic assumptions and shed light into socio-cultural processes. Figure 3.1 in chapter 3 demonstrates the steps of scenario creation. The following paragraphs briefly describe the process, while the fully detailed description can be found in chapter 3.

In the first phase, we collect drivers of change towards sufficiency for the German passenger transport system by consulting 15 transport and sufficiency experts from various disciplines. The guided brainstorming process results in 133 sufficiency drivers, encompassing infrastructure, social, individual, and systemic factors. These drivers are categorised as policy interventions, individual mindset changes, corporate actions, and consumption changes. To construct the storylines, we classify the drivers as traffic avoidance, mode shift, or both, with the help of expert knowledge. Three storylines are created: one with traffic avoidance drivers only, one with mode shift drivers only, and one incorporating all drivers of change. We employ the Multi-Level Perspective framework to analyse transition dynamics, considering the interactions between niches, regimes, and landscapes. The storylines provide insights into the outcomes, processes, and actors involved in achieving sufficiency in German passenger transport. A summary of the storylines can be found in table 3.1, while their written form is available in appendix A.

The translation of storylines into modelling scenarios involves quantifying model parameters. Out of the 133 sufficiency drivers, 64 are identified as model-affecting drivers, and each of them corresponds to one or more distinct model parameters. To enhance transparency and reproducibility, a survey method is used to inform the quantification process. The survey is distributed among participants of the sufficiency driver workshop and additional experts in transport sector transitions. The survey consists of 59 questions related to different action fields, and the responses from 12 participants are used to generate average values for the model parameters. These quantitative values define three modelling scenarios based on the sufficiency storylines, along with a reference scenario that serves as a comparison. Some parameters require implementation of specific levers into the model logic, which is – together with all other drivers, their specifications, corresponding survey question, and responses – accessible in the supplemental material.

B.5 Car stock modelling and assumptions

We construct a simplified car stock model in order to depict the private vehicle stock development towards the target year. Noteworthy, this model is not designed for accuracy, neither does it include elaborate methods. It is a simple collection of mathematical formulations that provides two things: a rough estimate about the total cost of new car sales, and an impression about the required sales rates per technology in each scenario. All assumptions and data sources are included in the supplemental material. Here is a brief summary.

We differentiate in three different drivetrain technologies: BEVs, plug-in hybrid electric vehicles (PHEVs), and internal combustion engine vehicles (ICEVs). Fuel-cell electric vehicles are not part of our vehicle stock because they are not expected to play a role by the year 2040 in the reference case of any major national scenario (e.g. Luderer, Kost, and Sörgel 2021; Gnann et al. 2022). The vehicle fleet's drivetrain composition of our Mix scenarios corresponds to the "Mix" scenario in the German national *Ariadne* project in the year 2040 (Luderer, Kost, and Sörgel 2021). This study employs the highly detailed *Vector21* car stock model and its assumptions are widely accepted in the community.

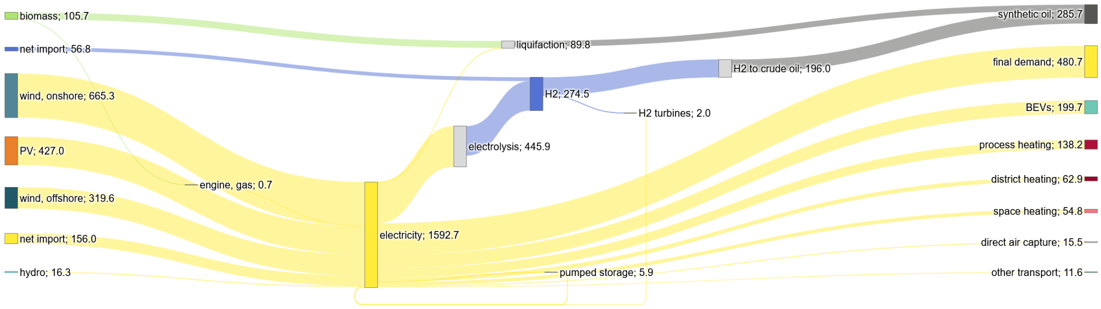
Our cost data stems from E3-Modelling (2020), linearly interpolated between five-year steps, as can be seen in the supplemental material. The source diversifies into three vehicle size groups (small, medium, and large), which we adopt. The reference and Shift scenarios retain the same size distribution as of 2020 in Germany (KBA 2021), while the Avoid and Avoid+Shift scenarios shift 50 and 100 % of large vehicles to small vehicles, respectively. The shift occurs linearly towards 2040.

BEV adoption is not linear, but a progressive exponential function that is tuned to yield the final year's BEV proportion of the corresponding scenario's total vehicle stock. The latter comes from the transport demand scenarios (sec. B.4) and we assume a linear decrease in car ownership. The adoption function is capped to the scenario's maximum car sales per year, which is the final year's total car stock divided by the lifetime of a vehicle (15 years, in line with input data of the energy system model). PHEVs are linearly adopted towards the final stock and ICEVs make up the rest.

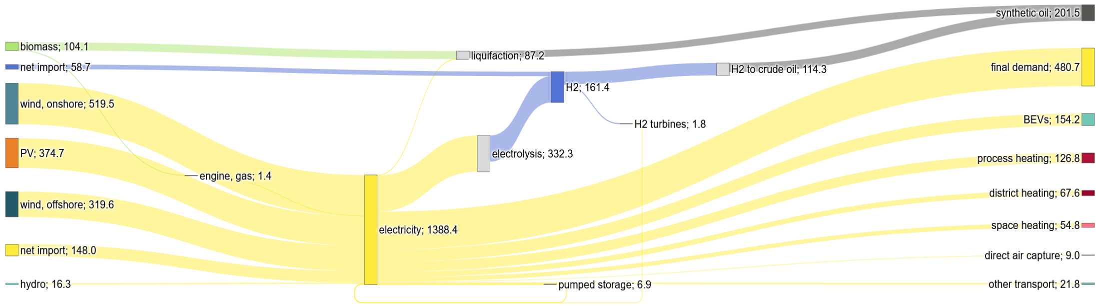
We do not account for BEV production capacities because they stay uncertain and the global BEV distribution is up to future market dynamics. All Mix scenarios stay within bounds of foreseeable BEV availability in Germany by 2030 (Windt and Arnhold 2020). In the Improve case, only the Avoid+Shift scenario stays under the threshold of 9.6 mio. BEVs in 2030, which the authors of the study find reasonable after confidential dialogues with car manufacturers. The reference+Improve scenario accounts for 15.9 mio. BEVs, exceeding this threshold by two thirds.

B.6 Energy system results analysis

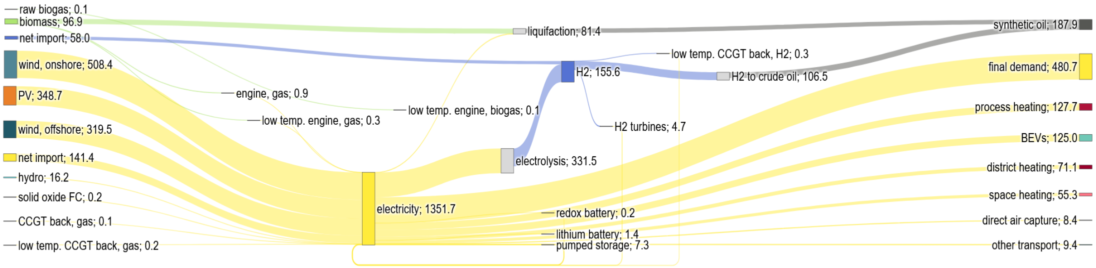
Even though we summarise the most important results of the energy system model in the article, it is difficult to sketch a full picture of the resulting energy system configurations. Sankey diagrams allow for a more intuitive understanding of these configurations by depicting energy inputs, outputs, flows, intermediate steps, efficiencies, and technologies. Figures B.2 and B.3 describe energy flows in the Mix and Improve scenarios, correspondingly.



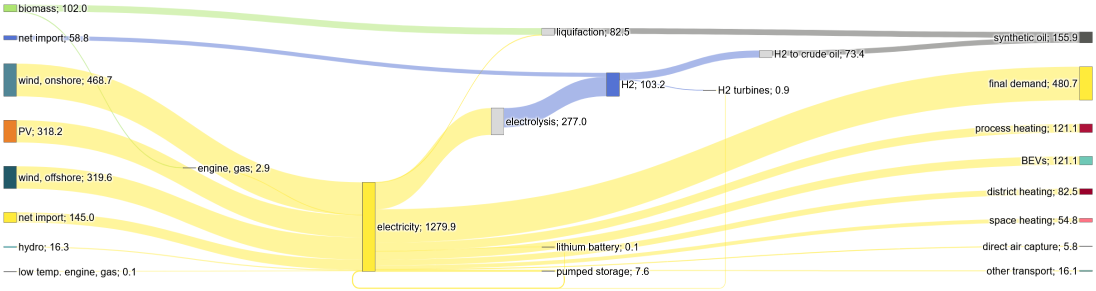
(a) reference+Mix



(b) Shift+Mix

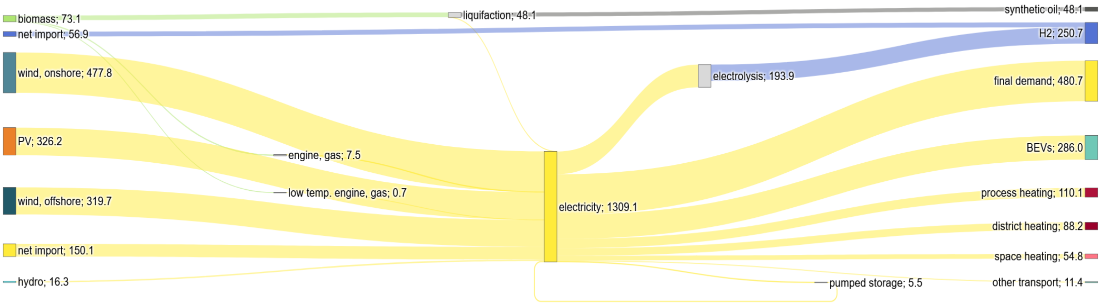


(c) Avoid+Mix

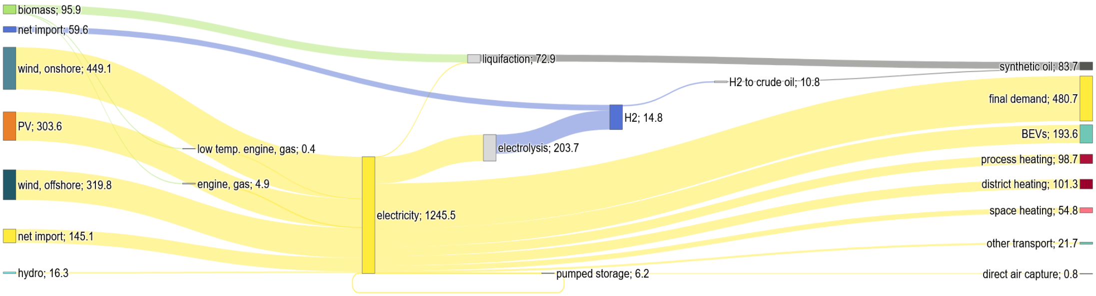


(d) Avoid+Shift+Mix

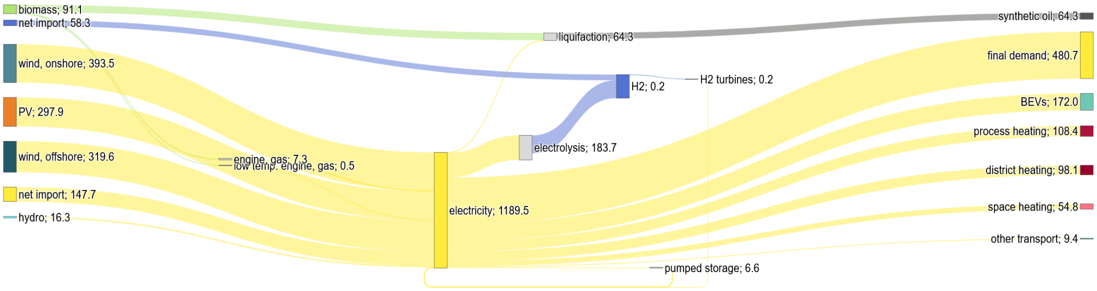
Figure B.2: Mix scenarios have a vehicle stock drivetrain composition of 56 % BEVs, 14 % PHEVs, and 30 % ICEVs.



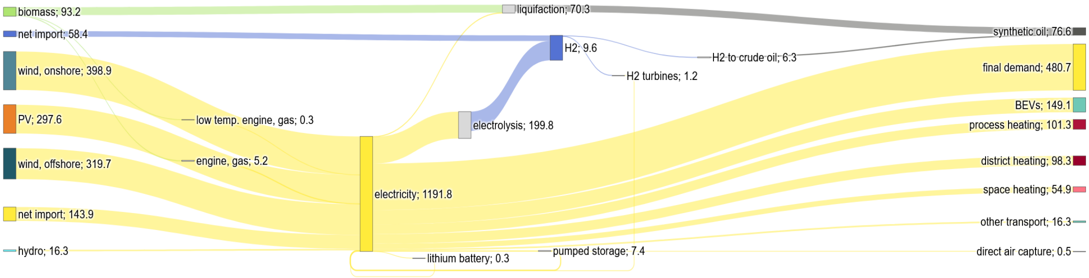
(a) reference+Improve



(b) Shift+Improve



(c) Avoid+Improve



(d) Avoid+Shift+Improve

Figure B.3: Improve scenarios have a 100 % BEV share.

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