Doctoral Thesis

# The role of a Sustainable Mobility Guarantee in the social-ecological transformation of the transport sector

submitted in satisfaction of the requirements for the degree of
Doctor of Science
of the TU Wien, Faculty of Civil and Environmental Engineering

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Dissertation

# Die Rolle einer Nachhaltigen Mobilitätsgarantie in der sozial-ökologischen Transformation des Verkehrssektors

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von

Dipl.-Ing. **Barbara Laa**, BSc
Matr.Nr.: 00925912

Supervisor: Ao.Univ.-Prof. Univ.-Prof. Mag. Dr. **Günter Emberger**
Institut für Verkehrswissenschaften
Technische Universität Wien
Karlsplatz 13/230, 1040 Vienna, Austria

Reviewer: Univ.Prof. Dr. **Michael Getzner**
Institut für Raumplanung
Technische Universität Wien
Karlsgasse 11, 1040 Vienna, Austria

Reviewer: Univ.Prof. Dr.rer.pol. **Astrid Gühnemann**
Institut für Verkehrswesen
Universität für Bodenkultur Wien
Peter-Jordan-Straße 82/III, 1180 Vienna, Austria

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*Remember, always, that everything you know, and everything everyone knows, is only a model. Get your model out there where it can be viewed. Invite others to challenge your assumptions and add their own.*

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*Donella H. Meadows*

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# Kurzfassung

Die Dissertation untersucht das Konzept einer Nachhaltigen Mobilitätsgarantie (*Sustainable Mobility Guarantee*, SMG) als Instrument zur sozial-ökologischen Transformation des Verkehrssektors. Der Fokus liegt auf dem Personenverkehr in Europa, wobei Österreich als Fallstudie für quantitative Analysen dient. Ziel der SMG ist es, allen Menschen eine zugängliche, nachhaltige Alltagsmobilität zu gewährleisten, vor allem durch Stärkung des öffentlichen Verkehrs (ÖV), der aktiven Mobilität (Radfahren und Zufußgehen) und gemeinschaftlich genutzter Mobilitätsformen (Sharing).

Die Arbeit verwendet einen Methodenmix, um folgende Bereiche zu analysieren: (1) Definition und Umsetzungsszenarien der SMG, (2) Auswirkungen auf Verkehrssystem und Mobilitätsverhalten sowie (3) ökonomische und ökologische Effekte. Eine umfassende Literaturrecherche zeigt, dass Mobilitätsgarantien bisher unterschiedlich definiert sind – von sehr spezifischen Garantien für einzelne Verkehrsträger, Strecken oder Nutzergruppen bis hin zu umfassenden gesetzlichen Regelungen, die ein allgemeines Mobilitätsrecht verankern. Darauf aufbauend entwickelt die Dissertation eine SMG-Definition, die soziale und ökologische Nachhaltigkeit sowie die besonderen Bedürfnisse ländlicher Regionen berücksichtigt. Die SMG umfasst Parameter wie Erreichbarkeit (räumlich und zeitlich), Infrastrukturqualitäten, Leistbarkeit (Nutzerkosten) und einfache Tarif- und Buchungssysteme.

Zur Analyse möglicher Auswirkungen der SMG auf das Verkehrssystem werden qualitative Ansätze (System Dynamics, Multi-Level Perspective) sowie quantitative Simulationen mit dem Verkehrsmodell MARS für Österreich genutzt. Je nach Ausgestaltung der SMG können unterschiedliche Effekte erzielt werden. Die Ergebnisse zeigen, dass eine flächendeckende Verbesserung des öffentlichen Verkehrs (ÖV) zu einer Steigerung dessen Nutzung führt, jedoch ohne starken Einfluss auf den Autoverkehr. Eine Fokussierung auf die Förderung der aktiven Mobilität hingegen, führt zu einer stärkeren Verlagerung von Autofahrten auf nachhaltigere Verkehrsmittel. Externe Faktoren wie die Entwicklung der E-Pkw-Flotte beeinflussen die Ergebnisse zusätzlich. Als zentrales Ergebnis der Simulationen zeigt sich, dass die Wirkung der SMG im Sinne von ökologischen Zielen, wie der Reduktion von Treibhausgas-Emissionen, sich nur entfalten kann, wenn die zusätzlichen Angebote im ÖV und bei aktiver Mobilität mit restriktiven Maßnahmen für den Autoverkehr kombiniert werden.

Volkswirtschaftliche Effekte wurden in einer Kosten-Nutzen-Analyse untersucht. Die Ergebnisse zeigen, dass die substanziellen Investitionen zur Realisierung einer SMG in mehreren Szenarien durch geringere Klimaschäden, niedrigere Fahrzeugbetriebskosten und reduzierte Unfallkosten sowie weiterer positiver Effekte mehr als kompensiert werden können.

In der Dissertation wird der Schluss gezogen, dass die SMG ein vielversprechendes Instrument ist, um die sozial-ökologische Transformation des Verkehrssektors voranzutreiben, jedoch mit Limitierungen. Ihre Umsetzung erfordert politische Zusammenarbeit und sollte Teil eines umfassenderen Maßnahmenpaketes sein, um volle Wirksamkeit zu entfalten. Empfehlungen umfassen die Schaffung eines klaren Rechtsrahmens, Investitionen in den öffentlichen Verkehr, den Ausbau der Infrastruktur für aktive Mobilität und Maßnahmen zur Reduzierung der Pkw-Nutzung. Die Ergebnisse liefern wertvolle Erkenntnisse für eine nachhaltige Verkehrspolitik und unterstützen Klimaziele, Lebensqualität und soziale Gerechtigkeit.

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# Abstract

The dissertation examines the concept of a Sustainable Mobility Guarantee (SMG) as a tool for the social-ecological transformation of the transport sector. The focus is on passenger transport in Europe, with Austria serving as a case study for quantitative analyses. The SMG aims to ensure accessible, sustainable everyday mobility for all, primarily by strengthening public transport, active mobility (cycling and walking), and shared mobility options.

The study employs a mixed-methods approach to analyze the following areas: (1) the definition and implementation scenarios of the SMG, (2) its impacts on the transport system and mobility behavior, and (3) its economic and environmental effects. A comprehensive literature review reveals that mobility guarantees are currently defined in diverse ways — ranging from very specific guarantees for individual modes of transport, routes, or user groups to broad legislative frameworks that establish a general right to mobility. Building on this, the dissertation develops an SMG definition that incorporates social and ecological sustainability as well as the specific needs of rural regions. The SMG includes parameters such as accessibility (spatial and temporal), infrastructure quality, affordability (user costs), and simplified fare and booking systems.

To analyze potential impacts of the SMG on the transport system, the study uses qualitative approaches (System Dynamics, Multi-Level Perspective) and quantitative simulations with the MARS transport model for Austria. Depending on the SMG's design, varying effects can be achieved. The findings show that comprehensive improvements to public transport lead to increased public transport usage but have little effect on car traffic. In contrast, focusing on promoting active mobility results in a more pronounced shift from car trips to sustainable transport modes. External factors, such as the development of the electric vehicle fleet, also influence the outcomes considerably. A key finding from the simulations is that the ecological goals of the SMG, such as reducing greenhouse gas emissions, can only be achieved if additional public transport and active mobility offerings are combined with restrictive measures for car usage.

The economic effects were evaluated through a cost-benefit analysis. The results indicate that the substantial investments required to implement an SMG can be offset in several scenarios by reduced climate change damage, lower vehicle operating costs, decreased accident costs, and other positive effects.

The dissertation concludes that the SMG is a promising instrument for advancing the social-ecological transformation of the transport sector, albeit with limitations. Its implementation requires political collaboration and should be part of a broader package of measures to achieve full effectiveness. Recommendations include the creation of a clear legal framework, investments in public transport, the expansion of infrastructure for active mobility, and measures to reduce car usage. The findings provide valuable insights for sustainable transport policy and support climate goals, quality of life, and social equity.

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## List of Abbreviations

**ARE** *Bundesamt für Raumentwicklung* - Federal Office for Spatial Development (Switzerland)

**BAU** Business as Usual

**BCR** Benefit-cost ratio

**bnEUR** Billion euros

**BMK** *Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie* - Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology

**$CO_2$e** Carbon dioxide equivalents

**DRT** Demand-responsive transport

**EC** European Commission

**EU** European Union

**EXT** External scenario

**FDR** Financial Discount Rate

**GRH** Guaranteed Ride Home

**HH** Household(s)

**ICE** Internal Combustion Engine

**inh.** Inhabitants

**IRR** Internal rate of return

**LOM** *Loi d'orientation des mobilités* - French Mobility Orientation Law

**LUTI** Land-use Transport Interaction

**MaaS** Mobility as a Service

**MARS** Metropolitan Activity Relocation Simulator - a LUTI model

**MCA** Multi-criteria analysis

**mEUR** Million euros

**NPV** Net present value

**ÖBB** *Österreichische Bundesbahnen* - Austrian Federal Railways

**PKT** Passenger-Kilometers Traveled

**PT** Public Transport

**PTAL** Public Transport Accessibility Level

**PTQC** (Swiss) Public Transport Quality Classes

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**PTSQL** (Austrian) Public Transport Service Quality Level

**pkm** Person-Kilometers

**SDR** Social Discount Rate

**SMG** Sustainable Mobility Guarantee

**SOCC** Social Opportunity Cost of Capital

**SUMP** Sustainable Urban Mobility Plan

**TTB** Travel Time Budget

**UBS** Universal Basic Services

**VKT** Vehicle-Kilometers Traveled

**vkm** Vehicle-Kilometers

**VTTS** Value of Travel Time Savings

**VSS** Schweizerischer Verband der Strassen- und Verkehrsfachleute

**WAM** With Additional Measures

**WEM** With Existing Measures

**WTP** Willingness-to-Pay

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# Chapter 1

# Introduction

Mobility is essential for humans to fulfill their needs, but the way we get around has dramatically changed within the past 100 years. Today, societies all over the world rely on fossil-fuel based transport systems that shaped our economies but brought along negative effects such as accidents, climate change and social challenges of inequality. Increasingly, new concepts are put forward in search of a social-ecological transformation in the transport sector. One of them is the idea of a "Sustainable Mobility Guarantee". The term and the associated concept have not been established in literature yet. However, the idea is gaining relevance with current societal challenges. In this chapter, I first present those challenges, the concept of car dependence and the relationship between the two as well as the academic criticism on car dependence and associated concepts. The idea of a Sustainable Mobility Guarantee is then introduced, pointing out the expectations and knowledge gaps concerning the topic. Finally, I present the research objectives and research questions of this thesis and describe the methodological approach.

## 1.1 Societal challenges

Society is constantly confronted with a variety of crises that both affect and are affected by transport systems. This includes the climate and biodiversity crisis as well as the Covid-19 pandemic and ensuing economic crisis along with social inequality. Sheller (2018) referred to a triple crisis of parallel crises in climate, urbanization and migration, all dealing with mobility and involving unjust power relations. Current transport systems based on fossil fuel propulsion and more specifically the extensive use of private cars is increasingly seen as one of the problems embedded in these intricate crises.

### 1.1.1 Environmental degradation

#### Climate crisis

Anthropogenic global climate change has already caused substantial damage to people and poses the imminent threat of rendering large parts of our ecosystem uninhabitable. The latest IPCC report formulates the urgency of the matter:

> *"The cumulative scientific evidence is unequivocal: Climate change is a threat to human well-being and planetary health. Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a livable and sustainable future for all."* (IPCC, 2022a, p.33)

Climate change is driven by greenhouse gas (GHG) emissions such as $CO_2$ and land use change due to human activity. The effects of such are global warming as well as the increased frequency, intensity and duration of extreme weather events such as droughts, wildfires, heatwaves, cyclones and floods. Such events lead to the damage and irreversible loss of ecosystems, threaten food security and human health, as well as contribute to displacement, migration and increased inequality (IPCC, 2022a).

Despite a history of global agreements to lower GHG emissions (starting in 1992 with the United Nations Framework Convention on Climate Change), $CO_2$ emissions from fossil fuel combustion and industrial processes have reached their highest ever annual level in 2021 with 36.3 $GtCO_2$ (IEA, 2022c). In 2015, an international community of 195 states committed to the so called Paris Agreement (UNFCCC, 2015) with the goal to limit global warming to well below 2°C, although preferably to contain it to 1.5°C compared to pre-industrial levels. The promised reduction in emissions by countries, the so-called nationally determined contributions are, however, projected to reduce global GHG emissions by a mere 0.5 $GtCO_2e$ by 2030 (UN Environment Programme, 2022a). Even though these nationally determined contributions are insufficient to meet the Paris Agreement limits of 1.5°C and 2°C, the countries are still off track to achieve them. According to the 2022 Emissions Gap Report by UN Environment Programme (2022a), current policies would result in a global warming of 2.8°C.

Member states of the European Union agreed to lower their emissions by at least 55 % by 2030 compared to measurements in 1990 as well as become climate-neutral by 2050. These goals set out in the "European Green Deal" have been written into law as the European Climate Law (Regulation (EU) 2021/1119) which became effective in July 2021.

Anthropogenic causes for climate change are not evenly distributed among national demographics. Countries and people who are at risk of experiencing the earliest and most severe consequences of climate change are the least responsible for them (Gore et al., 2020; Oswald et al., 2020). An analysis comparing cumulative historic emissions with national "fair shares" until 2015 shows that the USA was responsible for 40 % of excess global $CO_2$ emissions, while the European Union was responsible for 29 % (Hickel, 2020a). That being said, other countries, especially in Asia, are catching up, exhibiting accelerating rates of $CO_2$ emissions (Lamb et al., 2021).

The transport sector and use of private cars play a major role in the perpetuation of anthropogenic global climate change, accounting for 25 % of $CO_2$ emissions from fuel combustion in 2020 (IEA, 2021). Between 1970 and 2010 direct GHG emissions from the transport sector have risen by 250 % worldwide. This is a greater increase than any other sector (Sims et al., 2014, p. 606). Emissions have mainly risen due to road transport, aside for a temporary decrease in 2020 resultant of the COVID-19 pandemic (IEA, 2022b). In 2021, the global 7.65 $GtCO_2$ emissions of the transport sector were divided into 77 % road transport, 11 % shipping, 9 % aviation, 2 % pipeline and 1 % rail transport (IEA, 2022a). The majority of emissions from road transport can be attributed to passenger cars with 3.0 $GtCO_2$ (51 %) in 2020, as well as to medium- and heavy trucks with 1.6 $GtCO_2$ (27 %) (IEA, 2022b).

Aside from the direct emissions produced by vehicles, the construction of transport infrastructure is also $CO_2$-intensive due to the reliance on asphalt, cement, steel and heavy construction machinery. In a meta-study, Aryan et al. (2023) analysed 67 Life-Cycle-Assessments of road infrastructure and found an average global warming potential for flexible pavements (asphalt) of 1,043 $tCO_2e$/km/lane (ranging from 52 - 3,230 $tCO_2e$/km/lane) as well as an average of 1,398 $tCO_2e$/km/lane (ranging from 400 - 3,800 $tCO_2e$/km/lane) for rigid pavements (concrete). Although these "grey" emissions are much lower than traffic emissions themselves (less than 5 %, e.g. see (Gruber & Hofko, 2023; Milachowski et al., 2011)), they still contribute to a significant amount of GHG emissions.

Additionally, transport infrastructure occupies land which can no longer be used for agriculture and renders surfaces impervious to rainwater, preventing it from infiltrating the soil thus the eventual absorption of $CO_2$. Such surfaces absorb and retain heat rather than helping to cool the environment, therefore aggravating heat waves and urban heat island effects (Shuster et al.,

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2005). The construction of road infrastructure sets in motion a dynamic, self-reinforcing cycle of land use change such as urban sprawl and induced traffic (Baing, 2010; EEA, 2006; Litman, 2013; Mattioli et al., 2020; Newman & Kenworthy, 2015). The area of built-up land per capita (i.e. buildings and roads) has been found, after GDP, to be the most important predictor of $CO_2$ emissions (Haberl et al., 2023).

Therefore, transforming our transportation systems as well as the way people move around are imperative in the prevention of accelerated climate change. A meta-review analysing 53 studies on climate change mitigation by Ivanova et al. (2020) showed the high potential of leverage transport has in reducing GHG emissions. Transitioning to a car-free lifestyle and increased usage of public transport are among the options with the highest mitigation potential.

#### Biodiversity crisis

The biodiversity and climate crises are closely linked. Biodiversity refers to the heterogeneity of life on Earth, which is imperative for ecological balance. Living organisms interact in dynamic ecosystems and if individual species disappear, there are severe possible consequences for entire ecosystems. World biodiversity has been rapidly declining in recent years due to human activity, which has resulted in land-use change, pollution and climate change (Reid et al., 2006). In 2019, a report by the IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) stated that *"Nature and its vital contributions to people, which together embody biodiversity and ecosystem functions and services, are deteriorating worldwide"* (IPBES, 2019, p. XIV) and warned that one million species are threatened with extinction, many within decades.

At the end of 2022, a landmark agreement for the protection of biodiversity was reached. The $15^{th}$ Conference of Parties to the UN Convention on Biological Diversity adopted the "Kunming-Montreal Global Biodiversity Framework" (GBF), including four goals and 23 targets for achievement by 2030 (UN Environment Programme, 2022b). The targets include effective conservation and management of at least 30 % of the world's lands, reducing the loss of areas of high biodiversity importance to near zero, and progressively phasing out or reforming subsidies that harm biodiversity by 2030. These targets address both, the protection of habitats and mitigating climate change.

While the role of transportation in climate change has been described above, the connection to habitat protection is mainly linked to land use change. Transport infrastructure can fragment or destroy natural habitats (IPBES, 2019, p. 60), both, directly by taking up space and indirectly, by spurring dynamics of urban sprawl and other land use change.

Apart from GHG emissions and land use changes, the large resource quantities required to construct transport infrastructure and produce vehicles place a burden on the environment by extracting raw material from natural resources. The material footprint of nations shows that construction minerals and metal ores account for the majority of extracted material (Wiedmann et al., 2015).

### 1.1.2 Human health

Aside from the threats of climate change and biodiversity loss, there is also a direct negative impact on human health by motorized vehicles usage via both, pollution and road accidents, while also indirectly through their contribution to sedentary lifestyles.

Vehicles with internal combustion engine (ICE) emit a variety of harmful pollutants, including particulate matter (PM), carbon monoxide (CO), as well as nitrogen oxides ($NO_x$), which pose serious risks to health, particularly for people who live in areas with high levels of road traffic.

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These pollutants can contribute to respiratory illness, heart disease, as well as a variety of other conditions (Colvile et al., 2001; Woodcock et al., 2009). According to the WHO, air pollution is the biggest environmental risk to health in the European Union (WHO, 2016), resulting in 400,000 premature deaths each year due to excessive air pollutants (EEA, 2017). For the year 2021, the mortality due to exposure to PM2.5 is estimated with 293,000 attributable deaths and to $NO_2$ with 69,000 attributable deaths (EEA, 2023). Road transport is one of the most significant sources of air pollution in the EU (EEA, 2017).

The Zero Pollution Action Plan[1] focuses on reducing exposure to fine particulate matter ($PM_{2.5}$), with the target of reducing the number of attributable premature deaths caused by exposure to $PM_{2.5}$ in the EU by at least 55 % until the year 2030.

Another form of pollution linked to traffic is noise, which can be a significant source of stress for people living near busy roads or highways. Long-term exposure to noise pollution has been linked to a variety of physical and mental health issues such as sleep disturbance, stress, cardiovascular diseases, tinnitus and reduced cognitive development in children (WHO, 2018a). In the European Union, at least one in five people are exposed to environmental noise levels considered harmful to health, resulting in 12,000 premature deaths per year. An estimated number of 113 million people are affected by noise levels of road traffic of 55 dB(A) and higher (EEA, 2020). WHO guidelines recommend noise levels produced by road traffic stay below 53 dB(A) during day time and below 45 dB(A) at night (WHO, 2018a).

With the Zero Pollution Action Plan, the European Commission proposed the policy target to reduce the number of people chronically disturbed by transport noise by 30 % compared to 2017.[2] The EU, however, is not on track to reach this target. Based on the agreed measures, the likely maximum reduction is only 19 %. In the less ambitious scenario, the number of people affected by noise are even predicted to increase by 3 %. The European Energy Agency recommends a combination of measures including better urban and transport planning, as well as significant reductions in road traffic.[3]

Moreover, accidents are another direct impact to human health. It is estimated that around 85 million people have died in car accidents since the invention of the automobile; approximately 60 million in the $20^{th}$ century and 25 million since the beginning of the $21^{st}$ century (Braun and Randell, 2022b). In 2018, the global annual death toll amounted to 1.35 million people (WHO, 2018b), 100,000 more than in 2015, when it was believed that road deaths had plateaued (WHO, 2015). During the Covid-19 pandemic road accidents declined with the sharp decrease in traffic volumes (ITF, 2021). This trend, however, cannot be expected to continue with traffic volumes returning to former levels. Death and injury can lead to significant negative impacts that affect not just the parties involved in the accident, but also their families and communities. More people die from road crashes than from war or other forms of violent death (Braun & Randell, 2022b). The WHO and United Nations Regional Commissions (2021) developed a "Global Plan for the Decade of Action for Road Safety 2021-2030" focused on the objective of reducing road traffic deaths and injuries by 50 % within the aforementioned time frame which was agreed upon by the UN General Assembly Resolution 74/299. Recommended actions go beyond the classic measures that mainly regard vehicle and road design or human behaviour. They include the encouragement of multi-modal transport and land use planning to reduce exposure to crashes through policies that promote compact urban design, prioritize pedestrians, cyclists and public transport, discourage the use of private vehicles in high density urban areas as well as provide

[1] EC, URL:https://environment.ec.europa.eu/strategy/zero-pollution-action-plan/zero-pollution-targets_en, accessed 18.11.2024

[2] idem.

[3] EEA, URL:https://www.eea.europa.eu/publications/outlook-to-2030/outlook-to-2030-can-the, accessed 18.11.2024

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alternatives that are accessible, safe, and easy to use. These alternatives include walking, cycling, buses and trams.

High levels of car usage can also contribute to harmful sedentary lifestyles, in which people spend a large part of their day sitting, such as when driving a car, working at a desk, watching television or using a computer. Sedentary behaviour and lack of physical activity increases the risk of a variety of health conditions, including obesity, heart disease, diabetes, cancer, and mental health problems (Bassett et al., 2008; Park et al., 2020; Tremblay et al., 2010). Conversely, studies have shown the health benefits associated with walking and cycling more instead of driving a car (e.g. Fishman et al., 2015; Mueller et al., 2017; Warburton et al., 2006; Woodcock et al., 2009).

### 1.1.3 Social and economic challenges

Social and economic challenges relate to inequality, both globally and within countries, as well as the (in)ability of economic systems to care for the well-being of both humans and the environment. I will address several dimensions of these challenges related to transport by first explaining its interrelation to the economy and will then highlight inequalities. At the end of the section, I present new economic approaches that attempt to address human well-being as well as ecological challenges.

#### Transport and economy

Transport systems are connected with not only economic but also social activity. Access to and distribution of goods and services, as well as the mobility of people rely on transportation networks. Transport infrastructure is therefore seen as fundamental for development; which is defined as *"improving the welfare of a society through appropriate social, political, and economic conditions"* (Rodrigue & Notteboom, 2020, Chapter 3.1). Transport systems provide economic and social opportunities, as well as benefits with positive multiplier effects *"such as better accessibility to markets, employment, and additional investments. When transport systems are deficient in terms of capacity or reliability, they can have an economic cost, such as reduced or missed opportunities and lower quality of life."* (Rodrigue & Notteboom, 2020, Chapter 3.1).

In the beginning of industrialization, countries relied mainly on railways as transport systems. Later, the automotive industry played an important role in the economic development of industrialized countries. Productivity-enhancing innovations in technology and labor organization that were first introduced in car companies have spread to other sectors. This, for instance, includes the standardized mass-production of Fordism or multi-divisional company organization that was first implemented at General Motors (Mattioli et al., 2020; Standage, 2021). The industry is also linked to other sectors, such as steel, rubber and glass production in the supply chain, as well as to oil consumption and real-estate development as downstream effects. Still, today, the scale and economic significance of the automotive industry makes it an important factor in national economies comprised of a few large global conglomerates that are considered "too big to fail" since governments depend on the jobs, growth and state revenue that they provide (Mattioli et al., 2020).

Economic development, or growth, is primarily measured in GDP (Gross Domestic Product). While the automotive industry plays a part in economic growth, many studies show that new transport infrastructure is also associated with increased GDP in a region (e.g. Acheampong et al., 2022; Aschauer, 1989; Pradhan & Bagchi, 2013; Zhang & Cheng, 2023). GDP growth and traffic growth are tightly coupled. Even though there have been ambitions in the past to reduce energy consumption and emissions in the transport sector by making traffic more efficient

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with technical innovations, such as ITS (Intelligent Transport Systems) applications or improved engines, those reductions have been outweighed by growth in traffic. Schwedes argues, that *"the transportation system cannot be conceived as a social subsystem; rather, it constitutes the basic framework of capitalist societies"* (Schwedes, 2023, p. 15). He concludes that the current paradigm allows only for the regulation of transport in the interest of economic growth via transport policy. Indeed, the building of road infrastructure is argued for by proponents across the political spectrum, and in times of economic growth (to accommodate the growth), as well as in times of recession in order to stimulate economic growth (Mattioli et al., 2020).

However, the effects of transport infrastructure on GDP show a nonlinear relationship, dependant upon the location, network effect, as well as diminishing returns (e.g. Acheampong et al., 2022). Once networks are built, substantial growth can only be achieved above a certain threshold and tend to diminish above that threshold. In economic assessments of transport infrastructure, the impact on GDP is mostly considered for a limited area where the new infrastructure has been built without acknowledging wider effects of redistribution of economic activity and employment between regions. Accessibility is always relative, and while infrastructure investment in one location may help that location, it might be at the expense of a competing location (Banister & Berechman, 2001); this accounts primarily to differences in urban and rural development. Transport infrastructure - especially urban roads and major regional roads - can lead to economic concentration in cities and other already accessible core parts of a country (Banister & Berechman, 2001; Ding, 2012). While GDP can increase in both urban and rural areas, cities profit substantially more; furthermore, the economic gap between the two is widened.

Moreover, GDP as a measurement for development is heavily criticised, as it is a single quantitative indicator focused on the value of goods and services within the market of one country and fails to capture non-market activities such as unpaid household and care work, environmental sustainability, income inequality and distribution of wealth (e.g. England, 1998; Giannetti et al., 2015; Hickel & Kallis, 2019; Schepelmann et al., 2010; Schmelzer, 2015; Schwedes, 2023). Schwedes (2023, p.180) mentions the illustrative example of a traffic accident having a positive impact on GDP due to employment of police, doctors, car repair workshops, etc., while cost-causing effects on welfare are not sufficiently accounted for. The use of GDP as a single measurement of public well-being is inadequate. While there are many proposals for alternative indicators, GDP remains the leading mean of assessment for the paradigm of "development" in mainstream economics and most countries (Giannetti et al., 2015; Schmelzer, 2015).

Besides GDP assessments, other common appraisal tools for transport investments such as Cost-Benefit-Analyses (CBA) are also being criticised for weighing benefits biased, in favour of the expansion of car infrastructure (e.g. by valuing speed/time "savings" and "Level of Service" for cars higher than other aspects (Marohn, 2021)) and not considering "external costs", such as negative effects on the environment and society.

The reality of impacts from transport infrastructure on economic and social objectives should be assessed with a more diverse approach. A large number of studies finds that infrastructures for modes of transport other than private motorized vehicles - such as railways, cycling and walking - have an overall more positive impact on the economy (e.g. Bunker, 2001; Fishman et al., 2015).

#### Inequalities in transport

The connections of social inequality and transport have several aspects. Emissions from transportation are produced predominantly from affluent individuals, while the less privileged bear a disproportionate burden of the negative effects. Access to transport systems based on private cars is limited to people who are able to drive and afford a car, and can lead to social exclusion, as well as economic disadvantages in car-dependent environments.

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Oswald et al. (2020) showed that transport-related consumption is among the most unequal forms of consumption. In their analysis of energy footprints across 86 countries, transport-related activities and products stand out as having large energy intensities and income elasticity. This means that if income rises by 1 %, consumption of that good increases by more than 1 %. In contrast to heat and electricity for residential use, which show high energy intensity but small income elasticity, energy for transport is distributed very unequally. The top 10 % of the population use around 45 % of the observed energy for land transport and ca. 75 % for air transport. The authors recommend to implement type-specific policies. While the “high intensity, low elasticity” type of consumption should be addressed with large-scale public programs to retrofit buildings for non-fossil energy and heating, the “high intensity, high elasticity” type of consumption should be addressed with taxation and curtailment, as well as replaced with collective, low-carbon alternatives such as trains, buses and bicycles in the case of transportation.

In Austria, the situation is similar. A study commissioned by Greenpeace (Frascati, 2020) found that transport-related activities are the most unequal regarding $CO_2$-emissions. The top 10 % of Austrian private households emit an amount of GHG through vehicle fuel consumption and leisure activities (including holiday travel) alone, which is equal to the *total* emissions of the bottom 10 % of these households. Around 44 % of Austrian households in the lowest income quartile do not own a car, while 43% in the highest quartile are in possession of two or more cars (VCÖ, 2018). In addition, an analysis of Austrian micro census data from 2015 by Statistik Austria (2019) showed that higher disposable income is correlated to less frequent use of public transport and more frequent use of a car.

On the other side, people with lower incomes are often the ones who experience the greatest consequences of car traffic and the implicit impacts, such as noise and air pollution, as well as public areas lacking green space due to being dominated by car infrastructure. This has typically been linked to lower housing costs in such areas. A report by the European Environment Agency (EEA, 2020) looked into inequitable exposure to environmental noise in Europe and found evidence that house values are reduced in noisy areas and that ethnic minorities tend to be exposed to higher levels of environmental noise. Similarly, the Environmental Justice Atlas of Berlin (Senate Department for Urban Mobility, Transport Climate Action and the Environment, 2022) shows that areas in the city that show high noise and air pollution, bioclimatic burden and lack of green spaces are the ones with a higher share of the population experiencing social disadvantages (considering unemployment rate, child poverty and transfer benefits for non-unemployed individuals). For Austria, Statistik Austria (2019) looked into Environmental Justice indicators and found that households with lower income show higher exposure to odour fumes, exhaust fumes, dust and soot, as well as noise. Thereby, car traffic accounted for the highest values of traffic noise disturbance.

Extensive car use has two effects on social exclusion. Firstly, the design of public space with a focus on car traffic leads to a lack of pedestrian-friendly infrastructure and qualitative public space for leisure. This reduces opportunities for social interactions and can contribute to social isolation, thus weakening sentiments of community. The level of car traffic in a street has been shown to impact social relations and sense of home in residential neighborhoods, as well (B. Appleyard & Appleyard, 2021; D. Appleyard, 1981). D. Appleyard (1981) analysed three streets in San Francisco, which differ in the amount of car traffic they experience, while being otherwise comparable. Results have shown that with higher levels of car traffic, people have a lower number of friends in the street, meet less often in public space and view a smaller part of the streets as their ‘home’. In 2008, researchers repeated the study in Bristol, UK and replicated the primary findings of Appleyard: higher levels of motor vehicle traffic were associated with negative impacts on the social and physical environment and residents identified a wide range of harmful impacts on psychological and practical quality of life (Hart & Parkhurst, 2011).

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Secondly, people who are not able to drive a car in car-dependent residential areas are faced with limited access to jobs, education, healthcare and leisure activities. This reduces their capacity to take part in public life as well as to maintain relationships with friends and family (Lucas, 2012). The reasons as to why people have no access to a private car or cannot drive one are manifold. They include physical ability (permanent or temporary), age restrictions, financial constraints, legal consequences (such as past traffic violations), cultural factors (e.g. that women are not allowed to drive), etc.. In a transport system where there are no viable alternatives to the private car, people are prone to be socially excluded or depend upon others for transportation. Demographic prognoses of ageing societies suggest that the number of people who can't drive will increase in the future (Hjorthol, 2012).

From a system perspective, the necessity of car usage in car-dependent environments can exasperate inequities even further, trapping people in a vicious cycle by granting more economic advantage (access to work and other activities) to those who already possess an advantage (having access to a private car). This is not only a problem for disadvantaged persons, but for societies at large, as greater inequality in society seems to lead to higher rates of health and social problems, even for wealthier groups of the population (Pickett & Wilkinson, 2015).

The term "transport poverty" tries to capture the different dimensions of inequality in transportation, encompassing "mobility poverty" (lack of transport resources), "accessibility poverty" (difficulties in reaching key activities), transport affordability and disproportionate exposure to negative effects of transport (Mattioli, 2021).

#### Human well-being within planetary boundaries

GDP growth is associated with higher $CO_2$ emissions and a larger rate of consumption. Some countries show a decoupling of GDP growth and $CO_2$ emissions, meaning that GDP is still growing, while emissions are decreasing. There is, however, no evidence to support the decoupling of GDP from the material footprint or achieving absolute decoupling from $CO_2$ emissions at a rate sufficient enough to prevent global warming beyond the Paris Agreement limits of 1.5°C or 2°C (Hickel & Kallis, 2019; Vogel & Hickel, 2023). A growing number of researchers are therefore arguing for a paradigm change in economics to question GDP growth as the primary indicator, include other measurements for human well-being and the state of the environment, as well as deliberately shrink parts of the economy that are polluting or not serving human well-being. Such changes are mostly discussed as "Degrowth" to challenge the current growth paradigm (Hickel, 2020b; Hickel & Kallis, 2019; Kallis, 2018; Kallis et al., 2018; Research & Degrowth, 2010; Schmelzer et al., 2022). Advocates of Degrowth argue for supplementing strategies of efficiency and effectiveness with sufficiency.

Sufficiency means 'enough' and relates not only to a maximum but also a minimum, so basic needs are met for all people. An IPCC report from 2022 defines sufficiency policies as *"a set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human well-being for all within planetary boundaries"* (IPCC, 2022b, p.35) and mentions that policy packages need to combine such measures with efficiency and renewable energy measures to approach net zero GHG emissions by 2050.

New economic concepts emerged, which attempt to take sufficiency into account. Among them is the concept of "Doughnut Economics" (Raworth, 2017) which refers to a social foundation and an ecological ceiling, represented by a "doughnut" shape (see Fig. 1.1). The inner ring symbolizes the social foundation necessary for a good life. The assessment categories for this social foundation are derived from the Sustainable Development Goals (United Nations, 2015). If these minimums are not met, there is human deprivation. The outer ring represents the ecological ceiling beyond which we risk causing irreversible environmental damage. The assessment categories of the

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ecological ceiling are based on the nine planetary boundaries as defined by Rockstrom et al. (2009), which present potential tipping points in Earth's systems. The space in between the two limits is referred to as the *"safe and just space for humanity"*. We are currently operating neither globally, nor on a country-level within this "safe and just space" (Fanning et al., 2021). Richer nations tend to overshoot ecological limits while poorer countries show a tendency to not achieve all social thresholds.

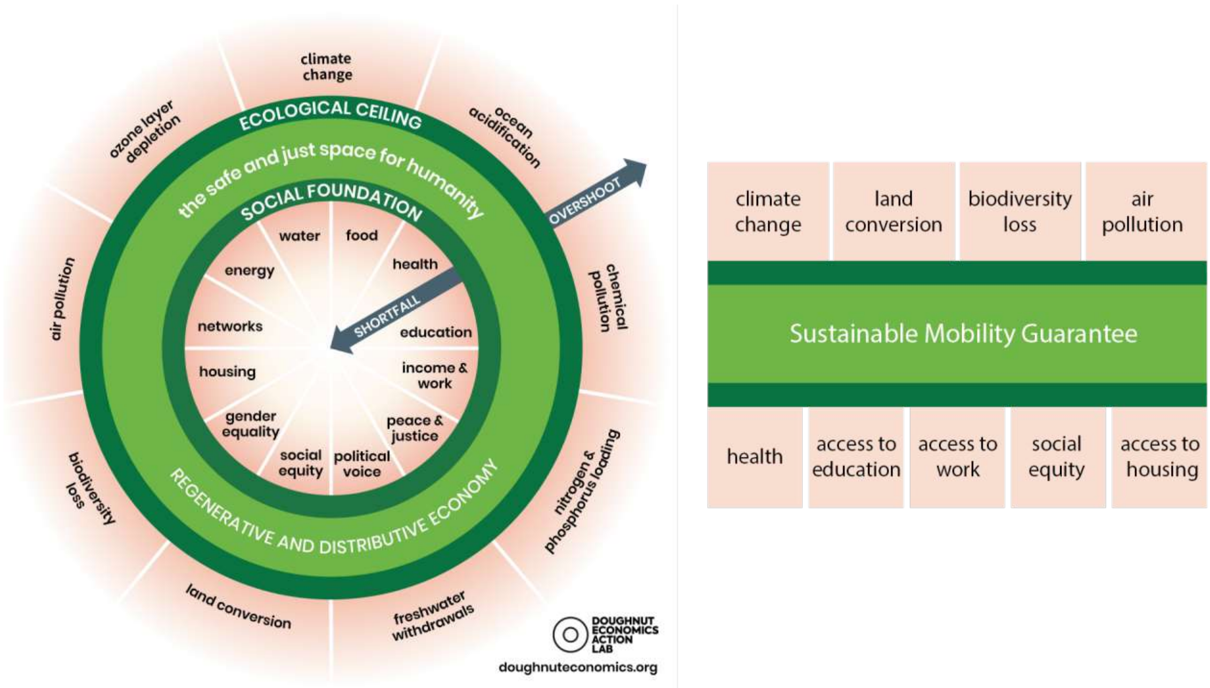


**Fig. 1.1:** Schema of "Doughnut economics" with social foundation and ecological ceiling (left) (Kate Raworth and Christian Guthier. CC-BY-SA 4.0); corridor where the concept of a Sustainable Mobility Guarantee is placed, showing the most relevant categories for transport (right) (own illustration, based on Raworth (2017))

The concepts of sustainable "consumption corridors" and "production corridors" also draw on the two limits of a social minimum basis and the ceiling of surpassing environmental capacities, referring to the corridor between the two in terms of consumption and production (Bärnthaler & Gough, 2023; Brand-Correa et al., 2020). The challenge lies in developing an economic system which is capable of staying within these limits. In regards to transport systems, this means that they need to be designed in a way that basic needs - such as access to work, education and housing as well as social equity and human health - are met, while GHG emissions, land-use and material use are reduced to meet the sustainability limits of climate change, land conversion, biodiversity loss and air pollution. The Sustainable Mobility Guarantee, as understood in this thesis, is conceptually placed in the corridor between the limits, see Fig. 1.1.

Universal Basic Services (UBS) (similar to the German concept of *"Daseinsvorsorge"*) offer a framework for understanding the potential of public consumption in this context (Coote, 2020). Coote addresses the transport sector in arguing that *"the ultimate goal of transport as a UBS is a well regulated, interconnected, frequent, reliable, and adequately funded scheme that also discourages car use and encourages safe walking and cycling alongside public transport."* (Coote, 2020, p.37). The idea of a Sustainable Mobility Guarantee fits well into this description and my analysis will draw from these concepts.

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## 1.2 Criticism of car dependence and changes in transport research

Section 1.1 showed that current societal challenges are closely intertwined with our transport systems. Change is necessary in the efforts to reverse the trend of continued growth in car traffic, stop environmental degradation and reduce social inequalities in line with sustainability goals. This realization is not entirely new. Criticism of extensive private car use has emerged before climate change was common knowledge; and the role of $CO_2$-emissions resultant of transport was clear. The list of academics and others warning of the negative effects of the mass adoption of private cars is extensive.

As early as the 1960s several anti-car books were published in the US, such as “Unsafe at Any Speed: The Designed-In Dangers of the American Automobile” (Nader, 1965) or “Highway Homicide - Surprising facts behind the increasing number of automobile deaths” (Kearney, 1966). The books focused on safety issues and the industry’s failure to address them, however they did not challenge the central role of cars in modern life, rather only demanded action to make them safer (Standage, 2021). Jane Jacobs’ influential book “The Death and Life of Great American Cities” (Jacobs, 1961), which is still seen as one of the standard works in urban planning, went further. This work resulted from her fight against highway building in New York City and heavily criticised car-centric planning policy by showing its negative effects on cities.

In the early 1970s, even before the oil shock of 1973, criticism grew louder, increasingly highlighting the systemic effects of car-centric planning leading to vicious circles of car dependence and its negative effects (Standage, 2021, pp. 204–205). In Austria, one of the pioneers of criticism of car-centric planning is Hermann Knoflacher. The transport engineer highlighted the dynamic complexities of car usage in the transport system and its long-term effects on land use, human health and the environment (Knoflacher, 1985, 1995, 1997, 2006, 2007).

Today, we can rely on decades of empirical data showing the negative effects of mass motorization and car-oriented transport planning. This - together with increasing concern about climate change - gave rise to new research fields looking into how we could change such unsustainable systems. A growing number of researchers is attempting to address social and ecological problems simultaneously within different fields, speaking of a ‘social-ecological transformation’ (Brand & Wissen, 2017). Regarding transportation, the German terms of *Verkehrswende* or *Mobilitätswende* (*’Wende’* meaning turnaround or a change of direction) are widely used to summarize necessary changes in the sector, while in English-speaking contexts, the terms transition and transformation are more widely used (although often interchangeably, see Hölscher et al. (2018)).

New terms emerged to describe and question the status quo of car-centric transport planning, such as ’car dependence’ or ’system of automobility’ (see Section 1.3 for definitions of different terms). With the 2006 edited volume of “Against automobility” (Böhm, Jones, Land, and Paterson, 2006) came extensive criticism from social science and humanities scholars on automobility (for more details, see Section 1.3). The 2012 edited volume “Automobility in transition?”(Geels et al., 2012) applied an interdisciplinary socio-technical lens to analyse the harmful state of automobility. The publication assessed if and how change is happening, concluding that the “automobility regime” was still stable because of lock-in mechanisms related to sunken investments, routine mobility patterns, protection of vested interests and belief systems from policymakers and transport planners. However, the book also leaves room for optimism by showing an increase in ‘change initiatives’: such as alternative propulsion technologies, socio-spatial innovations, car-free city centers and improved public transport.

Although many industry representatives, as well as some academics, still promote solely technological solutions to address climate change, such as electric vehicles or e-fuels, there is widespread acknowledgment across disciplines that the transport system must undergo fundamental transformation (Anable & Brand, 2022; Brand & Wissen, 2017; Geels et al., 2012; Loorbach,

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2022; Mattioli et al., 2020; Ryghaug et al., 2023; Stickler, 2020). Some scholars already talk about new paradigms; e.g. Banister (2008) wrote about a "sustainability paradigm" in transport and Sheller and Urry (2016) speak about a "New Mobilities Paradigm". Even though these first changes can be observed in academic literature and in transport planning practice, the trends of growing motorization and private car mobility continue worldwide (with the exception of a few cities and individual countries) and current political discourse and legal regulations are far from implementing this in most countries. Driscoll (2014) describes such lock-in mechanisms in the transport sector with the help of two case studies, in Copenhagen, Denmark and Boston, USA. Gössling and Cohen (2014) stated that EU policy for sustainable transport will fail and named "transport taboos" as the reason.

Even though more and more scholars, governments and institutions recognize the need for change, the pathway to a different future is not yet clear. This thesis is intended to add to the body of literature exploring possible pathways for a social-ecological transformation in the transport sector with a transport planning lens focusing on technical and economic contexts to draw conclusions on a policy level. The concept of a Sustainable Mobility Guarantee is assessed for its potential to transform car-dependence in transport planning and policy on a national level with the context of a European country, utilizing Austria as a case study. In order to define the research questions more precisely, the next sections explores different concepts and terms to describe the current status quo.

## 1.3 Car dependence, automobility and mobility regimes - definition of terms

Several concepts and theories intend to explain the situation we find ourselves in, problematizing the established norm of the private car as the focus of human transportation. To different degrees, they aim to offer new perspectives that can pave the way for alternative solutions. In this section, I introduce different definitions and theories of car dependence and related concepts as well as describe how car dependence will be used as the central concept for this study.

### 1.3.1 Car Dependence

The term car dependence emerged in academic literature in the 1990s as an "idea whose time has come" (Goodwin, 1995), arising from different fields of research which view high levels of car traffic as problematic. Mattioli (2016) defines a car-dependent transport system as *"one in which high levels of car use have become a key satisfier of human needs, largely displacing less carbon-intensive alternatives"*.

While early definitions emphasize the distinction between car-dependent people and car-dependent trips, recent literature points towards the multifaceted aspects of car dependence which are sustained by a self-reinforcing system derived of sub-systems (Jeekel, 2013; Mattioli et al., 2020). Mattioli et al. (2020) describe the political economy of car dependence on the basis of five systems of provision: (1) the rise of the automotive industry, (2) car infrastructure: the transformation of streets into spaces where car use is prioritized and the rapid expansion of road networks, (3) car-dependent land use patterns, (4) undermining of public transport and (5) cultures of car consumption.

### 1.3.2 Automobility as a system

The sociologist Urry (2004) coined the term "System of Automobility" describing it as a self-organizing non-linear system. He argues that the use of automobiles (private cars) is part of

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a broader system. This system involves various elements, including the production of cars, the infrastructure of roads and highways, petrol refining and distribution, car sales and repair workshops, urban design and planning, the social practices of driving, and the cultural significance of automobiles. He examines how this system has a character of domination and how it could be changed, referring to the difficulties due to path-dependencies and lock-in mechanisms. He argues for a complexity approach considering the many subsystems that sustain automobile dominance, and that by many small changes the system could tip into a "post-car mobility system".

Depending on their discipline and perspectives, various authors refer to "Automobility", sometimes explicitly defining it as a system with different subsystems, sometimes implicitly asking how systemic change - away from the private car as a dominant form of transportation - can be achieved. (e.g. Böhm, Jones, Land, Paterson, et al., 2006; Geels et al., 2012; Gössling et al., 2019; Sovacool & Axsen, 2018)

### 1.3.3 Car regime and automobility regime

The multi-level perspective (MLP) describes transitions in socio-technical systems in an evolutionary manner (Geels, 2002), and has been applied to "sustainability transitions" (Geels, 2011); also in the transport sector, see Section 4.2. The mainstream - or dominant - stage of a socio-technical system is referred to as a "regime". According to Rip and Kemp (1998), such a regime consists of rules embedded in a *"complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems"*. Depending on the object and problem of analysis, the view of what is part of the regime, niche or landscape might differ. Several studies in the field of transportation dealing with sustainability transitions define the established regime as a "car-regime" or "automobility regime" (Frey & Laa, 2021; Marletto, 2011; Sheller, 2012; Zijlstra & Avelino, 2012).

Böhm, Jones, Land, Paterson, et al. (2006) also refer to a "regime of automobility", however not in the context of MLP but rather as a distinction from "system". They criticise that the notion of a system might naturalize this system and take it for granted, while they also want to highlight the relations of power that make it possible and point towards the political character for allowing possibilities of moving beyond it:

> *"The notion of system tends to underplay collective human agency in the production of automobility and to avoid the political questions about the shaping of the automobile 'system'. At the extreme it can create a sense of 'lock-in' where the only possibilities for shaping automobility or of moving away from its dominance arise from within the system itself."* (Böhm, Jones, Land, & Paterson, 2006, p.5)

### 1.3.4 Automobility as an ontology

Some scholars describe the situation in ontological terms, meaning the metaphysical level, describing automobility as a sociotechnical imaginary: an imagined world we live in. Braun and Randell argue that automobility is a political ontology, one of the manifestations of "late-modernity" or the "Anthropocene" and argue in favor of imagining a post-automobility world (Braun and Randell, 2022a, 2022b). They describe the "ontos" of Automobility through five aspects: *Ontocracy* as the political order in which the harms and violence of automobility are reduced to the status of externalities; *Ontosphere* as the spatially visible political and social order, or space appropriated by automobility in the form of roads, bridges and other physical infrastructures that cannot be safely entered by non-automobile users; *Ontology* as a hegemonic, political imaginary; *Ontologists* as practitioners and personnel for developing and manufacturing

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technologies of movement and speed such as engineers, physicists, and corporate executives; *Ontography* as reality inscription, e.g. in the form of written texts such as books and articles, but also technical standards, drawings and planning manuals for engineers, as well as financial plans of companies; and *Ontopower* as constituting automobility as appropriate, normal and commonsense.

### 1.3.5 Use and definition of car dependence in this thesis

The concepts of car dependence, car regime and automobility are related but address different aspects or levels of the status quo, which has an impact on the travel behaviour of people, transport planning practices of professionals and transport policy of decision makers. Nevertheless, all three focus on the private car in transport systems; they all agree that the current situation needs to change if the world is to become more socially just and ecologically sustainable.

For the purposes of this study, the concept of car dependence is deemed most applicable, as the hypothesis and research questions are based on the scale of transport planning and its effects on the travel behaviour of people. Car dependence refers to the available mobility options of individuals which highly affects one's travel behaviour, as well as the characteristics of a location, shaped by transport planning decisions and which again can underlie the car dependence of planning practices. Subsequently I will mostly use the term car dependence to describe this status quo, and sometimes "car regime" in reference to the MLP. The Sustainable Mobility Guarantee is supposed to reduce car dependence by providing sustainable alternatives. In Chapter 2, I will present background information on the history and current state of car dependence in Europe and Austria.

## 1.4 The idea of a Sustainable Mobility Guarantee

Several concepts have emerged which could be viewed as potential guarantees for mobility; a literature review categorizing the different approaches and a definition of the Sustainable Mobility Guarantee (SMG) as understood in this thesis can be found in Chapter 3. For the purpose of this introduction, I will describe the general idea of an SMG in the following.

The Sustainable Mobility Guarantee is a transport policy aimed at providing infrastructure and mobility services in order to meet people's needs in a sustainable way; it is considered to guarantee people access to everyday life activities while shifting mobility behaviour away from car use. It is a policy approach that aims to reduce car dependence by providing alternatives. This includes the provision of safe and reliable public transport services supplemented by demand responsive transit, as well as high quality infrastructure for active mobility (walking and cycling). Combining transport modes should be facilitated not only through the creation of multi-modal hubs, but also through integrated booking, payment and usage in the sense of "Mobility as a Service" (MaaS).

While individual parts of the Sustainable Mobility Guarantee concept have been studied extensively in the past, the concept as a whole, a comprehensive approach to transport planning and policy on a national level - and its potential role in social-ecological transformations - are novel in scientific research.

## 1.5 Research objectives and questions

The objective of this thesis is to assess the concept of a Sustainable Mobility Guarantee as a a tool to challenge car dependence in the context of a social-ecological transformation of the

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passenger transport sector. The focus of the study deals with a European context, although the concept could be applicable in many different geographical and societal contexts. Austria is chosen as a specific case study for the quantitative assessments in Chapters 5 and 6 and as a reference for the transport planning and policy structures in the qualitative analysis in Chapter 4. The results, however, of the qualitative analysis are deemed generalizable for other countries: especially those with similar spatial and legal conditions. The quantified results present a baseline for further discussion in Austria but could also serve as a reference for other countries.

The assessment will be conducted in three parts (c.f. Fig. 1.2): (1) definition of the SMG and implementation scenarios, (2) analysis of changes in the transport system and travel behaviour and (3) economic assessment including analysis of environmental impact. The following research questions will be addressed:

1. Which different definitions of mobility guarantees or related concepts exist?
2. What are the key components of an SMG?
3. What different scenarios can be developed for an SMG introduction, focusing on design aspects, implementation scales and external uncertainties?
4. What potential impacts would an SMG have on transport planning and the patterns of travel behaviour?
5. How would the implementation of an SMG affect travel behaviour in Austria, including changes in modal split and vehicle kilometers, across different scenarios?
6. How effective is the Cost-Benefit Analysis (CBA) framework in evaluating the SMG, and what are the limitations of this method?
7. What are the key parameters of the CBA, the Net Present Value (NPV), Benefit-Cost Ratio (BCR) and (Internal Rate of Return) IRR for each SMG scenario?

## 1.6 Methodology and structure of thesis

I chose a mixed methods approach shown in Fig. 1.2. The research questions can be divided into three different parts, which will be addressed in separate chapters. Before the assessment, Chapter 2 will give background information on the mobility behaviour and car dependence in Europe and Austria. Chapter 3 will address the first research questions. A basic definition of the SMG is developed using a literature review to assess existing concepts and results from stakeholder workshops. Then, different implementation scenarios are derived. Chapter 4 deals with the qualitative analysis of the SMG impacting the transport system and travel behaviour. The Multi-Level-Perspective is used as a theoretical framework for analyzing the transformation of social-technical systems and the System Dynamics methods of Causal Loop Diagrams and Leverage Points to intervene in systems are applied to assess possible impacts. The quantitative analysis of changes in travel behaviour is presented in Chapter 5. The SMG scenarios are translated into scenarios that can be simulated using the strategic LUTI model MARS. Results show the impact on travel behaviour in a sensitivity analysis for individual measures and for the scenarios that combine several measures. Chapter 6 deals with the economic assessment of the SMG by means of a cost-benefit analysis. The results are discussed and interpreted in each of the chapters. Finally, Chapter 7 draws conclusions, gives policy recommendations and points to future research needs.

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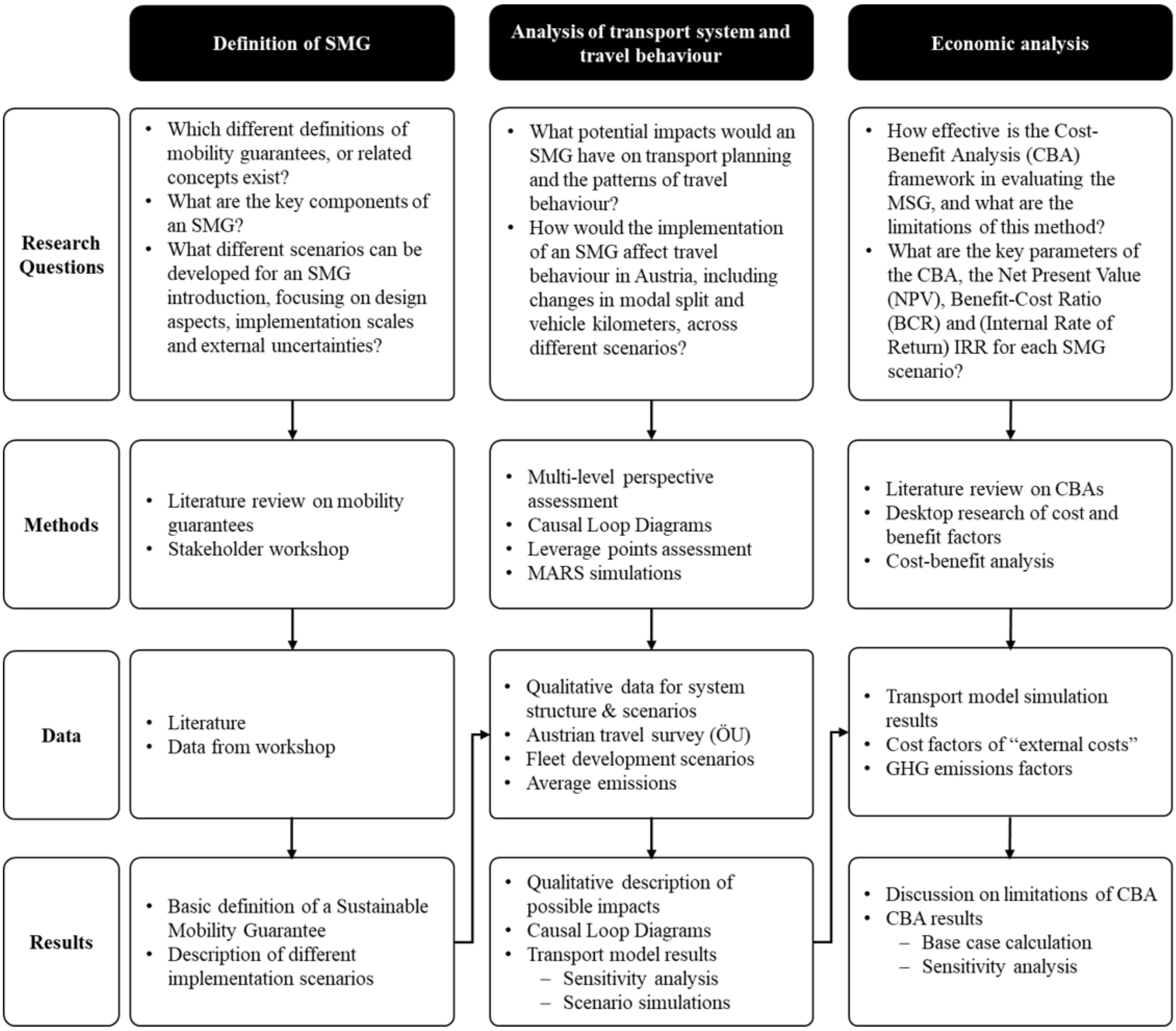


**Fig. 1.2:** PERT chart of methods

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# Chapter 2

# Mobility behaviour and car dependence in Europe and Austria

This chapter gives an overview of the current situation and historical developments around car dependence in Europe and Austria. With the use of descriptive statistics, relevant data and indicators are presented and the geographic differences of the Austrian transport system are discussed. This gives context for the following analysis and describes the status quo of mobility behaviour and systemic parameters for the case study region.

## 2.1 Development of motorization rate and mobility behaviour in Austria

### Motorization rate

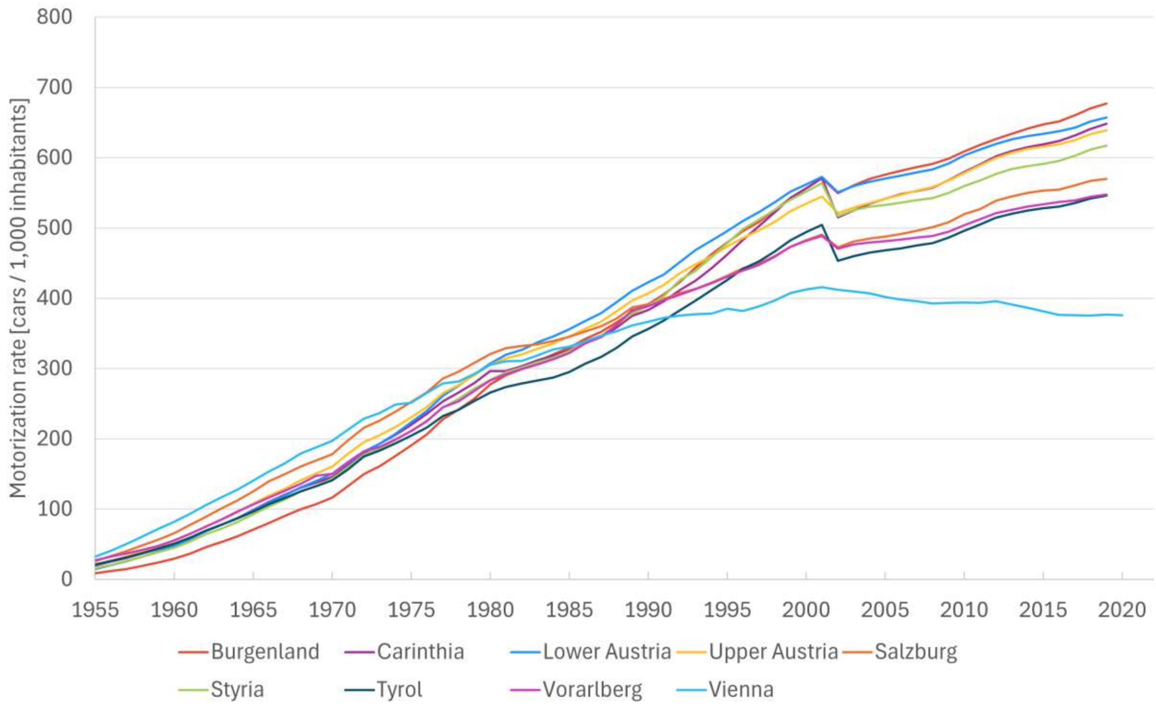


**Fig. 2.1:** Motorization rate in Austria for each province. Time series break in 2001/2002 due to changed recording method (own calculation and figure, based on WKO (2022) and Statistik Austria (2022a))

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Motorization rapidly increased in Austria with a total number of cars of 34,382 in 1948 to 5.15 million cars in 2022 (BMK, 2023c). The development in each province is shown in Fig. 2.1 with a break due to recording methodology in 2001/2002. In almost all districts, motorization rates were still rising until 2021, except for some districts in the cities of Vienna and Innsbruck. In 2022, the motorization rate was decreasing - for the first time - on average in Austria (from 572 cars/1,000 inhabitants in 2021 to 565 cars/1,000 inhabitants in 2022) and in each province (BMK, 2023a). The number of new cars decreased by 17.8 % between 2021 and 2022 and the total number of cars in the fleet increased only by 0.8 % (Heinfellner et al., 2023). However, this did not lead to less driving, as the vehicle-kilometers travelled (VKT) by car still increased in 2022 by 2.7 % compared to 2021 (Heinfellner et al., 2023).

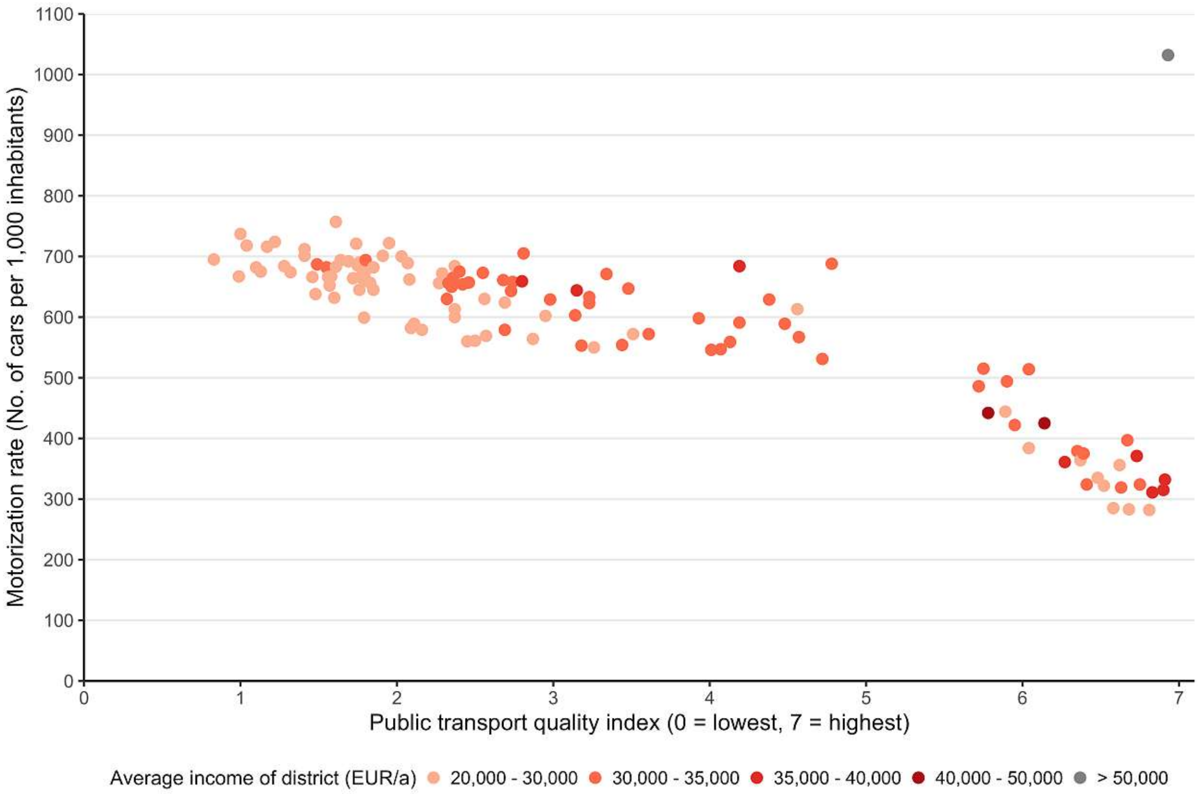


**Fig. 2.2:** Motorization rate in Austria per district, in relation to public transport quality (own figure, based on Högelsberger (2023a, 2023b))

While levels of motorization (car ownership) in the EU correlate even more with income (higher car ownership rates with higher income) than with geographic area (higher car ownership in rural areas) (Fiorello et al., 2016), numbers for Austria show high correlation of public transport

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availability and motorization rate. An analysis by Högelsberger (2023a)[1] shows that motorization rates in Austrian districts are lower with increasing public transport quality, see Figure 2.2.

Data points on the right side of the diagram with PT indices ranging between 5 and 7 can currently only be found in large cities, namely Vienna, Graz, Salzburg, Innsbruck and Linz. Even though some of the districts in these cities are in the higher income classes, motorization levels are low. Data points for rather rural districts are more scattered along the x-axis, although there is also a tendency of lower motorization rates for higher PT quality. The highest motorization rates are associated with low PT quality indices and lie in the lowest average income class. Whilst the graph shows a correlation - not causality - and studies have shown that settlement structure and residential self-selection influence mobility behaviour (Cao et al., 2009), we can note three observations. Firstly, higher PT quality is associated with lower motorization rates. Secondly, there is a divide in PT quality between urban and rural areas. Thirdly, the most car dependent districts are the ones with the lowest average income class - measures that aim to address ecologic and social sustainability at the same time have to take this into account.

## Mobility behavior

The most recent nationwide mobility survey in Austria was conducted in 2013 and 2014 and published in 2016 (Follmer, Gruschwitz, Kleudgen, et al., 2016). Results in the modal split[2] show that walking trips decreased from 27 % in 1995 to 17 % in 2013/14, while trips by motorized private transport (cars and motorcycles) increased from 51 % to 58 %, see Fig. 2.3. PT and cycling trips increased only slightly from 17 % to 18 % and 5 % to 6 %, respectively.

The distances travelled by the population (aged 6 and above) have increased by more than one-third to 273 million person-kilometers per working day since 1995. This is shown for each transport mode in Fig. 2.4. While the share of walking trips in the modal split has decreased dramatically, the total distance covered on foot has remained almost the same (decreasing slightly from 5.2 to 5.1 person-kilometers), which can be attributed to longer average walking distances. In 2013/14, 3 million more person-kilometers were covered by bicycle than in 1995, and in public transport - primarily due to increases in rail transport - there is a noticeable increase of 15 million person-kilometers.

[1]Högelsberger provided me with the data and method for the analysis, which was reproduced by me. The public transport quality index is calculated based on the ÖROK PT service quality levels (PTSQL) (Hiess, 2017) and the share of the population living in each quality class. Therefore, 0 represents the lowest quality, for districts with no access to PT according to the PTSQL and 7 represent the highest quality with a large share of the population in the district having access to high quality PT according to the PTSQL. The method for deriving the PTSQL is explained in detail in Section 3.1.7.2. The PTSQL range from A-G with A representing the best PT service quality and G the worst PT service quality. For the public transport quality index in 2.2, the PTSQL of A is defined with the multiplier 7, level B with 6, level C with 5 and so on, until level G with 1 and for areas with no access to PT according to PTSQL with 0. The data points for each Austrian district in 2.2 are calculated by multiplying the share of the population in the district living in an area covered by a certain PTSQL. To give an example: in the Viennese district of Alsergrund, 91.4 % of the population live in an area covered with PTSQL A (multiplier 7) and 8.6 % in an area covered with PTSQL B (multiplier 6), this results in a public transport quality index of 6.91. The data source for motorization is the *Pkw-Bestand* of Statistik Austria from 2021. The data source for average income is the *Integrierte Statistik der Lohn- und Einkommensteuer* of Statistik Austria in 2019. The data point for the first district in Vienna is an outlier, shown in grey. The motorization rate in the first district is very high with 1,032 cars/1,000 inhabitants in 2021, which can be explained by the large number of companies in the inner city and the high share of company cars registered on companies that have their offices in the first district.

[2]regarding the number of trips, average values for weekdays in autumn

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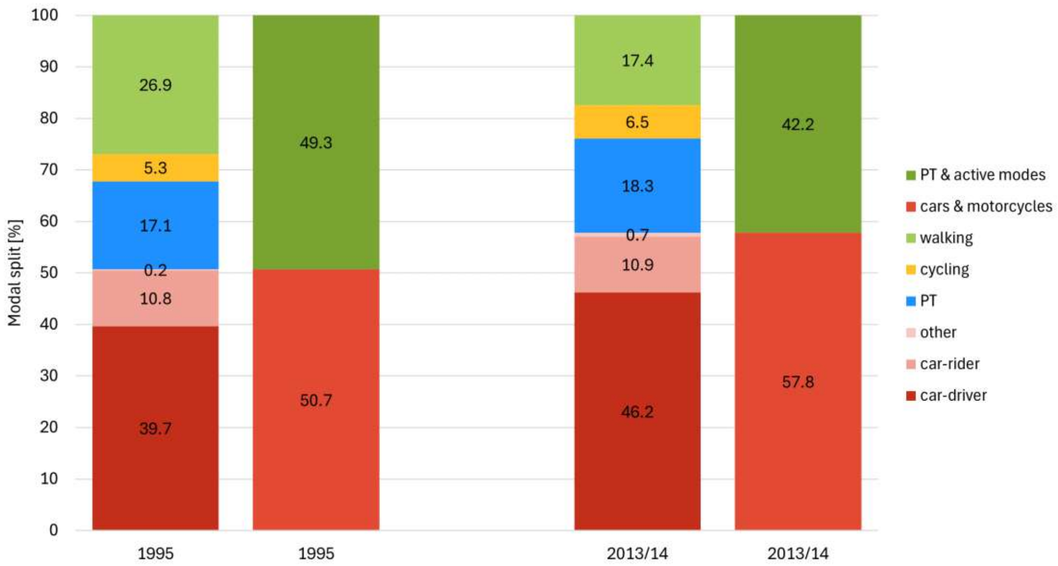


**Fig. 2.3:** Modal split on weekdays (own figure, based on Follmer, Gruschwitz, Kleudgen, et al. (2016))

In absolute terms, the largest increase of around 43 million person-kilometers on working days occurred among car drivers. In relative terms, this increase of approximately 37 % is lower than the percentage in rail transport, where it is approximately 48 %. Larger distances travelled by all means of transport except for walking is seen as a consequence of growing urban sprawl. A recent study by Brenner et al. (2024) showed the dramatic growth of urban sprawl with the area considered high or very high sprawl increasing fivefold in Austria between 1975 and 2020.

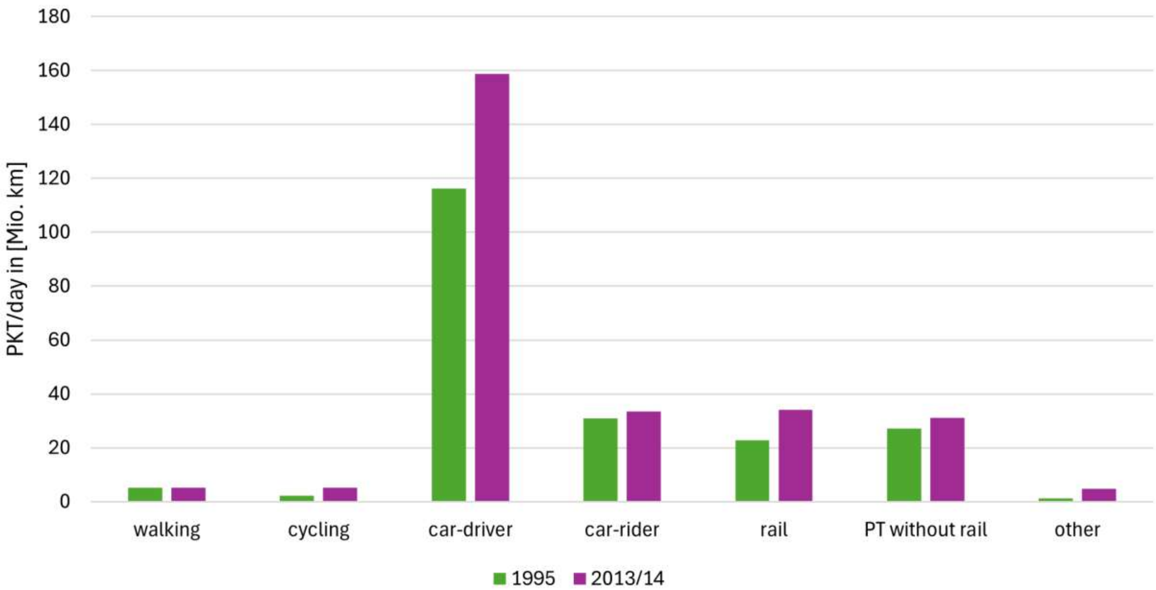


**Fig. 2.4:** Distances travelled per working day in Austria, per transport mode in 1995 and 2013/14 (own figure, based on Follmer, Gruschwitz, Kleudgen, et al. (2016))

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## 2.2 Infrastructure development in Austria

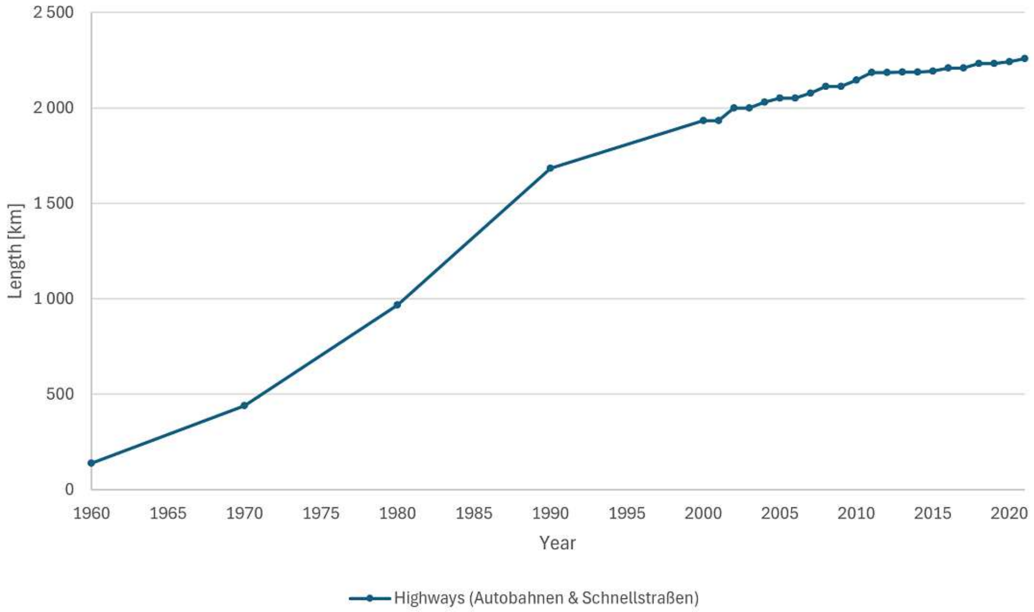


**Fig. 2.5:** Development of highway network in Austria (own figure, data from BMK (2023c))

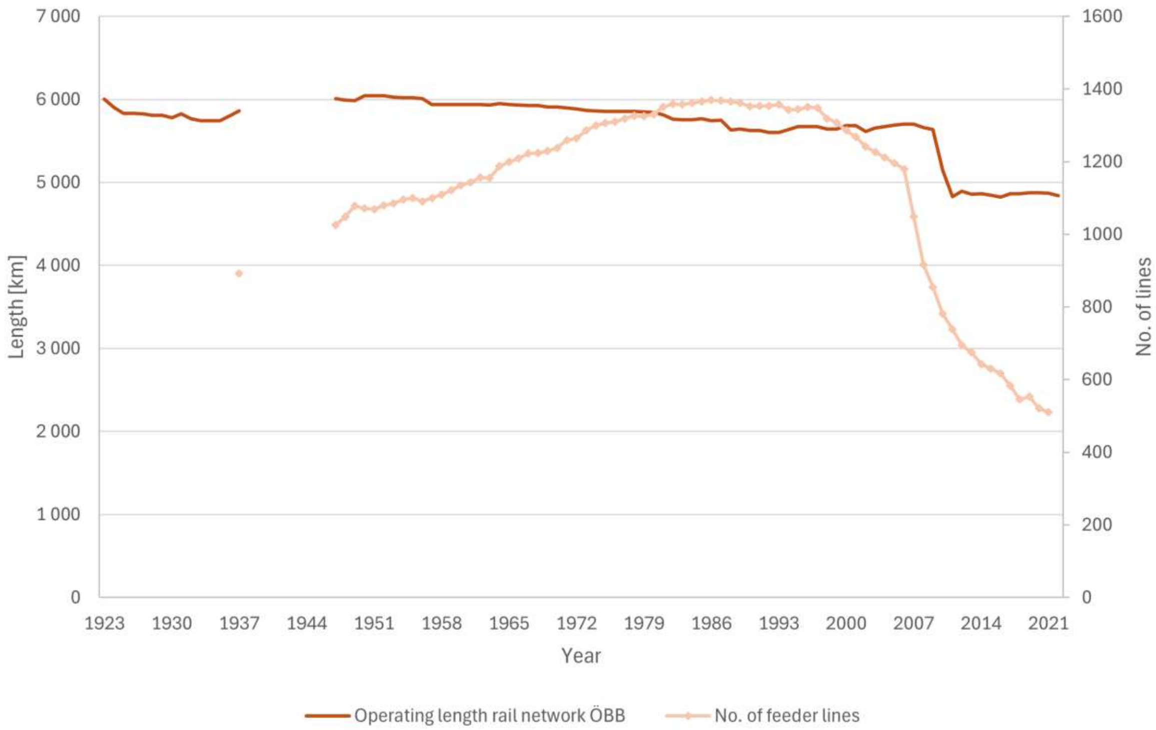


**Fig. 2.6:** Development of railway network in Austria: length of ÖBB railways and number of feeder lines (own figure, data from ÖBB Holding (2023))

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In the second half of the $20^{th}$ century, the focus of transport infrastructure provision changed from railways to car infrastructure. While the length of national roads (only highways i.e. *Autobahnen* and *Schnellstraßen*) increased from 139 km in 1960 to more than 2,200 km in 2020 (BMK, 2023c) (see Fig. 2.5), the length of the railway network of the Austrian State Railways ÖBB declined from 6,002 km in 1923 to 4,843 km in 2022 (ÖBB, 2022). The number of feeder lines, branching off the main railway network to loading stations and businesses increased continuously after World War II, peaking at 1,369 in 1986, followed by stagnation at around 1,300 connections until the late 1990s, and then a sharp decline, reducing to 782 feeder lines by 2010 and to 510 lines in 2021, see Fig 2.6.

## 2.3 Public transport coverage in Austria

Fig. 2.7 shows the results of an analysis by Schönfelder et al. (2021) on the share of inhabitants and employees in Austria within each Public Transport Service Quality Level (PTSQL) (Hiess, 2017, for methodology see also Section 3.1.7.2). Level A is the best and G the worst, with a minimum bus service every 4 hours in a maximum distance of 500 m or a minimum train service every 2 hours, in a distance up to 1,250 m from the home or workplace. The analysis shows that the share of population without access to public transport according to PTSQL is 15 % on weekdays during the school year and 20 % on weekdays during school holidays. Considering levels A - C as good quality PT, neither half of the inhabitants nor half of the employees are covered with such services.

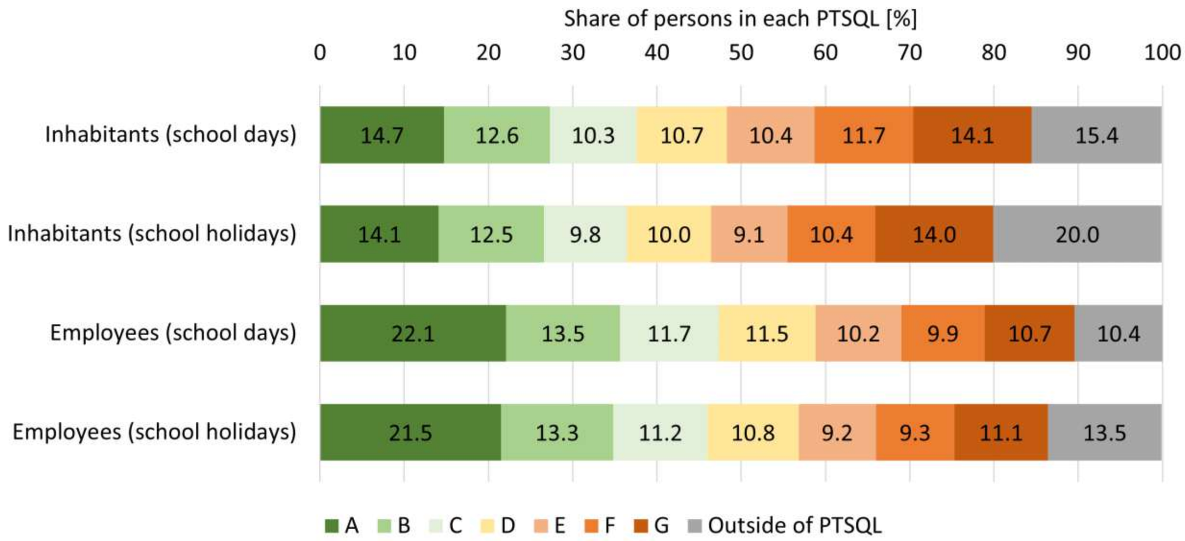


**Fig. 2.7:** Share of persons (inhabitants and employees) in Austria within Public Transport Service Quality Level (PTSQL) A (best) - G (worst) and outside; own figure, data from Schönfelder et al. (2021)

There is large spatial variation of the coverage with PT services, as shown in Fig. 2.8. Pink areas indicate municipalities that are totally covered by PTSQL classes A - G, while blue shaded areas indicate the share of population that is not covered with PT services according to the PTSQL assessment. Darker colours indicate that a larger share of inhabitants has no access to such PT services. Larger cities and valleys in mountainous regions are better served, whereas blue areas predominantly encompass rural regions, however with exceptions. Some rural areas,

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like those in Vorarlberg, have relatively high PT coverage. Conversely, certain less rural areas, such as the outskirts of the capital city Vienna, exhibit limited PTSQL coverage. (Laa et al., 2022)

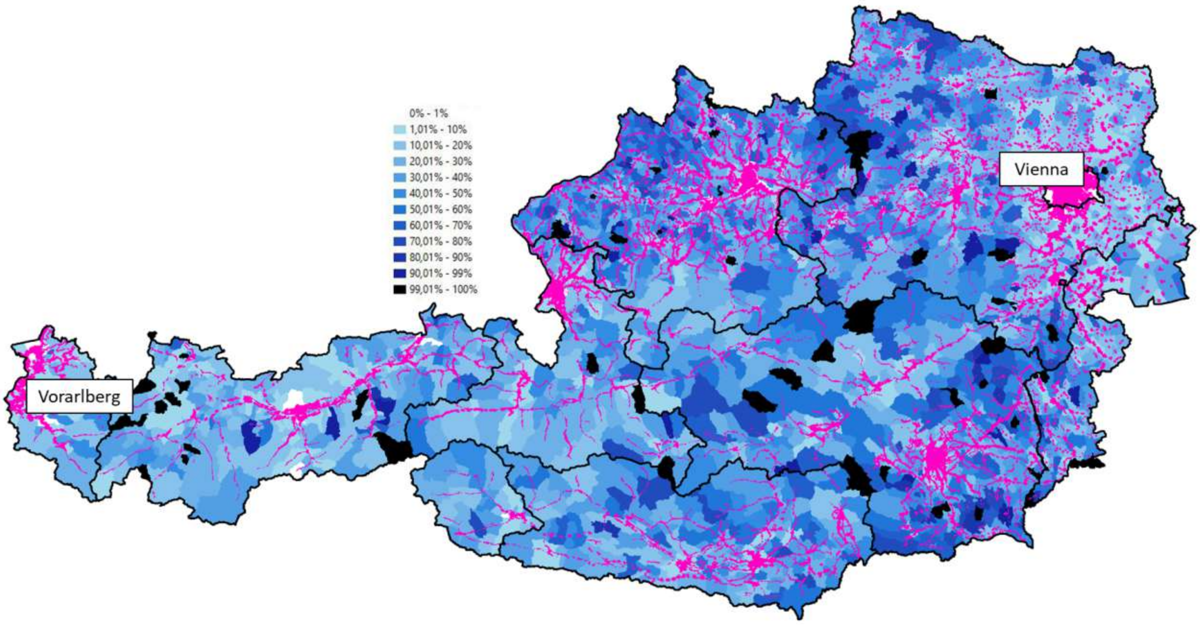


**Fig. 2.8:** Public transport coverage of inhabitants in Austria according to PTSQL, on a typical weekday. Pink areas are covered by PTSQL A-G, blue shaded areas show the share of inhabitants on municipality level that are not covered with public transport according to PTSQL; figure from Laa et al. (2022)

Friedwanger et al. (2018) made an assessment of average travel time to reach regional and supra-regional centers, comparing trips with PT and trips with private motorized transport (such as a car) for all districts in Austria. The overview of average travel times per province are shown in Tab. 2.1. With the exception of Vienna, average travel time by PT is longer in all provinces, with ratios of PT/car ranging from 1.28 to 1.99. Individual districts, however, show even larger ratios such as 3.3 in the district Jennersdorf in Burgenland to reach a regional center and 2.7 in Oberwart in Burgenland to reach a supra-regional center. Some concepts for mobility guarantees and PT quality standards define maximum ratios of travel time by PT compared to car travel (see Section 3.1.5.4 and 3.1.7.4). Recommended maximum ratios range from 1.3 to 1.5. In Austria, the 1.3 limit is currently only reached by the average values for Vienna and Vorarlberg.

## 2.4 Car dependence in Europe and Austria

While Europe, and especially European cities, are often referred to as pioneers of sustainable mobility, Mattioli (2021) demonstrates that European transport systems exhibit high levels of car dependence and even show an increasing trend. There is, however, a large variation between countries and across the urban-rural spectrum. The level of car dependence can be assessed by

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**Tab. 2.1:** Average travel time by private motorized transport (car) and PT, from Friedwanger et al. (2018)

| Comparison private motorized transport (car) and PT - average travel time in a regional center<br>Workday during school holidays, arrival 7 a.m. - 11 a.m. (data from 2016) | | | | | | |
|---|---|---|---|---|---|---|
| **Province** | **Travel time to regional center [min]** | | | **Travel time to supra-regional center [min** | | |
| | **Car** | **PT** | **Ratio PT/Car** | **Car** | **PT** | **Ratio PT/Car** |
| Burgenland | 12.7 | 25.3 | 1.99 | 34.5 | 62.5 | 1.81 |
| Carinthia | 16.3 | 25.6 | 1.57 | 31.3 | 43.8 | 1.40 |
| Lower Austria | 15.4 | 24.4 | 1.58 | 31.9 | 44.3 | 1.39 |
| Upper Austria | 12.9 | 22.7 | 1.76 | 31.2 | 45.4 | 1.46 |
| Salzburg | 12.9 | 20.1 | 1.56 | 39.2 | 54.2 | 1.38 |
| Styria | 14.4 | 23.8 | 1.65 | 35.8 | 50.6 | 1.41 |
| Tyrol | 17.1 | 23.7 | 1.39 | 41.6 | 56.1 | 1.35 |
| Vorarlberg | 16.5 | 21.2 | 1.28 | 16.9 | 21.1 | 1.25 |
| Vienna | 9.9 | 9.1 | 0.92 | 11.4 | 11.1 | 0.97 |
| **Total Austria** | **13.7** | **20.1** | **1.47** | **28.6** | **38.5** | **1.35** |
| **Total Austria without Vienna** | **14.7** | **23.5** | **1.60** | **33.3** | **47.0** | **1.41** |

data on car usage, perceptions of car ownership as a necessity of social inclusion and low quality of alternative modes of transportation. While the analysis by Mattioli (2021) provides a good overview of car dependence and transport poverty in Europe, for the purpose of this introduction, I will refer only to some of the relevant statistic for the EU and highlight Austrian data.

In 2014, 82 % of EU-28 residents had a driving license (Fiorello et al., 2016). In Austria, the share of people with a driving license has increased from 55 % in the 1980s to more than 80 % in 2014 (Follmer, Gruschwitz, Kiatipis, et al., 2016). The increase can mainly be attributed to the large increase in women obtaining driving licences, even though gender disparities still remain with 88 % of men and 75 % of women holding a driving license. In Austria, 79 % of households have at least one car. 45 % of households possess one car, 25 % 2 cars and 9 % of households have 3 or more cars (anaylsis by Schönfelder et al. (2021) based on Follmer, Gruschwitz, Kiatipis, et al. (2016)). On the other hand, only 21 % of persons over the age of 15 own a monthly or annual pass for PT (Follmer, Gruschwitz, Kleudgen, et al., 2016). The capital city of Vienna is an exception, with more than 50 % ownership rate of PT monthly or annual passes.

A survey conducted by the EC looked at the travel habits of people in the EU (European Commission, 2013). Results show that on average 76 % of the population use the car at least once a week, 50 % use the car at least once a day and 12 % never use a car. For Austria, 81 % of respondents use the car at least once a week, 57 % at least once a day and only 8 % never. A 2007 survey in all EU countries (European Commission, 2007) asked if people think that a car is necessary to have a decent standard of living in that country. In most countries more than 50 % agreed to that question with an average of 51 % (although only 36 % in Austria). Reasons car users cite for not using PT instead are lower perceived levels of convenience (74 %), lack of connection (72 %), low frequency of services (64 %) and lack of reliability (54 %) (Mattioli, 2021 based on European Commission (2011)).

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## 2.5 Conclusion

The number of people owning a car and using one in everyday life has grown rapidly in the past decades in Europe and Austria. Although a trend to decreasing motorization rates can be observed in inner city districts, in rural areas the trend of increased car use and dependence seems to continue. Overall, mobility behaviour in Austria, as shown in modal split and distance travelled, relies heavily on the use of private cars, especially in rural areas. The provision of high quality public transport is associated with lower levels of car use and car dependence. In conclusion, car dependence is an issue in the EU and Austria, although with high disparities between urban, suburban and rural areas.

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# Chapter 3

# Defining the Sustainable Mobility Guarantee

In this chapter, I first present a literature review of different types of existing mobility guarantees and related concepts (Section 3.1) as well as different approaches to assess quality standards for public transport. This, together with results from stakeholder workshops (Section 3.2) and an analysis of the legal framework in Austria (Section 3.3), serve as the basis for defining the Sustainable Mobility Guarantee as understood in this study. This definition is described in Section 3.4 and 3.5. Then, the implementation scenarios are presented (Section 3.6), followed by Section 3.7, which deals with the limitations of the SMG.

## 3.1 Literature review on existing concepts of mobility guarantees

The objective of the literature review was to gain knowledge on different existing concepts and to compare and classify them. The literature review was guided by the research question: *Which different definitions of mobility guarantees or related concepts exist?* This should serve as the basis for the definition of an SMG in this study and give hints to aspects that should be addressed in the assessment.

Four electronic databases were searched, two of which only included academic peer-reviewed articles (Web of Science Core Collections and Scopus) and two of which also include non-reviewed articles and grey literature (TRID - Transport Research International Documentation and Google Scholar). The searches started with the earliest possible date of the databases up until 20 July 2022. Non-peer-reviewed and grey literature was included since the idea of a mobility guarantee is relatively new and academic research on the topic is still quite rare.
The following keywords and string combinations were searched:

- "mobility guranatee"
- "mobility service guranatee"
- public transport quality level
- mobility standards for rural areas

Grey literature was identified through snowballing in reading the literature as well as internet search engines (google.com) and exchange with academic colleagues and mobility experts. For example a report on the concept of a mobility guarantee in Germany was published only in August 2023 (Agora Verkehrswende, 2023a) and added to the literature review after completing the initial search of academic publications in 2022. Furthermore, it is crucial to note that the scope of the reviewed literature is constrained by the proficiency of the author and co-workers in specific languages - specifically English, German, French, and Japanese. As a result, the case studies considered are confined to regions where these languages are prevalent, such as Europe, North America, and Japan. Articles and reports were eligible if they included a definition of a mobility guarantee or addressed related concepts such as quality criteria for public transport systems, laws guaranteeing mobility services or pilot projects for mobility guarantees.

A preliminary literature review and definition of the Sustainable Mobility Guarantee were presented and discussed at the World Conference on Transport Research (WCTR) (Shibayama & Laa, 2023), parts of it have been published by Shibayama and Laa (2024) and developed further for this thesis.

### 3.1.1 Guiding questions and classification criteria

In everyday language, a guarantee refers to a formal promise that specific conditions will be met or certain events will occur (Shibayama & Laa, 2024). It is mostly used as an assurance that a product will be repaired or replaced if a certain quality or functionality is not met. This may be mandated by law or provided voluntarily by manufacturers and is commonly referred to as a warranty when the guarantee is presented in written form. Other examples include "price match guarantee" or "best price guarantee", where retailers pledge to match competitors' prices for the same product. In finance and real estate, the term guarantee refers to an obligation to cover debt payments or assume payment responsibilities in the event of a default by the primary debtor. In constitutional law, the term guarantee can refer to the incorporation of fundamental rights into law as constitutionally protected rights, such as human rights (Constitutional Court of Austria, n.d.).

A key feature of a guarantee is the promise that something will be carried out or occur by one party for another (*Who guarantees what for whom?*). As is the case of product warranty, a guarantee can be given with temporal, spatial or other limitations (*Where and when is the guarantee given?*). The methods for implementing a guarantee efficiently and effectively may vary (*How is the guarantee implemented?*). Additionally, justification or reasoning for providing the guarantee can be offered (*Why is it guaranteed?*).

The questions written in italics were used as guiding questions for analysing and classifying the reviewed examples of mobility guarantees. They are referred to as the "6W1H"-framework ("Who", "What", "for Whom", "When", "Where","How" and "Why"). The guiding questions are summarized here again:

- *Who* guarantees *what* for *whom?*
- *Where* and *when* is the guarantee given?
- *How* is the guarantee implemented?
- *Why* is it guaranteed?

### 3.1.2 Overview of case studies and classification

Table 3.1 shows an overview of the analysed case studies. In the course of the analysis, three distinct types of guarantees could be discerned: specific guarantees with reimbursements, legal approaches and policies in the form of strategies, programs and concepts. Results of the literature review of existing mobility guarantees are presented in the following sections following these categories. Results can be visualized along the spectrum of answers to each question, as depicted in Fig. 3.1

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**Tab. 3.1:** Overview of different mobility guarantee approaches

| Where | | Name | Why & what & for whom | How | When | Year of first implementation /publication |
|---|---|---|---|---|---|---|
| Country | Level | | Objective / problem addressed | Approach | Validity period | |
| USA | Specific | Guranteed Ride Home-programs | Reimbursement of a taxi trip in case of cancellation of ride-sharing for return trip, usually by company for commuting | Cost reimbursement | Single ride | 1980s |
| France | Specific | Return trip guarantee covoiturage regulier | Companies/transport agencies cover an alternative service if ride-sharing is unexpectetly not available | Cost reimbursement | Single ride | 1980s |
| | National | Mobility Orientation Law | National law to ensure everyone's right to mobility and choice, promote health, and provide accessible, high-quality, and affordable transportation while reducing risks, noise, and pollution. | Legal | General | 2019 |
| Germany | Specific | Rural mobility guarantee Odenwaldkreis | Local taxis serve as DRT to guarantee trips from the current position of users to the next basic center or middle center of the district | DRT services | Operating hours | 2017 |
| | Specific | Reimbursement for cancelled PT services | Transport associations offer reimbursement in case of delay or cancellation | Cost reimbursement | Single ride | 2010 |
| | National | Demand for right to mobility house connection | A proposed consitutional right guaranteeing PT access for residences similar to existing utilities, with specific criteria for service frequency, travel times, and stop proximity | Legal | Operating hours | 2011 |
| | City | Berlin Mobility Law | City law to ensure mobility for main travel purposes (1) every day for 24 hours, (2) equally in all parts of Berlin and (3) independent of age, gender, income, and personal mobility impairments as well as of life situation; prioritzation of walking, cycling and public transport | Legal | General | 2018 |
| | Regional | Pilot project accessibility standards in rural districts | 18 rural pilot regions tested minimum access standards on the district level to secure mobility of rural areas | Pilot project | Operating hours | 2016 |
| | Regional | Baden-Württemberg Mobility Guarantee | Provincial government policy to guarantee minimum standards in PT | Pilot project | Operating hours | 2021 |
| Austria | National | National Mobility Guarantee strategy | National government policy to ensure sustainable mobility throughout the country with an hourly, all-day transport service in urban and rural areas through various mobility services | Policy manifestation | General | 2020 |
| | National | Transport Targets Law | Proposed federal law to establish minimum standards for public transport and cycling infrastructure by 2030 | Legal | Operating hours | 2021 |
| Latvia | National | National policy for PT targets | National policy targets for PT; minimum quality standard of PT and minimum frequency | Policy manifestation | *unknown* | 2013 |
| Switzerland | National | Swiss mobility laws | National laws and regulations for availability and accessibility of quality and affordable service for all social classes in all regions | Legal | Operating hours | 2004 |
| Belgium | Regional | Accessibility regulations Flanders | Basic mobility regulation guaranteeing minimum PT services | Legal | Operating hours | 2001 |
| Japan | National | Basic Act on Transport Policy | National law to implement well-planned, integrated transport policies to stabilize lives and the economy, ensuring non-automobile options, barrier-free facilities, security, safety, punctuality, support for local economies, and reduced environmental and disaster impacts. | Legal | General | 2013 |

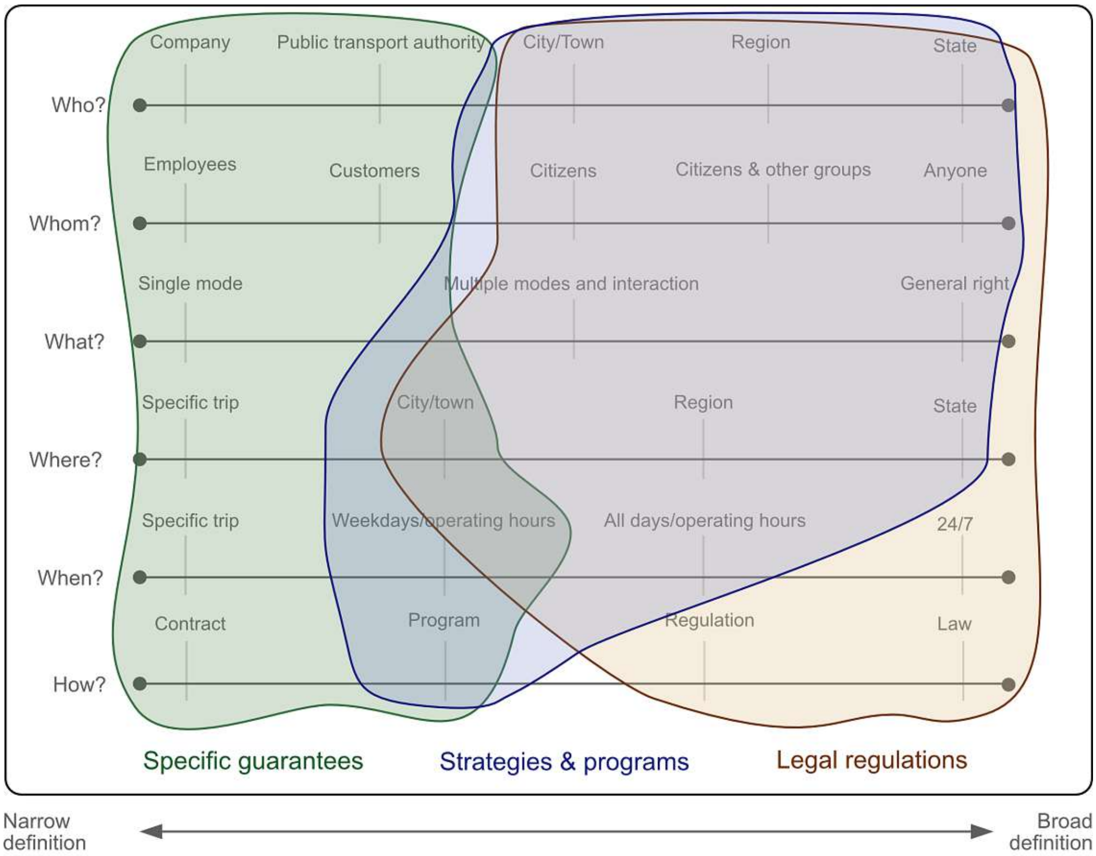


**Fig. 3.1:** Classification of mobility guarantees

### 3.1.3 Specific guarantees with reimbursements

Examples on the more narrow side of the spectrum of mobility guarantees are granted for specific travel purposes and/or usually as a reimbursement in case of a service cancellation or emergencies. Due to the narrow scope, it is mostly well defined who guarantees what for whom, when and where - usually as part of a contract.

#### 3.1.3.1 Guarenteed Ride Home programs in the USA

The "Guaranteed Ride Home" (GRH) programs have been established in the USA since the 1980s. They reimburse taxi trips in case of emergency or cancellation of another mobility service such as PT services or carpooling. Such guarantees can be organized and financed by transport associations, transport operators, cities or individual companies. They aim at reducing the use of private cars for commuting in minimizing the perceived risk of "being stuck" if an alternative transport service is not available for the return trip or an emergency trip (Kuzmyak et al., 1993; Schönfelder et al., 2021). Usually, full costs are reimbursed for registered users for a certain contingent (e.g., four times per year or up to a monetary limit). In the beginning of the 2000s, about half of US transport associations offered a GRH program (Haas, 2005). Menczer (2007) analyzed 55 such programs that serve the top 150 transit agencies in the USA. He found that only 4 - 5 % of registered commuters made use of the reimbursement. The average cost per claim was ca. USD 37 and the average cost per registered commuter was USD 31.69. Such programs are seen as a way of promoting PT use and ride sharing, although the effect on overall transport behavior seems to be low (Polena & Lawrence, 1991).

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#### 3.1.3.2 Return trip guarantee - Covoiturage Régulier in France

Similarly to GRH programs, "*Covoiturage Régulier*" (regular carpooling) programs in France target commuters for their daily trips to and from work and offer a "return trip guarantee" in case that the planned carpooling trip is not available. This means a free alternative service such as a ride with a different carpooling driver, a PT service or a taxi trip. (ADEME, 2017, p.50)

Such carpooling programs can be offered by transport associations or individual companies who offer booking platforms to their customers or by companies who offer the services to their employees. According to ADEME (2017), the return trip guarantee is hardly ever needed and used. A recent initiative is the "M'Covoit-Lignes+" in the region surrounding Grenoble.[1] It is a service of carpooling supported by private car drivers but with fixed routes and stops. Carpooling users benefit from an HOV-lane[2] reserved for them on the fixed routes. The guarantee is granted by the local transport association (Syndicat Mixte des Mobilités de l'Agglomération Grenobloise) during peak-hours (6.30 a.m. - 8.45 a.m. and 4.30 p.m. - 6.30 p.m.). (Maleysson, 2021)

#### 3.1.3.3 Rural mobility guarantee for specific trips in Odenwaldkreis, Germany

A German initiative that uses the term "mobility guarantee" is the project *"garantiert mobil!"* (guaranteed mobile) in the rural district of Odenwaldkreis in the south-west of Germany (in the province Hesse) that has been operational since 2017. It is based on commercial and private carpooling as an addition to conventional PT services. The guarantee aspect is covered by DRT (Demand-responsive transport) services of a local taxi company. The service covers the whole district and guarantees trips from the current position of customers to the next basic center or the next middle center of the district. Services can be booked up to 60 min. before the trip starts through the website or smartphone application of the regional transport association or with a telephone call. Operating hours are limited to 5 a.m. - 10 p.m. on weekdays, 6 a.m. - 10 p.m. on Saturdays and 8 a.m. - 10 p.m. on Sundays and holidays. Costs for a trip are based on the local PT tariff but with a surcharge for taxi trips depending on the distance travelled. (Krämer, 2019; Schönfelder et al., 2021)

#### 3.1.3.4 Reimbursement of alternative trips for cancelled PT services in Germany

Some transport associations in Germany provide reimbursements to passengers whose public transport connection was canceled or missed due to a delay, referring to this as a mobility guarantee (Schiefelbusch, 2011). This is usually regulated in the transport contract or in the terms and conditions.

One such example can be found in the province of North Rhine-Westphalia. In case of delays that exceed a certain threshold or if bus services are cancelled, travellers can use taxis or car-sharing services in order to reach their destination. The cost of such services are reimbursed by the transport company responsible for the delay or cancellation. (mobil.nrw, n.d.)

### 3.1.4 Policies - strategies, programs and concepts

Under the term policies, I subsume several different approaches that have a broader scope of the guarantee but that are not legally defined. There are examples of strategies, programs (often pilot projects) and rather theoretical concepts, that fall into this category. In general, they

[1] https://www.lignesplus-m.fr, accessed 20.05.2023
[2] HOV (High-Occupancy Vehicle) lanes are highway lanes for vehicles with multiple occupants, often allowing carpool vehicles, motorcycles, buses, and low-emission vehicles, with fines for unauthorized use.

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focus more on *What* to guarantee as well as *When* and *Where*, but do not always specify *Who* guarantees the services *for Whom*.

#### 3.1.4.1 Austrian strategy for a nationwide mobility guarantee

The current federal government of Austria has put the creation of a nationwide mobility guarantee on the political agenda (Bundeskanzleramt, 2020). They formulated the goal to ensure sustainable mobility throughout the country, with an hourly, all-day public transport service in urban and rural areas through various mobility services (train, bus, tram, car sharing, DRT, shared taxis, ride-sharing platforms, etc.). The Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (short BMK) commissioned an exploratory study (FLADEMO)[3] in order to gain more knowledge about possible designs and impacts of such a guarantee. However, no additional official policy on the matter has been published to date.

First results of the FLADEMO project concerning the definition and design scenarios have been published by Laa et al. (2022). They developed a framework definition for such a nationwide guarantee and different design scenarios for further analysis of potential impact and implementation challenges. Their concept spans traditional PT, DRT services and infrastructure for active mobility with defined quality standards. For the analysis of current PT provision, Laa et al. (2022) used the ÖROK classification system for PT Service Quality Classes (PTSQL, see also 3.1.7). The results of the FLADEMO project serve as a basis for the definition of a Sustainable Mobility Guarantee in this thesis.

In 2022, an "Assembly for Climate Action" - a citizen assembly that was commissioned by the Austrian government - formulated measures for a "climate-healthy future" as recommendations for the government. The Assembly consisted of 100 Austrians chosen to represent the population in terms of socio-economic characteristics. One of the measures that they formulated can be interpreted as a mobility guarantee. The Assembly recommended to implement PT services that can be accessed within a maximum walking distance of 15 minutes, 24 hours a day, 7 days per week, in cities as well as in regions. (ARGE Klimarat, 2022)

The federal administration assessed the implementation of the suggested measures and responded to the recommendations of the Climate Assembly (BMK, 2022). Regarding the mobility guarantee, they highlighted the limitations of the federal government in implementing such a guarantee due to the different levels of responsibility in Austria (BMK, 2022, p. 102). Municipalities and the nine provinces (*Bundesländer*) are responsible for infrastructure planning and mobility services, with limited competences of the federal government.

#### 3.1.4.2 National policy of Latvia

In Latvia, national policy concerning targets for public transport is published by the Transport Ministry for 6-year-periods in the form of Transport Development Guidelines (OECD, 2000). The Guidelines for the period 2014-2020 (Latvia Ministry of Transport, 2013) specified minimum quality standards for PT to ensure high-quality mobility opportunities throughout the country. All rural areas should have a minimum of two PT connections per day to a municipal center, and every municipality should have at least two PT connections per day to the regional center or capital. The new guidelines for 2021-2027 do not include such minimum standards. Instead, they emphasize MaaS-type measures aimed at creating integrated transport services. It is for example envisaged to create a nationwide unified ticketing service and mobility points to increase

[3] Project FLADEMO - Flächendeckende Mobilitäts-Servicegarantie: https://projekte.ffg.at/projekt/3992976. For final report, see Shibayama et al. (2022)

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PT attractiveness. Furthermore, they want to establish a National Mobility Data Access Point. (Latvia Ministry of Transport, 2020)

#### 3.1.4.3 German national policy, nationwide concept and pilot projects of mobility guarantees

A 2023 two-part report by Agora Verkehrswende (2023a, 2023b), summarized the legal basis, policy discourse, pilot projects and existing quality standards regarding PT in Germany and proposes a "nationwide mobility guarantee" covering PT services. The German legal system refers to basic services as part of the welfare state (Art. 20 Abs. 1, Art. 28 Abs. 1 GG) and explicitly mentions "adequate provision of local public transport services" as a responsibility for the provinces (§1 RegG) and that "the accessibility of facilities and basic services for all population groups, must be adequately guaranteed" (§2 Abs. 2 Satz 3 ROG). However, there is no specification of what adequate means. The German federal consumer advice center has been demanding a right to a "mobility house connection" (*Hausanschluss Mobilität*) since 2011 (Rödl & Partner, 2020). This is described further in Section 3.1.5.4.

Some German provinces have established accessibility standards, but they are not legally binding and PT supply in the provinces differs a lot (Gipp et al., 2020). Those standards usually correspond to the guidelines of FGSV and VDV guidelines (see also Section 3.1.7.4). The German government committed in their coalition paper (Bundesregierung, 2021) to defining quality standards for everyday mobility together with the provinces and municipalities in order to create a full alternative to individual motorised transport and equal living conditions in all regions. However, this has not been implemented so far (status end of 2023).

More concrete concepts and pilot projects in Germany are described in the following. The think tank Agora Verkehrswende suggests a nationwide mobility guarantee for PT and several pilot projects in rural areas have been implemented.

##### Agora mobility guarantee for Germany

The German think tank Agora Verkehrswende published a two-part analysis and recommendations for a "Mobility guarantee for Germany" (Agora Verkehrswende, 2023a, 2023b). The suggested guarantee covers nationwide basic services by bus and rail with minimum standards of the following aspects (Agora Verkehrswende, 2023a, p. 22):

- **Guaranteed intervals**, e.g. hourly services or DRT
- **Guaranteed operating hours**, e.g. 06:00 - 22:00 on weekdays
- **Guaranteed access**, e.g. for all municipalities with more than 200 inhabitants
- **Guaranteed destinations**, e.g. trips to the next center

##### Pilot project of accessibility standards in rural districts

During a project supported by the German Federal Ministry of Transport and Digital Infrastructure, 18 rural pilot regions tested minimum access standards on the district level between 2016 and 2018 (German Federal Ministry of Transport and Digital Infrastructure, 2018). The main objective was to secure the supply and mobility of rural areas in the long term, facing demographic changes. While all of the pilot regions made their own accessibility analysis of the status quo and developed their own mobility concepts, there were several meetings where they received input and exchanged their work as part of the project.

All regions adopted a layered approach similar to the one in Flanders (see Section 3.1.5.7), consisting of three layers: main connections (e.g., rail or regional bus services), secondary

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connections (linking regional centers), and feeder lines that connect towns to these centers. While the first two layers are designed to be served by PT with fixed routes and schedules, the local feeder services can vary more. The report by the German Federal Ministry of Transport and Digital Infrastructure (2018) highlights modes of transport for local feeder services, including DRT services, shared taxis, community buses, park and ride facilities, carpooling, cycling infrastructure, and shared public vehicles.

The minimum standards of mobility services were defined differently in each region. In the Bautzen/Görlitz district in Saxony, for example, the first layer offers a minimum interval of hourly services on weekdays, the second layer a 2-hour interval and the third layer consists of DRT services. The regions also defined quality criteria for maximum distances to PT stops - e.g., in Holzminden 1,500 m to train stations and 500 m to bus stations.

The districts introduced measures to reach the objectives on each of the three layers. In addition, some of the pilot regions implemented IT services such as mobile applications as booking platforms and some developed mobility hubs for connecting different modes of transport. Target group for the project were the inhabitants, however, the services are open to anyone travelling in the regions. (German Federal Ministry of Transport and Digital Infrastructure, 2018)

#### Baden-Württemberg mobility guarantee

The German province of Baden-Württemberg decided in 2021 to realize a "mobility guarantee". This was manifested in the coalition contract of the current government (BÜNDNIS 90/DIE GRÜNEN und CDU, 2021). The province selected 13 pilot regions for implementation, where accessibility standards of PT are planned to be implemented. Standards include a minimum 15-minute-interval in agglomerations and a 30-minute-interval in rural areas for operating hours between 5 a.m. and midnight (Staatsministerium Baden-Württemberg, 2022). The goal was to implement such a guarantee for workday peak-hours until the end of the legislative period in 2026. The goal, however, had to be postponed to the year 2030 due to a shortage of bus drivers.[4]

### 3.1.5 Legal approaches

Legal approaches of mobility guarantees can be found on the national level in Switzerland, France and Japan as well as on a more local level in the German capital Berlin and the Belgian region of Flanders. Proposals of new similar laws can be found in Germany with the right to a mobility house connection and a Transport Targets Law for Austria, proposed by one of the opposition parties in parliament. The laws usually define minimum standards or targets to be reached for PT services or other transport modes.

#### 3.1.5.1 Swiss mobility laws

Switzerland implemented legal regulations for basic mobility services on several levels. Firstly, the Federal Council defined the term "public service" (*Service public* in French and German) which represents the basic provision of infrastructure goods and services, that should be accessible to all social classes and regions of the country, based on the same principles, in good quality and with fair prices (Schweizer Bundesrat, 2004). This includes the post, telecommunication, and roads as well as public transport. The principle, that basic services must be available to all people in a comparable manner is also laid down in the Swiss Constitution (Art. 431 Abs. 4).

Secondly, minimum standards for public transport services are defined in order to guarantee PT access for the whole country. The federal Public Transport Act (*Personenbeförderungsgesetz*)

[4] See https://www.swr.de/swraktuell/baden-wuerttemberg/personalmangel-mobilitaetsgarantie-in-bw-kommt-spaeter-100.html

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mandates that transport operators must comply with minimum standards (Article 18, Paragraph 1b). Those standards are defined by the Federal Council and are laid down in the Offer Regulation (*Angebotsverordnung*) which applies to PT on rail and road. The quality standards are defined with reference to population density. It is mandatory to provide at least one PT station if a settlement area has a minimum of 300 inhabitants, work- and educational places (Article 4, Paragraph 1). Maximum distance to PT stops is defined according to the rank of PT service with 400 m for the secondary PT network and 750 m for major PT axes (Article 5). Operating hours are set from 6 a.m. to 0 a.m. (Article 8).

#### 3.1.5.2 French mobility orientation law

The French mobility orientation law LOM (*Loi d'orientation des mobilités*) - which was passed in December 2019 - is a comprehensive law for the future mobility strategy of the country and includes aspects of a sustainable mobility guarantee. The LOM includes amendments to several other French laws. Article L1111-1 of the French Road Code (*Code des transports*) was changed to specify that mobility across the country must be organized to meet user needs and ensure the right of every individual to mobility and the freedom to choose their mode of transport. This explicitly includes people with reduced mobility or disabilities and extends to active modes of transport. The text further states that this goal must be achieved under the most advantageous economic, social, and environmental conditions for the public, while also aligning with objectives to combat sedentary lifestyles and reduce risks, accidents, nuisances (especially noise), pollutant emissions, and greenhouse gases. Article L1111-2 of the Road Code was changed by the LOM to clarify that the implementation of the right to mobility must enable users to travel under reasonable conditions of access, quality, price, and cost for the public, particularly when using publicly accessible transport modes. The LOM thus represents a comprehensive approach that guarantees the right to mobility while adhering to social and environmental objectives. It establishes specific measures for active mobility infrastructure and gives special reference to multimodal, connected and innovative mobility services. However, since it is a quite recent law, it is not yet clear what the impact will be in practice. Legal scholars criticize that the LOM mostly refers to other laws and did not establish a new legal framework for mobility. The impact in practice is questioned since the formulations in the legal text are rather general and local regions and communities are responsible for implementing the federal law. (Izembard, 2020; Schönfelder et al., 2021)

#### 3.1.5.3 Japanese legislation on mobility service quality

The Japanese Basic Act of Transport Policy[5], while not explicitly using the term "guarantee", sets similar goals. The objective of the law is to *"implement transport policy measures in an integrated and well-planned manner to stabilize people's lives and national economy"* (Article 1). In its Part 2, the act outlines various aspects to be ensured by the national government, including non-automobile means of transport for everyday activities, barrier-free transport facilities, safety and hygiene of public transport, convenience and seamlessness of services, logistics infrastructure for local economic development, disaster impact mitigation, and environmental impact reduction in the transport sector. This act primarily concentrates on ensuring the socio-economic functions of the transport system with a significant emphasis on maintaining the service level and quality of public transport and active modes, while the sustainability aspect of transport is somewhat limited.[6]

[5] Kotsu-Seisaku-Kihon-hou, 2013 Act. No. 92, URL: https://elaws.e-gov.go.jp/document?lawid=425AC0000000092 (accessed 04.01.2024)

[6] The Japanese law was analyzed together with the native speaker Takeru Shibayama.

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#### 3.1.5.4 German concept for a right to a mobility house connection

Following an approach that is common for properties or houses to be connected to water and energy grids, Schwedes and Daubitz (2011) developed a concept for a universal basic service as a “mobility house connection” (*Hausanschluss Mobilität*). The mobility house connection applies the logic of guaranteed network connection to public transport, guaranteeing a certain connection by bus, rail or DRT to houses. As described in Section 3.1.4.3, the German federal consumer advice center (*Verbraucherzentrale Bundesverband*) has been demanding a right to such a mobility house connection since 2011. An expert report from 2020 (Rödl & Partner, 2020) made suggestions on how to implement such a right in the constitution. The guarantee should therefore include the following aspects:

- Connection for all municipalities with at least 500 inhabitants
- Hourly services from 6 a.m. to 10 p.m. on weekdays
- Maximum travel times should not exceed 1.3x travel time by car
- Maximum distance to PT stop of 300 metres for at least 80 % of the inhabitants
- DRT services can be implemented as an alternative to traditional PT lines

For implementation, the authors recommend additional financing instruments and new institutions for monitoring and fair distribution of funding. (Agora Verkehrswende, 2023a; Rödl & Partner, 2020)

#### 3.1.5.5 Austria - Proposal for a Transport Targets Law

In 2021, the oppositional social democratic party of Austria (SPÖ) made a proposal for a new federal law addressing what can be viewed as an SMG. They put forward a motion in parliament for a new law guaranteeing minimum standards in public transport and cycling infrastructure [7]. The motion has not been adopted or rejected yet, since it was postponed in all of the meetings of the transport committee (with the last one in October 2023). The minimum standards include:

- In all municipalities: Public transport minimum intervals of 30 min. between 5 a.m. and 12 p.m. (or a minimum of 34 trips in each direction) on weekdays, Sundays and public holidays
- In all district capitals: at least one train station or rapid bus (*Schnellbus*) station
- Train connections between regional capitals that are at least 20 % faster than by car
- Train connections between regional capitals and district capitals that are at least as fast as by car
- In rural areas: barrier-free transport with DRT with maximum 30 min. waiting time, in the diameter of 15 km of every residence
- Mobility hubs: PT stations with a frequency of at least 2,500 persons/day have to be adapted to include park and ride facilities, lockable bicycle parking and access to cycling lanes and DRT services

[7] Bundesgesetz, mit dem besondere Ziele für den Verkehr erlassen werden (Bundesverkehrszielegesetz, 2174/A XXVII. GP), https://www.parlament.gv.at/gegenstand/XXVII/A/2174

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- New residences have to be within a maximum distance of 500 m[8] to PT stations (starting in the year 2025)
- Cycling: along roads with at least 10,000 vehicles/day, a cycling path has to be built (until the year 2030)

#### 3.1.5.6 Berlin mobility law

The City of Berlin in Germany took a far-reaching legal approach, however on a more local level. After a citizen's initiative successfully launched a referendum to implement a cycling law (*Volksentscheid Fahrrad*) (Strößenreuther, 2019), the government issued the Berlin Mobility Law (*Berliner Mobilitätsgesetz*) (MobG BE, GVBl. 2018), which includes regulations not only for cycling but also for pedestrian traffic, "new mobility" and commercial traffic. The objective of the law is defined as the advancement of a safe, barrier-free transport system that is oriented towards the mobility needs of the city and its surroundings and is designed to be compatible with the city, the environment, society and the climate and to guarantee (*Gewährleistung*) equal mobility opportunities in all parts of Berlin. It is stated in the preamble that the law secures the priority of sustainable modes (the German term *Umweltverbund* is used, which includes walking, cycling and public transport).

The first section of the law is a general section describing the main objectives of the "goal-oriented integrated mobility guarantee" and the planning approach, which includes the creation of concepts for different transport modes. Regarding the guarantee aspect, it is stated that mobility for main travel purposes in Berlin shall be guaranteed (1) every day and around the clock, (2) equally in all parts of Berlin and (3) independent of age, gender, income and personal mobility impairments as well as of life situation (Paragraph 3, MobG BE, GVBl. 2018). Paragraph 5 includes rules for public transport data, which is seen as a basis for MaaS services.

Further sections of the Berlin mobility law outline more specific objectives for individual transport modes. For PT and walking, those objectives are formulated in a rather qualitative way. Regarding PT the goals are *"frequent, regular, punctual, fast, comfortable, environmentally friendly, barrier-free and secure services"*. Concerning tariffs, the needs for people with low incomes shall be considered. It is explicitly stated that PT should take priority over motorized private transport, particularly in terms of road space allocation and traffic light programming. There are no concrete minimum standards written in the mobility law, however, the law determines the parameters for the "local transport plan" (*Nahverkehrsplan*), where such standards are defined. The plan is enacted by the Berlin Senate and acts as both a political commitment and the foundation for contracts with PT operating companies.

The latest local transport plan is in effect for the period from 2019 until 2023 (Senatsverwaltung für Umwelt, Verkehr und Klimaschutz, 2019). The plan includes specifications for minimum intervals for PT lines, depending on time of day and mode (commuter rail, metro, tramway, bus), operating hours of PT depending on the mode and targets for the share of population that should have access to PT within a maximum distance to PT stops, depending on time of day and population density. In the current plan, maximum distances to PT stops range from 300 m to 500 m, PT intervals from 10 min (e.g. for the metro during peak hours) to 120 min (for regional trains at off-peak hours). Targets for PT coverage include that 80% of the population should have access to PT stops with 10 min intervals.

The section on cycling in the MobG includes very specific objectives, that emerged from the demands of the citizen's initiative. The goal is to create an encompassing cycling network covering all districts until the year 2030. The law states concrete objectives of how many

[8] Not specified if beeline or routed distance

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kilometres of cycling paths should be constructed per year and includes quality criteria - e.g. concerning dimensions, routes and surfaces. Regarding pedestrian traffic, it is stated that all people in Berlin should be able to reach their destinations using direct and connected pedestrian infrastructure. Additionally, the law includes paragraphs concerning target conflicts with existing regulations and it defines competences and additional financial and personnel resources for successful implementation.

#### 3.1.5.7 Flanders legal accessibility regulations

The Belgian region of Flanders has introduced a basic mobility legislation in the year 2001, guaranteeing minimum PT services including maximum distance to the nearest PT stop and frequency of services, depending on the area and time of day (peak/off-peak, work-week/weekend). "*For example, the maximum walking distance to a bus stop in a rural area was fixed at 750 metres. The operator had to offer at least two trips per hour during peak hours, one trip per hour during off-peak times and at least one trip every two hours at weekends.*" (ITF, 2021, p.48).

In 2019, a new Decree on Basic Accessibility (*Decreet betreffende de basisbereikbaarheid*) came into effect (Government of Flanders, 2019). This changed the approach from being supply-oriented to a more demand-oriented one and established 15 transport regions covering Flanders. Three layers of mobility are defined: (1) the core PT network umanaged by the Flemish government, includes rail and bus services that complement the federal train network; (2) the supplementary network, managed by the transport regions; and (3) flexible first- and last mile-services such as DRT and bike sharing, also under the responsibility of the transport regions. The Flemish government set up a Mobility Centre to collect and provide information and manage transport operators but the transport regions are responsible to choose transport offer on level 2 and 3 (supplementary network and first-/last-mile services).(Government of Flanders, 2019; OECD, 2000)

### 3.1.6 Summary of the literature review based on 6W1H framework

In the following, the results of the literature review are summarized based on the 6W1H framework presented in Section 3.1.1 on page 42.

#### Who guarantees what for whom?

Answers to the first 3Ws of *Who*, *What* and *for Whom* are usually interdependent due to scope and competences of public authorities. Who guarantees services for whom is also connected to the *Where* - the geographic scope, as city or regional government can only regulate their territoriality and provide services for people living, working or visiting this limited area. Specific guarantees are quite limited in their scope and answer the questions precisely, for example, carpooling programs where companies offer free return trips for commuting for their employees in case of an emergency or a dismissed carpooling service. In this case, also the *What* is clearly defined and usually corresponds to specific trips or routes. Broader concepts range from regions guaranteeing minimum standards of PT for anyone who is traveling in their territory to the state granting its citizens a right to sustainable mobility.

The *What* is not always defined in quantitative terms. However, if this is the case, usually there are minimum standards or quality criteria defined, that often correspond to established standards and guidelines, see also Section 3.1.7.

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### Where and when the guarantee is given?

The response to *Where* a guarantee is given corresponds often to who is offering the guarantee. This can range from specific trips and routes, to cities, regions, provinces or whole countries. Sometimes there is a defined minimum share (e.g. 80 %) of the population of the concerned territory that should be covered by the guarantee. Regarding the temporal aspect (the *When*), some - such as the City of Berlin - claim to offer a 24/7 guarantee, but it remains highly conceptual. Usually, there are operating hours defined, in which a service is provided, such as between 5 a.m. to 0 a.m. in the example of Baden-Württemberg. These operating hours, however, can also be different for workdays and weekends. Again, on the narrow end of the spectrum, specific guarantees apply only to specific trips and their time frame (e.g., only for commuting as part of Guaranteed Ride Home (GRH) programs).

### Why is it guaranteed?

Motives and reasons for *Why* the guarantee is granted differ between private benefit, social and/or environmental aspects and the conception of mobility as a basic right. GRH programs are seen as a way of promoting PT and ride sharing, although the effect on overall transport behavior seems to be low. However, the focus is primarily on the individual benefits of users.

The emerging concept of a Sustainable Mobility Guarantee goes beyond individual benefits and is rather motivated by combining social, economic, and environmental objectives. This is reflected in the more recent legal approaches, such as in the Berlin Mobility Law. Its objective is defined as the advancement of a safe, barrier-free transport system that is oriented towards the mobility needs of the city and its surroundings. It is designed to be compatible with the city, the environment, society and the climate, and to guarantee equal mobility opportunities in all parts of Berlin. Similarly, the French Mobility Orientation Law (LOM - *Loi d'orientation des mobilités*) also represents a far-reaching approach, guaranteeing the right to mobility in alignment with social and environmental objectives.

Strategies and programs also often mention social and environmental objectives, although the most common motive seems to be to create (sustainable) mobility options in rural communities that have been mostly car dependent and to create better conditions and higher quality of life in such areas.

### How is the guarantee implemented?

The tools to implement a mobility guarantee include contracts, programs and legal regulations. GRH programs or other specific guarantees and reimbursements are usually regulated in a contract or in terms and conditions of a contract. In this case, the contract may be established between a company or a PT authority and its customers, or between an employer and an employee. Legal approaches can include individual laws, multiple laws, or even a complex combination of constitutions, laws, decrees, and concepts that work together to establish a mobility guarantee with specific parameters, as seen in Switzerland or Berlin. In between, strategies and programs offer a wide range of implementation tools, although these are often limited to pilot projects. Therefore, they are risking to lack support when the projects end or political decision makers change. Strategy documents often lack a legal basis and are not binding.

### Synthesis

Focusing on the *What*-question, specific guarantees are mostly focused only on single modes such as carpooling or PT services, while the broader approaches include several modes and often the

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integration between them. The *Who* and *for Whom* aspects correspond to this. Focusing on the *How* aspects, a range of contractual and legal approaches can be observed. Three distinct approaches were identified: (1) specific guarantees with financial reimbursement, (2) broad legal regulations and (3) policies (strategies, programs and concepts using accessibility standards). While some of the parameters are interdependent, there is variation within the three distinct approaches. The constellation of each approach is shown in Fig. 3.1.

The first category of specific guarantees is a narrow, yet tangible approach. Legal regulations mostly target a wider group of people, cover more transport modes and range up to the intangible "right to mobility" where it is not yet clear if such rights can be individually enforced and what the effects on transport planning practices will be. Policy approaches such as strategies and programs lie between those two categories, although overlapping with them. Compared with the other approaches, they encompass larger spatial scope and target groups with very tangible criteria drawing on different concepts of accessibility assessments and standards. Geographically and temporarily speaking, we find approaches of the second and third category (policies and laws) discussed prominently in Europe and Japan, while the approach of specific guarantees can be found mainly in the US and in Europe. For the purposes of this study and a holistic approach of providing a Sustainable Mobility Guarantee, such specific guarantees are not feasible due to the narrow definition and lack of addressing ecological sustainability. The other two approaches are largely overlapping (see Figure 3.1) and should be viewed in context to one another. Policies often have a character of pilot projects to test the idea, while laws are mostly broad and less concrete. Policy manifestations and laws are more likely to encompass environmental goals in the last years, while older laws tend to embed the right for mobility or assurance of minimum mobility services only from a socio-economic point of view. This may be interpreted as the different status of developments depending on the elapsed time from the advent of the two different origins of the idea. The two approaches may potentially be well merged in the future (e.g., in creating a legal basis for programs) or set up as synergetic approaches (e.g., with a national law as a basis and more concrete local regulations for specific quality criteria).

Regarding the impact of mobility guarantees on travel behaviour, very limited information is available. Studies on GRH programs show low effects on mode choice (Polena & Lawrence, 1991), which is not surprising due to its limited scope. Pilot projects of broader mobility guarantees have been implemented more recently and did not (or not yet) publish data on their effects on travel behaviour. However, there is a clear correlation of higher PT quality and lower car ownership and car use (see also Chapter 2) in general. While this thesis assesses the concept with the help of simulations using an existing national transport model (MARS-UBA), future research should collect empirical data on the effects of implemented mobility guarantee projects.

### 3.1.7 Accessibility quality standards

Although accessibility quality assessments and the definition of standards do not guarantee anything *per se*, they often provide the tools which guarantees are based on (especially the *What*, *Where* and *When*) and can inform transport policy. Since the definition of the Sustainable Mobility Guarantee in this thesis also draws from quality standards, some examples are presented here.

#### 3.1.7.1 Swiss Public Transport Quality Classes

The Swiss "Public Transport Quality Classes" (PTQC) are an indicator for accessibility by public transportation, usually depicted through maps with areas coloured according to their respective class. The PTQC have been established initially in 1993 with the Swiss standard SN

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640 290 of the Association of Swiss Road Professionals (Schweizerischer Verband der Strassen- und Verkehrsfachleute - VSS) for the calculation of parking requirements (ARE, 2022). In 2006, the norm was replaced by the new standard SN 640 281, which no longer included the Public Transport Quality Classes. Currently, the Public Transport Quality Classes are calculated by ARE, the Federal Office for Spatial Development. The methods are described in a publicly available report by ARE (2022).

The quality assessment combines three different aspects in two steps: firstly, the type of transportation departing from a PT stop and service intervals are combined into the indicator "PT stop category" (*Haltestellenkategorie*). The different categories range from I to V with I representing the highest quality and V the lowest quality. The categories are shown in Table 3.2. To calculate the service interval at a stop, departures on all lines are counted from the electronic timetable on the reference day between 6.00 a.m. and 8.00 p.m. To determine the average number of departures in one direction, the total number of departures is halved. For terminal stops and stops only served in one direction, corresponding adjustments are made.

**Tab. 3.2:** Swiss PT stop categories I - V

| | **Type of transportation** | | | |
|---|---|---|---|---|
| | **Group A** | | **Group B** | **Group C** |
| **Interval** | **Railway nodes** | **Railway lines** | **Tramways, buses, post cars, DRT and ships** | **Cable cars** |
| $< 5$ min. | I | I | II | V |
| $\geq 5$ to $< 10$ min. | I | II | III | V |
| $\geq 10$ to $< 20$ min. | II | III | IV | V |
| $\geq 20$ to $< 40$ min. | III | IV | V | V |
| $\geq 40$ to $\leq 60$ min. | IV | V | V | V |

In a second step, the PT stop category is combined with the distance to the PT stop, to derive the PTQC - according to Table 3.3. The classes range from A to D with A representing the best class and D the worst. Certain combinations of low PT stop categories and long distances to PT stops are considered of too low quality for practical PT and are defined with "none" of the quality classes.

**Tab. 3.3:** Swiss Public Transport Quality Classes (PTQC) A - D

| | **Distance to PT stop** | | | |
|---|---|---|---|---|
| **PT stop category** | **<300 m** | **300 - 500 m** | **501 - 750 m** | **751 - 1,000 m** |
| **I** | A | A | B | C |
| **II** | A | B | C | D |
| **III** | B | C | D | none |
| **IV** | C | D | none | none |
| **V** | D | none | none | none |

#### 3.1.7.2 Austrian Public Transport Service Quality Levels

The Austrian Conference on Spatial Planning (short ÖROK) developed an assessment very similar to the Swiss approach (Hiess, 2017; Schwillinsky et al., 2018). The Public Transport Service Quality Levels (*ÖV Güteklassen*) - short PTSQL - have been introduced nationwide in 2017 as routed distance buffers around PT stops. Austrian PTSQL are also based on the hierarchy of PT mode and time interval classes - as in Switzerland, but with slight differences.

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In the Austrian PTSQL, type of PT mode and time interval lead to stop category, ranging from the highest category I to the lowest category VIII (see Tab. 3.4). Stop categories and routed surfaces around these stops lead to PTSQL, ranging from the highest class A to the lowest class G (see Tab. 3.5).

PTSQL are quite similar to the Swiss PTQC, however, there are more PT stop categories and more quality levels. While intervals in the Swiss model reach only until 60 minutes, the Austrian PTSQL consider intervals until 210 minutes. The upper limit for distances to PT stops in the Swiss PTQC reach until 1,000 m, while the Austrian PTSQL consider PT stops until 1,250 m. It could be argued that the assessment of PT quality in a country is oriented towards the existing service quality, with overall PT quality in Austria being lower than in Switzerland.

**Tab. 3.4:** Austrian PT stop categories I - VIII

| | **Type of transportation** | | | |
|---|---|---|---|---|
| **Interval** | **Long-distance rail** | **Railway lines, metro, BRT** | **Tramways, metro-buses, o-buses** | **Buses** |
| $< 5$ min. | I | I | II | III |
| $\geq 5$ to $\leq 10$ min. | I | II | III | III |
| $> 10$ to $< 20$ min. | II | III | IV | IV |
| $\geq 20$ to $< 40$ min. | III | IV | V | V |
| $\geq 40$ to $\leq 60$ min. | IV | V | VI | VI |
| $> 60$ to $\leq 120$ min. | V | VI | VII | VII |
| $> 120$ to $\leq 210$ min. | none | VII | VIII | VIII |

PTSQL are calculated annually, with their regional uses on the rise (Bednar et al., 2022). In the Vienna metropolitan area, PTSQLs have been combined with the spatial distribution of amenities and current zoning classifications to pinpoint potential development sites for transit-oriented development (Verracon, 2021).

**Tab. 3.5:** Austrian Public Transport Service Quality Levels (PTSQL) A - G

| | **Distance to PT stop** | | | | |
|---|---|---|---|---|---|
| **PT stop category** | **<300 m** | **301 - 500 m** | **50 - 750 m** | **751 - 1,000 m** | **1,001 - 1,250 m** |
| **I** | A | A | B | C | D |
| **II** | A | B | C | D | E |
| **III** | B | C | D | E | F |
| **IV** | C | D | E | F | G |
| **V** | D | E | F | G | G |
| **VI** | E | F | G | none | none |
| **VII** | F | G | G | none | none |
| **VIII** | G | G | none | none | none |

#### 3.1.7.3 London Public Transport Access Level

The Public Transport Accessibility Level (PTAL) is a metric developed by Transport for London to evaluate the accessibility of public transport across different areas of the city, influencing urban planning and development strategies (Transport for London, 2015). Scores, ranging from 0 (poor access) to 6b (excellent access), are calculated based on walking time to transport stops, service frequency, and availability of various transport modes.

The calculation assumes that people will walk a maximum of 640 metres (routed) to a bus service and 960 metres to a rail or metro service ("Tube"). The standard PTAL is based

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on the period between 8.15 a.m. and 9.15 a.m. on a weekday, with standard waiting time estimated as half the time interval between arrivals of the service and consideration of a reliability factor to calculate average waiting times. Walking time and waiting time are added up to total access time (TAT) and converted into equivalent doorstep frequency (EDF), i.e. $EDF = 0.5 \cdot (60/TAT)$. EDFs of different available modes are then combined into the Access Index (AI) as $AI = \text{Largest EDF} + 0.5 \cdot \Sigma(\text{all other EDFs})$. Separate AIs are then summarized for the total AI $AI_{total} = \Sigma(AI_{bus} + AI_{rail} + AI_{Tube} + AI_{tram})$. In a final step, the AI range is converted to PTAL score according to the values in Tab. 3.6. (Transport for London, 2015)

**Tab. 3.6:** Conversion of the Access Index (AI) to PTAL (Transport for London, 2015)

| PTAL | Access Index range | Map colour |
|---|---|---|
| 0 (worst) | 0 | |
| 1a | 0.01 – 2.50 | |
| 1b | 2.51 – 5.0 | |
| 2 | 5.01 – 10.0 | |
| 3 | 10.01 – 15.0 | |
| 4 | 15.01 – 20.0 | |
| 5 | 20.01 – 25.0 | |
| 6a | 25.01 – 40.0 | |
| 6b (best) | 40.01+ | |

The metric is calculated and displayed based on 100-meter squares for the urban area. The results can be viewed in an interactive online map, the WebCAT[9]. The PTAL score guides decisions on housing densities and commercial developments to ensure they are well-served by public transport.

#### 3.1.7.4 German guidelines and recommendations for quality standards

There are several German guidelines and recommendations for PT quality, which are described below. Tab. 3.7 shows an overview.

**Tab. 3.7:** Overview of different German guidelines and recommendations for PT quality

| | FGSV | VDV | ADAC |
|---|---|---|---|
| lower limit [inhabitants] | 200 | 200 | 500 |
| coverage of population [%] | 80 | 80 | 80 |
| minimum interval [min.] | 5 - 120 | 5 - 120 | 60 |
| max. distance to PT stop [m] | 300 - 1,200 | 300 - 1,000 | 300 |
| access time central places [min.] | 30/45/90 | 40/60/90 | - |
| max. ratio travel time PT/car | 1.5 | 1.5 | 1.3 |
| operating hours | - | - | 6 a.m. - 10 p.m. |

**FGSV RIN - guidelines for integrated network design**

FGSV (Research association for roads and traffic - *Forschungsgesellschaft für Straßen- und Verkehrswesen*) is a German association that develops diverse guidelines and recommendations for transport planning and traffic engineering which are considered state of the art. They developed

[9]https://tfl.gov.uk/info-for/urban-planning-and-construction/planning-with-webcat/webcat

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the RIN (guidelines for integrated network design - *Richtlinien für integrierte Netzgestaltung*) (FGSV, 2008), which covers the network design of private motorized traffic, PT, walking and cycling and give recommendations for the temporal accessibility of towns and regional centers for different transport modes. Regarding PT standards, FGSV developed recommendations for planning and operations of local PT (*Empfehlungen für Planung und Betrieb des öffentlichen Personennahverkehrs*) (FGSV, 2010). In Germany, "central places" are categorized into basic centers, middle centers and upper centers. FGSV recommend a maximum time to reach local centers by PT within 30 minutes for basic centers, 45 minutes for middle centers and 90 minutes for upper centers. Recommendations for accessibility by private car, on the other hand, range from 20 minutes for basic centers to 60 minutes for upper centers. Maximum distances to PT stop are considered depending on the classification of a center or other municipalities from 400 m to 1,200 m. While it is recommended that walking time to a bus stop does not exceed 5 - 10 minutes, it is considered appropriate to walk 20 minutes to a train station in rural areas. Minimum intervals for PT range from 5 minutes to more than 60 minutes. In areas with low demand for PT, they recommend to introduce DRT services. The threshold for implementing PT access is considered at 200 inhabitants and should cover at least 80 % of the inhabitants.(Agora Verkehrswende, 2023a; FGSV, 2010)

### VDV recommendations

VDV (the association of German transport organisations - *Verband Deutscher Verkehrsunternehmen*) developed several recommendations for the operational quality of local PT. The most recent publication is "Verkehrserschließung, Verkehrsangebot und Netzqualität im ÖPNV" (VDV, 2019). The recommendations include aspects of access quality such as distance to PT stops, service quality such as timetables and connections and network quality such as travel time ratio compared to travel by car.

They consider an area accessible if 80 % of the people live or work within a "reasonable" distance to PT stops. This reasonable distance depends on the type of PT (rail, metro, tramway, bus) population density and centrality of the location. Recommended maximum (beeline) distance to the next PT stop range from 300 m for bus and tramway stations in densely populated areas to 1,000 m for railway stations in rural areas. Recommended intervals depending on the density *"Nutzungsdichte"* and time of day range from 5 minutes in high density areas during peak-hours to 120 minutes in rural areas. Similar to the FGSV recommendations, the threshold for implementing PT access is considered at 200 inhabitants or commuters. Guidelines for PT intervals are presented depending on the time of day and population density ranging from 5 minutes to 120 minutes. DRT services are considered a good alternative if demand is low throughout the day. (Agora Verkehrswende, 2023a; VDV, 2019)

VDV further provides guidelines for travel time between towns and cities, similar to the approach of FGSV but with slightly longer times. Recommendations for maximum time to reach them by PT are 40 minutes for basic centers, 60 minutes for middle centers and 90 minutes for upper centers. The maximum ratio of accessibility by PT compared to car travel is recommended with 1.5. (VDV, 2019)

### ADAC standards for rural mobility

The German ADAC (motoring club - *Allgemeiner Deutscher Automobil-Club*) commissioned a study in 2020 to develop a concept for "future proof" public mobility outside of agglomerations. Gipp et al. (2020) developed a concept for modernizing PT services in rural areas with the central research question of "Is the current mobility financing in Germany suitable for adequately

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ensuring mobility outside urban areas?". A central part of the study deals with mobility standards for PT such as the RIN and VDV recommendations (see above). The authors argue that higher standards should be established in order to reach environmental and transport policy objectives (especially a modal shift from car to PT) and provide PT services in line with the demands and needs of rural areas.

The proposed mobility standard includes three aspects (a-c): (a) the obligation to provide services for municipalities above a certain size. The authors suggest a threshold population of 500, although the services do not have to be traditional public transport services but could be provided as DRT or community buses; (b) guaranteed accessibility standards based on travel times, frequency of connections and PT stop density:

**Travel times:** Each municipality meeting the obligation to provide services must be reachable by PT to a regional center within a specified time. The proposed criterion is that the maximum travel time to the nearest central or major center should not exceed the travel time in private vehicles by more than 30 %.

**Connection quality:** Minimum interval for reaching a regional center is considered at 60-minutes. This minimum service must be consistently available, both on weekends and during holidays. Reaching a middle or upper center should require a maximum of two transfers, provided that connections are guaranteed. Services should be available from 6 a.m. to 10 p.m., with additional nighttime services offered Fridays to Sundays.

**PT stop accessibility:** For at least 80 % of the residents in a municipality with the obligation to provide services, the distance to the nearest stop should not exceed 300 meters.

And (c) a "mobility guarantee" - which deals with the mode of transport that are recommended for providing the services. The defined standards can be achieved through flexible PT services (such as DRT services, shared taxis, etc.) or through intermodal options such as ridesharing. The only requirement is to demonstrate the functional interchangeability of the services. For services based on collaboration with private providers, the authors argue that an additional "mobility guarantee" is necessary, without describing what they mean by that.

## 3.2 Stakeholder workshops

In the course of the project FLADEMO (*Flächendeckende Mobilitäts-Servicegarantie*)[10], stakeholder workshops with experts working in the field of transportation and with citizens as potential "everyday users" of a Sustainable Mobility Guarantee were conducted to inform the definition and challenges of an SMG in Austria. These discussions informed scenario development around legal frameworks, service quality, and geographic coverage of the SMG. First results have been published in Szalai (2021) and Laa et al. (2022). The definition of the SMG and scenarios in this thesis are based on these works but have been further developed for this thesis.

A total of seven workshops were conducted between April and June 2021, four sessions with professionals from the transport sector (referred to as "expert workshops") and three sessions with citizens ("user workshops"). Significant distinctions emerged between the workshops. In the expert workshops, the primary focus was on the distribution of responsibility and funding for mobility services between federal and regional governments, along with public transport agencies. Professionals also placed considerable emphasis on defining a clear goal for the guarantee and

[10] Project FLADEMO - Flächendeckende Mobilitäts-Servicegarantie: https://projekte.ffg.at/projekt/3992976. For final report, see Shibayama et al. (2022)

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determining the target group. They also emphasized the challenges of providing access to remote and rural areas and the division of responsibilities between federal and regional governments. In contrast, user workshops focused on affordability, ticketing complexity, comfort, safety, and accessibility of transport systems. Participants voiced concerns about service coverage beyond urban areas, interval frequency, and connectivity of PT systems. These findings underscore a significant gap between expert priorities, centered on policy and funding, and user concerns, which revolved around practical transport issues and everyday convenience.

## 3.3 Legal framework

In order to make the concept of a "Sustainable Mobility Guarantee" more tangible, I will first describe the idea in regard to three different layers and their according legal regulations, based on the analysis by Damjanovic and Peck (2021). The layers are displayed in Fig. 3.2.

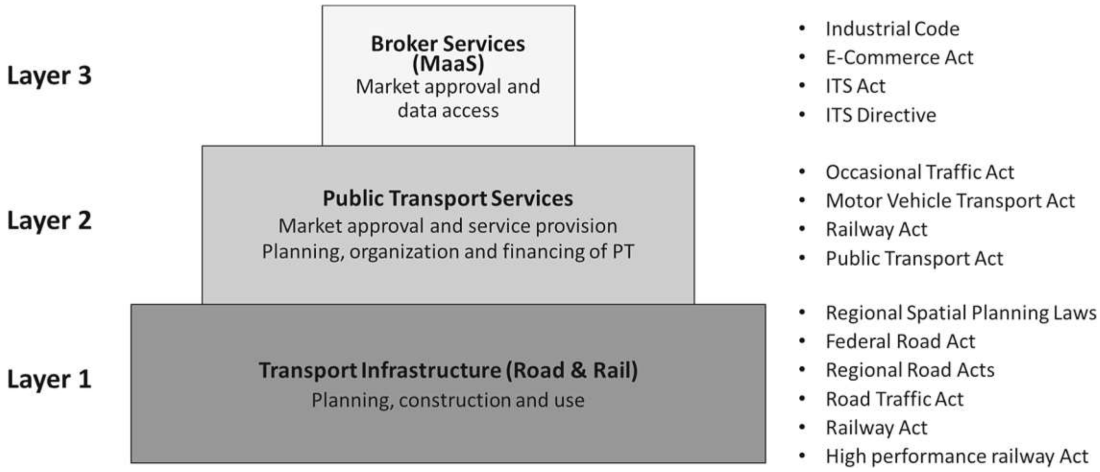


**Fig. 3.2:** Three legal layers in the Austrian transport sector and corresponding laws and regulations, from Laa et al. (2022)

Layer 1 (at the bottom) refers to legal regulations governing the planning, construction, and utilization of transport **infrastructure**, encompassing both roads and railways. Notably, the regulations are often distinct for each mode. Within the context of a Sustainable Mobility Guarantee, infrastructure for pedestrians, cyclists, and railways hold significant relevance. Spatial planning laws, varying across provinces, serve as foundational guidance for transport planning. Presently, infrastructure regulations establish general objectives concerning the assurance of specific transport infrastructure without specifying concrete means of achievement or legal consequences for non-fulfillment. National and regional regulations primarily emphasize service quality for private motor vehicles, with some regional acts considering sustainable transport aspects, such as the Road Act of Vorarlberg (*V-StrG - Gesetz über den Bau und die Erhaltung öffentlicher Straßen sowie über die Wegefreiheit*), incorporating public transport, cycling, and walking.

The second layer governs the organization and provision of passenger transport **services**, encompassing both private and public services on roads and railways, including regular transport services and Demand-Responsive Transport (DRT). Federal laws on this layer establish the conditions for transport services of general interest, predominantly financed by national and regional governments. This layer aligns with the Public Service Obligations Regulation (EU Regulation 1370/2007), outlining the general framework for publicly financed public transport

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services. While the exact scope of these services and the obligation to provide nationwide services lack systematic anchoring, the legal basis ensures adherence to specific quality criteria and the implementation of uniform tariffs set within public transport associations.

The third layer addresses the regulation of digital mobility **platforms**, which is particularly relevant to information and broker services related to transport within the context of a Sustainable Mobility Guarantee. The legal framework of Intelligent Transport Systems (ITS) outlines aspects of platform guarantee, including data accessibility, and mandates non-discriminatory presentation of data to aid end users in making unbiased decisions regarding transport services and routes. However, certain elements crucial for a guarantee in the realm of Mobility as a Service (MaaS) platforms, such as real-time data provision, are inadequately addressed or not regulated within the existing legal framework. The absence of real-time data poses challenges for MaaS platforms in delivering services as expected (Goodall et al., 2017; Hensher, 2017; MaaS Alliance, n.d. Shibayama & Emberger, 2020).

While the practical implementation of a Sustainable Mobility Guarantee has to address all of these layers, different legal constructs are envisageable. One approach is a *de facto* guarantee by developing transport services through programmatic approaches. For this, setting quantitative targets in a time-bound manner serves as a guidance for implementation. A consensus for targets is needed to give transparency and legitimacy – this is common to the concept of Sustainable Urban Mobility Plans (SUMP; Shibayama (2020)). The report by OECD-ITF (2021) mentions a possibility of Sustainable Regional Mobility Plans as an analogy to the SUMP. This is a bottom-up approach and thus rather voluntary. But a government may mandate an obligation to develop such a plan, e.g. as the European Commission intends to do with SUMPs (COM(2021) 811). Two further approaches are a *de jure* approach with legal regulations and political manifestation. These are top-down approaches to impose a certain level of service set by key parameters that may include minimum service levels (service frequency, operating hours, etc.), a threshold for spatial development only in a near proximity to guaranteed mobility services, and so on. As is the example of Switzerland, the target value may differ depending on demographic and geographic conditions. Legal implementations can take various forms, ranging from individual laws to a combination of constitution, laws, decrees, and concepts, intricately woven together to establish a mobility guarantee with defined parameters. This is exemplified in regions like Switzerland or Berlin.

In contrast, strategies and programs exist as a diverse array of implementation tools but are frequently confined to pilot projects. Consequently, they entail the risk of losing support once the projects conclude or when there are changes in political decision-makers. Notably, strategy documents often lack a legal basis and are non-binding documents. The programmatic approach can be embedded as part of a transitional process towards a *de jure* guarantee.

## 3.4 Framework definition

In contrast to many existing definitions of mobility guarantees (see Section 3.1), the definition of a Sustainable Mobility Guarantee for the purpose of this study takes a more holistic approach, in line with the mobility acts in Berlin and France that base their regulations on social *and* ecological sustainability, rather than focusing only on specific aspects such as financial compensations. Considering the "nationwide" aspect in the Austrian context, special attention is required for areas outside major cities where PT coverage is currently limited. To address differences between cities and rural areas, different parameters for geographic variations are proposed in various scenarios. In the stakeholder workshops (see Section 3.2), the importance of considering accessibility, affordability, clarity, and simplicity of tariff and booking was emphasized. In light

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of these insights, the goals of the Sustainable Mobility Guarantee are defined threefold, based on Laa et al. (2022):

1. To ensure a sufficient level of mobility services, serving as a condition for equal participation of the population in public life without owning a private car (provision of Universal Basic Services (UBS); socio-political dimension)

2. To provide non-discriminatory access to these mobility services for everyday journeys, with a special consideration of barrier-free access (provision of UBS; socio-political dimension)

3. To create an incentive to switch to sustainable forms of mobility (ecological dimension)

The services under the SMG are intended to be provided in a safe and reliable manner to all, under non-discriminatory conditions and at affordable prices, maintaining a certain minimum quality. (Laa et al., 2022)

To achieve these goals, specific foundations are proposed in reference to the three legal layers. Concerning the first layer, there must be a guarantee of sufficient provision and maintenance of transport infrastructure for PT and active modes (e.g., cycling lanes, bicycle parking, footpaths, and sidewalks) at a certain level of quality. High-quality infrastructure for active modes contributes to environmental goals and social goals by ensuring mobility for door-to-door travel and access to PT services.

The second layer, PT services, constitutes the core aspect of the Sustainable Mobility Guarantee. It serves as the foundation for providing a minimum level of PT services nationwide, accessible to all individuals within defined settlement areas. Parameters such as the maximum distance to PT stops, minimum density of PT stops, frequency of services, and operating hours need to be established, with variations based on regional characteristics. The potential for compensation for cancelled services or missed connections, similar to existing forms such as the "Guaranteed Ride Home"-programs may also be incorporated into the guarantee, and be extended to Demand-Responsive Transport (DRT) and carpooling services.

In connection with the third layer of broker services, the Sustainable Mobility Guarantee guarantees a framework for the development of open and neutral mobility platforms, ensuring information and brokerage of transport services in a non-discriminatory and undistorted manner. This entails no preferential treatment for specific service providers on these platforms, granting all platforms access to information from all service providers. Additionally, the Sustainable Mobility Guarantee may include platforms facilitating the networking of private vehicles for carpooling.

## 3.5 6W1H Classification

With regard to the classification system presented in the literature review, the definition of the Sustainable Mobility Guarantee as understood in this thesis is shown in Fig. 3.3 in pink. This definition does not fit into one of the three categories derived from the literature review (specific guarantees, policies and legal approaches, see Section 3.1). The SMG is an approach that encompasses more than a specific guarantee but should be more concrete than a general right given by law. Within this range, different practical implementation is possible, shown as coloured area and dotted lines.

- *Who?* A guarantee that is given by the public, be it the state, a region or a city.

- *for Whom?* The guarantee is granted to anyone within the geographic scope, encompassing citizens and other groups.

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- *What?* The SMG encompasses infrastructure and mobility services for multiple modes as well as their interaction and a legal framework for mobility platforms. Minimum quality standards for PT services and infrastructure for active mobility should be specified.
- *Where?* The guarantee is given in the territory of the guarantor, e.g. nationwide, within a region or city boundaries. Limitations for sparseley populated areas might be given.
- *When?* The guarantee is available on all days of the week, but operating hours for services apply. They might be differentiated based on density of settlement structures.
- *How?* The practical implementation of the SMG can be a program, a regulation or a law.
- *Why?* (not shown in the Figure) The *Why* is what differentiates the SMG approach from most existing approaches. The SMG is not only seen as a Universal Basic Service to provide mobility for all but explicitly as a policy to promote sustainable mobility - the ecological dimension.

The *Where* will be specified in the following for the case study of Austria to the nationwide scope, with different limitations for rural areas in the scenarios, see also next section. The *What* and *When* will also be differentiated in the scenarios. The *How* and *Who* can have possibly different answers.

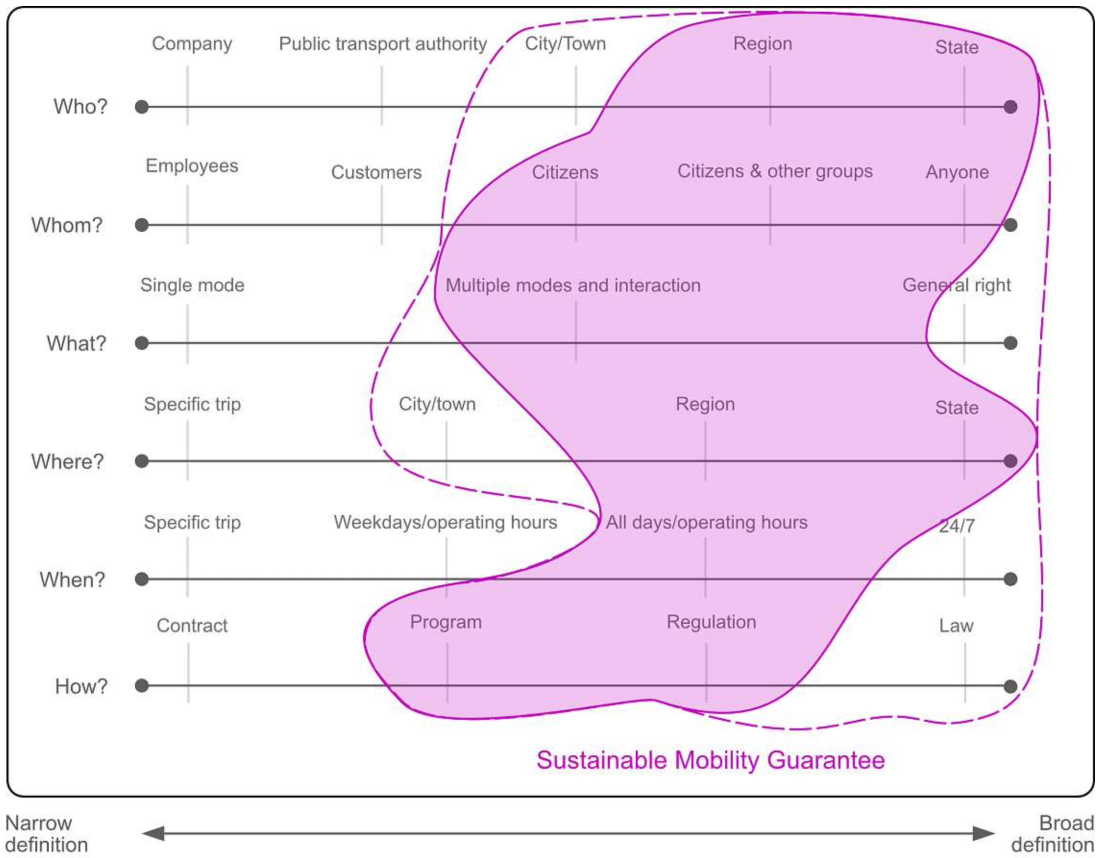


**Fig. 3.3:** Classification of the Sustainable Mobility Guarantee

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## 3.6 Implementation scenarios

In order to discuss and assess different intensities of implementation, five Sustainable Mobility Guarantee (SMG)-Scenarios were defined. For reference facilitation, the scenarios are numbered and named depending on the intensity. They build on one another, with Scenario 1 showing the least intensity and Scenario 5 the highest, while Scenario 0 is a reference scenario representing "Business as Ususal" (BAU) without implementing a Sustainable Mobility Guarantee. Fig. 3.4 shows an overview of the five scenarios. Scenario 0 - *BAU* represents the current transport system and prognosis of trends. Scenario 1 - *All regions aboard* and Scenario 5 - *Utopia* delineate the plausible lower and upper limits, with the former as the most basic version of a Sustainable Mobility Guarantee and the latter as a rather utopian scenario regarding mobility services, where PT is available around the clock, every day for everyone and all travel needs. Scenarios 2 and 3 are intermediate, with the former emphasizing active mobility, as modes in themselves and as important feeder modes for PT, and the latter considering increased carpooling as a substitute for PT in rural areas. Scenario 4 - *Goodbye private car* envisions a substantial PT supply coupled with far-reaching restrictive measures to discourage private car usage.

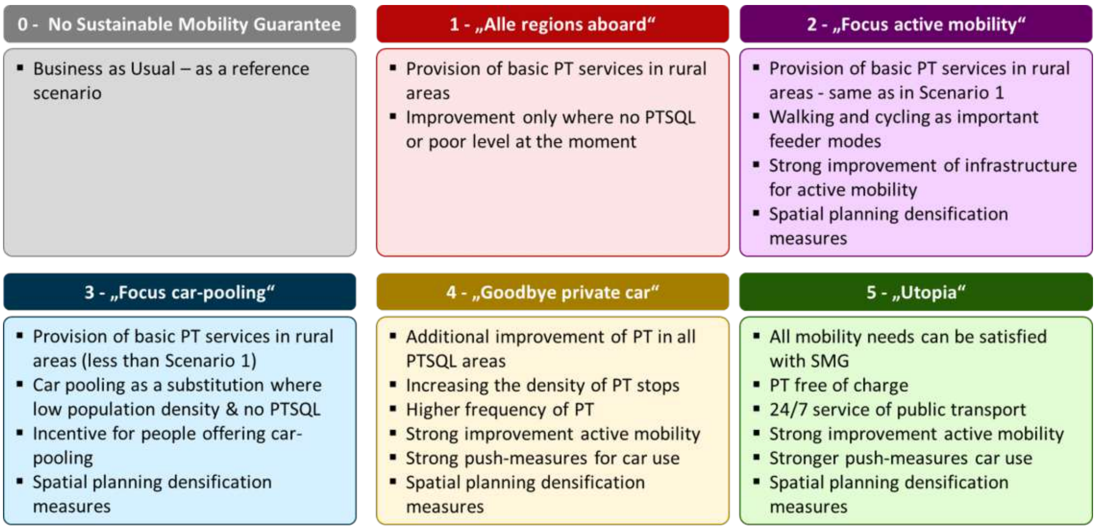


**Fig. 3.4:** Overview of the five SMG-Scenarios and the BAU reference scenario

### Scenario 1 - All regions aboard

This scenario focuses on providing basic mobility services in rural areas where such services are currently limited. It represents a lower limit in the scenario comparison and serves primarily to illustrate the impact of an improved public transport offer without extensive push measures, but it might not be a recommended implementation scenario. Nevertheless, valuable insights for conclusions can be gained from simulating this scenario.

### Scenario 2 - Focus active mobility

In this scenario, public transport is moderately improved compared to the status quo, particularly in rural areas. However, there is a strong emphasis on active mobility, specifically walking and cycling. Bicycles are considered a crucial feeder mode for public transport, and infrastructure for walking and cycling is significantly enhanced. This includes the expansion of cycling networks, improvement of existing facilities such as widening sidewalks and cycling paths, traffic calming

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measures in cities and the provision of secure bicycle parking facilities (covered, lockable, or monitored) at all train stations and parking areas near bus stops, along with ample public space parking.

#### Scenario 3 - Focus carpooling

In Scenario 3, the public transport offering is moderately enhanced, slightly less than in Scenario 1, particularly in rural areas. Pooling, in the form of carpooling with private vehicles, is considered a crucial complement, especially in areas where the quality of PT services is low.

#### Scenario 4 - Goodbye private car

This scenario envisions a future where all individuals can be mobile without access to a private car. The public transport offering (both scheduled and demand-oriented) is not only improved in rural areas but across all public transport quality classes, including urban areas. In comparison to previous scenarios, the guarantee here ensures shorter access routes to public transport, a reduced minimum frequency, and extended operating hours. This enhanced offering is combined with robust push measures against private car usage such as road pricing and lower speed limits.

#### Scenario 5 - Utopia

Scenario 5 serves as the upper limit in the scenario comparison. Similar to Scenario 1, it primarily serves as a comparative model to illustrate extremes in thought rather than a recommendation for practical implementation. In this scenario, public mobility services are provided 24/7 for everyone free of charge, accompanied by strong measures encouraging a shift away from private car usage.

## 3.7 Limitations

The Sustainable Mobility Guarantee primarily addresses the daily journeys of individuals living and/or working in Austria. It specifically concerns the physical movement of persons, excluding "virtual" mobility such as teleworking and teleshopping. While occasional trips (e.g., tourism) and virtual mobility, and freight transport share similarities with everyday mobility and may contribute to sustainability goals, the scope for this study is limited.

In alignment with social and sustainability goals, private motorized transport (mostly concerning private cars) as a mode is not part of the Sustainable Mobility Guarantee. The SMG exclusively considers public transport (both regular and Demand-Responsive Transport), cycling, and walking, primarily as feeder modes for public transport. However, the guarantee may extend to carpooling services to enhance car occupancy rates during a transitional period before the guarantee is in full effect. Recognizing the time required to implement measures to achieve the defined service level of the Sustainable Mobility Guarantee in all regions, leveraging carpooling in the interim could contribute to reducing overall vehicle kilometers traveled. Yet, potential rebound effects during the transition must be considered, as pooling services might make car trips more attractive than available public transport.

In the proposed definition, the guarantee may encompass digital mobility platforms for carpooling but excludes those for vehicle sharing and the provision of vehicle sharing services. The current forms of vehicle sharing services, such as station-based and free-floating services, cannot guarantee vehicle availability in sparsely populated areas across the country. Moreover, driver's license requirements for vehicle sharing services, like car sharing, exclude individuals

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without licenses, such as children and elderly people. This contradicts the non-discriminatory goal of the Sustainable Mobility Guarantee. Additionally, sharing services can encourage the use of private motorized modes. In a meta-review, Javaid et al. (2020) found that shared mobility has had a relatively minor positive impact on conventional transport forms, particularly in reducing car usage. There are indications that a notable portion of shared mobility trips replaces public transport usage, with instances of potential walking or biking alternatives if car-sharing were not available. However, shared mobility has shown a more definitive influence on reducing vehicle ownership, with urban car-sharing programs associated with a lower rate of ownership (estimated between 10% and 30% decrease). For the purposes of this study, vehicle sharing is seen as a welcome addition but not as part of the Sustainable Mobility Guarantee.

Several other crucial aspects related to the Sustainable Mobility Guarantee go beyond the scope of this study. These include the comfort and added-value services of public transport (e.g., ambient design, onboard air conditioning) and disruption management. Another vital consideration is the synergy between the guarantee and spatial planning. Travel needs are influenced by the dispersion of uses in space, suggesting that minimizing travel needs may involve creating more mixed-use areas with essential services like grocery stores and medical facilities in rural areas, rather than solely focusing on providing mobility services to reach such distant uses. These aspects necessitate further exploration in subsequent research on the topic.

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# Chapter 4

# Qualitative analysis

In this chapter, the impact of a Sustainable Mobility Guarantee (SMG) is examined qualitatively. In Section 4.1, I introduce the transition and transformation research agenda. This is followed by an assessment of the SMG on the basis of three different frameworks to assess systemic change or transformation. The first one is the Multi-Level Perspective in Section 4.2. This is followed by a general description of System Dynamics Methods (Section 4.3) and the assessment of the SMG with the two System Dynamics Methods of Causal Loop Diagrams (in Section 4.4) and leverage points in systems (in Section 4.5). The chapter is finished with a short conclusion.

## 4.1 Theories of change, transitions and transformations

Though the scientific literature is largely in agreement that there is the need for fundamental changes in our society, including our transport systems (see Chapter 1), the pathways for how such changes can be achieved are still argued about, but are increasingly studied. Markard et al. (2012) discuss the rise and significance of sustainability transition research. Due to path dependencies and lock-in effects, established systems tend to change incrementally rather than radically. However, incremental changes are insufficient to meet sustainability challenges promptly. In political discussions and scientific literature, the terms 'transition' and 'transformation' have become prominent to highlight the need for radical changes. While the terms are sometimes used interchangeably, Hölscher et al. (2018) assessed that they provide nuanced views on describing, interpreting, and supporting significant, non-linear societal change. While their differences may partly come from their etymological roots, they mostly arise from the distinct research communities focusing on either transition or transformation. Both concepts often involve normative ideas to highlight the desirability of transition and transformation. They contrast the unsustainability of current societal systems with a collectively defined vision of sustainability for preferred transitions and transformations. Transition focuses on the dynamics of moving from one state to another while transformation emphasizes systemic change outcomes. They are not mutually exclusive but complementary, offering nuanced perspectives on achieving desirable societal change (Hölscher et al., 2018).

While in this thesis I assess the role of an SMG in the social-ecological *transformation* of the transport sector, I also refer to literature using the concept of sustainability *transitions*, usually applied to large socio-technical systems such as the transport sector.

## 4.2 Multi-Level Perspective

The Multi-Level Perspective (MLP) describes transitions in socio-technical systems in an evolutionary manner (Geels, 2002) and has been applied to "sustainability transitions" (Geels, 2011). In its first applications to technological transitions, the MLP has been already applied to transport systems such as "from sailing ships to steamships" (Geels, 2002) or "from the horse and cart to the motor vehicle" (Geels, 2005), focusing on technological innovations. In another article,

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Geels (2007), who uses MLP to describe changes in the Dutch Highway System, is highlighting the role of social protest movements. Later publications focus on sustainability transitions in the transport sector. One example by Geels (2012) introduced the MLP for "low-carbon transitions" and concluded that *"the automobility regime is still dominant and stable"*. The book *Automobility in Transition? A Socio-Technical Analysis of Sustainable Transport* (Geels et al., 2012) includes several studies on the topic on different scales and levels. (Geels, 2012)

The MLP comprises three levels: landscape, regime, and niches (see Fig, 4.1). The central regime includes dynamically stable, established, and dominant practices, discourses, institutions, and artifacts. Rip and Kemp (1998) define technological regimes as the "rule-set" embedded in engineering practices, production technologies, product characteristics, skills, procedures, and ways of handling artifacts and people, as well as problem-solving methods. Within the regime, there are three distinct dimensions: (1) tangible technologies (e.g., road infrastructure, cars), (2) actors and social groups, and (3) formal and informal rules, such as laws and planning guidelines. Institutional structures within the regime connect artifacts, rules, and actors. A transition is the shift from one regime to another, with niches and landscapes defined in relation to the regime. (Geels, 2011)

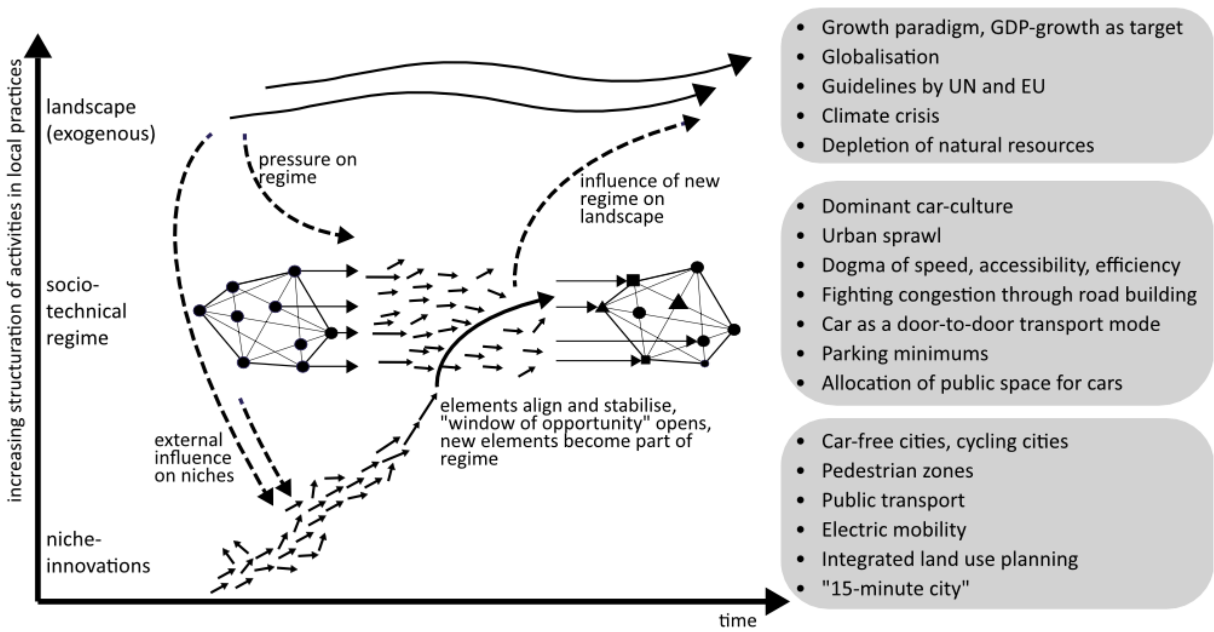


**Fig. 4.1:** Illustration of change processes according to the Multi-Level Perspective applied to the transport sector, from Frey and Laa (2021), based on Geels (2002)

The landscape represents external factors that influence the regime but are not part of it. The distinction between landscape and regime is discussed in the literature but remains loosely defined. This distinction varies depending on the system being analyzed and the perspective of the analyst. In the classic approach by Geels and Schot (e.g. Geels & Schot, 2007), socio-technical systems are the focus, with economic conditions considered as exogenous. Vandeventer et al. (2019) extend the theory to describe changes in socio-economic systems, incorporating economic parameters, such as the capitalist growth paradigm, into the regime.

The landscape can exert pressure on the regime, potentially breaking its internal connections and order. This destabilized state creates a "window of opportunity" to establish a new regime that incorporates innovations or niche developments. Niches are technologies or practices that significantly differ from the existing regime and can either support or oppose it. Within the

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regime, various individuals and groups act independently and uncoordinatedly but can form networks and align their actions to create a stable dominant form, increasing the likelihood of “leaping” to the regime when a window of opportunity opens. The MLP has been proven to be a useful tool for identifying regime components and distinguishing between landscape and niche elements, as well as describing path dependencies.

The dominant mainstream in transport systems is often referred to as a “car regime” or “automobility regime” (Marletto, 2011; Sheller, 2012; Zijlstra & Avelino, 2012). This regime favors private cars with combustion engines, and legal, financial, and infrastructural systems are oriented towards car use. This preference inhibits effective measures to reduce $CO_2$ emissions and mitigate climate change. Despite efforts towards sustainability, this regime has remained resistant to change. Self-reinforcing elements in the regime create a growing dependency on cars. Individual measures often fail because the system counteracts them, a phenomenon known as “policy resistance” (Sterman, 2000). Other terms to describe this situation include “carbon lock-in” (Driscoll, 2014) or “political economy of car dependence” (Mattioli et al., 2020). These terms all describe a complex, self-reinforcing system that cannot be changed by standalone policies or reformative approaches.

Frey and Laa (2021) described challenges of a sustainability transition in the Austrian transport sector based on the MLP, see Fig 4.1. The regime is considered as car-oriented, where transport policy decisions are based on planning and engineering principles that favor the priavte car. These principles are often codified in legal regulations such as the Road Code and industry standards such as the RVS (Guidelines and regulations for road construction - *Richtlinien und Vorschriften für das Straßenwesen*), maintaining a hierarchy of values that supports car dependence. At the same time, concepts of sustainable mobility currently only exist in niches. These include, for instance, car-free cities, bike-friendly cities, transit-oriented structures, integrated urban and transportation planning, the 15-minute city concept, and electric vehicles. In the landscape, as exogenous factors, Frey and Laa (2021) mention the economic growth paradigm, international guidelines and regulations by the UN and EU as well as environmental factors such as the climate crisis and depletion of natural resources.

### 4.2.1 Assessment of Sustainable Mobility Guarantee with MLP

Currently, the SMG can be considered as a niche-innovation that receives some attention from academia and is being tested in parts in pilot projects - on the niche level. The concept of an SMG is in opposition to the current regime where priority is given to private cars. While some elements that are considered part of the SMG might be incorporated into the regime without facing barriers, in case of conflicting interests, the regime still favors the private car. This means that an additional provision of PT services or cycling infrastructure is possible if the car regime is not undermined by it. For example, if there is not enough budget to cater for all transport modes, money will be allocated to car infrastructure rather than to providing alternative services. If there is a spatial conflict, e.g. in cities with limited public space, the regime generally favours to keep parking places and driving lanes for cars instead of building cycling lanes, wider sidewalks or better PT stations. The political struggle concerning pop-up bike lanes and temporary shared space streets in Vienna during the COVID-19 pandemic exemplifies this (Frey et al., 2024); even the temporary conversion of driving lanes and car parking spaces to be used by other transport modes during confinement measures was highly contested and cancelled after a short period of time.

Depending on the implementation of an SMG, it could act for example as a legal tool that leaps from the niche development as a theoretical concept to the regime level as an official national law. This could help further niche-innovations to make it into the regime such as high

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quality PT services and active mobility infrastructure as a standard. It would also mean that the current legal framework undermining policy to counter car dependence needs to be altered, e.g. by removing parking mandates for new buildings and adapting the Road Code.

Another option could be a cultural shift within the regime, that breaks connections within the regime and allows for individual elements of an SMG as niche-innovations to be incorporated into a new regime and create a *de facto* SMG. This means that there is no formally legally defined SMG but new transport planning standards and decision making are changed in a way that creates the same conditions as a law would, e.g. through implementation of minimum standards for PT, walking and cycling or through a new approach for rural areas to provide sustainable mobility options. It could be argued that a *de facto* mobility guarantee providing high quality alternatives to the private car already exists in some cities or parts of cities and countries (e.g. with the Swiss mobility laws). However, this does not necessarily mean that the transport system and mobility behaviour is ecologically sustainable. The essential factor of a *Sustainable* Mobility Guarantee is to not only incorporate sustainable mobility options into the existing regime, but to transform it in a way that eliminates privileges of the private car and minimizes its negative effects.

What might cause a window of opportunity on the landscape level to make this possible is not clear. Pressure might be exerted due to climate change or social problems such as high inflation, which could lead to people not being able to afford to drive cars anymore. It can be argued that not only pressure from the landscape can cause windows of opportunity to break open the regime, but also pressure from niche developments. The discussion of an SMG and maybe even assessment tools such as PT quality standards could act as a factor in changing the regime.

To conclude, viewed through the lens of MLP, it seems that the opportunity to introduce an SMG in the current regime is rather narrow and that - if implemented - the impact of the SMG on the regime seems limited. Individual components of the SMG are necessary to achieve a transformation of the regime but the concept alone cannot achieve such far-reaching change. This does not mean that it shouldn't be pursued but rather that supporting action is needed on different levels.

## 4.3 System Dynamics

System dynamics is a methodology and modeling approach to understand and analyze the behavior of complex systems over time and includes qualitative as well as quantitative methods. It helps in identifying how different components of a system interact with each other, leading to certain patterns of behavior. System dynamics was developed in the 1950s by Jay W. Forrester, at the Massachusetts Institute of Technology (MIT). Forrester's work initially focused on industrial systems, where he applied feedback concepts to understand the cyclical nature of business processes and production systems. While his pioneering book, "Industrial Dynamics" (Forrester, 1961), laid the groundwork, the method became popular in 1972 with the publication of "Limits to Growth" (Meadows et al., 1972). By creating a model of the whole world, the authors applied System Dynamics to global environmental and economic issues showing the long-term impacts of exponential growth and resource depletion.

Since then, System Dynamics methods have been applied in diverse fields such as business, healthcare, public policy, environmental studies and transport planning. The research community is organized in the System Dynamics Society, which also features a Transport Special Interest Group[1] of professionals who use the methodology in their work related to transport systems. The group organizes periodic workshops and special sessions at academic conferences.

[1] https://systemdynamics.org/special-interest-groups/transportation/

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In the following, the qualitative approaches of Causal Loop Diagrams and Leverage Points in systems are described and applied to assess possible impact of a Sustainable Mobility Guarantee.

## 4.4 Causal Loop Diagrams

A Causal Loop Diagram (CLD) is a qualitative model of a system commonly used in System Dynamics. Such diagrams are used as a visual tool to represent the feedback loops within complex systems. They help in understanding the interactions and interdependencies between different elements of a system, highlighting how changes in one part of the system can affect the whole. CLDs are practical to show the impact of policy measures on a system, explain time delays and self-reinforcement as well as rebound effects. They can be used for discussions with stakeholders, to support decision-making processes and as a basis for quantitative modeling. (Meadows, 2008; Sterman, 2000)

In a Causal Loop Diagram (CLD), the individual entities of the system (usually represented as text) and their connections to each other are depicted with arrows and polarities (positive "+" and negative "-"). A positive polarity indicates that an increase in the cause leads to an increase in the effect, or a decrease in the cause leads to a decrease in the effect. A negative polarity indicates that the relation is inverse (an increase in the cause leads to a decrease in the effect and vice versa). A distinct characteristic of complex systems is the feedback. This means that a resulting entity is connected to an entity at the beginning of a causal chain, leading to a closed loop. For example, in a population system, the relationship between the population and births is positive: the larger the population, the greater the number of births, and conversely, the smaller the population, the fewer the births. The births at the end of the causal chain feed back into the population size. This signifies a reinforcing (or positive) feedback loop. If the total polarity is negative, it is called a balancing (or negative) feedback loop. While positive feedback loops lead to continuous growth or decline, negative feedback loops counteract changes in the system, promoting stability and equilibrium.

Amongst others, CLDs can be used to analyze systems in the following way:

- **Identify key variables**: determine the main entities that influence system behaviour
- **Identify feedback loops**: look for positive and negative feedback loops
- **Analyze dynamics**: understand the interaction of feedback loops and their influence on system behaviour over time (e.g. with the help of system archetypes, see below)
- **Simulate change**: assess potential changes in the system
- **Develop interventions**: based on the insights gained from the CLD, design interventions for systemic change

CLDs can be analyzed using the concept of system archetypes, which describe recurring patterns of behavior found in different systems. They provide a way to identify and understand common dynamics that often occur in various contexts, such as businesses, environmental systems, and social structures. A common archetype is for example "Fixes that Fail". It is used to describe the situation when a solution is applied to a problem that temporarily alleviates symptoms but eventually leads to unintended consequences that worsen the situation. In transport planning, this archetype can be illustrated by the common practice of expanding road infrastructure to reduce traffic congestion. The symptomatic fix is an expansion of road infrastructure with the intention to reduce traffic congestion. While in the short-term, congestion is reduced, the unintended consequences lead to induced demand. The improved traffic flow makes driving

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on the road more attractive, the enlarged capacity is filled up and in the long-term congestion returns to a condition that is even worse than before. (Pfaffenbichler, 2011; Sterman, 2000)

MARS, the transport model used for quantification in this thesis (see Chapter 5) is based on System Dynamics and its parts have been described as CLDs (Pfaffenbichler et al., 2008). These diagrams also provide the basis for the CLD used in the qualitative analysis in this chapter, see sections below.

### 4.4.1 Method for creating the Causal Loop Diagram

The basis for the CLDs created in the course of this thesis were existing and validated CLDs of the national land use and transport system (e.g. Pfaffenbichler, 2011; Pfaffenbichler et al., 2008, 2010). The concept of an SMG as defined in Chapter 3 and possible impacts discussed in the stakeholder workshops (see Section 3.2) were analyzed by drawing and assessing CLDs. The qualitative system structure and parts of the Causal Loop Diagram were discussed with System Dynamics professionals in the course of a workshop presentation of the "Transportation Special Interest Group" of the System Dynamics Society (Laa, 2021).

### 4.4.2 Causal Loop Diagram for the Sustainable Mobility Guarantee

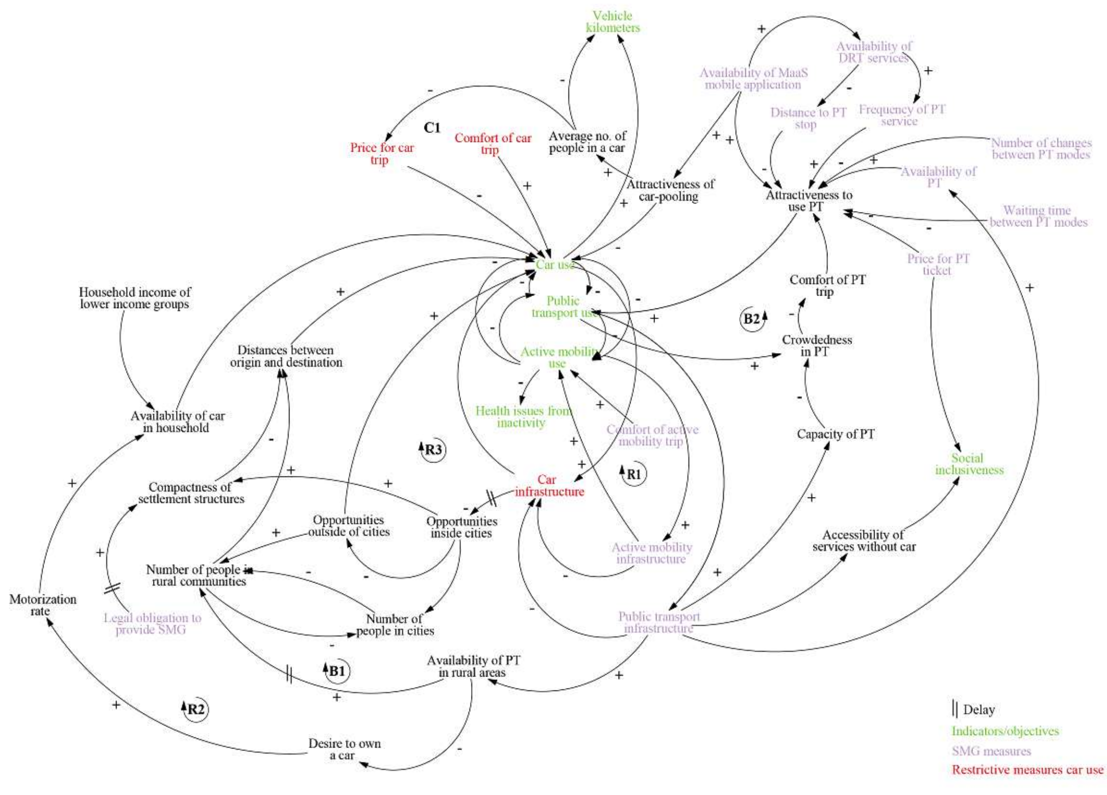


**Fig. 4.2:** Causal Loop Diagram of transport system and measures of a Sustainable Mobility Guarantee, own illustration

The CLD in Fig. 4.2 represents a part of the transport and land use system, focusing on individuals choosing transport modes for their everyday mobility and a place to live depending on

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accessibility. The diagram shows elements that are introduced or influenced by the Sustainable Mobility Guarantee (depicted in purple) and their impact on travel behaviour. Restrictive measures for car use, which might be implemented together with an SMG are colored in red, while sustainable mobility indicators are shown in green. The central elements represent mode choice: a trip can only be made with one transport mode and therefore, the mode use is connected with negative relations to the other mode uses. Elements influencing mode use, such as infrastructure, services, distances and cost are connected to the mode use elements. Mode choice is depending on the relative attractiveness of each mode. On the left side of the diagram, elements regarding land use are shown. Some individual loops are explained in more detail in the next sections.

### 4.4.3 (Desired) causal chains

With the introduction of an SMG, several beneficial effects are desired. This section describes how the measures implemented as part of an SMG show causal effects along the chain of system elements to the indicators, with the following signs:

$\uparrow$ Quantitative increase

$\downarrow$ Quantitative decrease

$\xrightarrow{+}$ Positive relationship/polarity

$\xrightarrow{-}$ Negative relationship/polarity

**More public transport - less car use**

$\uparrow$ *Attractiveness to use PT* $\xrightarrow{+}$ $\uparrow$ *Public transport use* $\xrightarrow{-}$ $\downarrow$ *Car use* $\xrightarrow{+}$ $\downarrow$ *Vehicle kilometers driven by car*

For the desired effects, this should be read as: “With increasing attractiveness to use PT, PT use increases, leading to a reduction of car use and a reduction of vehicle kilometers driven by car.” It has to be considered, however, that causal links can act in both directions. The same system structure can lead to the opposite effect:

$\downarrow$ *Attractiveness to use PT* $\xrightarrow{+}$ $\downarrow$ *Public transport use* $\xrightarrow{-}$ $\uparrow$ *Car use* $\xrightarrow{+}$ $\uparrow$ *Vehicle kilometers driven by car*

In this case, the causal chain should be read as: “With decreasing attractiveness to use PT, PT use decreases, leading to an increase in car use and an increase of vehicle kilometers driven by car”

**More PT - less motorization**

$\uparrow$ *Public transport infrastructure* $\xrightarrow{+}$ $\uparrow$ *Availability of PT in rural areas* $\xrightarrow{-}$ $\downarrow$ *Desire to own a car* $\xrightarrow{+}$ $\downarrow$ *Motorization rate* $\xrightarrow{+}$ $\downarrow$ *Availability of car in household* $\xrightarrow{+}$ $\downarrow$ *Car use* $\xrightarrow{+}$ $\downarrow$ *Vehicle kilometers driven by car*

For the desired effects, this should be read as: “An increase in PT infrastructure leads to an increase in availability of PT in rural areas, leading to a decreased desire to own a car and a

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decrease in motorization rate and in the following to a decrease of availability of a car in the household and less car use as well as a decrease in the vehicle kilometers driven by car." The same structure could lead ultimately to an increase of vehicle kilometers driven by car if the causal chain is started with a decrease in PT infrastructure.

#### MaaS mobile applications - less car use

$\uparrow$ *Availability of MaaS mobile applications* $\xrightarrow{+}$ $\uparrow$ *Attractiveness of car-pooling* $\xrightarrow{+}$ $\uparrow$ *Average no. of people in a car* $\xrightarrow{-}$ $\downarrow$ *Vehicle kilometers driven by car*

For the desired effects, this should be read as: "With an increase in the availability of MaaS mobile applications, the attractiveness of car-pooling increases, leading to a higher number of people in a car which reduces the vehicle kilometers driven by car". As shown with the other examples, the opposite effect would occur if the causal chain satrts with a decrease of the availability of MaaS mobile applications.

#### Less car dependence - more social inclusiveness

$\uparrow$ *Public transport infrastructure* $\xrightarrow{+}$ $\uparrow$ *Accessibility of services without car* $\xrightarrow{+}$ $\uparrow$ *Social inclusiveness*

The desired effect in this causal chain is an increased social inclusiveness through more PT infrastructure which would lead to higher accessibility of services without car. Started in the other direction, less PT infrastructure would lead to less social inclusiveness.

#### Cheaper PT tickets - more social inclusiveness

$\downarrow$ *Price for PT ticket* $\xrightarrow{-}$ $\uparrow$ *Social inclusiveness*

This causal chain describes the desired effect of increased social inclusiveness due to lower prices for PT tickets. In contrast, increases in ticket prices would lead to decreased social inclusiveness.

#### More active mobility - better health

$\uparrow$ *Active mobility infrastructure* $\xrightarrow{+}$ $\uparrow$ *Active mobility use* $\xrightarrow{-}$ $\downarrow$ *Health issues from inactivity*

For the desired effects, this should be read as: "An increase in active mobility infrastructure leads to an increase in active mobility use, which leads to a decrease in health issues from inactivity". Contrary, a decrease in active mobility infrastructure would ultimately lead to an increase in health issues from inactivity.

### 4.4.4 Feedback Loops

The feedback loops are shown in the CLD (Fig. 4.2). B indicates a balancing (negative) feedback loop and R a reinforcing (positive) feedback loop. In the following, the loops are described.

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**R1 - Infrastructure provision**

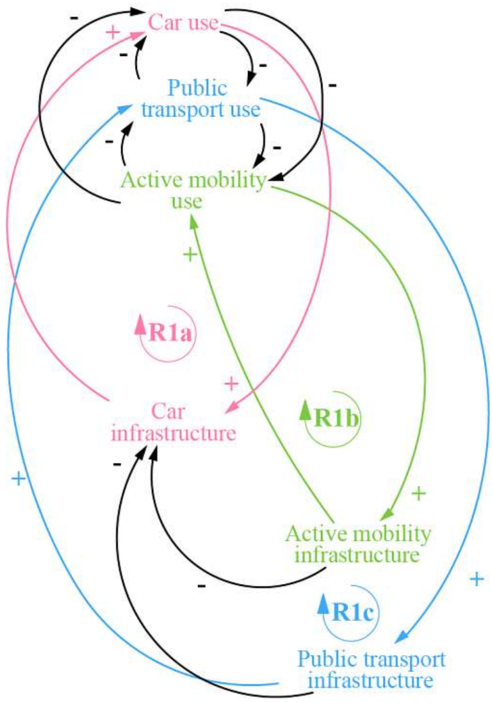


**Fig. 4.3:** Reinforcing loop R1, own illustration

There are three connected reinforcing feedback loops about infrastructure provision shown in the CLD, representing the three modes: car (R1a), active mobility (R1b) and PT (R1c). Due to the qualitative nature of the CLD, it is not clear which loop will dominate system behavior. Mode choice depends on the comparative attractiveness of the modes. Historically and arguably also in the current situation, the loop is driven by providing more infrastructure for cars, leading to more car use, which is seen as the reason to build even more car infrastructure to create more capacity to accommodate growing car traffic. With introducing an SMG, there would be provision of more infrastructure for PT and active mobility, leading to increased use of those modes and then to more infrastructure for walking, cycling, buses and trains. And on the other hand, the change would also lead to a change in direction of the positive feedback loop of car infrastructure; meaning less car use leading to less infrastructure for cars. This behavior could be accelerated by using car infrastructure for other modes such as by creating bus lanes, cycling paths, or wider sidewalks instead of car lanes or parking lanes in cities. The loop also shows the connection between active modes and PT, potentially competing for users. This points towards a possible rebound effect: with increased attractiveness of PT, people switch from walking and cycling to using PT. Therefore, mitigation policies should be considered when the objective is to increase PT use as well as the use of active mobility.

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### R2 - Motorization

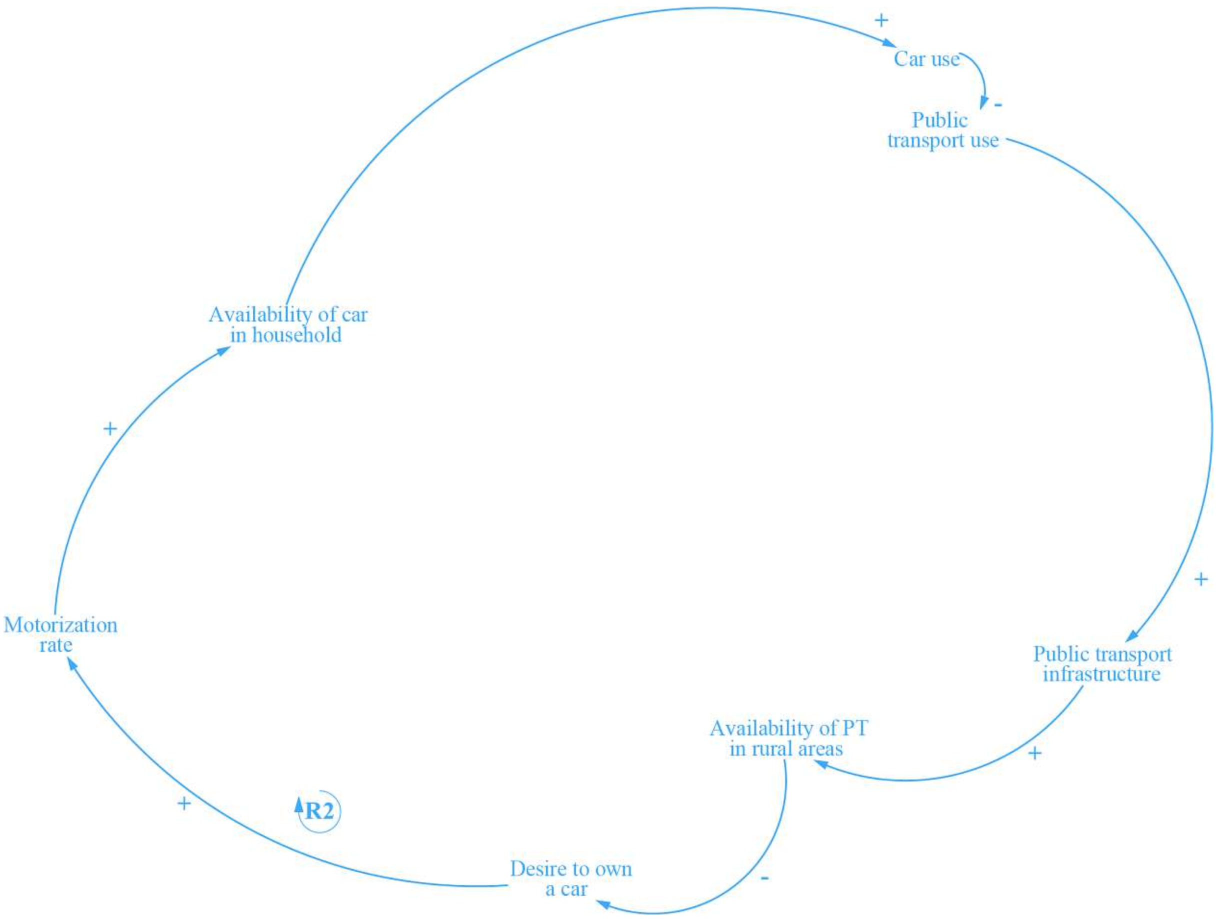


**Fig. 4.4:** Reinforcing loop R2, own illustration

The availability of a car is an important factor in mode choice. Therefore, the causal chain described above as “More PT - less motorization” also acts in a loop. The entity *Motorization rate* connects to the *Availability of car in household* which connects to the mode choice (decrease in car use). This again connects back to more use of other modes, which leads back to more infrastructure for other modes. It should be assessed carefully in the future if the introduction of an SMG actually shows such effects on motorization rates.

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### B1 and R3 - Moving to rural areas

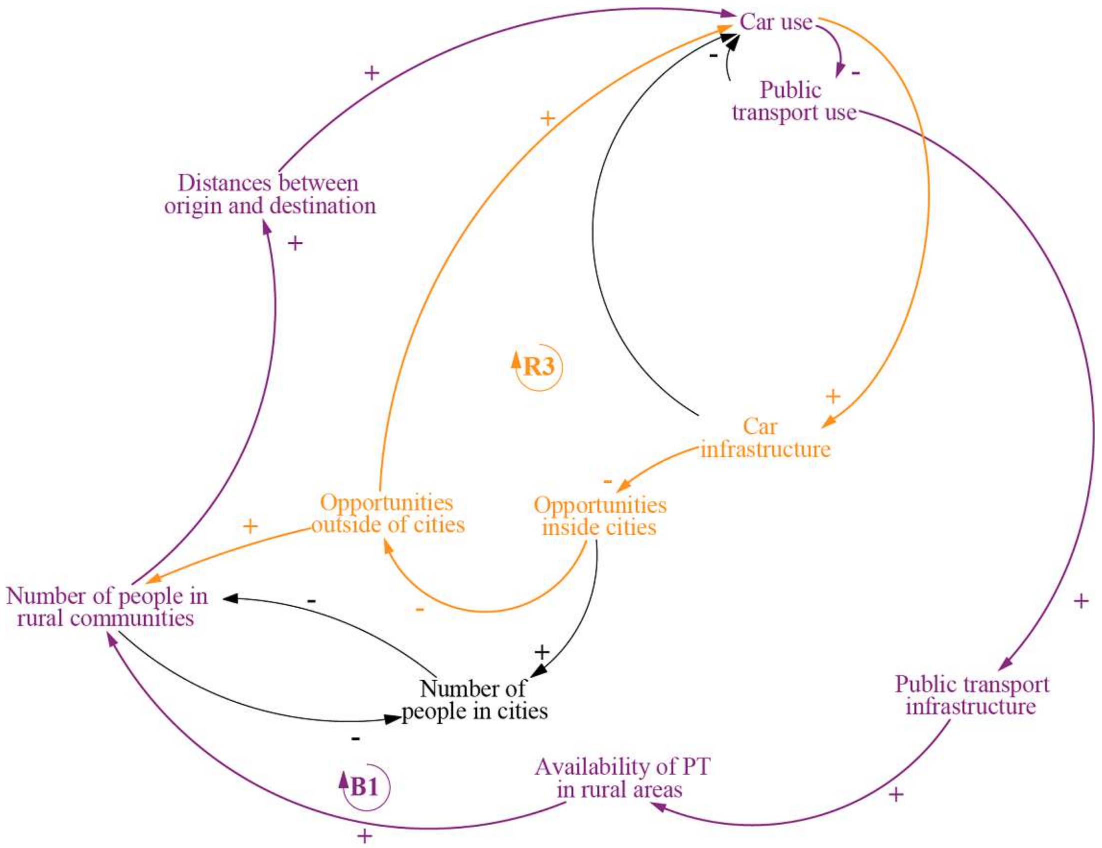


**Fig. 4.5:** Feedback Loops B1 and R3, own illustration

B1 is a balancing feedback loop with a connected reinforcing feedback loop (R3) that has to be considered. The system behaviour describes a rebound effect that is similar to the system archetype “Fixes that Fail”: an intended solution that reduces a symptom in the short-term creates a positive feedback loop with delay that increases the initial problem. The intention of PT provision in rural areas is to reduce car use, which is shown in the CLD with the causal chain described above as “More public transport - less car use” and “More PT - less motorization” and in R2. Availability (or better quality) of PT in rural areas might, however, also lead to a larger number of people living in rural communities, where distances between origins and destinations are still larger than in cities. Even if PT availability serves as a factor in deciding where to move and is used for some trips, this might still induce more car trips overall due to larger distances. In the balancing feedback loop, this leads to less PT use which can lead to less PT infrastructure provision. However, the connection with car use might again lead to the positive feedback loop of more car infrastructure being built to accommodate growing car traffic in rural communities and more opportunities outside of cities. The introduction of an SMG therefore requires additional policies to mitigate such developments.

**B2 - Crowdedness in PT**

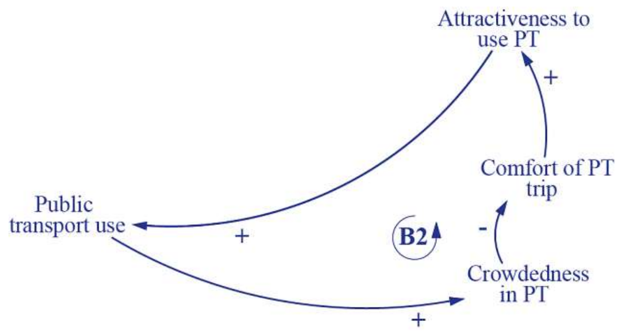


**Fig. 4.6:** Balancing feedback loop B2, own illustration

A balancing feedback loop can be found by looking at the attractiveness to use PT. With increasing PT use, there is more crowdedness in PT, reducing the comfort of PT trips and therefore the attractiveness to use PT. This is a similar loop to the common example of congestion on roads serving as a balancing feedback loop to car use (not shown in the CLD).

**C1 - Car pooling rebound effect**

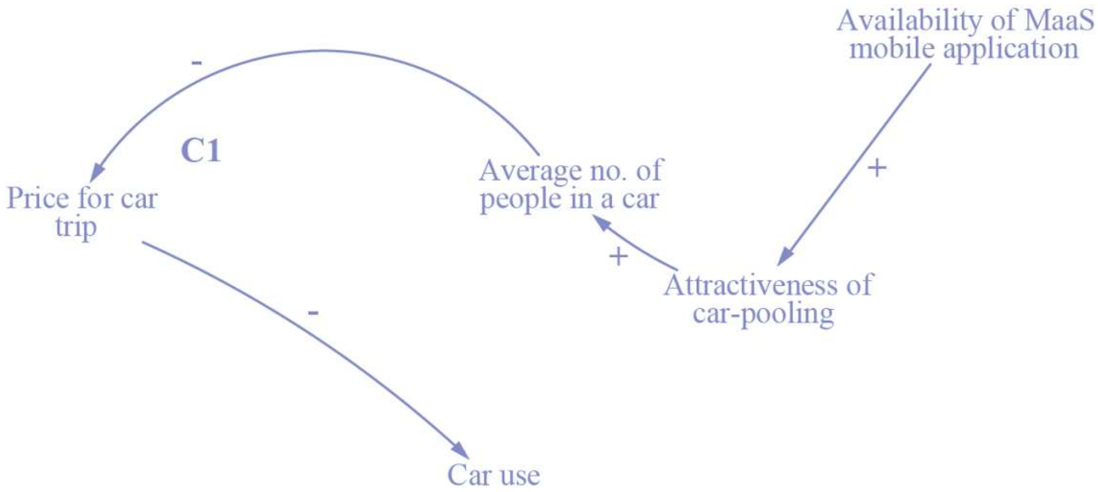


**Fig. 4.7:** Causal chain C1, own illustration

The intended impact of promoting car pooling with MaaS mobile applications as part of an SMG is to provide mobility services to people and reduce vehicle kilometers travelled by car by increasing the average no. of people in a car (see causal chain "MaaS mobile applications - less car use"). Unintended consequences are shown in the causal chain C1, where it is shown that increasing the number of people in a car reduces the price for a car trip, which increases car use and reduces the use of other modes; and again connecting to the entity of car infrastructure which can spur further growth in car traffic.

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## 4.5 Leverage Points: Places to Intervene in a System

Leverage points are understood as places to intervene in a system where a small change could lead to a large shift in behaviour like the leverage effect, see illustration in Fig. 4.8. Meadows (1999) introduced a ranked list of leverage points, ranging from lowest impact to highest impact when trying to achieve systemic change that has been slightly adapted since. The leverage points according to Meadows (2008) are (from lowest to highest impact):

**Numbers:** Constants, parameters, numbers (such as subsidies, taxes, standards)

**Buffers:** The sizes of buffers and other stabilizing stocks, relative to their flows

**Stock-and-Flow Structures:** The structure of material stocks and flows (such as transport networks, population age structures)

**Delays:** The lengths of delays, relative to the rate of system change.

**Balancing Feedback Loops:** The strength of negative feedback loops, relative to the impacts they are trying to correct against.

**Reinforcing Feedback Loops:**The gain around driving positive feedback loops

**Information Flows:** The structure of who does and does not have access to information

**Rules:** The rules of the system (such as incentives, punishments, constraints)

**Self-Organization:** The power to add, change, or evolve system structure

**Goals:** The purpose or function of the system

**Paradigms:** The mindset out of which the system — its goals, structure, rules, delays, parameters — arises

**Transcending Paradigms**

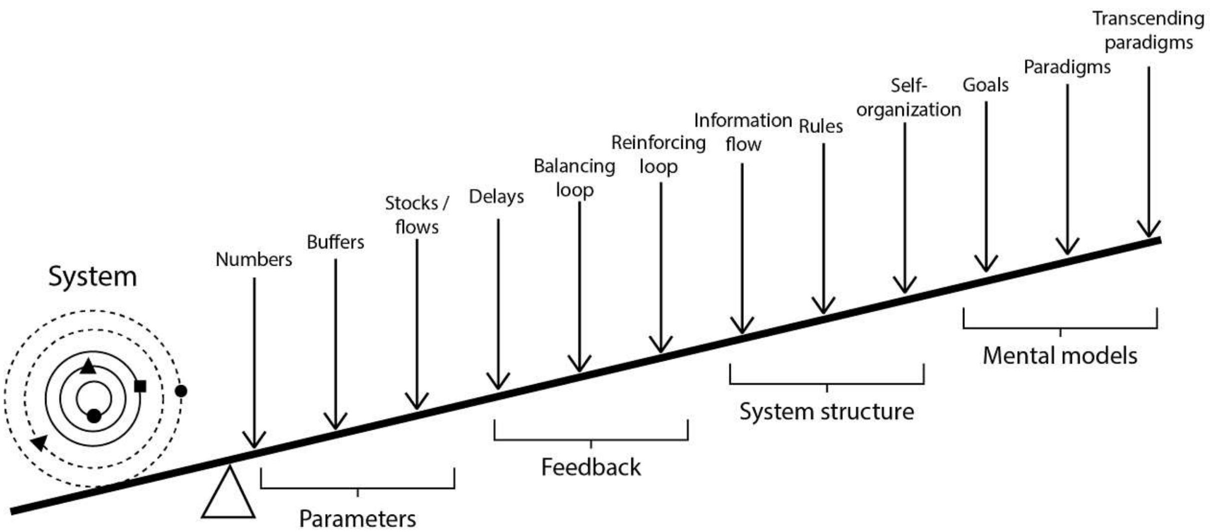


**Fig. 4.8:** Leverage points to intervene in systems. Own illustration based on Angheloiu and Tennant (2020) and Meadows (1999)

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While some leverage points are part of the system structure as usually depicted in CLDs (Numbers, Buffers, Stock-Flow Structures and Delays), others have to be considered as outside of it. In reference to the MLP, the first three (Numbers, Buffers and Stock-Flow Structures) could be considered as parameters that can be replaced by niche-innovations. Some leverage points relate to feedback, structure and organization within the regime (Delays, Feedback Loops, Information Flows, Rules and Self-Organization). The three with the highest leverage can be summarized as mental models that are comparable to the landscape level of the MLP, considered exogenous to the system but able to exert pressure on it. While the higher leverage points have a larger impact on the system, they are considered to be more difficult to change. Policy measures therefore tend to address lower leverage points which are easier to implement (Frey & Laa, 2021).

The concept of leverage points has been already applied to address systemic change or transformations in transport systems and related fields. For example Angheloiu and Tennant (2020) use leverage points as an analytical framework for a literature review on analyzing system changing interventions in the context of urban sustainability futures. They found that most interventions proposed in literature are addressing parameters, the lowest leverage points (46% of interventions), followed by feedback loops, system structure and mental models (only 4% of interventions). Brömmelstroet et al. (2022) argue to find new narratives regarding mobility in order to address deeper leverage points.

Another recently developed framework by Brand-Correa et al. (2020) draws from the leverage points concept and uses the transport system as an example. It is based on the idea of Mattioli (2016) for a new framework to combine climate action and social aspects in the transport sector referring to different orders of "need satisfiers". Need satisfiers are considered objects, activities, structures or systems that are used to fulfill human needs. This framework was extended by Brand-Correa et al. (2020) who discuss their analysis of need satisfiers in transport systems using the leverage points concept of Meadows (2008). Similar to leverage points, they describe four orders of need satisfiers as connected, different sized cogs (or gears):

1. Socio-technical provisioning systems
2. Activities
3. Energy and material services
4. Specific technologies

The first order and smallest cog are socio-technical provisioning systems. The second order (and second-largest) are activities, the third order energy and material services and the fourth order (with the largest cog) are specific products or technologies. On the one hand, the cog metaphor illustrates the interconnection of different satisfier orders. On the other hand, the size of the cogs represents two factors: the leverage potential, where a small change in a first order cog can cause a significant change in a fourth order cog, and the relative difficulty of moving each cog, with smaller cogs being harder to move.

In the example of transport systems and the car, this means that the car as a specific product is located at the lowest level, the fourth order of need satisfiers. A different need satisfier on that level could be a different vehicle, such as a bus, a train or a bicycle. The second order is represented by mobility - as the service of travel that fulfills the need to get from one location to another. The third order (activities) is described as car-dependent practices and related cultures of car use and the first order as provision of car infrastructure and car-dependent land-use patterns. (Brand-Correa et al., 2020)

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### 4.5.1 Application of Leverage Points to the SMG

In the following, the leverage points framework is used to assess the SMG concept in terms of transformative change.

#### Parameters: Numbers, Buffers and Stock-and-Flow structures

The three lowest leverage points can be summarized as parameters. They include numbers, buffers and stock-and-flow structures. Individual parameters that play a role in the SMG concept are for example the prices of public transport tickets, the $CO_2$ price and subsidies for car use (e.g. commuter allowance, company car benefits). Target values and quality standards are also part of numbers in the context of leverage points. This includes quality standards to be met in PT services (such as the PTSQL) or in infrastructure for active mobility, such as minimum widths for sidewalks and cycling paths. Climate targets in the transport sector and indicators in SUMPs such as a target modal split might be added to the list. Those numbers can serve in the interest of the objectives that the SMG is trying to achieve, however, only changing individual parameters does not lead to behaviour change of the whole system. A characteristic example are GHG emission reduction targets. Although the UN states have committed to the Paris Agreement and the EU states to specific emission reductions, the GHG emissions are currently not on track to achieve them (UN Environment Programme, 2022a).

Buffers represent the size of stabilizing stocks relative to their flows. In terms of the SMG, the stock of transport infrastructure and buildings are possibly the most important buffers. Transport infrastructure includes the length and capacity of roads, railways, amount of car parking, etc. The existing stock of infrastructure that is predominantly used for private cars is very large and has been growing for decades, while railway networks have declined in Austria (see Section 2.2). While the introduction of an SMG would change the infrastructure stock, e.g. by adding more rail lines and cycling paths, and there might be an influence on land use developments (see feedback loop B1 of the CLD), such processes take a long time. This is why buffers are seen as a low leverage point. But SMG measures could also take advantage of buffers by adapting existing car infrastructure to be used by other modes, as explained below.

The *structure of material stocks and flows* can be interpreted as the transport network in Austria. Currently, there is a transport network of most direct lines used by car infrastructure such as highways, roads and city streets. These streets and roads can legally be used also by other road users such as PT buses or cyclists but have been usually built intentionally for cars. Especially vulnerable road users such as cyclists don't feel safe or comfortable to use them and are therefore restricted in its usage. While the highways are planned in the most direct ways, cycling routes are often meandering or located in crooked side streets where priority needs to be given to vehicles on crossing main streets. Even though the public transport infrastructure and services in Austria and other European countries might show decent quality, compared to the car infrastructure network it is usually still at a disadvantageous position. This is one of the main aspects that the SMG is aiming to change: to have a nationwide network of sustainable mobility options available to everyone. This means that PT and active mobility infrastructure has to be seen as a priority. A valuable strategy to achieve this might be the conversion of car infrastructure, e.g. into dedicated bus lanes instead of car lanes on highways and city streets, or to create cycling lanes instead of car lanes and remove curbside car parking in favor of cycling lanes or bike parking. Curbside car parking could also be transformed into space for PT stops or to broaden side walks and add green space. This way, the same action would increase the stock of infrastructure for active mobility and PT as well as reduce the stock for car infrastructure.

While such changes could be implemented rather easily and rapidly in theory, the example of pop-up bike lanes and temporary shared spaces that have been introduced in Vienna during the

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Covid-19 pandemic shows that the political feasibility of adapting car infrastructure to be used by other modes remains a large challenge (Frey et al., 2024). The redesign of individual streets and building additional infrastructure such as new cycling lanes or tramway lines seems to be easier, but shows change much more slowly and remains limited in its effect compared to scaling up infrastructure change to a whole country.

Another important stock that acts as a buffer is the stock of cars. Car ownership has been shown to have a large influence on travel behavior. While the SMG would not directly reduce the number of cars, better PT services could lead to lower motorization rates (see also Section 2.1) and the existence of an SMG as a broad guarantee to be mobile without a private car might also lead to a changed perception regarding the desire to own one.

#### Feedback: delays and feedback loops

Delays and feedback loops are shown in the CLD (Section 4.4.2). Delays that refer to a significantly longer causal relation than the rest of the system structure affect mostly land use dynamics. A currently dominant positive feedback loop is the process of urban sprawl. This includes the provision of car infrastructure, such as new roads, which leads to less opportunities inside cities, and more opportunities outside of cities. This again leads to more car use, which leads to the provision of even more car infrastructure. The process of changing zoning and building new homes and amenities usually set in not directly after new roads have been built but take longer than creating new PT services or providing parking spaces. This signifies a delay in the system. While the introduction of an SMG is aimed at reducing car dependence - implementation has to be planned and observed carefully to not influence delays in an undesirable direction. As shown in the CLD with loop B1, an SMG might also influence land use in a way that more people move to rural areas, which could lead unintentionally to more car use. Such tendencies should be monitored and if needed counter-policies introduced, e.g. targeting service provision in rural areas.

Regarding positive feedback loops, it is important to understand that they can act in both directions, leading to growth or decline. This often presents a threat to objectives such as in the case with accelerated car dependence, however, the power of positive feedback loops can also be harnessed for achieving desired change. The goal of an SMG would be to implement a set of measures that enables to change the direction of such loops, e.g. less car use leading to less infrastructure for cars, leading to more opportunities in cities and denser settlement structures. This might be achieved by changing the system in a way that PT and active mobility infrastructure are proactively implemented and lead to a change in direction of the feedback loop - leading to more use of PT and active mobility. It has to be considered, however, that the loops are connected and act in a balancing way where PT and active modes are in competition. This means that only increasing the attractiveness of either those modes would lead to a reduction in the use of the respective other mode, while car use is left unchecked. This is one reason why the introduction of an SMG has to be accompanied by restrictive measures for car use.

#### Power over system structure: information flows, rules and self-organization

The leverage points regarding information flows, rules and self-organization are external to the system description in the CLD and I suggest to summarize them as “power over the system structure”. Information flows are often described by adding new feedback loops, giving information to people who take decisions. In the case of the SMG, information plays a role regarding MaaS mobile applications, where the SMG should create a framework for the development of open and neutral mobility platforms, ensuring information and brokerage of transport services in a

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non-discriminatory and undistorted manner. This would give people information on different transport modes, such as the real-time information of PT services, options of shared mobility, routing options and ticketing information as well as booking. While this provides information that impacts mode choice of individuals, it is not addressing information that can change the structure of the system.

Angheloiu and Tennant (2020) refer to participation methods with regard to the information flow leverage point. Participation can take on different forms ranging from only providing information to put the decision in the hands of citizens. Interestingly, the participatory format of the Austrian Climate Assembly recommended to implement comprehensive PT services that can be interpreted as a mobility guarantee ((ARGE Klimarat, 2022), see also Section 3.1.4.1). However, the results of the assembly remain only proposals with the government not being obliged to implement them.

This brings us to the next leverage point of rules - or rather to who has the power to change the rules of the system. Some parts of the SMG would need to be implemented on a legal level, the most formal rules of how the transport system works. But also informal rules are important. Referring to the CLD, this means for example who has the power to decide if the positive relation between car use and car infrastructure remains? Or if instead this triggers the conversion of driving lanes into bus lanes? This concerns the practical implementation of an SMG, which is out of scope of this thesis to analyze.

Self-organization refers to distributed power to change (parts of) the system and is sometimes also referred to as "the distribution of power over the rules of the system" (Meadows, 1999). Regarding the transport and land use system, this power lies mostly in the legislation on national and provincial level. There might be a lesson here for implementation of a Sustainable Mobility Guarantee to allow for self-organization by provinces or communities to create customized mobility solutions as part of the SMG in their territory and/or in cooperation with neighboring municipalities. This approach is also encouraged in the report by OECD-ITF (2021) for implementing a mobility guarantee in rural areas. Communities are already experimenting with new forms of DRT services.

### Mental models: goals and paradigms

In terms of mental models, I argue that these are outside of the analysed system and therefore not directly affected by the introduction of an SMG. Although it is envisageable that the SMG could have indirect impacts on those levels as well. The current goal of the transport system can be interpreted as continuous flow of car traffic and maximization of motorized traffic, following the paradigm of economic growth (Schwedes, 2023). Brömmelstroet et al. (2022) argue in favor of "identifying, nurturing and empowering alternative mobility narratives" to overcome the current paradigm. The introduction of an SMG or even already the discussion of the concept might be able to help change narratives and the goal of the system in a direction of providing access to services or sustainable mobility options to everyone while staying within planetary boundaries.

Mental models regarding the transport system are, however, of course not independent from our economic system, which still pursues growth as the main goal. As some countries already have and suggested by frameworks such as donut economics and the degrowth community (see Section 1.1.3), introducing alternative indicators as part of a new paradigm could help to change the goal of the transport system as well. The SMG might serve as a policy that fits into a new paradigm but cannot alone achieve such a change.

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## 4.6 Conclusion

The MLP showed that the impact of an SMG for a transformation remains limited and has to be embedded in wider actions for change but could play an important role. This is also highlighted by the Leverage Points framework. While the implementation of an SMG is located rather at the lower leverage points, there might be some effect on mental models changing from car centric point of views in transport planning and politics to a different view that is in line with a social-ecological transformation. The SMG alone cannot achieve this, however, but could be a useful tool if higher leverages/the landscape level offer opportunities for change. The leverage point concept helps to critically reflect on the chosen research approach, as this thesis joins the ranks of research addressing mostly lower leverage points, while far-reaching transformation needs to also address higher leverage points.

The CLD helped identifying system behaviour and rebound effects such as land use change (people and opportunities moving to rural areas) due to better PT provision in rural communities and more attractive car use due to the promotion of car pooling. The implementation of an SMG should be done in a way to counter these tendencies. The qualitative analysis is limited when it comes to loop dominance, since it is not clear which variables have a larger impact when two counteracting effects occur. This will be analysed for some loops in Chapter 5.

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# Chapter 5

# Quantitative model of travel behaviour

This chapter deals with the quantification of possible impacts of a Sustainable Mobility Guarantee on travel behaviour, on a national level in Austria. Simulations are carried out with MARS, the *Metropolitan Activity Relocation Simulator*. The first section describes the model, its basic assumptions and mathematical implementation. Then, in Section 5.2, assumptions and variations for external scenarios are described. This is followed by Section 5.3 which presents the different elements/measures of the Sustainable Mobility Guarantee (SMG), including the "translation" of the SMG concept into the model and sensitivity testing of individual parameters. Section 5.4 shows the results of the five SMG scenarios. The chapter is concluded with a discussion of the results.

## 5.1 Model Description

MARS[1] is a dynamic Land Use and Transport Interaction (LUTI) model that has been developed at the Research Center of Transport Planning and Traffic Engineering at TU Wien by Paul Pfaffenbichler and Günter Emberger (Pfaffenbichler et al., 2008, 2010). It was initially created to assess transport policy and land use measures for metropolitan areas but has since been applied on the regional and national level as well. Mayerthaler et al. (2009) developed the first national model for Austria (see also Mayerthaler (2013) for a detailed model description).

The model version that is used in this thesis is based on the so called MARS-UBA Model Austria that has been realized for the Environment Agency Austria (*Umweltbundesamt*) in order to assess the impact of transport measures on the Austrian climate goals (Heinfellner et al., 2018). Afterwards, it was modified minimally and was used in a back-casting approach for the latest Austrian Mobility Master Plan (*Mobilitätsmasterplan 2030*) with the goal of reaching climate neutrality in 2040 (Angelini et al., 2022; BMK, 2021). The model has been calibrated with the most recent nationwide mobility survey in Austria, which was conducted in 2013/2014 (Follmer, Gruschwitz, Kiatipis, et al., 2016).

In the model, the territory of Austria is mapped on the basis of 120 zones representing the administrative districts. The classic time frame in the model is 30 years in time-steps of one year with 2010 as the base year, until 2040. The simulation maps passenger traffic on a typical working day and takes into account four different transport modes: walking, cycling, public transport (bus and train) and motorized private transport. A detailed mathematical description of the MARS-UBA model can be found in Pfaffenbichler (2017). A description of the current calibration based on data from the Austria-wide mobility survey "Austria on the Move" (Follmer, Gruschwitz, Kiatipis, et al., 2016) can be found in Pfaffenbichler (2018). In the following, I will describe the parameters, assumptions and equations relevant for the purpose of this study.

[1] Detailed information on the model can be found here: https://www.fvv.tuwien.ac.at/forschung/mars-metropolitan-activity-relocation-simulator/overview/, accessed 08.01.2024

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### 5.1.1 Basic assumptions - System Dynamics methodology

MARS is based on the methods of System Dynamics (Forrester, 1961; Sterman, 2000). System Dynamics is a methodology for modeling and analyzing complex systems by emphasizing feedback loops, time delays, and the dynamic interactions between different entities. Developed by Forrester (1961), it uses stock and flow diagrams to represent accumulations and rates of change, incorporates both qualitative and quantitative elements, and employs simulation to understand how a system's behavior evolves over time. Widely applied across various disciplines, System Dynamics is particularly useful for exploring long-term behavior and informing policy decisions.

The underlying assumption for MARS is that settlements and activities within them are self-organizing systems that can be represented by such stock-flow diagrams. Transportation and land use systems are closely connected and show mutual influence. Feedback loops and delays are prevalent in these systems. There are eight subsystems that can be differentiated by the speed at which they undergo change, ranging from immediate (goods transport, travel), over fast (employment, population), medium speed (workplaces, housing) to slow (networks, land use) (Pfaffenbichler et al., 2010). Within the transport sector, cars, roads, and public transport supply are considered as stocks, while processes such as road and public transport construction and changes in car ownership are seen as flows.

In terms of land use, population, workplaces, housing units, and land are considered stocks, while changes in these stocks - such as population growth or decline, workplace developments, and the construction or demolition of housing units - are treated as flows. Within the System Dynamics methodology, the model incorporates two essential components: the structure of the system being modeled (qualitative aspect) and its parameters (quantitative aspect), making them explicit for the reader.

### 5.1.2 Technical specifications

The MARS-UBA model is implemented in the software Vensim®, a System Dynamics programming environment. The visual programming environment allows users to create entities and connect them via arrows, representing cause-effect relations. These relations are defined quantitatively by equations, entered by the user.

In contrast to many classic transport models and agent-based models, MARS is a highly aggregated, strategic model and therefore input data is also highly aggregated. It is not suitable for analysing details in terms of spatial resolution, socio-economic groups or route-choice. Its strengths lie in assessing a wide array of policy measures for long time frames and large geographic areas, while maintaining short model run-times. On the aggregated level, simulation results show a good fit with observed real-world developments (Pfaffenbichler et al., 2008, 2010).

The key parameters in MARS are:

- 120 zones (representing administrative districts)
- 2 household types: those with access to a car and those without access to a car
- 2 times of day: peak hours and off-peak hours
- 4 transport modes: walking, cycling, public transport (PT), car[2]

The software version used for this study is Vensim® DSS 9.2.1. The MARS model used in this thesis has 600 variables. The model includes 13 different subscripts. The depth of the

[2]The car mode includes other private motorized vehicles such as motorcycles that are insignificant in Austria (less than 1%); PT includes three different types of feeder mode: walking, cycling and car (park and ride)

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sub-scripts ranges from 2 (e.g. time of the day) to 120 (number of zones). The highest number of subscripts for a variable is 115,200 [3]. The file size of the model (.mdl) is 791 kB, the size of simulation output (.vdfx) is about 3,68 GB. Run-time for the scenarios used in this thesis are about 01:42 min for 30 time steps (representing 30 years). Input data is retrieved from Microsoft Excel files (.xslx).

### 5.1.3 Land use model

Although some versions of MARS can be run as a LUTI model with endogenous interaction of the transport sub-model and land use change, in the current version of MARS-UBA, land use development is generated using external scenarios. The scenario used in this thesis is based on the prognosis of the Austrian Conference on Spatial Planning (*ÖROK - Österreichische Raumordungskonferenz*). For a more detailed description, see 5.2.2.

### 5.1.4 Transport model

Classic four stage transport models include the stages of trip generation, distribution, mode choice and assignment (Lohse & Schnabel, 2011). MARS simulates only the first three steps: trip generation, distribution and mode choice. The final step of assignment to specific routes is not included due to the high aggregation level. The assignment is basically reduced to one link between each origin-destination (O-D) pair (each of the 120 zones with every other zone) for each mode and time of day. Intrazonal (within one zone) trips are differentiated for five distance-classes.

#### 5.1.4.1 Trip generation

Trip generation in MARS is based on the theory of constant travel time budgets (Marchetti, 1994; Metz, 2008; Mokhtarian & Chen, 2004; Schafer, 2000; Zahavi & Talvitie, 1980). Therefore every person has a constant budget of time spent for mobility every day. The travel time budget is assumed for each of the nine Austrian provinces (*Bundesland*) according to data from the nationwide mobility survey in Austria (Follmer, Gruschwitz, Kiatipis, et al., 2016). The average travel time is 67.4 min/d. Constant trip rates for commuting (0.85 trips/business day) are used and the rest of the time budget is allocated to other trips.

#### 5.1.4.2 Distribution and mode choice model

The trip distribution and mode choice are calculated simultaneously using a combination of the analogy to the law of gravity and Kirchhoff's law from electrical engineering. This is shown in Equation (5.1). The number of trips between each O-D pair is calculated for the different trip types (commuting and other) and for the two different times of day (peak and off-peak).

[3] Number of zones origin x number of zones destination x time of day x modes of transport $= 120 \cdot 120 \cdot 2 \cdot 4 = 115,200$

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$$T_{ij}^{m} = P_i \cdot \frac{\frac{A_j}{f(t_{ij}^{m}, c_{ij}^{m})}}{\sum_{mj} \frac{A_j}{f(t_{ij}^{m}, c_{ij}^{m}))}} \tag{5.1}$$

where:

$T_{ij}^{m}$ = Number of trips by mode $m$ from source $i$ to destination $j$
$P_i$ = Production of trips at source $i$
$A_j$ = Attraction of zone $j$ as destination
$t_{ij}^{m}$ = Travel time by mode $m$ from $i$ to $j$ (min)
$c_{ij}^{m}$ = Travel costs for a trip by mode $m$ from $i$ to $j$ (EUR)
$f(t_{ij}^{m}, c_{ij}^{m},)$ = Friction factor for a trip by mode $m$ from $i$ to $j$ (min)

Regarding the two different types of person/household groups, the mode choice model considers those with access to a car and those without access to a car. The group without access to a car can only choose from other modes, those with access to a car can choose from all modes. The share of people with access to a car is calculated depending on car ownership rates, car occupancy rates and the share of people with driving license.

$$Ac^{PC} = \frac{ow^{PC} \cdot o^{PC} \cdot p^{drl}}{1000} \tag{5.2}$$

where:

$Ac^{PC}$ = Share of people with access to a car (%)
$ow^{PC}$ = Car ownership rate (cars per 1,000 residents)
$o^{PC}$ = Car occupancy rate (persons per car)
$p^{drl}$ = Share of driving license holders (%)

The friction factors are calculated based on the work of Walther (1991) and Walther et al. (1997) as generalized cost with different formulas for each transport mode. The general form of friction factor for the time component (Walther et al., 1997) is shown in Equation 5.3

$$f(t_{ij}^{m}) = t_{ij}^{m} \cdot e^{t_{ij}^{m}} \tag{5.3}$$

where:

$f(t_{ij}^{m})$ = Friction factor for a trip by mode $m$ from $i$ to $j$ (min)
$t_{ij}^{m}$ = Travel time by mode $m$ from $i$ to $j$ (min)

The general form of friction factor for the cost component is shown in Equation 5.4

$$f(c_{ij}^{m}) = \frac{c_{ij}^{m}}{\alpha \cdot Inc_i} \tag{5.4}$$

where:

$c_i j^m$ = Cost for trip $i$ to $j$ by mode $m$ (EUR)
$\alpha$ = Factor for value of time
$Inc_i$ = Household income in zone $i$ (EUR/min)

#### Walking and cycling

Maximum distance for walking to be an option is 5 km and for cycling 10 km. Friction factors for walking and cycling are based on Walther et al. (1997) and calculated according to the following equations. The subjective valuation factors have been derived from calibration results.

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$$f(t_{ij}^w) = t_{ij}^w \cdot (\alpha + \beta \cdot e^{\gamma \cdot t_{ij}^w}) \tag{5.5}$$

where:

$\alpha, \beta, \gamma$ = Subjective valuation factors
$t_{ij}^w$ = walking time from i to j (min)

$$f(d_{ij}^c) = \alpha + \gamma + \beta \cdot d_{ij}^c \tag{5.6}$$

where:

$\alpha, \beta, \gamma$ = Subjective valuation factors
$d_{ij}^c$ = distance cycling from i to j (km)

### Public transport

For the friction factors of public transport, the whole trip chain is considered. The four different steps of the trip chain are:

1. From source to PT stop (walking, cycling or car)
2. PT drive from entrance stop to destination stop
3. Changing time
4. From PT stop to destination (walking, cycling or car)

The components are shown in Fig. 5.1.

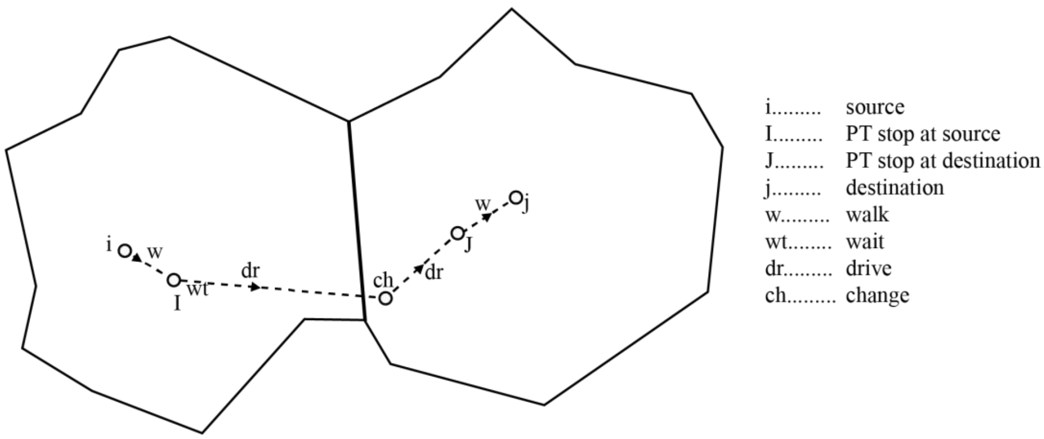


**Fig. 5.1:** Trip chain components for public transport from origin $i$ to destination $j$ based on Walther et al. (1997)

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Equation 5.7 shows the formula for the calculation of the PT friction factor.

$$\begin{aligned} f(t_{ij}^{PT}, c_{ij}^{PT}) = t_{iI}^{PT,w} \cdot SV_{iI}^{PT,w} + t_{I}^{PT,wt} \cdot SV_{I}^{PT,wt} + \sum t_{IJ}^{PT,dr} \\ + \sum t_{IJ}^{PT,ch} \cdot SV_{IJ}^{PT,ch} + t_{Jj}^{PT,w} \cdot SV_{Jj}^{PT,w} + Z_{ij}^{PT} \end{aligned} \tag{5.7}$$

where:

$t_{iI}^{PT,w}$ = Walking time from source $i$ to public transport stop $I$ (min)
$SV_{iI}^{PT,w}$ = Subjective valuation factor walking time from source $i$ to public transport stop $I$
$t_{I}^{PT,wt}$ = Waiting time at public transport stop $I$ (min)
$SV_{I}^{PT,wt}$ = Subjective valuation factor waiting time at public transport stop
$t_{IJ}^{PT,dr}$ = In-vehicle time from PT stop $I$ to PT stop $J$ (min)
$t_{IJ}^{PT,ch}$ = Changing time from PT stop $I$ to PT stop $J$
$SV_{IJ}^{PT,ch}$ = Subjective valuation factor changing time
$t_{Jj}^{PT,w}$ = Walking time from PT stop $J$ to destinatin $j$ (min)
$SV_{Jj}^{PT,w}$ = Subjective valuation factor walking time from public transport stop to destination
$Z_{ij}^{PT}$ = Impedance from costs travelling from $i$ to $j$ by public transport (min)

Subjective valuation factors are based on Walther et al. (1997), with adaptations from model calibration. In general, the functions describe overestimation of access/egress, waiting and changing time (compared to physical time) that increases with physical time, following the natural logarithm, similar to Weber-Fechners law of perception (Knoflacher (2007)). These factors are differentiated for PT modes separated from car traffic (such as metro lines) and ones that are not separated from car traffic (such as tramways and buses). Equations 5.8 to 5.10 show examples for the subjective valuation factors for walking to a public transport stop ($SV_{iI}^{PT,w}$), waiting at the station ($SV_{I}^{PT,wt}$) and changing between two PT modes ($SV_{IJ}^{PT,ch}$) for PT modes that are not separated from car traffic.

$$SV_{iI}^{PT,w} = 0.506502 + 0.268792 \cdot e^{0.459240 \cdot t_{iI}^{PT,w}} \tag{5.8}$$

$$SV_{I}^{PT,wt} = 1.632673 + 0256768 \cdot e^{0.459240 \cdot t_{I}^{PT,wt}} \tag{5.9}$$

$$SV_{IJ}^{PT,ch} = 0.744725 + 0284470 \cdot e^{0.459240 \cdot t_{IJ}^{PT,ch}} \tag{5.10}$$

### Car trips

The attractiveness of choosing the private car (PC) as a transport mode for a trip depends on three elements: the availability of a car (and driving license/occupancy rate), the (weighted) travel time and the (weighted) cost of the trip.

Friction factors are differentiated along the trip chain with the following steps:

1. From origin to parking space (walking)
2. Car drive from parking space at origin to destination
3. Search time for parking space
4. From parking space to final destination (walking)

The components are shown in Fig. 5.2.

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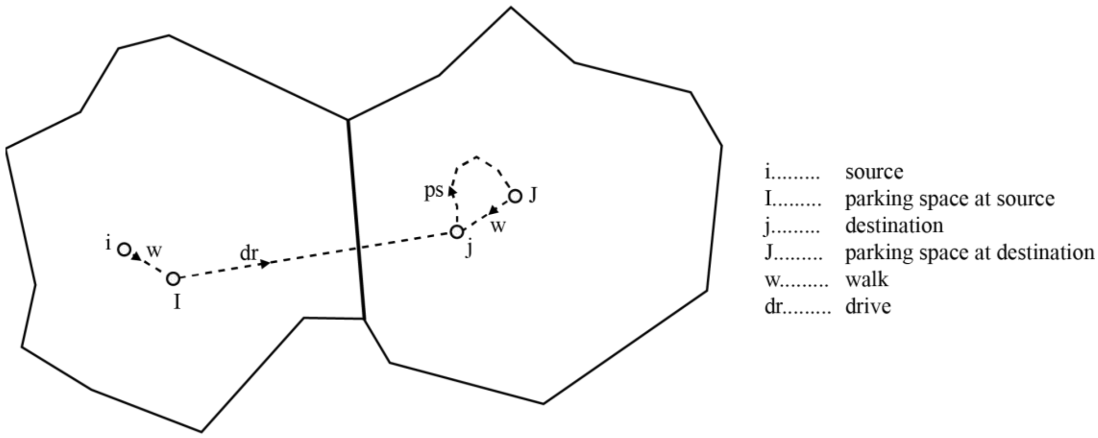


**Fig. 5.2:** Trip chain components for car trips from origin $i$ to destination $j$, based on Walther et al. (1997)

Equation 5.11 shows the formula for the calculation of the car friction factor.

$$f(t_{ij}^{PC}, c_{ij}^{PC}) = (t_{iI}^{PC,w} \cdot SV_{iI}^{PC,w} + t_{Ij}^{PC,dr} + t_{jJ}^{PC,ps} \cdot SV_{jJ}^{PC,ps} + t_{Jj}^{PC,w} \cdot SV_{Jj}^{PC,w}) \cdot SV_{ij}^{PC} +^{k} Z_{ij}^{PC} \tag{5.11}$$

where:

$t_{iI}^{PC,w}$ = Walking time from source $i$ to parking space $I$ (min)
$SV_{iI}^{PC,w}$ = Subjective valuation factor walking time from source $i$ to parking space $I$
$t_{IJ}^{PT,dr}$ = In-vehicle time from $I$ to destination $J$ (min)
$t_{jJ}^{PC,ps}$ = Search time for parking space at $I$
$SV_{jJ}^{PC,ps}$ = Subjective valuation factor parking space search time
$t_{Jj}^{PT,w}$ = Walking time from parking space at $J$ to destination $j$ (min)
$SV_{Jj}^{PT,w}$ = Subjective valuation factor walking time from parking space to destination
$SV_{ij}^{PC}$ = Aggregated subjectve valuation factor private car for origin-destination pair $ij$
$Z_{ij}^{PC}$ = Impedance to travel by car from $i$ to $j$ caused by cost component $k$ (min)

Subjective valuation factors differ for walking to (and from) a parking space and parking search time as well as for the aggregated trip chain. The one for walking from the origin $i$ to the parking space $I$ is assumed constant, with 1.

$$SV_{iI}^{PC,w} = 1.0 \tag{5.12}$$

This means that time is not overestimated but valued the same as physical time.

The subjective valuation factor for parking search time is based on the formula by Walther et al. (1997):

$$SV_{jJ}^{PC,ps} = 2.0 + 10^{-4} \cdot e^{0.8 \cdot t_{jJ}^{PC,ps}} \tag{5.13}$$

The subjective valuation factor for walking from the parking space $J$ to the final destination $j$ is calculated with the same formula:

$$SV_{Jj}^{PC,ps} = 2.0 + 10^{-4} \cdot e^{0.8 \cdot t_{Jj}^{PC,w}} \tag{5.14}$$

The aggregated subjective valuation factor for an origin-destination pair $ij$ is calculated as follows:

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$$SV_{ij}^{PC} = 0.8507 \cdot (1 - e^{-0.1879 \cdot D_{ij}^{PC}}) \tag{5.15}$$

where:

$D_{ij}^{PC}$ = Travel distance by car from $i$ to $j$ (km)

## 5.2 Assumptions for external scenarios

The model includes many assumptions that influence mobility behaviour but are not impacted by the scenarios modelling the Sustainable Mobility Guarantee. The most relevant variables in MARS reflecting these assumptions are:

- Population and workplaces
- Car fleet (motorization rate and share of electric vehicles)
- Car occupancy rate
- Prices for fuel and electricity
- Household income
- Availability of infrastructure

These parameters might be affected by social and economic developments as well as impacts of climate change. Such developments are uncertain and considered external to the analysis conducted in this study. The assumptions and variations used for the simulations are described in detail in the following.

### 5.2.1 BAU - Business As Usual Scenario

The BAU Scenario reflects existing trends and official prognoses by Austrian institutions or scenarios from previous projects such as "Transition Mobility 2040" by the Environment Agency Austria (Angelini et al., 2022). Details about the BAU forecasts and variations in the simulations are described in the following. To account for the uncertainty of the parameters and show the level of impact, some of the parameters are varied. An overview table of all varied parameters in the simulations can be viewed in Table 5.3.

External scenarios are referred to in the terminology of the Environment Agency Austria. The three different abbreviations used are WEM19 ("with existing measures" in the year 2019), WAM ("with additional measures") or "Transition 2040", referring to scenarios that have been developed to explore climate neutrality of the transport sector in 2040 in the course of the "Transition Mobility 2040" project (Angelini et al., 2022).

### 5.2.2 Population and workplaces

Development of population and workplaces are exogenous variables in the model used in this thesis. For the BAU Scenario, the 2021 population prognosis from the Austrian Conference on Spatial Planning (ÖROK, 2021) is used. The parameter is entered into the model with a population growth rate for each of the 120 zones (administrative districts).

According to the prognosis, the total population growth in Austria between 2020 and 2040 amounts to 7.8 % from 8.42 million inhabitants (over the age of 6 years) in 2020 to 9.07 million in

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2040. While 38 districts show a decline in population, 82 districts show growth. In Table 5.1, the average growth rates are shown for the different region types. The capital city Vienna shows the highest growth rate while rural areas with low PT service show an overall decline.

**Tab. 5.1:** Average population growth rate per region type 2020 - 2040

| Region type | Population growth rate |
|---|---|
| Vienna | 0.42 % |
| Urban | 0.29 % |
| Suburban | 0.28 % |
| Rural with good PT service | 0.20 % |
| Rural with low PT service | -0.06 % |

### 5.2.3 Car fleet and occupancy rate

In the model, the number of cars is calculated by multiplying the population with the motorization rate. The number of cars influences the availability of vehicles and is an important factor in mode choice. The basic external scenario used in BAU is called "WEM19" which shows and increased motorization rate following the long-term trend, from 608 cars per 1,000 inhabitants[4] in 2020 to 666 in 2040. In this study, I also use a variation of the motorization rate development - the "WAM+" scenario - based on the assumption that the trend is dampened due to additional measures. Although there is no endogenous causal link in the model, it can be argued that the availability of a Sustainable Mobility Guarantee or similar measures can have an impact on the attitude towards car ownership and finally lower motorization. In the WAM+ Scenario, the motorization rate decreases from 2020 onward and amounts to only 577 cars/1,000 inhabitants in the year 2040, see Figure 5.3. The WAM+ scenario for motorization (external variable EXT_1 in the model) is used in the SMG Scenarios 2-5.

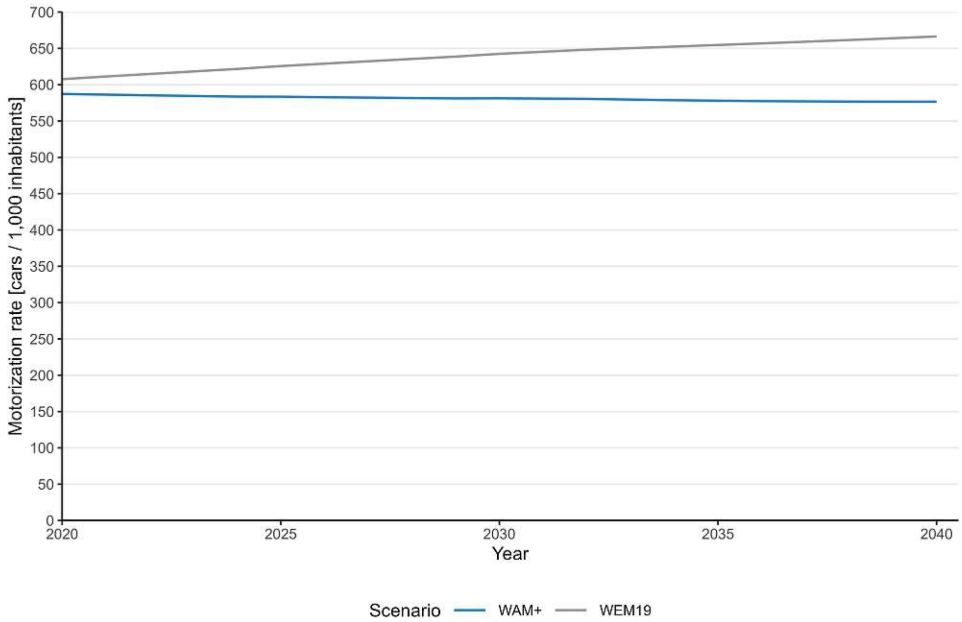


**Fig. 5.3:** Assumed development of motorization rate in external scenarios WEM19 and WAM+

[4]Note that the motorization rate here is calculated with the MARS Austria population, which includes only inhabitants older than 6 years

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Not only the number of cars but also the car types influence other parameters and mode choice. For example propulsion technology, size and fuel consumption influence the cost of fuel and maintenance cost (see next section) and the specific $CO_2$-emissions. Again, MARS is an aggregated model that does not differentiate between specific car types. The only differentiation is made between ICE (internal combustion engine) cars and electric cars (e-cars), influencing mainly the fuel costs and $CO_2$-emissions.

The external scenario "WEM19" defines the development of the share of e-cars in the fleet for the BAU Scenario. The variation used in this study is based on the Transition 2040 project, which assumes almost full electrification by the year 2040. The two different developments are shown in Figure 5.4. The two characteristic kinks in the curve of e-car share of the Transition 2040 scenario (in year 2038 and 2039) are visible in the mode choice result diagrams (e.g. Figure 5.5) - as electricity is assumed to cost less than fossil fuels (see next section).

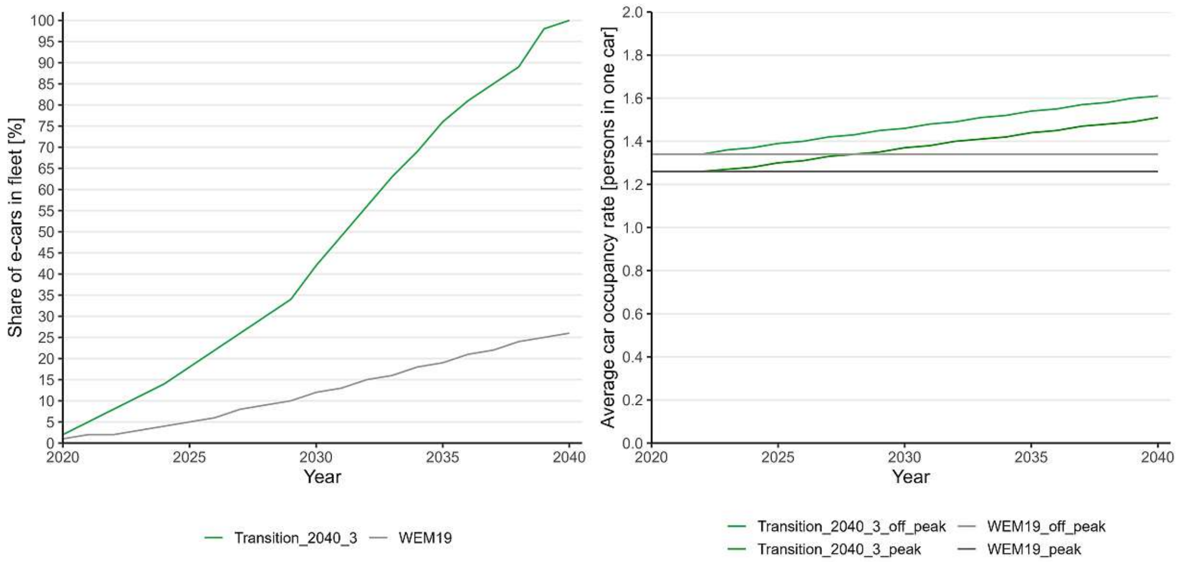


**Fig. 5.4:** Assumed development of share of e-cars and car occupancy rates scenarios WEM19 and Transition_2040_3

Car occupancy rates also influence the trip costs for users and can increase or decrease the overall VKT (vehicle-kilometers traveled), since it makes a difference if two persons make a trip alone and need two cars or if they share the ride and need only one car for the same trip. The average number of people in a car has historically declined and differs depending on the type of trip.

In MARS, the occupancy rate is differentiated for each zone and time of day (peak and off-peak). The "WEM19"-Scenario assumes that there is no change between the years 2020 - 2040. The average occupancy rate in peak-hours is 1.26 and off-peak 1.34.

As a variation, the "Transition_2040_3" Scenario in this study assumes that the car occupancy rate increases, due to higher prices, carpooling incentives or a changed attitude concerning car travel. The car occupancy rate increases by 20 % from 2023 to the year 2040. The rate increases linearly every year, resulting in an average of 1.51 during peak hours and 1.61 off-peak in 2040, see also Figure 5.4.

To show the sensitivity of mode choice results in MARS, the variations have been simulated separately. Results can be seen in Figure 5.5. The external scenario regarding share of e-cars and

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car occupancy rate is named EXT_2_3 here. The two external scenarios in combination are named EXT_1_2_3.

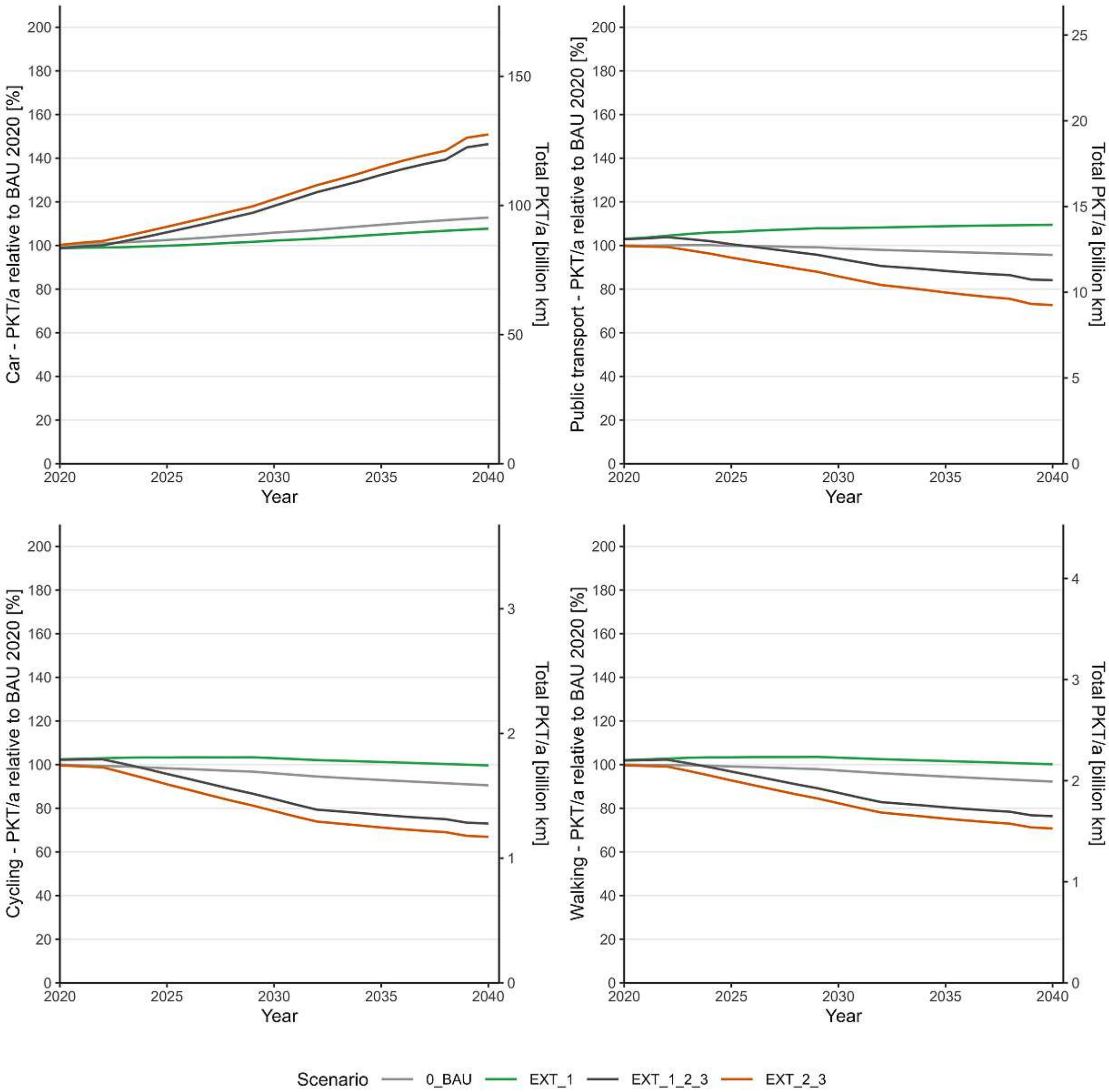


**Fig. 5.5:** Sensitivity of external scenarios regarding reduced motorization rate in comparison to the BAU scenario

The motorization rate has a considerable effect on mode choice and PKT (Person-kilometer traveled) of all modes. The reduced motorization rate (EXT_1, green curve) shows a reduction of car PKT by 4.5 % compared to BAU in 2040 and increases for other modes (8 - 14 %). Scenario EXT_2_3 (orange) on the other hand shows large increases of car traffic compared to the BAU Scenario (+33.8 % in 2040). This can be explained due to reduced cost, since electricity is regarded cheaper than fossil fuels and if people pool in one car (increased occupancy rate), the cost per person is also lower. This signifies a rebound effect: with the intention of reducing $CO_2$-emissions by shifting to e-cars and reducing the VKT by increasing occupancy rates, the cheaper travel costs make driving in a car more attractive. The combined scenario shows that

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the decreased motorization rate can reduce car PKT by 2.9 % compared to EXT_2_3 in 2040 but the overall trend is still increasing car traffic.

### 5.2.4 Prices for fuel and electricity

The cost of driving a car consists of several elements in MARS. The price for fuel or electricity, road pricing (which includes $CO_2$-pricing in the current model structure), parking fees and "other perceptible costs" (fixed with EUR 0.084/km). The development of prices for fuel and electricity in the simulations follow the external scenario "WEM19" and are not varied as an exogenous variable. This is a major limitation, especially in consideration of sharply increased prices in the recent past. This is discussed in detail in Section 5.5.2.

Net fuel price in the model is EUR 1.38/l. The fuel price growth rate following the "WEM19"-scenario ranges from 2.5 % - 3.6 % p.a., reaching 2.56 EUR/l in 2040. Electricity prices are set to EUR 0.17/kWh in the year 2020 and increase between 1.8 % p.a. and 2.8 % p.a. until they reach EUR 0.26/kWh in 2040.

$CO_2$ pricing as implemented in Austria[5] is added to the fossil fuel price.

The development for the $CO_2$ price is as follows:

- From October 2022: EUR 30/t$CO_2$
- From 2023: EUR 35/t$CO_2$
- From 2024: EUR 45/t$CO_2$
- From 2025: EUR 55/t$CO_2$

The effect of the $CO_2$ price on actual fuel prices ranges between EUR 0.11/l and EUR 0.20/l (net) additionally with the assumption of emitting on average 2.37 kg$CO_2$/l.

The net fuel prices for car users are shown in Figure 5.6 for the two different external scenarios regarding car fleet development. With rising numbers of e-cars in the Transition 2040 scenario, the prices go down because electricity is cheaper than fossil fuels.

[5] Ökosoziales Steuerreformgesetz 2022 Teil I - ÖkoStRefG 2022, BGBl. I Nr. 10/202 2

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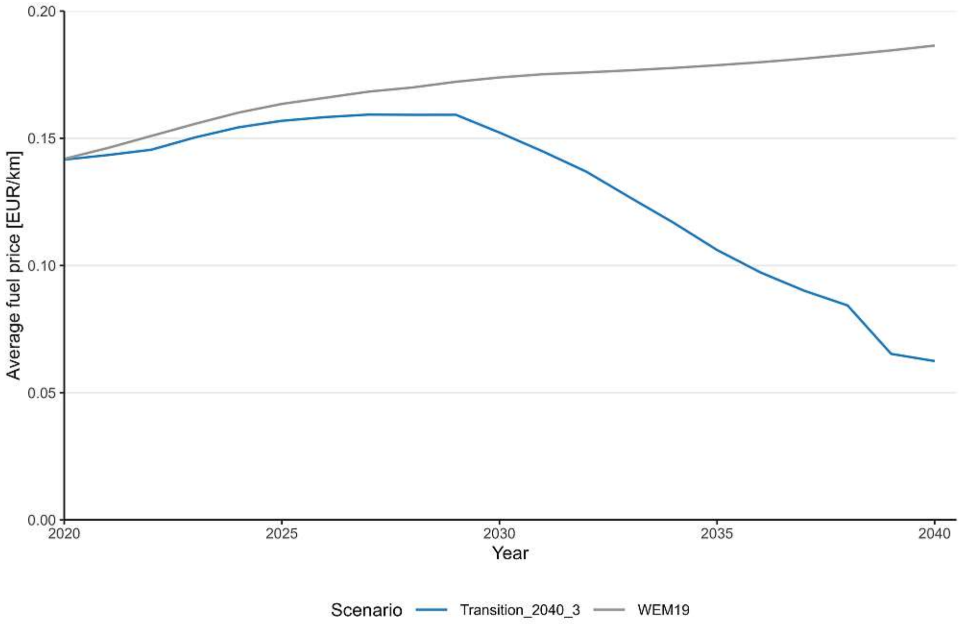


**Fig. 5.6:** Average (gross) fuel price for the external scenarios "WEM19" and "Transition_2040_3", differing in fleet composition

### 5.2.5 Household income

Hosehold income development is based on the WIFO model DYNK, referenced in MARS-UBA as "WEM19". The parameter is entered as an average for each administrative district, based on the year 2010[6] with an annual growth rate that is the same for every district. It is 1.0 % p.a. for the years 2023 - 2029 and 1.4 % p.a. for the years 2030 - 2040.

The introduction of $CO_2$ pricing in Austria in 2022 was combined with the so-called "climate bonus" - returning the revenue from the $CO_2$ price to the citizens with distributional effects. The bonus is paid to every person living in Austria (registered at least 183 days) and is regionally differentiated depending on public transport service quality.

In MARS, the bonus was added to the household income with a new variable in MARS that is added to the monthly available household budget in each district, according to the regional differences.[7]

In the year 2022, the state paid every adult citizen EUR 500 (EUR 250 as a climate bonus and EUR 250 as inflation relief) and children 50 % (EUR 250) - this outlier was not considered in the simulations as well as other inflation-relief payments have not been considered, since inflation was not considered.

### 5.2.6 Availability of infrastructure

In the BAU scenario, there are no changes of the transport infrastructure. This means that the BAU scenario does not include the provision of new infrastructure such as roads and railroads.

[6] Statistik Austria. Verfügbares Haushaltseinkommen und äquivalisiertes Nettohaushaltseinkommen 2008 - 2022. URL: https://www.statistik.at/statistiken/bevoelkerung-und-soziales/einkommen-und-soziale-lage/haushaltseinkommen)

[7] Statistik Austria (2021) Kombinierte Darstellung Urban-Rural-Typologie und ÖV-Anbindung. URL: https://www.statistik.at/atlas/?mapid=topo_urt_oev&layerid=layer1&sublayerid=sublayer0&languageid=0&bbox=858553,5773174,2032626,6346145,8

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Neither is the reduction of infrastructure part of the scenarios. In reality, several large scale highway projects and regional road projects are planned to be built in Austria. Concerning railroads, there are plans to extend the network on large routes, but smaller railroads have seen a decline in the past centuries (see Chapter 2). This also means that changes in infrastructure due to damages, which are likely to occur more often due to climate change impacts, are not part of the simulations.

As described above, MARS only features O-D links between zones, characterized by travel time and distance. New infrastructure or the removal of infrastructure would impact these links. For the car mode, these links are not changed, neither in the external scenarios for BAU, nor in the Sustainable Mobility Guarantee (SMG) scenarios. Foreseeable changes such as shorter travel times between Graz and Klagenfurt due to the finished Koralmtunnel are not included in the external scenarios. Obviously this is an inconsistency, but the assumption of BAU using only existing infrastructure is deemed appropriate for the scope of analysing the effects of the SMG on travel behaviour on an aggregated, strategic level for Austria as a whole. Changes in the infrastructure such as new highways and railroads would change behaviour on certain routes and in specific regions. However, within the scope of the study, the general policy recommendations follow the nationwide assessment of large-scale changes in transport planning which render individual changes in the network negligible for these purposes.

Provision of public transport infrastructure (and therefore the O-D links) are varied according to the SMG scenarios, using the parameters of *Distance to public transport stop* and *Waiting time*. The links between zones regarding PT are only changed accordingly in the PT trip chain, not in terms of travel time and distance between zones.

The availability of small-scale infrastructure such as streets in city development areas can be considered as being implicitly part of the scenario where population growth and changes of workplaces are happening, since the model does not include routing but only aggregate zones for O-D pairs and intrazonal trips without routing.

## 5.3 Parameters of the Sustainable Mobility Guarantee

### 5.3.1 Translation of measures to MARS

Not all elements that were verbally attributed to the scenarios in Chapter 4 can be modelled in MARS. The parameters that were available for creating the Sustainable Mobility Guarantee scenarios and their implementation in the model are described in Table 5.2. The right columns indicate the start and end date of implementing the measure. Measures that are introduced stepwise are linearly increasing over the implementation period until they are in full effect.

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**Tab. 5.2:** Parameters of the Sustainable Mobility Guarantee and their implementation in MARS

| Element name | Scenario parameters | Implementation in MARS | Start of measure | End date (full effect) |
|---|---|---|---|---|
| SMG_1 | Adjustment of PT cost | Percentage factor reducing the ticket fares | 2023 | 2040 |
| SMG_2 | PT minimum intervals | Minimum intervals depending on urban/rural classification of district (zone) and time of day (peak/off-peak) | 2023 | 2040 |
| SMG_3 | Maximum distances to PT stops | Factor increasing the no. of persons living in distance classes less than 15 min away from PT stops | 2023 | 2040 |
| SMG_4 | Integrated interval timetable | Maximum transfer time for train trips based on a 1-hour-interval | 2025 | 2025 |
| - | DRT services | Not defined as a separate means of transport, but implemented as part of PT | - | - |
| EXT_3 | Promotion of car pooling | Percentage factor increasing the occupancy rate for private cars | 2023 | 2040 |
| SMG_5 | Quality improvement of active mobility | Percentage factor reducing the subjective evaluation factors of friction factors for walking and cycling in generalized cost | 2023 | 2040 |
| SMG_6 | Spatial planning densification measures | Percentage factor increasing the share of destinations that are accessible within 5 km - affecting only changes in land use, not the stocks of population and workplaces | 2023 | 2040 |
| RES_1 | Lower speed limits | Reduced average speed according to speed limit for road type | 2024 | 2024 |
| RES_2 | Road pricing | Cost of driving per km for car mode | 2023 | 2040 |

### 5.3.2 Sensitivity testing - fail of automatic Vensim tools

Initially, it was planned to use the built-in "Optimizer" function in Vensim[8] for sensitivity testing, to assess the effects of individual measures on travel behaviour. Unfortunately, this was not successful and eventually, the sensitivity testing has been done manually (see Section 5.3.3).

There are different optimization functions in Vensim, to detect model errors, adjust parameters based on data (e.g. for calibration), find best policy levers or test parametric sensitivity. Sensitivity concerning single measures (parameters) in MARS was of interest to find out which effect on travel behavior can be attributed to which individual changes as well as to find the synergetic effects of combined measures. For sensitivity testing, the chosen Optimizer payoff type was "Policy" (in contrast to calibration). When clicking on "Optimizer" in Vensim, the first decision is to choose Policy. Then the payoff-variable should be selected. In the next step, the type of sensitivity to be tested can be chosen. The option "param percent" was selected and set to 10. This means, that the tested variable will be changed by 10 % and the according change of

[8] https://www.vensim.com/documentation/ref_optimization.html, accessed 06.05.2024

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the payoff-variable will be calculated. The user can select to receive a “Payoff Report” of the simulation results. Vensim saves a file in the .tab-format (a tab-separated text-based file format) showing results of the payoff-variable for changing the tested variable by -10 % and +10 % of the initial value. Users can select several payoff-variables to show the effect on different indicators.

One of the problems encountered when trying to use the Optimizer for parameter sensitivity testing with MARS was that only constants can be chosen as parameters. However, most parameters that should be tested are not constants but change over time and are loaded into MARS from Excel sheets. As far as the author looked into it, it is not possible to use dummy-values or set a base value for the Optimizer when dealing with non-constant parameters. In order to find out if and how the Optimizer could be used with constants in the model, several constant variables were chosen as testing variables. This always resulted in the error message *“ERROR: Cannot find constant in model: ’Name of constant’.”*. One of the reasons for this could be that also constant values are loaded into MARS from Excel sheets. However, to change that, it would have been necessary to make significant changes in the model structure. It was therefore deemed more efficient to conduct the sensitivity testing manually. In order to assess the impact of each policy measure/parameter in MARS individually, several different values for the parameters of the Sustainable Mobility Guarantee (“SMG-parameters”) were chosen, based on actual policy decisions with realistic values or to explore limits and saturation effects (e.g. when considering the spatial coverage of PT stations).

### 5.3.3 Description of parameters and sensitivity testing

In order to see the isolated effects of single measures, element testing for each measure as part of the SMG as well as for restrictive measures for cars (“RES”) was conducted. Table 5.3 shows an overview of the measures and intensities as implemented in the MARS models for all scenarios.

In the following sections, results of the sensitivity simulations are shown for the four modes car, public transport, cycling and walking in PKT (Passenger-kilometer traveled) in reference to the BAU value in 2020 (y-axis on the left side) and in total PKT per year (y-axis on the right side).

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**Tab. 5.3:** Overview of parameters, measures and intensities as simulated in MARS. Varied parameters highlighted in colour.

| | External scenarios | | | | | | | | Sustainable Mobility Guarantee parameters | | | | | | Restrictive measures | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EXT_1 | EXT_2 | EXT_3 | | | | | | SMG_1 | SMG_2 | SMG_3 | SMG_4 | SMG_5 | SMG_6 | RES_1 | RES_2 |
| Scenario | Motorization rate | Share of e-cars | Car occupancy rate | Specific CO2-Emissions | Fuel prices | Household income development | CO2 pricing and climate bonus | Population development | PT ticket prices | PT frequency [min peak/off-peak for urban and rural] | PT distances [densification factor] | PT changing time [min peak/off-peak] | Attractiveness increase active mobility [Change in subjective evaluation factor Walking / cycling] | Densification/Spatial planning | Lower speed limits [km/h for inside settlement areas/outside/highway] | Road pricing [EUR/km] [peak/off-peak] |
| 0_BAU | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | 60/- | - | - | - | - |
| Ext_1 | WAM+ | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | - | - |
| EXT_2_3 | WEM19 | Transition_2040_3 | Transition_2040_3 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | - | - |
| EXT_1_2_3 | WAM+ | Trans_2040_3 | Trans_2040_3 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | - | - |
| SMG_1_1 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | -50% | - | - | - | - | - | - | - |
| SMG_1_2 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | -100% | - | - | - | - | - | - | - |
| SMG_2_1 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | 15/30 and 210/210 | - | - | - | - | - | - |
| SMG_2_2 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | 15/30 and 120/210 | - | - | - | - | - | - |
| SMG_2_3 | WEM19 | WEM19 | WEM19 | WAM3 20 | WEM19 | WEM19 | WEM22 | WEM19 | - | 10/30 and 30/60 | - | - | - | - | - | - |
| SMG_2_4 | WEM19 | WEM19 | WEM19 | WAM3 21 | WEM19 | WEM19 | WEM22 | WEM19 | - | 10/30 and 30/30 | - | - | - | - | - | - |
| SMG_2_5 | WEM19 | WEM19 | WEM19 | WAM3 21 | WEM19 | WEM19 | WEM22 | WEM19 | - | 15/30 and - | - | - | - | - | - | - |
| SMG_2_6 | WEM19 | WEM19 | WEM19 | WAM3 21 | WEM19 | WEM19 | WEM22 | WEM19 | - | - and 210/210 | - | - | - | - | - | - |
| SMG_3_100 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | 100 | - | - | - | - | - |
| SMG_3_250 | WEM19 | WEM19 | WEM19 | WAM3 20 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | 250 | - | - | - | - | - |
| SMG_3_400 | WEM19 | WEM19 | WEM19 | WAM3 21 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | 400 | - | - | - | - | - |
| SMG_3_900 | WEM19 | WEM19 | WEM19 | WAM3 22 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | 900 | - | - | - | - | - |
| SMG_3_2000 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | 2000 | - | - | - | - | - |
| SMG_3_3000 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | 3000 | - | - | - | - | - |
| SMG_4_1 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | 30/60 | - | - | - | - |
| SMG_4_2 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | 20/30 | - | - | - | - |
| SMG_4_3 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | 15/30 | - | - | - | - |
| SMG_5_1 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | 30% / - | - | - | - |
| SMG_5_2 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | 70% / - | - | - | - |
| SMG_5_3 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - / 30% | - | - | - |
| SMG_5_4 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - / 70% | - | - | - |
| SMG_5_5 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | 30% / 30% | - | - | - |
| SMG_5_6 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | 70% / 70% | - | - | - |
| SMG_6_1 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | 0.25 | - | - |
| SMG_6_2 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | 0.5 | - | - |
| RES_1_1 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | 30/ - / - | - |
| RES_1_2 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | - /80/ - / | - |
| RES_1_3 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | - / - /100/ | - |
| RES_1_4 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | 30/80/100 | - |
| RES_2_1 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | - | 0.1/0.0 |
| RES_2_2 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | - | 0.5/0.0 |
| RES_2_2t | WEM19 | Transition_2040_3 | Transition_2040_3 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | - | 0.5/0.0 |
| RES_2_3 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | - | 0.1/0.1 |
| RES_2_3t | WEM19 | Transition_2040_3 | Transition_2040_3 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | - | 0.1/0.1 |
| RES_2_4 | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | - | 0.5/0.5 |
| RES_2_4t | WEM19 | Transition_2040_3 | Transition_2040_3 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | - | - | - | - | - | - | 0.5/0.5 |
| 1_All regions aboard | WEM19 | WEM19 | WEM19 | WAM3 19 | WEM19 | WEM19 | WEM22 | WEM19 | - | 15/30 and 210/210 | 300 | 60/- | - | - | - | - |
| 2_Active mobility | WAM+ | WEM19 | WEM19 | WAM3 19 | WEM20 | WEM19 | WEM22 | WEM19 | - | 15/30 and 120/210 | 300 | 60/- | +70% | 0.25 | 30 | - |
| 3_Car pooling | WAM+ | Transition_2040_3 | Transition_2040_3 | WAM3 19 | WEM21 | WEM19 | WEM22 | WEM19 | - | 15/30 and 120/210 | 250 | 60/- | +30% | 0.25 | - | - |
| 4_Goodbye car | WAM+ | Transition_2040_3 | Transition_2040_3 | WAM3 19 | WEM22 | WEM19 | WEM22 | WEM19 | -50% | 10/30 and 60/120 | 400 | 60/- | +70% | 0.5 | 30/80/100 | 0.5/0.0 |
| 5_Utopia | WAM+ | Transition_2040_3 | Transition_2040_3 | WAM3 19 | WEM23 | WEM19 | WEM22 | WEM19 | -100% | 10/30 and 30/60 | 400 | 60/- | +70% | 0.5 | 30/80/100 | 0.5/0.5 |

### SMG 1 - Public transport ticket prices

Two different testing scenarios were analysed, corresponding to the ones used in the SMG-scenarios. In Scenarios 0 - 3, constant fares were assumed for the entire period. In Scenario 4, the fare is reduced by about 3 % per year from 2023 until a reduction of 50 % of the initial level is reached in 2040. In Scenario 5, public transport is offered free of charge. Here, too, the gradual reduction is carried out in the model from 2024 until a reduction of 100 % is achieved in 2040. The two intensities of price reductions were simulated separately (SMG_1_1 with -50 % and SMG_1_2 with -100 %). Results are shown in Figure 5.7, in comparison to the BAU scenario.

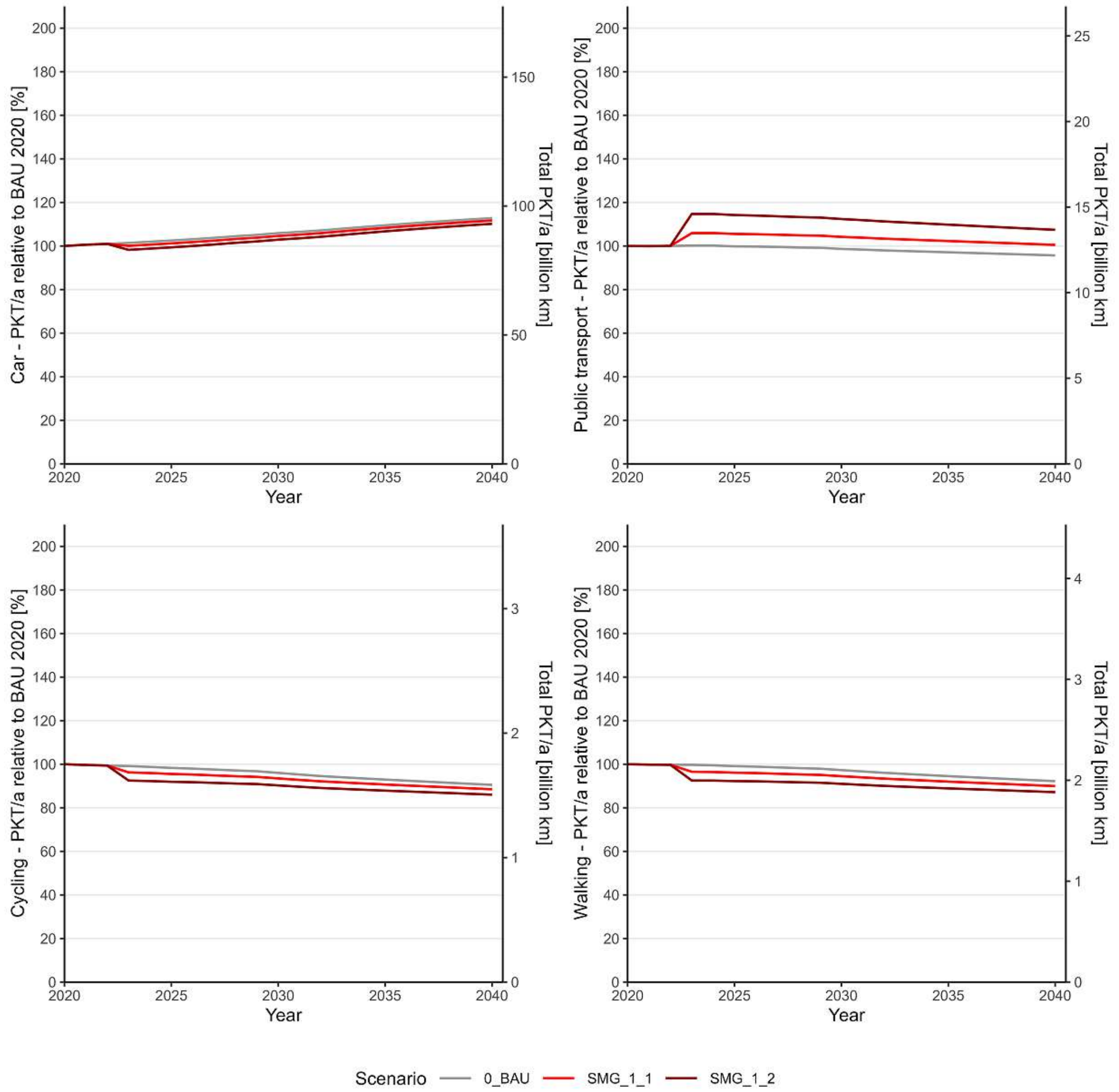


**Fig. 5.7:** Sensitivity public transport ticket prices; BAU, SMG_1_1: ticket prices -50%, SMG_1_2: free public transport

The overall impact of the individual measures are not very large, but can be seen in the PKT curves with distinct kinks in the start year of 2023. PKT of car travel is reduced by only 1.0 %

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and 2.3 % compared to BAU in 2040, however the overall increasing trend is not changed. PKT of public transport is initially going up by 14.5 % with free PT, and about 5.8 % in the scenario with ticket prices reduced by 50 %. Nevertheless, the long-term trend of decreased PT travel until 2040 is still present. Active modes also show reduced PKT, by 2.2 % and 5.0 % for cycling and 2.5 % and 5.5 % for walking in 2040 compared to BAU.

### SMG 2 - Public transport frequency/waiting time

For the definition of the minimum intervals, a distinction is also made in the model between urban and rural regions. For this purpose, the classification according to Table 5.4 was adopted, combining the five categories in MARS (based on the EISERN project (Müller et al., 2012)) to the differentiation of urban and rural.

**Tab. 5.4:** Definition of urban and rural regions

| No. | Category MARS | Region type |
|---|---|---|
| 0 | Vienna | urban |
| 1 | urban | urban |
| 2 | suburban | rural |
| 3 | rural with good PT service | rural |
| 4 | rural with bad PT service | rural |

From 2023 onward, the minimum intervals are adjusted linearly until they reach the target value in 2040. Minimum intervals define the maximum waiting time for public transport users at the station. Intervals in MARS are only adjusted where they are currently longer than the minimum, while shorter intervals will stay the same, so the service level is not decreased. Table 5.5 shows the minimum intervals during operating hours for each simulation element for urban and rural areas and peak and off-peak hours.

**Tab. 5.5:** Public transport minimum intervals during operating hours

| Element name | Urban<br>Peak/Off-peak [min] | Rural<br>Peak/Off-peak [min] |
|---|---|---|
| SMG 2_1 | 15/30 | 210/210 |
| SMG 2_2 | 15/30 | 120/210 |
| SMG 2_3 | 10/30 | 30/60 |
| SMG 2_4 | 10/30 | 30/30 |
| SMG 2_5 | 15/30 | - |
| SMG 2_6 | - | 210/210 |

Figure 5.8 shows the PKT results for the simulations. The effect is not very distinct, except for public transport use. PKT of car travel differs only by 1.9 % with the BAU value in 2040, at the highest impact of SMG_2_4. Cycling and walking PKT are decreased by 5.7 % each, while PKT of public transport increases by up to 10.4 % in SMG_2_4. The difference between tested elements shows an earlier impact of shorter intervals, while there seems to be a saturation effect. There are no large differences between the intensities of interval shortenings of SMG_2_2, SMG_2_3 and SMG_2_4. SMG_2_1 shows almost no difference to BAU until the year 2040, when there is almost a convergence with the other curves. Looking at the curves of SMG_2_5 (only urban changes) and SMG_2_6 (only rural changes) we can see that the relevant change is a minimum interval of 210 min in rural areas, which is reached in 2040 in scenario SMG_2_6. PKT of PT in 2040 in the scenarios SMG_2_4 and SMG_2_6 differ by only 2.9 %.

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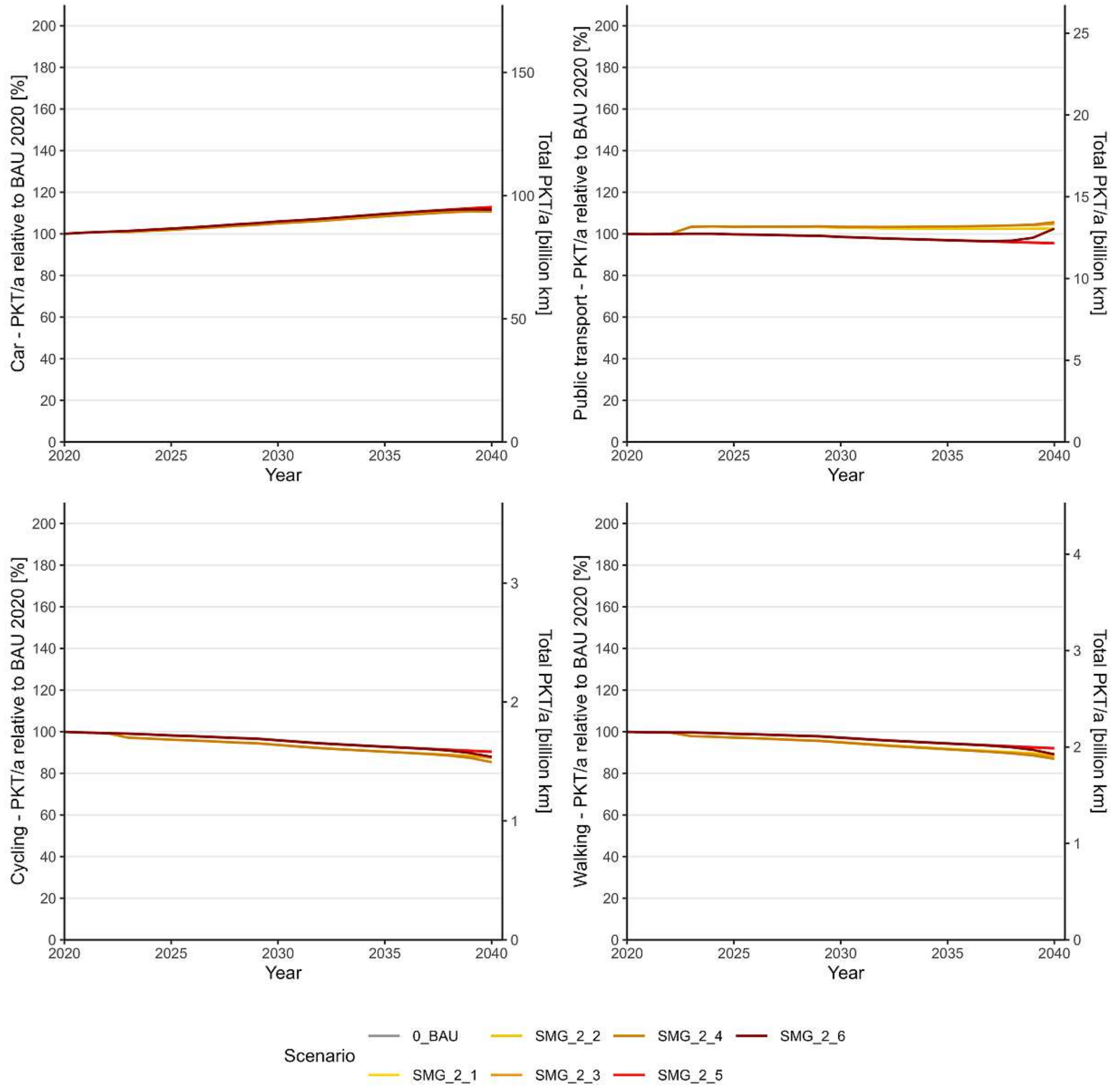


**Fig. 5.8:** Sensitivity public transport frequency / waiting time at station

### SMG 3 - Distance to public transport stop

The distance to bus stops and railway stations is divided into 4 distance classes in MARS. Measures can influence how large the share of the population is in the respective distance band: up to 375 m, up to 750 m, up to 1,500 m and up to 3,000 m. A further distinction is made between the share of people living within a walking distance less than 15 minutes (classes up to 375 m and up to 750 m) and more than 15 minutes (classes up to 1,500 m and up to 3,000 m) of a transport stop. Based on a factor, the measure to increase PT stop density influences the share of the population living in the distance class of "less than 15 minutes". In the course of this study, it was out of scope to adapt the model structure so that it corresponds to a more detailed definition with the differentiation between urban and rural areas and between bus and rail with concrete maximum distances. Therefore, on the basis of the distance classes, factors were used to estimate

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the change in access distances, which also apply to on-demand transport. Six different intensities were assessed, see Table 5.6.

**Tab. 5.6:** Factors increasing public transport stop density / decreasing distance to PT stops

| Element name | PT density factor |
|---|---|
| SMG_3_100 | 100 |
| SMG_3_250 | 250 |
| SMG_3_400 | 400 |
| SMG_3_900 | 900 |
| SMG_3_2000 | 2,000 |
| SMG_3_3000 | 3,000 |

Factor 100 refers to doubling the share of population living within less than 15 minutes walking distance to a public transport stop. Table 6.1 shows which effect the factors (100 to 3,000) have on the access to PT stops for the population in exemplary districts. One district in each urban/rural type is shown.

**Tab. 5.7:** Effect of factor to increase PT stop density on the population living within less and more than 15 minutes walking distance to a PT stop for five exemplary districts

| Urban/rural type | District name | Factor | BAU | 100 | 250 | 400 | 900 | 2000 | 3000 |
|---|---|---|---|---|---|---|---|---|---|
| 0 | Floridsdorf (Vienna) | < 15 min | 97.03% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% |
| | | > 15 min | 2.97% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| 1 | Linz (City) | < 15 min | 48.46% | 96.91% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% |
| | | > 15 min | 51.54% | 3.09% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| 2 | Innsbruck Land | < 15 min | 24.74% | 49.48% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% |
| | | > 15 min | 75.26% | 50.52% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| 3 | Bruck an der Mur | < 15 min | 13.33% | 26.67% | 77.65% | 100.00% | 100.00% | 100.00% | 100.00% |
| | | > 15 min | 86.67% | 73.33% | 22.35% | 0.00% | 0.00% | 0.00% | 0.00% |
| 4 | Feldkirchen | < 15 min | 2.23% | 4.46% | 13.00% | 18.12% | 22.32% | 72.73% | 100.00% |
| | | > 15 min | 97.77% | 95.54% | 87.00% | 81.88% | 77.68% | 27.27% | 0.00% |

Floridsdorf is a district on the outskirts of the capital city Vienna (Type 0 represents Vienna). Linz is a large city and capital of the province Upper Austria (Urban/rural type 1 signifies urban areas). Innsbruck Land is the district surrounding the city of Innsbruck (Type 2 signifies suburban areas). Bruck an der Mur is a rural district with good access to PT (Type 3) and Feldkirchen a rural district with low PT service (Type 4). While the districts of Type 0 - 2 already show 100 % of population within less than 15 Minutes walking distance to a PT stop with a factor of 250, the share of people living within that distance in the example of Bruck an der Mur (Type 3) can be increased to 77.65 % and in Feldkirchen (Type 4) only to 13 %. With a factor of 400, all except for the Type 4 district show 100 % of the population living within less than 15 Minutes walking to a PT stop. This can be increased with the factor 2,000 to slightly more than 50 % and with 3,000 to 100 %.

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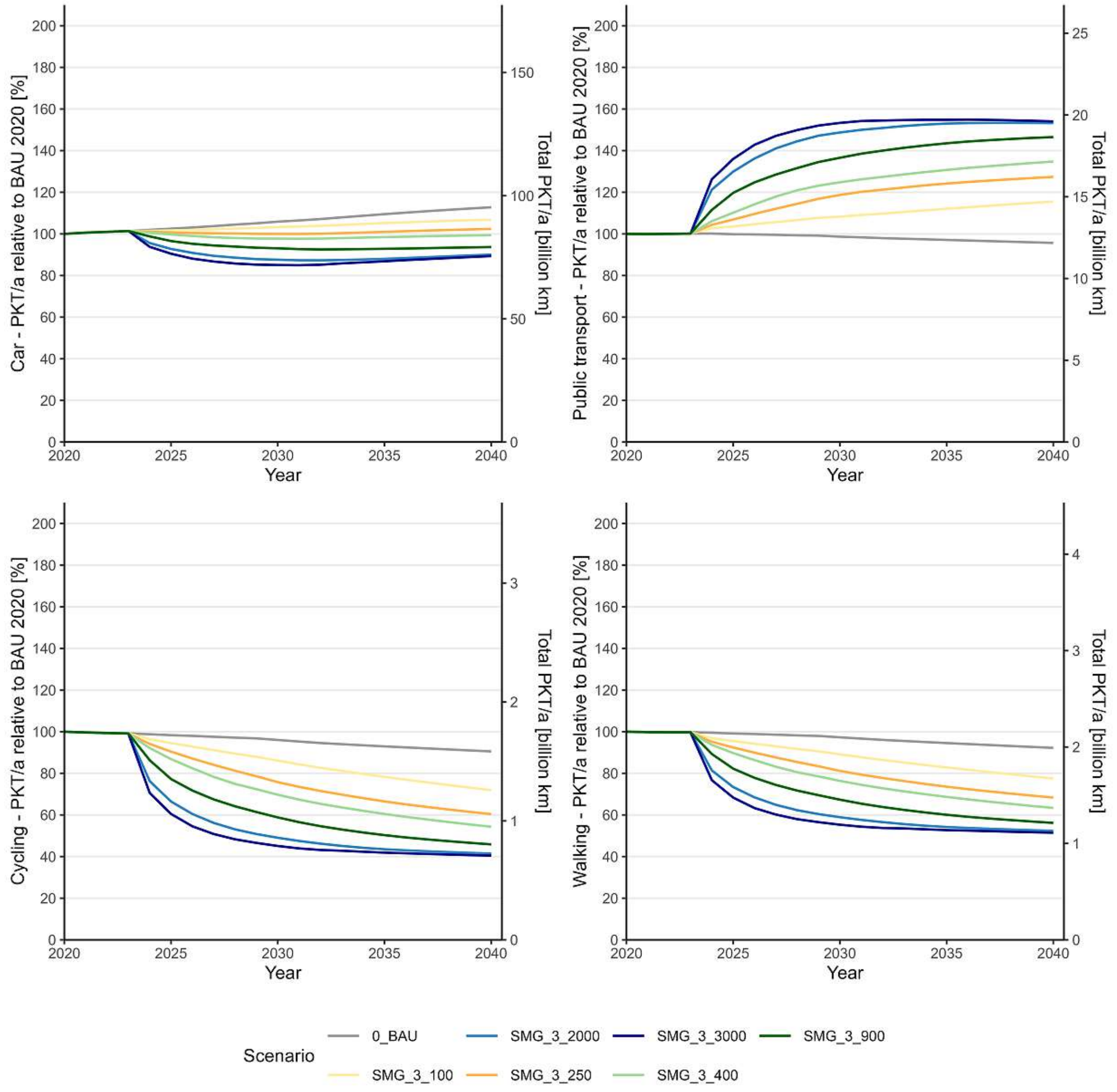


**Fig. 5.9:** Sensitivity distance to PT stop; BAU, SMG_3_100 - SMG_3_3000: factor 100 - 3,000

Results (see Figure 5.9) show high impact on use of PT and reduction of other modes. PKT for PT increases by 20.8 % in SMG_3_100 in the year 2040 compared to BAU and by 61.0 % in SMG_3_3000. Cycling and walking are reduced significantly by 20.6 % and 16.0 % respectively in SMG_3_100 and by 55.3 % and 44.2 % in SMG_3_3000. Car use is also reduced, however more limited by only 5.3 % (SMG_3_100) to 20.8 % (SMG_3_3000). A certain saturation effect can be viewed towards 2040 with curves becoming flatter and SMG_3_2000 and SMG_3_3000 converging almost at the end, differing only by 0.6 - 2.4 %. This sheds light on the large effect of increasing density of public transport stops, especially in rural areas. Nevertheless, future research is needed to include geographic details and assess the impact of actual new PT stops.

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### SMG 4 - Public transport waiting times at interchanges

The SMG 4-parameter influences the maximum and average waiting time on PT when changing from one mode of PT to another such as from a bus to the train or between trains or buses. This waiting time at interchanges shows a factor for subjective time valuation higher than the one for walking but lower than the one for waiting at the first PT stop of the trip chain (see Equation 5.10).

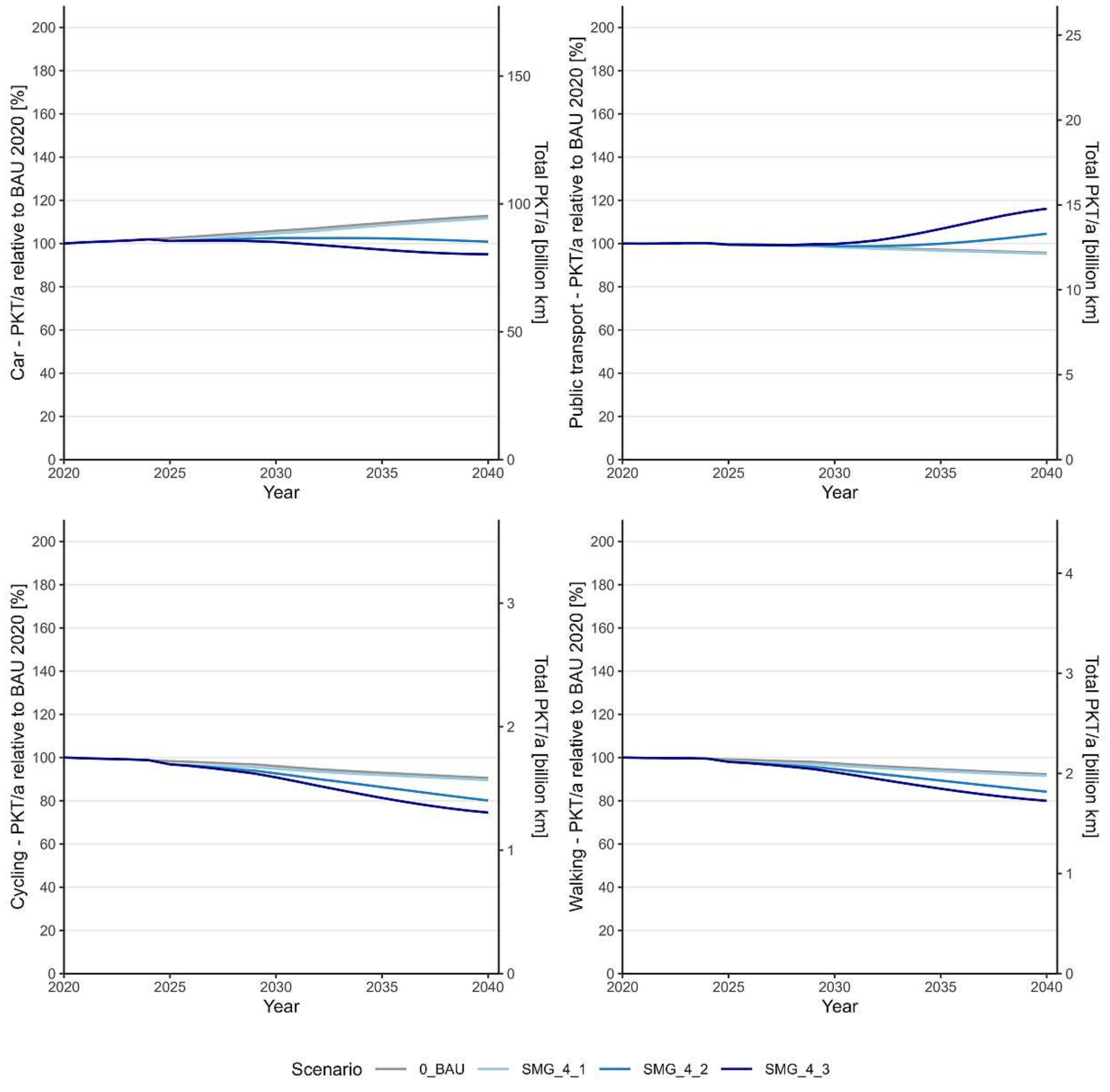


**Fig. 5.10:** Sensitivity waiting time at PT interchanges

In the simulations, the introduction of the “integral interval timetable” (*Integrierter Taktfahrplan*) from 2025 is taken into account in the BAU as well as in all SMG-scenarios with a maximum waiting time of one hour at interchanges[9]. The waiting time at interchanges is not varied in the scenarios, but has been tested as a single measure in three different intensities.

[9] As planned by the Austrian Railway Agency, see ÖBB (2011)

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The values shown in the table Table 5.8 correspond to the final values in 2040. The measure is introduced iteratively in the model, starting in 2025 and increasing linearly. Results of the simulation are shown in Figure 5.10.

**Tab. 5.8:** Parameters of maximum waiting times at interchanges for public transport

| Element name | Maximum waiting time at interchanges urban [min.] | rural [min.] |
|---|---|---|
| BAU | 60 | 60 |
| SMG_4_1 | 30 | 60 |
| SMG_4_2 | 20 | 30 |
| SMG_4_3 | 15 | 30 |

While SMG_4_1 shows almost no effect, changing the maximum waiting time to 20 and 30 minutes for urban and rural regions respectively (SMG_4_2), yields a decrease in PKT for cars by 10.6 % in 2040 and reducing it further to 15 and 30 minutes (SMG_4_3), results in a reduction by 15.7 %. Conversely, PKT in PT are increase by 9.3 % and 21.4 % in the year 2040, while active modes show a decrease (by up to 17.7 %). Impact of these variations seem relatively high compared to other measures. However, it has to be considered that the implementation of shorter waiting times has to be coordinated with PT frequencies and are a difficult endeavour restricted by the possibilities of the geometry of the network, availability of rolling stock and staff.

### SMG 5 - Active mobility

Equations for mode choice regarding active mobility in MARS do not have elements that correspond to the type of infrastructure, see Section 5.1.4. In order to simulate improvements in infrastructure for walking and cycling, which render those active modes more attractive, the subjective valuation factors of friction factors are varied. This is done for the element testing in 6 different intensities, for walking and cycling separately and in combination, reducing the subjective time valuation factor by 30 % and 70 %, as shown in Table 5.9.

The reduction of subjective time valuation factor is an abstract parameter that denotes a qualitative improvement. In reality, behind this quality improvement or lower resistance rating, there must be measures implemented that make walking and cycling more attractive. This can be the construction of cycling lanes, the installation of safe bike parking facilities in public space and at train stations, wider sidewalks and safe pedestrian crossings. Non-infrastructural measures such as campaigns to promote active mobility can also have beneficial effects. For a discussion on mode choice behavior regarding active mobility, see Section 5.5.5.

**Tab. 5.9:** Element testing for active mobility - reduction of subjective time valuation factor

| Element name | Walking | Cycling |
|---|---|---|
| SMG_5_1 | 30 % | - |
| SMG_5_2 | 70 % | - |
| SMG_5_3 | - | 30 % |
| SMG_5_4 | - | 70 % |
| SMG_5_5 | 30 % | 30 % |
| SMG_5_6 | 70 % | 70 % |

Results of the testing simulations are shown in Figure 5.11. Naturally, the single mode measures increase PKT for the respective mode. PT use also profits from higher attractiveness of walking

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and cycling, since they are used as feeder modes. All of the simulated measures are capable of reducing car use, ranging between by only 1.1 % for SMG_5_3 (cycling 30 %) and by up to 29.3 % with the combined 70 % reduction of the subjective time valuation factor for walking and cycling. Interestingly, the combined scenario SMG_5_5 shows a decrease in cycling PKT (-13.7 %), since increasing attractiveness of walking shows much larger impacts on cycling (-55.9 % and -68.9 %) than the other way around (-3.6 % and -15.5 %).

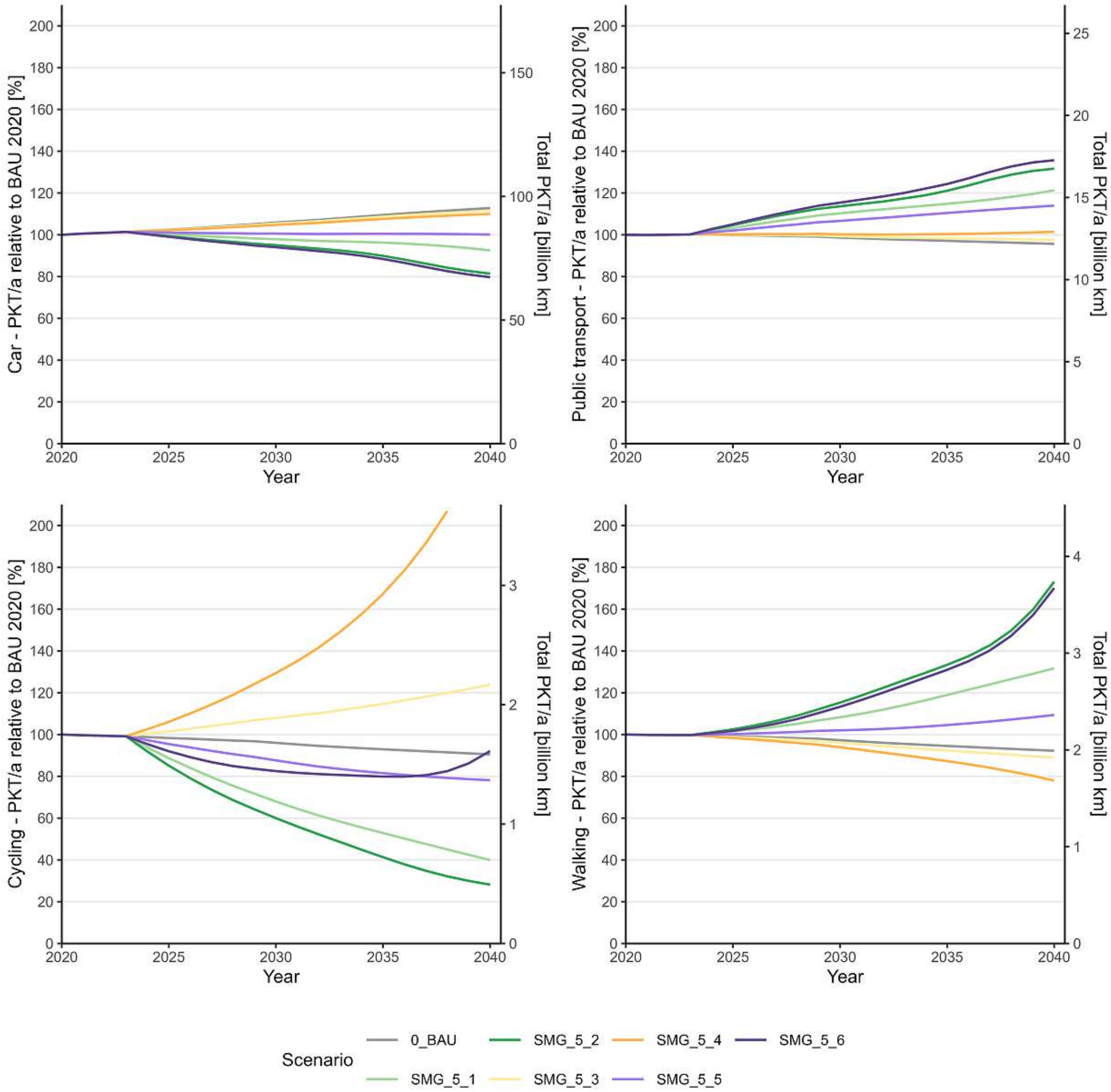


**Fig. 5.11:** Sensitivity active mobility

These results have to be viewed cautiously. Since cycling rates in Austria have been quite low in the past - and the model has been calibrated with survey data from the past - the model might underestimate effects concerning cycling. Further analysis regarding the effect of new infrastructure on walking and cycling should be conducted in future research.

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### SMG 6 - Spatial planning/denser settlement areas

This parameter represents measures in spatial planning that create denser settlement structures with mixed use such as changed zoning regulations and regeneration of town centers. This affects mobility behaviour, since origin and destination might be closer, reducing the distances to travel. In scenarios 0 and 1, the spatial planning remains unchanged. For scenarios 2 - 5, denser town centres and thus a shortening of distances are assumed in two different intensities. Denser settlement areas for new buildings were taken into account as a percentage factor in spatial planning. In MARS, this is only relevant for intrazonal trips. They are organized in five distance classes, see Table 5.10.

**Tab. 5.10:** Distance classes in MARS for intrazonal trips

| Distance class | from [km] | to [km] |
|---|---|---|
| d_1 | 0 | 2.5 |
| d_2 | 2.5 | 5.0 |
| d_3 | 5.0 | 7.5 |
| d_4 | 7.5 | 10 |
| d_5 | 10 | 14 |

For SMG_5, the number of destinations accessible within the distance classes d_1 and d_2 (less than 5 km) is increased in the model. It is assumed that 25 % (Scenario 2 and 3) or 50 % (Scenario 4 and 5) of existing destinations such as jobs, education, shopping, etc. shift from the distance class above 5 km to the distance class below 5 km. The introduction of the measure will start in 2023 and gradually increase until the final value is reached in 2040.

Results are shown in Figure 5.12. In the time frame until 2040, there are no large effects, but high leverage in the long term can be anticipated. In 2040, the simulations show a decrease of car PKT by 2.3 % and 4.6 % compared to BAU and a decrease in PT by and 2.6 % and 4.9 %. Spatial planning measures for densification are the only tested element, that increases walking PKT (by 6.2 % and 11.8 %) while not increasing PT use. There is also a slight decrease in cycling (-3.2 % and -5.2 %), which has to be regarded cautiously - as discussed in Section 5.5.5, the model shows high inertia of cycling. Shorter distances combined with more attractive cycling infrastructure is suspected to yield higher levels of cycling.

Even though changes in spatial planning usually require long periods of time, the impact on mobility behavior has been shown on several levels. Hackl et al. (2019), for example, showed that walking and cycling is promoted by denser, mixed-use environments and that the number of out-commuters (who do not have a job in the municipality of residence) increases car use and decreases use of active modes.

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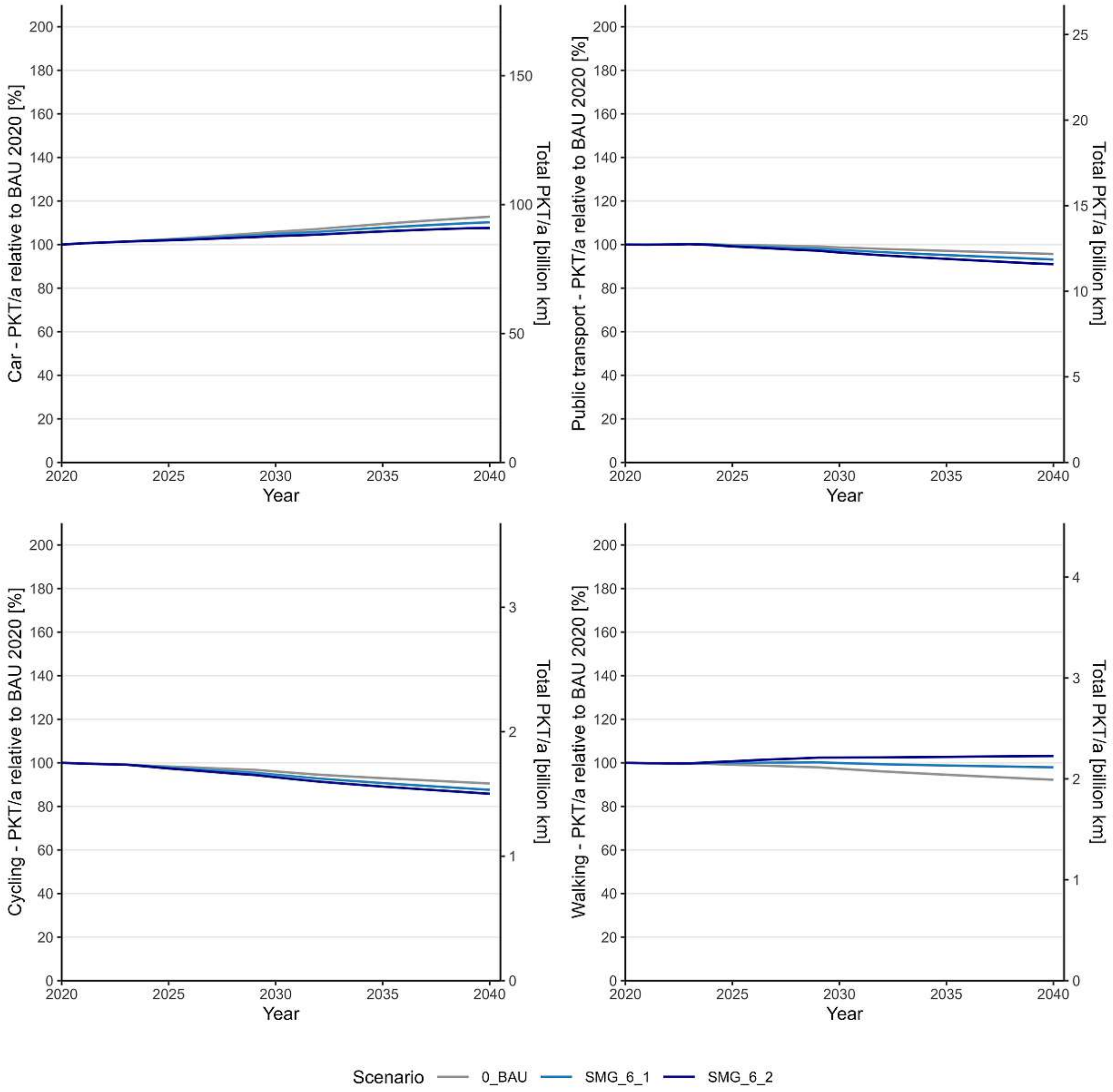


**Fig. 5.12:** Sensitivity spatial planning/densification measures

### 5.3.4 Restrictive measures for car use

Studies have shown that it is most effective to combine "push" and "pull" measures (often referred to as "carrots and sticks") in order to have a mode shift towards PT and active mobility (e.g. Kuss & Nicholas, 2022; Piatkowski et al., 2017; Rasmussen, 2022; Xiao et al., 2022). Even though the SMG is primarily looking at a better offer of PT and active mobility, scenarios are combined with restrictive measures for car use (push or stick-measures) in order to show the full potential and necessity for $CO_2$-reduction. In this study, there are two different types of measures included: lower speed limits and road pricing.

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### RES 1 - Lowering of speed limits

The adjustment of the maximum speed limit to 100 km/h on highways, 80 km/h on open country roads and 30 km/h in settlement areas (currently 130 km/h, 100 km/h and 50 km/h respectively according to StVO 1960) has an effect in the model via the factor of time costs. Journeys by private car become longer and thus less attractive relative to connections by other means of transport. The general speed limit of 30 km/h in the local area is also included in Scenario 2 - *Focus on active mobility*, as it acts both as a push measure against car use and as a pull measure for the active modes, as walking and cycling become more attractive as a result through an increase in safety such as a reduction in accidents, lower severity of accidents as well as more pleasant walking and cycling in mixed traffic with private cars and a higher willingness of car drivers to stop (such qualitative effects are not represented directly in the model).

For element testing, four different types were simulated: each of the speed limits separately and all of them together, as shown in Table 5.11

**Tab. 5.11:** Element testing for lower speed limits

| | **Reduced speed limit [km/h]** | | |
|---|---|---|---|
| **Element name** | Settlement areas | Country roads | Highways |
| RES_1_1 | 30 | - | - |
| RES_1_2 | - | 80 | - |
| RES_1_3 | - | - | 100 |
| RES_1_4 | 30 | 80 | 100 |

Results (see Figure 5.13) show a considerable effect on reducing car use, although almost no effect on the other modes. Reduction of PKT for cars range between 1.7 % for the 100 km/h single-measure (RES_1_3) up to 6.9 % in the combined scenario (RES_1_4). The non-reduction of other modes means that there is not a shift in mode choice but rather, car trips show shorter distances (due to the constant travel time budget).

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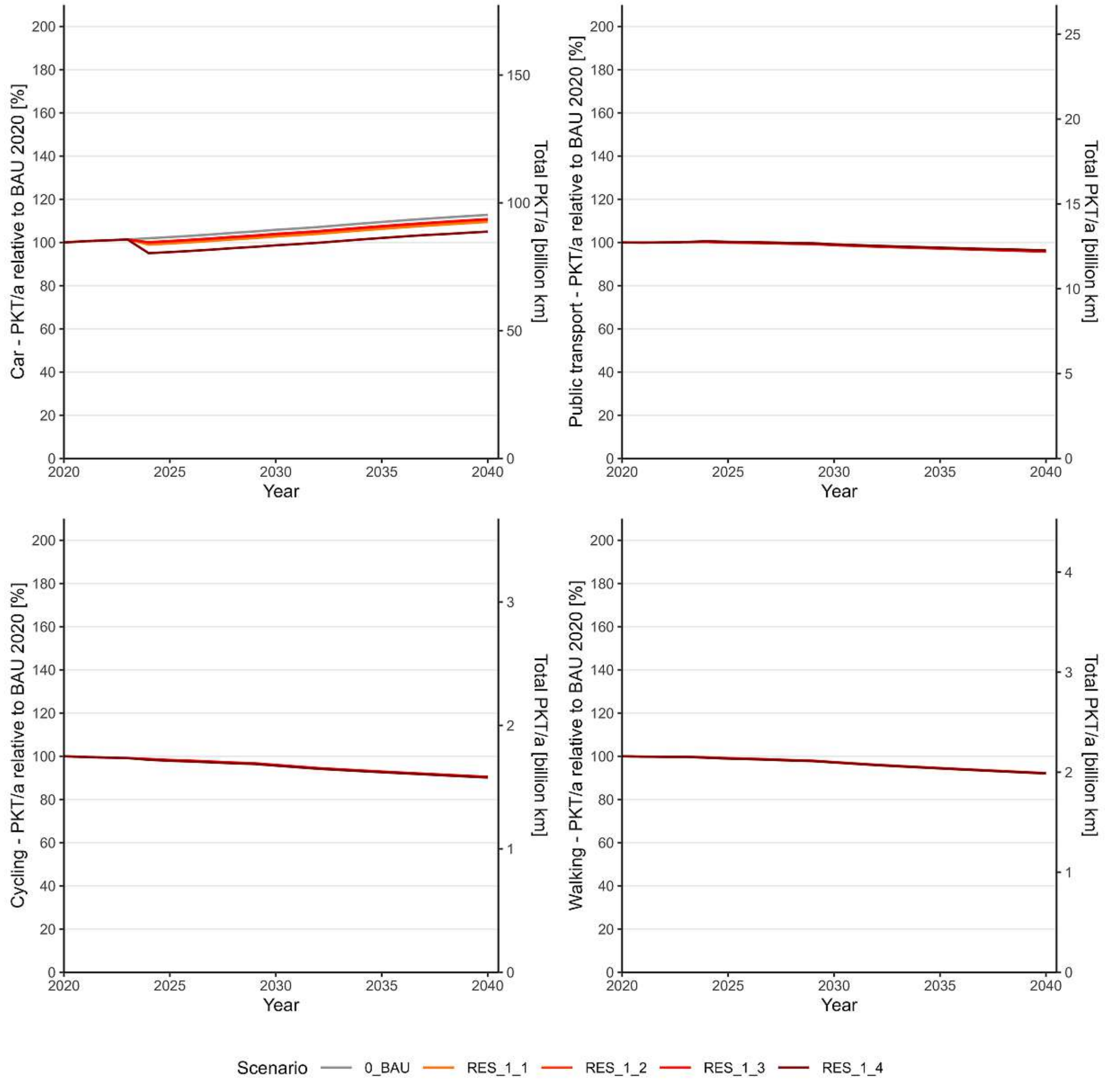


**Fig. 5.13:** Sensitivity lower speed limits

### RES 2 - Road pricing

The road pricing applies to all (private) motorized vehicles (including e-cars) and is to be paid on all roads, on highways as well as on streets in cities. It increases linearly every year to the final value in 2040. Four intensities were tested: EUR 0.1/km and EUR 0.5/km[10], for only peak-hours and all times of day, see Tab. 5.12. Results compared to BAU are shown in Fig. 5.14. Effects of road pricing for the lower intensity and for only peak-hours are rather small, reducing PKT by only 0.9 % (RES_2_3), 3.2 % (RES_2_3) and 3.9 % (RES_2_2) in 2040. With a price of EUR 0.5/km for all times of day (RES_2_4), however, a reduction of 12.3 % in PKT by car in 2040 can be achieved.

[10] For comparison: today the annual price for using the Austrian highway network is EUR 92, which amounts to only EUR 0.018/km with an assumed average of 5,000 km/a

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**Tab. 5.12:** Element testing for road pricing

| | Road pricing [EUR/km] | |
|---|---|---|
| **Element name** | Peak hours | Off-peak hours |
| RES_2_1 | 0.1 | - |
| RES_2_2 | 0.5 | - |
| RES_2_3 | 0.1 | 0.1 |
| RES_2_4 | 0.5 | 0.5 |

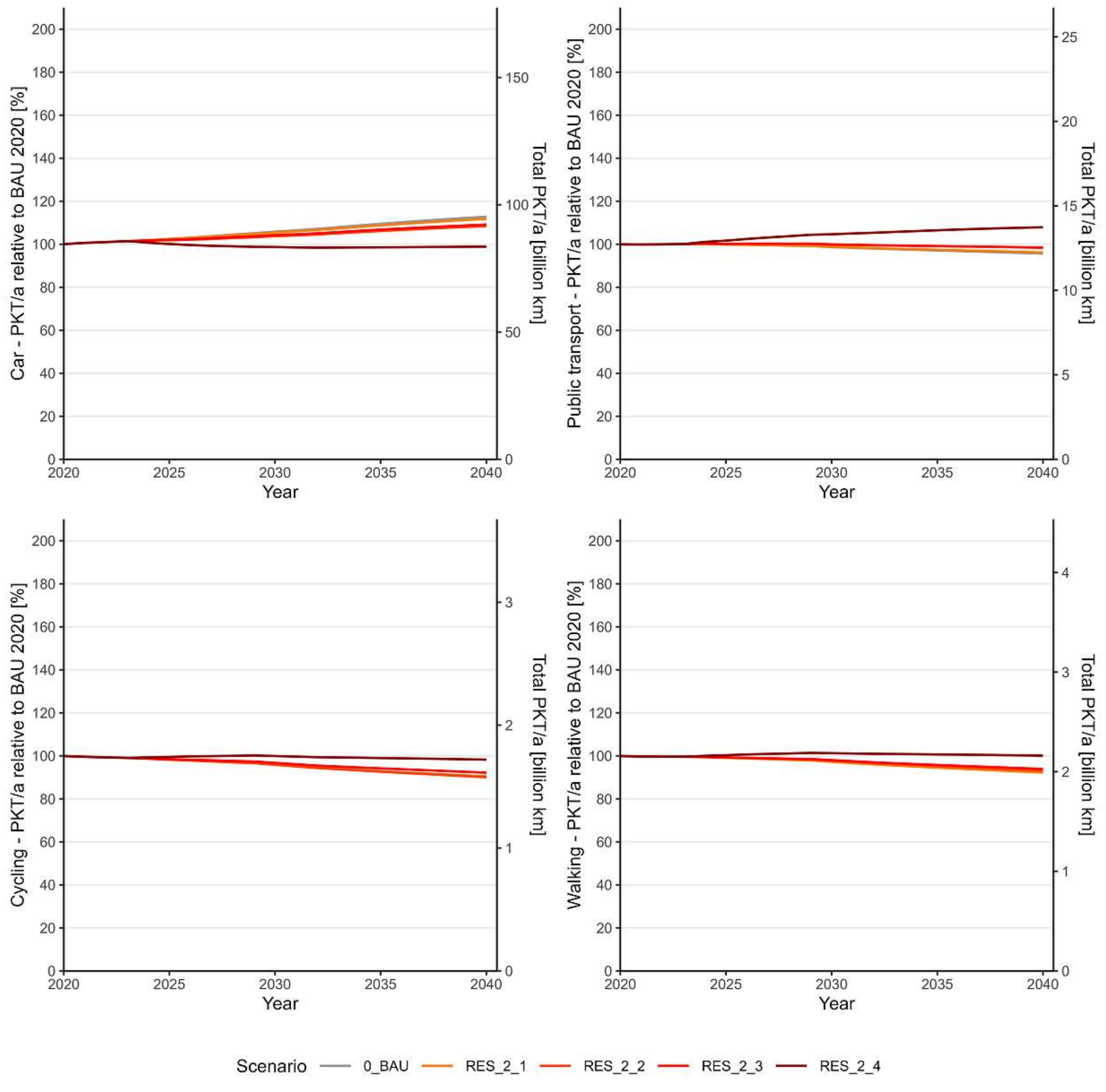


**Fig. 5.14:** Sensitivity road pricing

Road pricing becomes important with increased e-cars in the fleet, therefore I also tested the combination of road pricing with the external parameter of increasing the share of e-cars and occupancy rate (which both makes driving cheaper) in the external scenario EXT_2_3.

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This was done for the intensities of RES_2_2, RES_2_3 and RES_2_4. Results are shown in Figure 5.15. Compared to the EXT_2_3 baseline in 2040, car PKT can be reduced by 4.9 %, 7.7 % and 22.1 %, respectively.

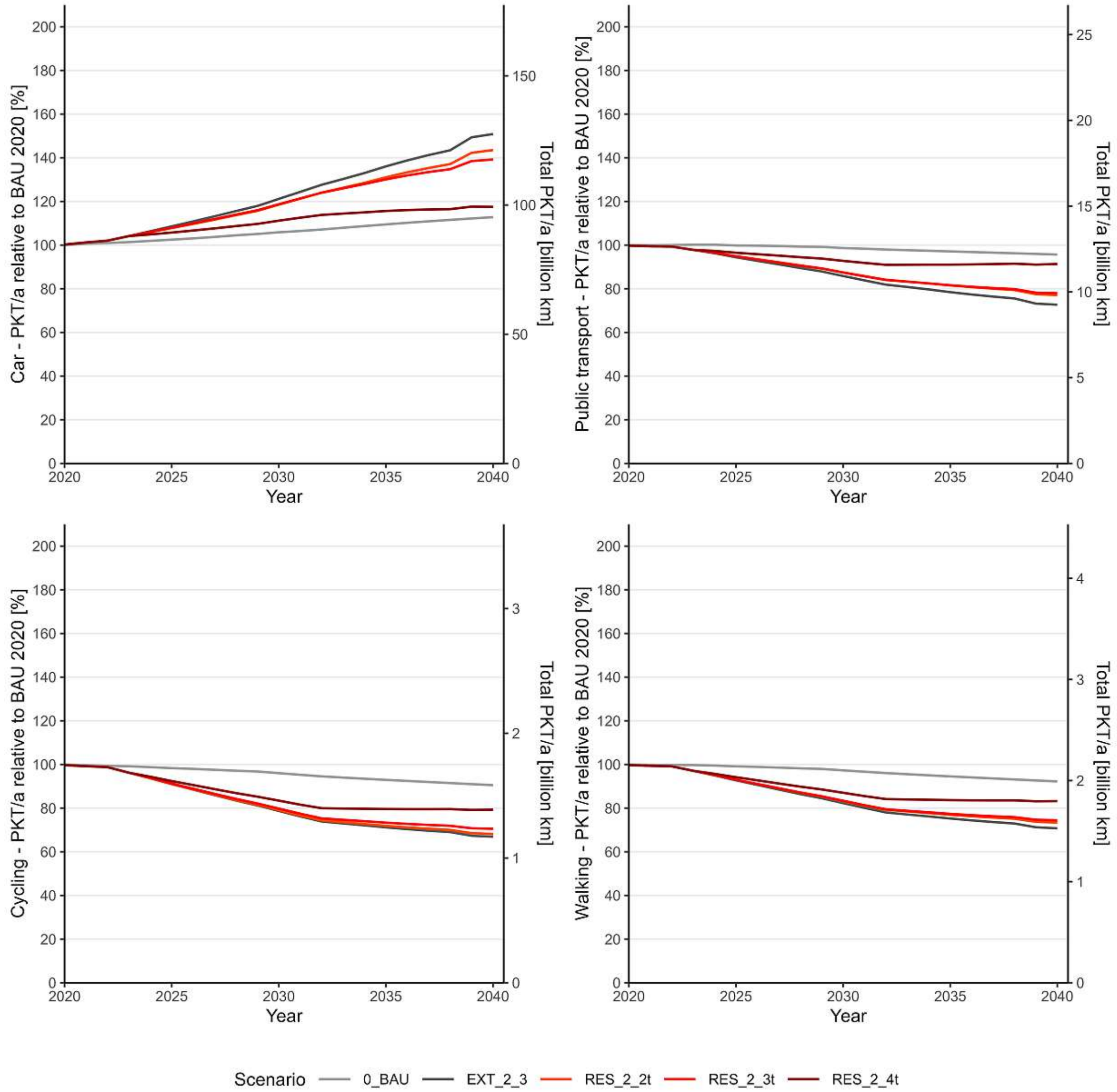


**Fig. 5.15:** Sensitivity road pricing with EXT_2_3

### 5.3.5 Summary of sensitivity testing

Results of the sensitivity testing of each individual element show that an interplay of different measures is necessary to achieve a substantive reduction of car usage, necessary for sustainability goals such as the climate targets (BMK (2021)). Individual effects on car use range from +0.1 % (SMG_2_5 - the only increase) to decreases of -0.9 % (RES_2_1) up to -29.3 % (SMG_5_6). While the impact of most measures lies beneath 10 %, higher impact on car usage can only be achieved by measures regarding PT density, changing time and active mobility. The highest impact could be shown for increasing the attractiveness of active mobility (SMG_5_6 with

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-29.3 %), followed by the densificaton of PT stops i.e. shortening the distances from source to PT stops for individual trips (SMG_3_3000 with -20.8 %). Compared to the extensive effect of increased share of e-cars and higher car occupancy rates (external scenario EXT_2_3 with +33.8 % PKT in 2040 compared to BAU in 2020), it is clear that single measures alone are not able to counter such developments. It has to be kept in mind that the combination of measures can show synergetic effects, which means that the potential to reduce car usage of two measures is higher than the sum of individual effects. On the other hand, the combined effect of two measures can also reduce the total effect, e.g. when there is a modal shift between active modes and PT. This is shown in the scenarios in Section 5.4.

## 5.4 Results of Sustainable Mobility Guarantee scenarios

Based on different combinations of the measures and their intensities, five Sustainable Mobility Guarantee scenarios have been analysed. The scenarios are based on the FLADEMO project[11] (see Section 3.6 for a verbal description of the scenarios). A first version of the scenarios has been developed for discussion and simulation in MARS. This draft has been presented and discussed with peers at a workshop[12] and has been peer-reviewed and published (Laa et al., 2022). The implementation of the scenarios in MARS and first simulation results were presented at a conference and discussed with peers (Laa & Pfaffenbichler, 2022). Based on the the received feedback from peers, the scenarios were slightly adapted and refined.

Figure 5.16 shows an overview of the scenarios as steps, building on one another. The scenarios were developed in order to show combinations of measures and different intensities of implementing a Sustainable Mobility Guarantee. Scenario 0 - *Business as Usual* is the baseline, the scenario without a Sustainable Mobility Guarante to compare the effect that it has. The external parameters in the BAU scenario follow the "WEM" (with existing measures) assumptions in terms of population development, motorization rate, car fleet, etc. Scenario 1 shows no difference to BAU in terms of external parameters. For Scenario 2, the motorization rate is smaller ("WAM+") than in BAU. For Scenarios 3, 4 and 5, the motorization rate is smaller and the share of e-cars and car occupancy rate are higher ("Transition_2040_3").

[11] Project reports in German can be found here: https://projekte.ffg.at/projekt/3992976

[12] SIG G2 National and Regional Transport Planning and Policy Mid-Term Workshop. *Ensuring sustainable mobility in urban periphery and rural areas and remote regions.* Institut für Verkehrswissenschaften, TU Wien (Online Conference), Austria, September 2021.

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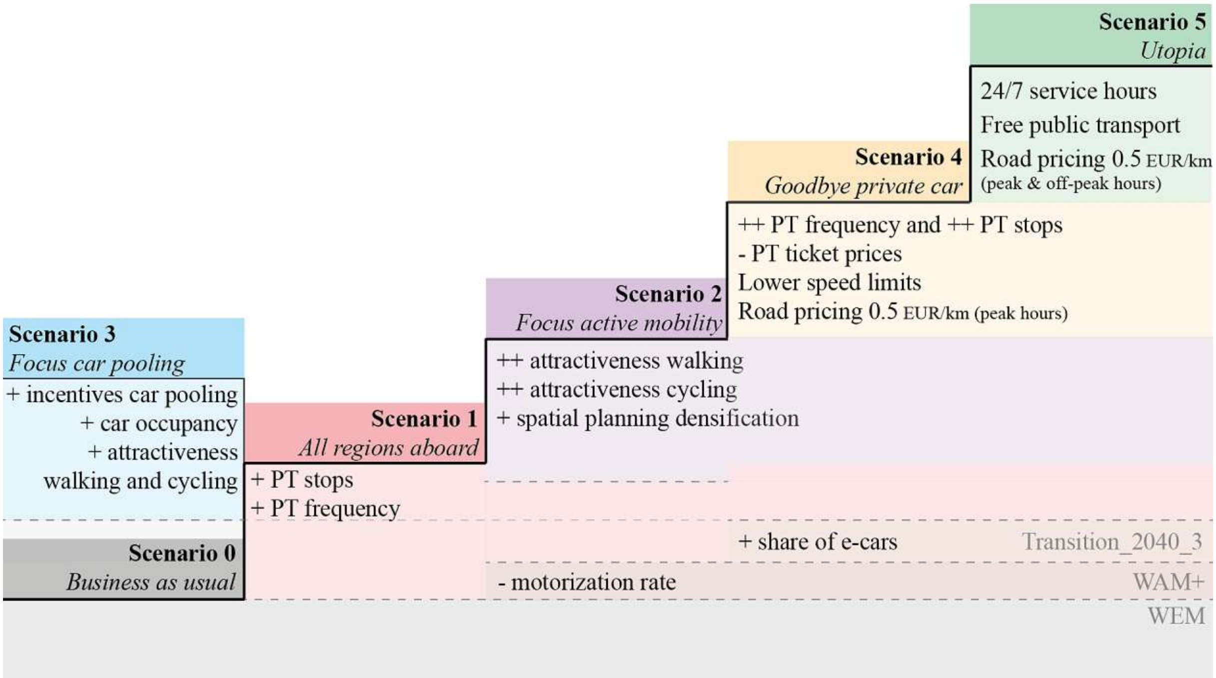


**Fig. 5.16:** Overview of the scenarios as steps, building on one another

Scenario 0 - *Business as usual* is the reference scenario (without SMG) with the parameters described in Section 5.2.1. Scenario 1 - *All regions aboards* serves as a lower limit scenario to show the most basic version of a Sustainable Mobility Guarantee as described in Chapter 4. The difference to the BAU scenario is basically only public transport provision in rural areas where people now don't have access to PT according to the PTSQL definition. Scenario 2 - *Focus active mobility* consists of the same extended PT provision in rural areas as in Scenario 1 with additional measures to make active mobility more attractive. Walking and cycling are seen as an important feeder mode for PT with improved access to PT stations for those modes and infrastructure such as safe bike parking at the stations. Additionally, they are seen as important modes on their own for shorter distances. Therefore, the scenario also features spatial densification measures to allow for shorter distances to reach activities. Scenario 3 - *Focus carpooling* shows the implementation of a Sustainable Mobility Guarantee with carpooling as an important mode in rural areas with low population densities. In contrast to Scenario 1, such areas are not served by PT services but there are incentives for private car users to share rides with other people, in order to reach higher occupancy rates in existing vehicles. The rationale behind the scenario is that PT is not sensible in areas of low density and many people already own vehicles and can share them with other people. Scenario 4 - *Goodbye private car* is a far reaching implementation of the Sustainable Mobility Guarantee that should render the use of private cars obsolete. It includes not only improved PT in rural areas but in all PTSQL areas. This means an increase in the density of PT stops as well as higher frequency of PT services. Additionally, active mobility is promoted by high quality infrastructure as well as spatial densification measures. These supply side measures are complemented by restrictive measures to make car use less attractive, implemented as road pricing during peak-hours and lower speed limits. Scenario 5 - *Utopia* serves rather as an upper limit for the scenarios than a realistic implementation scenario. It features all of the measures of Scenario 4 plus service time extension of PT to 24/7 and PT free of charge as well as an extension of road pricing to off-peak hours.

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In the following, the simulation results of the Sustainable Mobility Guarantee scenarios are presented. First, for every scenario with effects for individual measures and their combination in the scenario and then for all scenarios to compare them to one another. The overview of measures and scenarios is shown in Table 5.2 on page 99 and helps to keep track of the parameters when analysing the diagrams.

### 5.4.1 Scenario 1 - All regions aboard

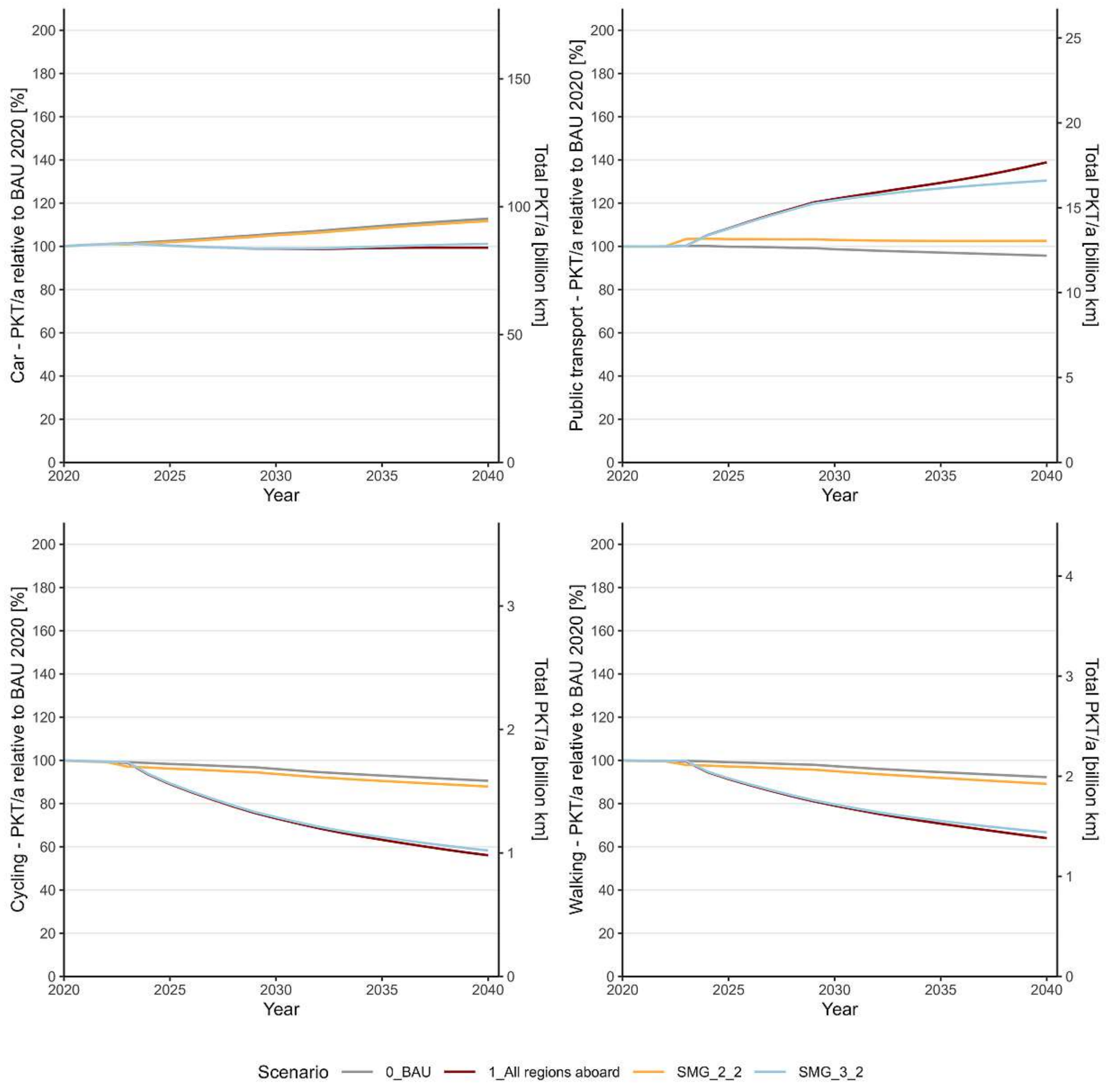


**Fig. 5.17:** Simulation results Scenario 1 - All regions aboard

Figure 5.17 shows the simulation results for Scenario 1 - *All regions aboard* changes in passenger kilometers traveled (PKT) (public transport, cycling and walking) for the simulation run time and in reference to the baseline (Scenario 0 - Business as usual in the year 2020). The diagrams show results for BAU in grey, for all measures of the scenario combined (1_All regions aboard)

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in dark red and for the individual measures in other colours, named according to Table 5.2. It is clearly shown that the increased frequency of public transport services (SMG_2_2) shows very little effect compared to the increased density of PT stops (i.e. reduced distance to PT stop) (SMG_3_2). Almost all of the effect in the scenario stems from the measure of increased density of PT stops. However, the combination of the two measures achieves a larger decrease of car use than the effect individual measures added (-1.0 % and -10.3 % compared to -11.9 % car PKT in 2040). PKT of cars is reduced only slightly compared to the baseline in 2020, whereas the increase in the BAU scenario can be dampened. Not surprisingly, the simulation results show a large increase in PT use with passenger kilometers increasing by 45.2 % compared to BAU in 2040, while cycling and walking kilometers are starkly reduced by 38.1 % and 30.6 % respectively.

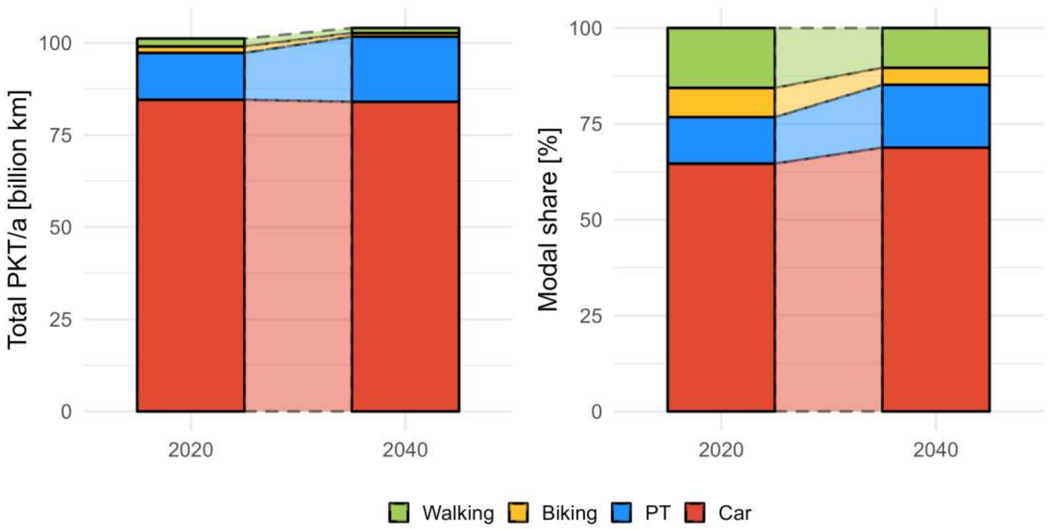


**Fig. 5.18:** Simulation results PKT and Modal Split for Scenario 1 - All regions aboard

Figure 5.18 shows the results of Total PKT/a per mode and the modal share for the start year 2020 and end year 2040 in comparison. Overall, the PKT are increased in Scenario 1, with a slight decrease in car use and a considerable increase in PT use. Modal share shows an increase in car and PT use and decreases in walking and cycling.

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### 5.4.2 Scenario 2 - Focus active mobility

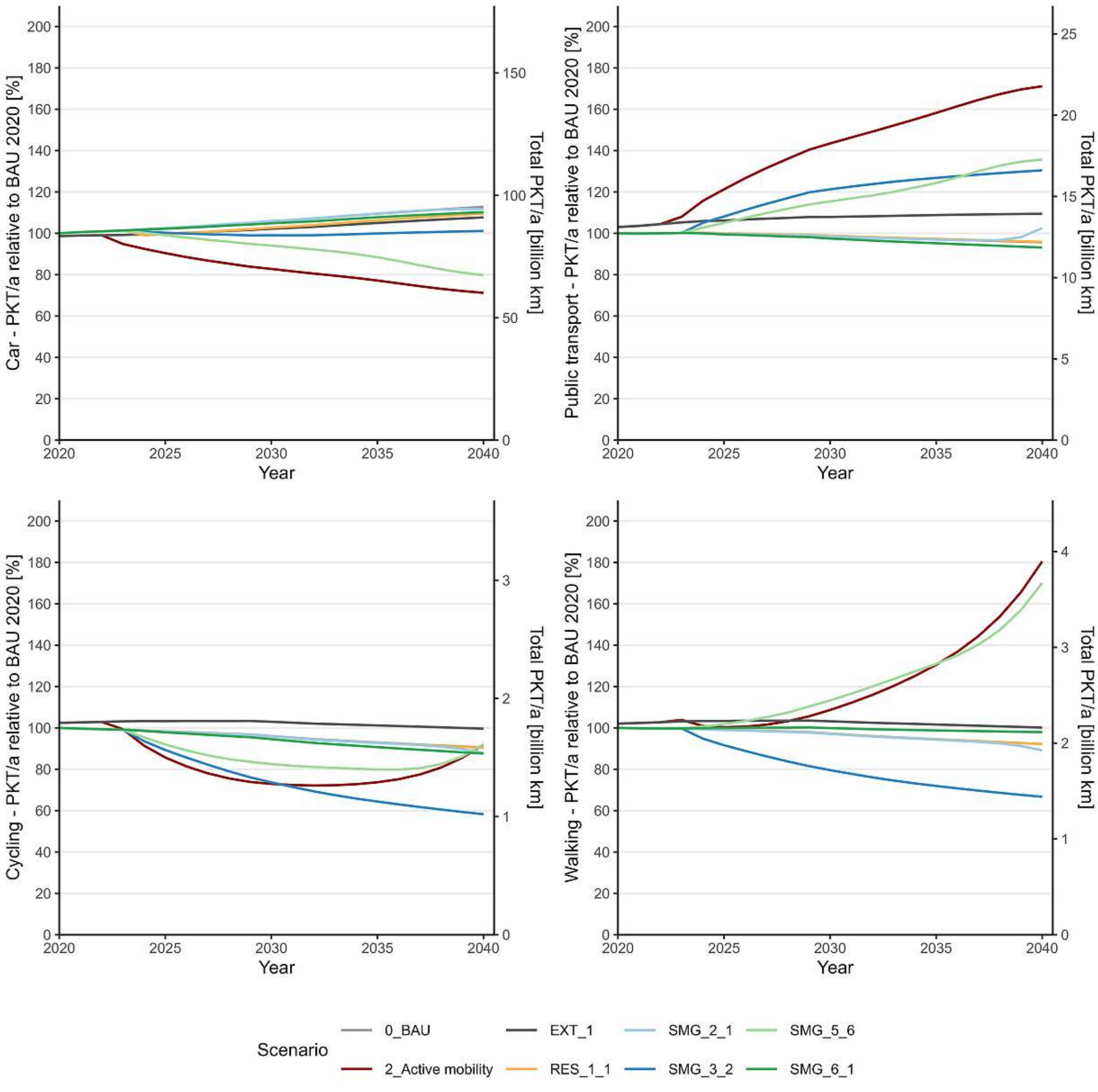


**Fig. 5.19:** Simulation results Scenario 2 - Focus active mobility

In Figure 5.19 and Figure 5.20, the simulation results for Scenario 2 - *Focus active mobility* are shown in the same manner as for Scenario 1 in the section before.

The external scenario with lower motorization rate than BAU (EXT_1) is shown in dark grey in the diagrams. This baseline has to be considered to identify the effects of individual measures. Only small impacts result for the lower speed limit of 30 km/h in settlements areas (RES_1_1) and spatial planning densification measures (SMG_6_1). Spatial planning densification measures take a long time to show effects since the construction of new buildings and people or offices moving show a time lag compared to other system variables. The impact until 2040 is relatively low but the measure could be important for the more distant future in order to allow for shorter distances. Although the speed limit affects only vehicle speed in the model directly, it can

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be argued that lower speeds and corresponding street design also influence the attractiveness of walking and cycling, which is modeled in the measure of increasing attractiveness of active mobility (SMG_5_6), which impacts the combined results the most.

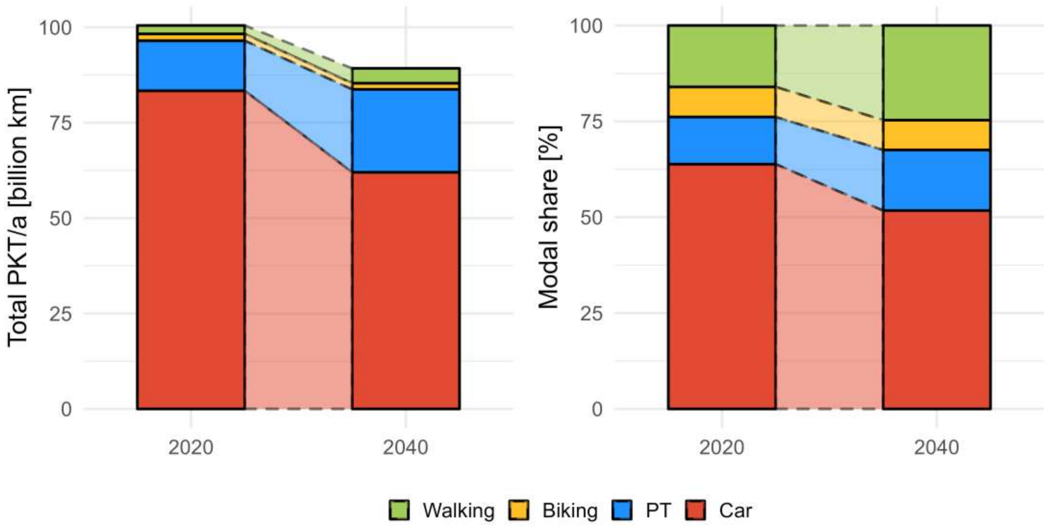


**Fig. 5.20:** Simulation results PKT and Modal Split for Scenario 2 - Focus active mobility

While all measures decrease PKT of cars and increase PKT of PT, the effects are not that clear for active modes. While the promotion of active modes increases walking and PT use, the measures to increase PT use, higher frequency (SMG_2_1) and shorter distances to PT stops (SMG_3_2 - corresponding to factor 300) decrease walking and cycling. In combination, the scenario results show a decrease of car PKT by 34.9 % in 2040 compared to BAU and an increase of passenger kilometers in PT of 78.5 %. PKT of walking and cycling are increased by 95.6 % and 1.7 % respectively.

Overall PKT are reduced by 19.6% (from 111 billion km in 2020 to 89 billion km in 2040). The modal share of car trips is reduced from 64 % in 2020 to 52 % in 2040 while the one for PT is increased to 16 %, cycling to 8 % and walking to 25 % (total larger than 100 % due to rounded values).

### 5.4.3 Scenario 3 - Focus carpooling

Results of the simulations for Scenario 3 - *Focus carpooling* are shown in Figure 5.21 and 5.22. The baseline is represented by the external scenario EXT_1_2_3 (sown in dark grey), which shows a strong increase in car use due to decreased costs of driving (because of a larger share of e-cars and higher car occupancy rates).

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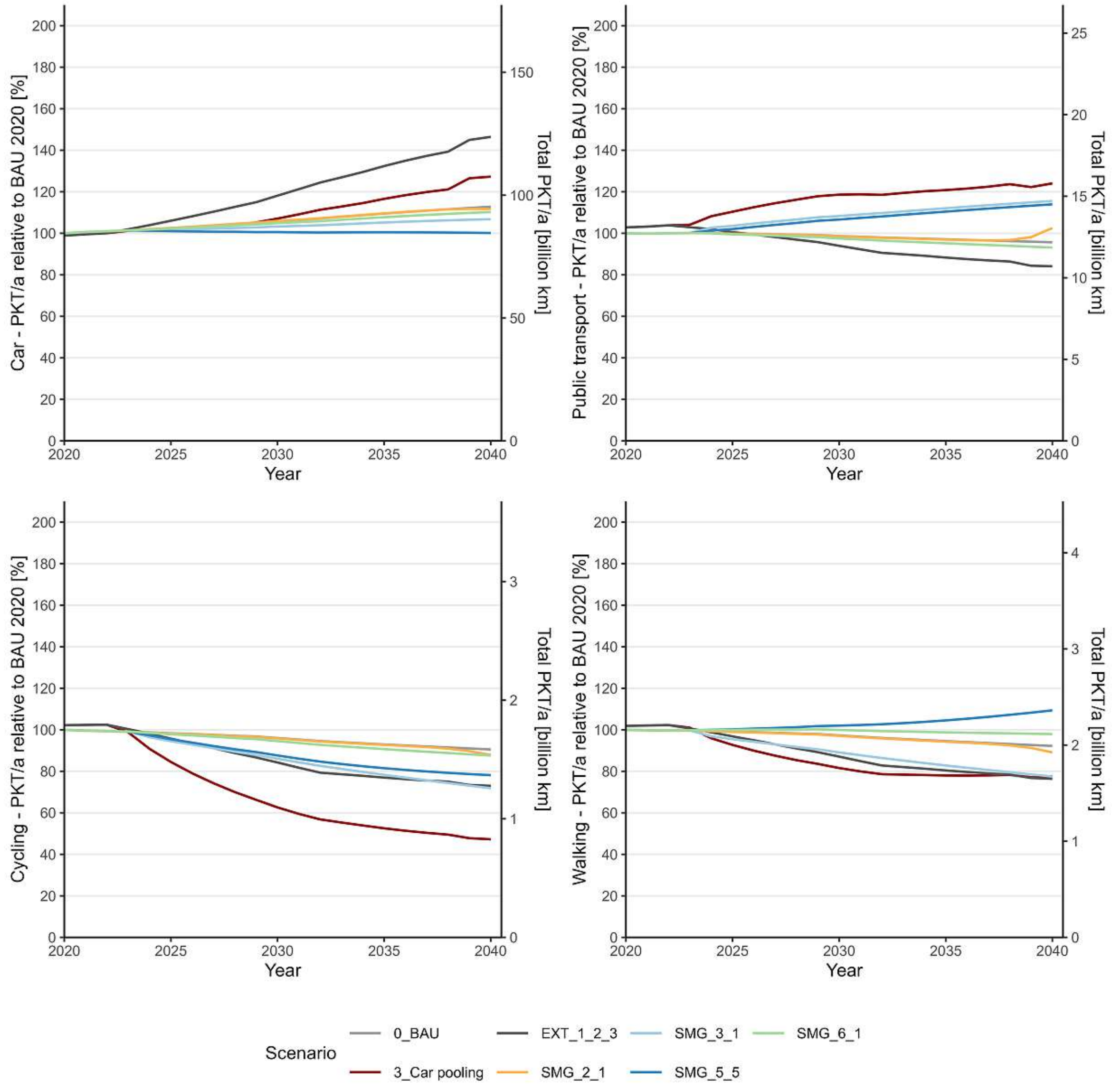


**Fig. 5.21:** Simulation results Scenario 3 - Focus carpooling

The other individual measures that make up this scenario all show a decreasing effect on car use but the overall increasing trend on car PKT can be dampened only by 13 %, while being still 12 % higher than in the BAU-scenario. However, due to carpooling, the overall VKT can be reduced compared to BAU (see also Figure 5.27). The largest effects are due to lower distances to PT stations (SMG_3_1) and increased attractiveness of active mobility (SMG_5_5). Total PKT/a increase by 13 % to 126 billion km in 2040. The modal shares of car trips (71 %) and PT (14 %) increase, while walking (11 %) and cycling (4 %) decrease.

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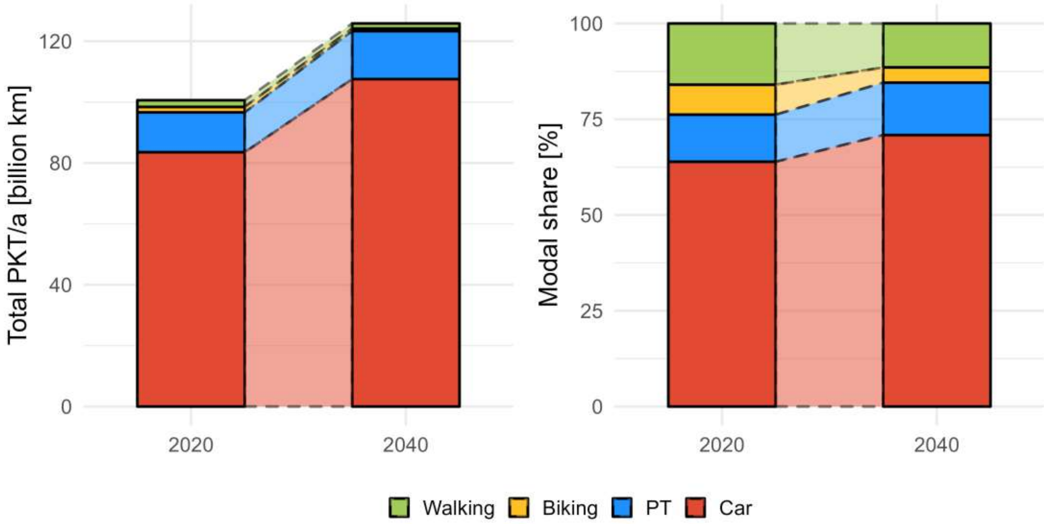


**Fig. 5.22:** Simulation results PKT and Modal Split for Scenario 3 - Focus carpooling

### 5.4.4 Scenario 4 - Goodbye private car

Figure 5.23 and Figure 5.24 show the simulation results for Scenario 4 - *Goodbye private car*. The external scenario baseline is the same as in Scenario 3 (EXT_1_2_3), shown in dark grey. But the combined measures in Scenario 4 are capable of changing the trend of increased car use to lower it even under the baseline of BAU in 2020 by 10.7 % of car PKT and by 20.8 % compared to BAU in 2040. Overall, PT use is increased starkly by 63.2 % compared to BAU in 2040. Walking is increased by 57.7 % while cycling decreases by 27.8 %. The largest effects are due to lower distances to PT (SMG_3_400) and higher attractiveness of active modes (SMG_5_6).

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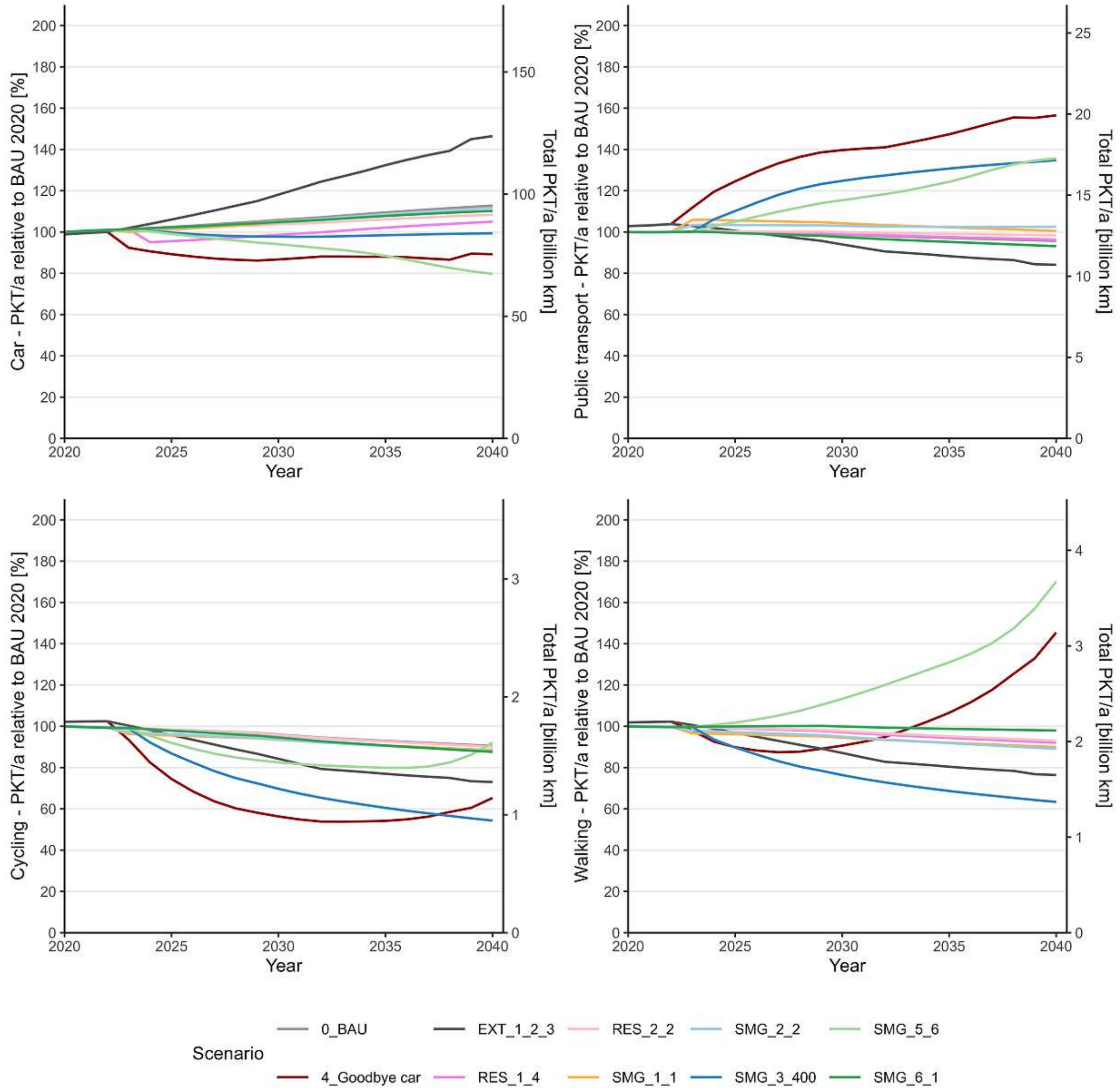


**Fig. 5.23:** Simulation results Scenario 4 - Goodbye private car

Overall PKT in Scneario 4 are slightly decreasing from 2020 to 2040. Modal shares show a large increase of walking to 21 %, a slight decrease of cycling to 6 % an increase of PT to 16 % and a decrease of car trips to 57 %.

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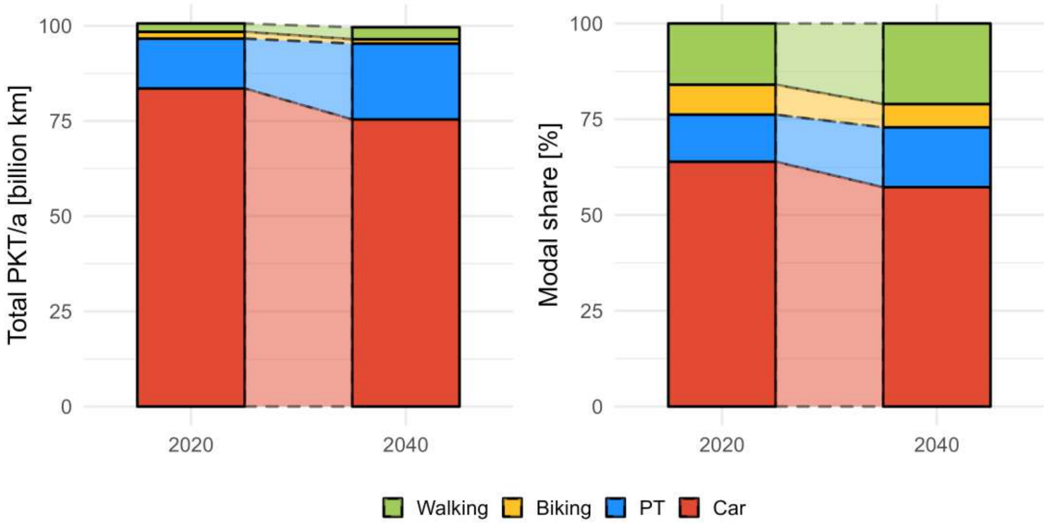


**Fig. 5.24:** Simulation results PKT and Modal Split for Scenario 4 - Goodbye private car

### 5.4.5 Scenario 5 - Utopia

Results of Scenario 5 - *Utopia* are shown in Figure 5.25 and 5.26. Changes compared to Scenario 4 are the introduction of free PT (SMG_1_2) and higher PT frequency (SMG_2_3) as well as road pricing also for off-peak hours (RES_2_4). The combined measures show a large impact on reducing car use (by 47.6 % compared to BAU in 2040) and increasing PT use (by 113.4 %) as well as walking (+63.3 %). Cycling PKT are reduced by 21.5 % compared to BAU in 2040.

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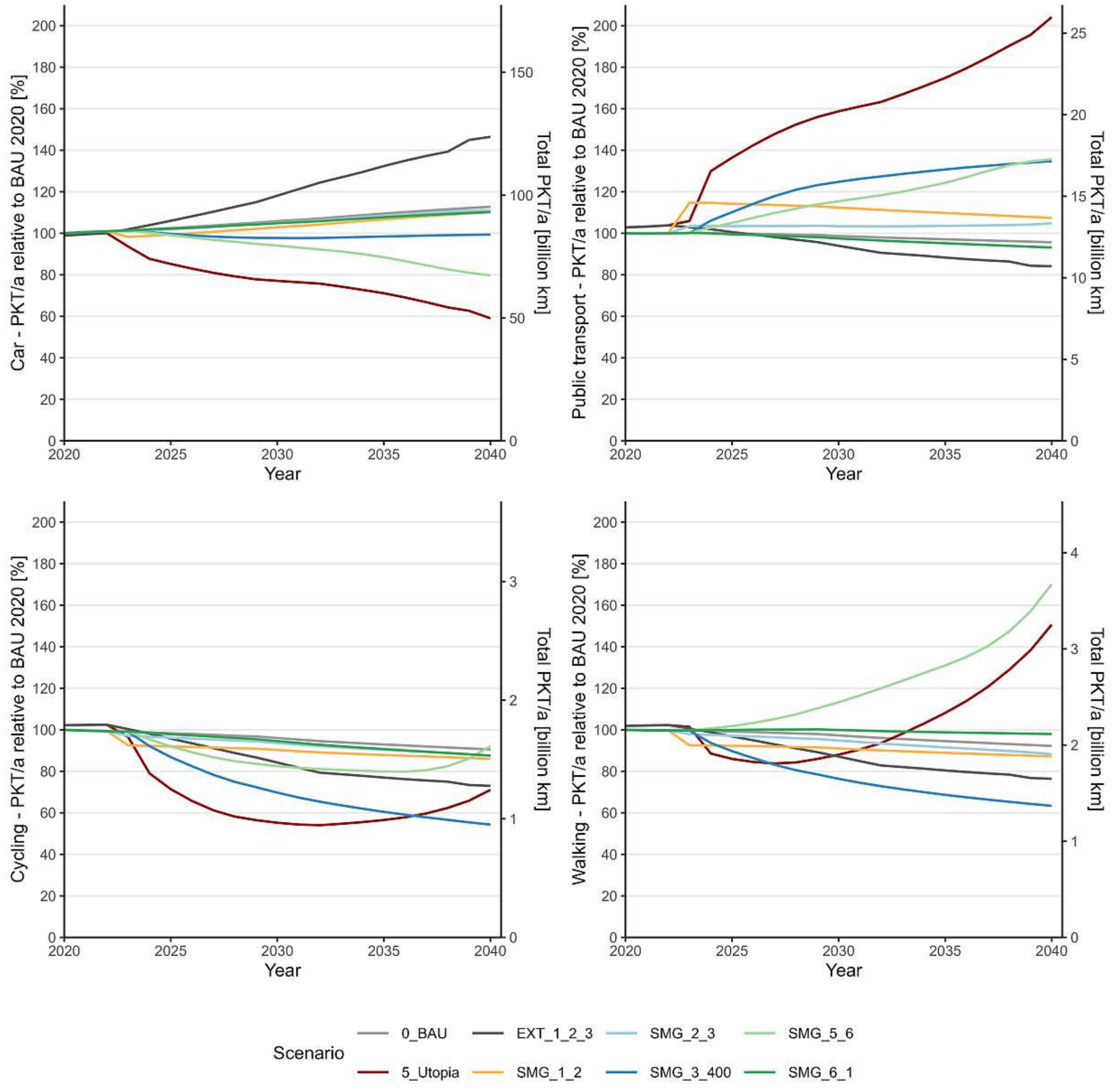


**Fig. 5.25:** Simulation results Scenario 5 - Utopia

Overall PKT are reduced to 80 billion km, with car use decreasing starkly (by 55 % to 50 billion km) while PT and walking show increases. Modal share show a large increase of walking to 23 %, a very slight decrease of cycling (7 %) an increase of PT to 20 % and a decrease of car trips to 50 %.

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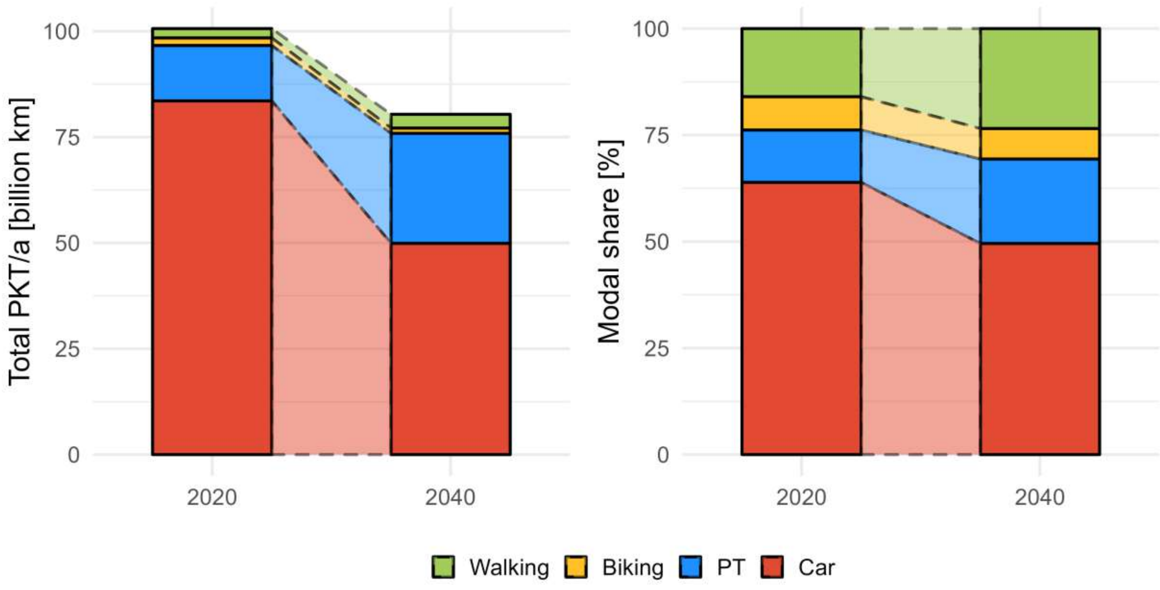


**Fig. 5.26:** Simulation results PKT and Modal Split for Scenario 5 - Utopia

### 5.4.6 Comparison of scenarios

In Fig. 5.27 the results of all scenarios are shown for comparison. Please note that the graph on the upper left side is showing VKT and not PKT. VKT will be an input for the calculation of $CO_2$-emissions and other parameters for the Cost-Benefit Analysis (CBA) in Chapter 6.

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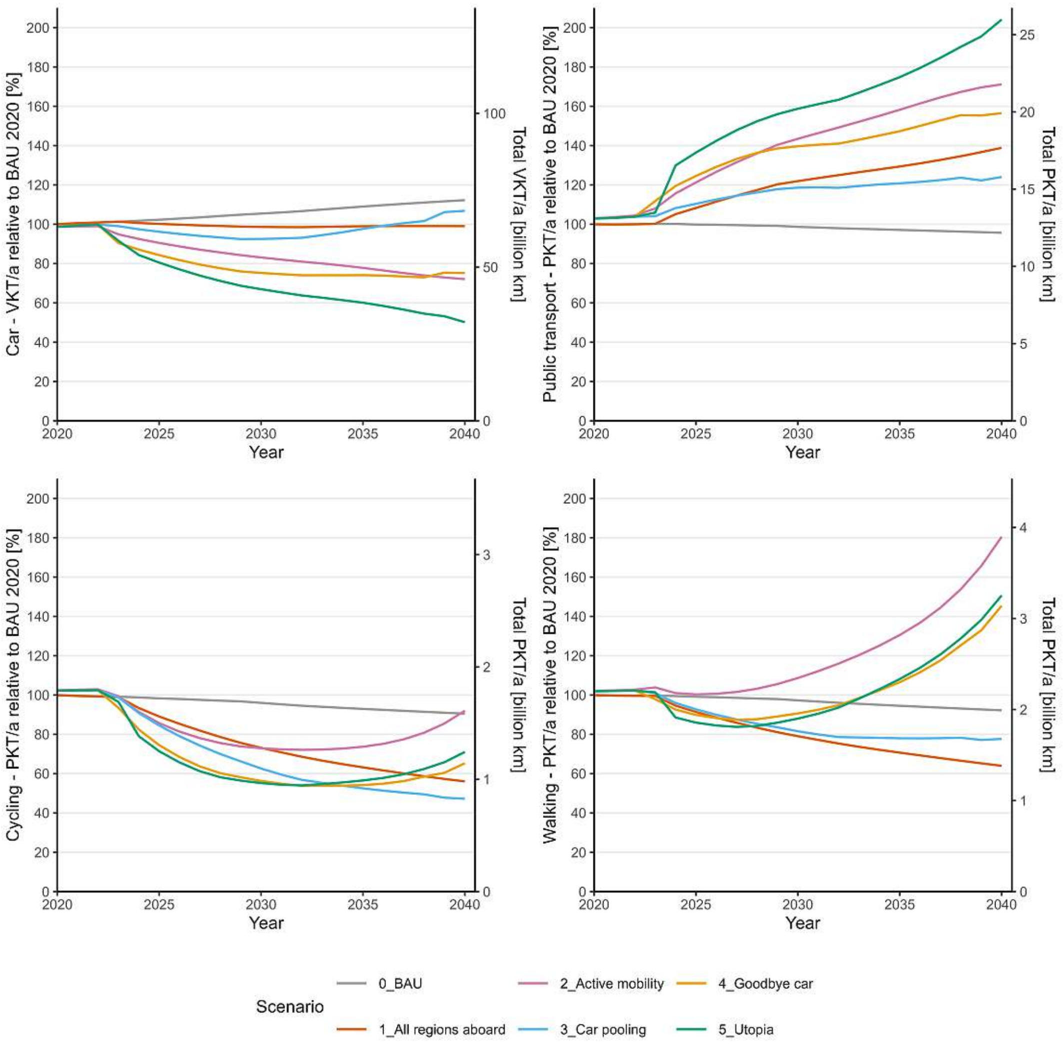


**Fig. 5.27:** Simulation results comparing the scenarios regarding VKT car and PKT for other modes

For easier comparison of VKT, Fig. 5.28 shows the results of VKT by car in each scenario in the year 2040 (left) and cumulative as the sum of VKT in the years 2020 - 2040.

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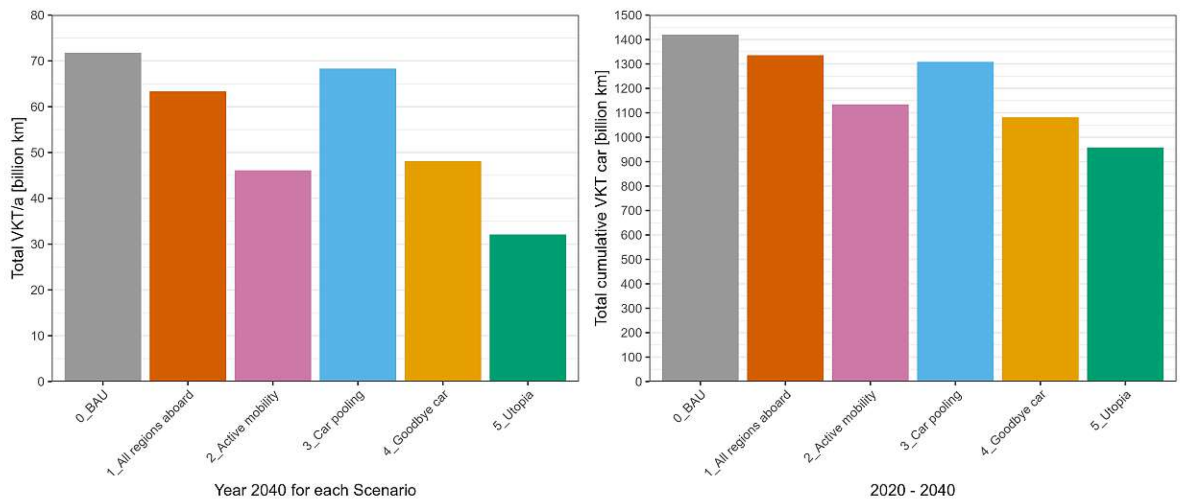


**Fig. 5.28:** Simulation results comparing the scenarios regarding VKT car. Left: VKT/a in the target year 2040, Right: cumulative VKT car for each scenario (sum of the years 2020 - 2040)

Fig. 5.29 compares the results of PKT by each mode in each scenario in the year 2040. It might be striking that the PKT by car in Scenario 3 - *Car pooling* are the highest, even though the VKT are lower than in the BAU. This is due to the higher occupancy rate of cars assumed for the promoted car pooling. While the average car occupancy rate (number of persons in one car) in the year 2040 is 1.26 during peak-hours and 1.34 during off-peak hours in the BAU scenario, it is 1.51 and 1.61 persons/car respectively, in 2040 in the Scenario 3 - *Car pooling* (see also Section 5.2.3).

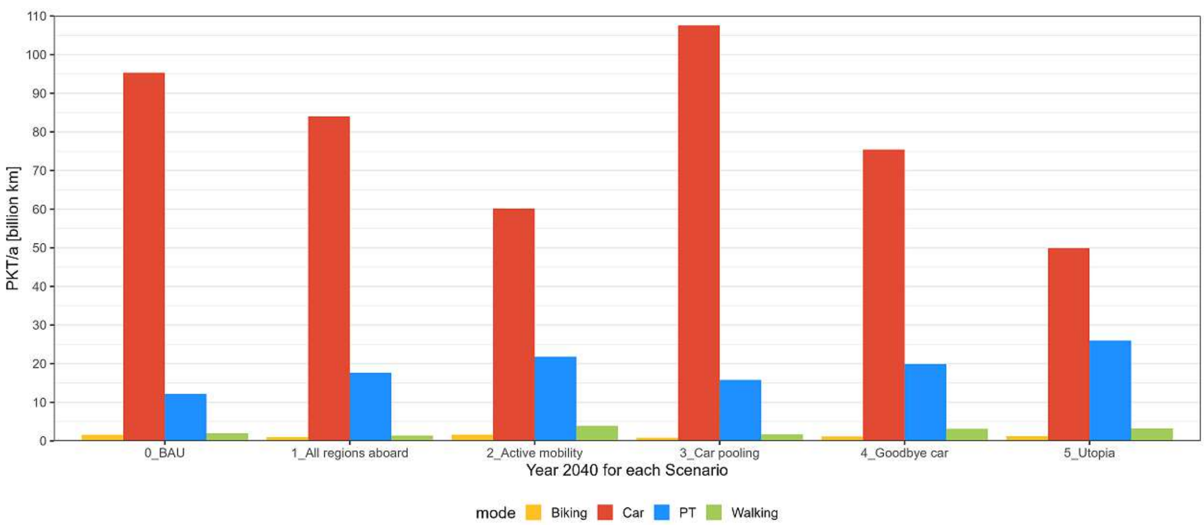


**Fig. 5.29:** Simulation results comparing the scenarios regarding PKT by all modes in the target year 2040

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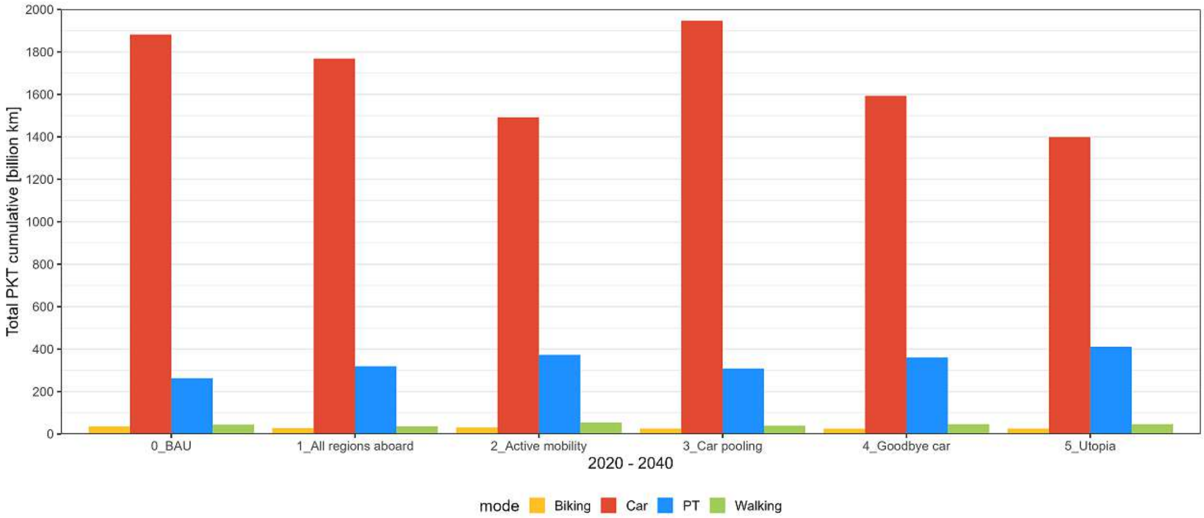


**Fig. 5.30:** Simulation results comparing the scenarios regarding PKT by all modes cumulative for each scenario (sum of the years 2020 - 2040)

Table 5.13 shows an overview of the results in 2020 and 2040 in each scenario and for each mode.

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**Tab. 5.13:** Overview of results for the scenarios

| Scenario | Indicator | Year | Walking | Cycling | PT | Car | Total |
|---|---|---|---|---|---|---|---|
| **Scenario 0: Business as Usual** | Modal Split (trips) | *2020* | *16%* | *8%* | *12%* | *65%* | *100%* |
| | | 2040 | 13% | 6% | 11% | 69% | 100% |
| | PKT [billion km] | *2020* | *2.16* | *1.75* | *12.73* | *84.50* | *101.14* |
| | | 2040 | 1.99 | 1.58 | 12.18 | 95.30 | 111.05 |
| | VKT [billion km] | *2020* | - | - | - | *63.95* | *63.95* |
| | | 2040 | - | - | - | 71.78 | 71.78 |
| | Trips [billion] | *2020* | *1.20* | *0.58* | *0.93* | *4.93* | *7.64* |
| | | 2040 | 1.11 | 0.53 | 0.97 | 5.90 | 8.51 |
| **Scenario 1: All regions aboard** | Modal Split (trips) | 2040 | 10% | 4% | 16% | 69% | 100% |
| | PKT [billion km] | 2040 | 1.38 | 0.98 | 17.68 | 83.99 | 104.03 |
| | VKT [billion km] | 2040 | - | - | - | 63.34 | 63.34 |
| | Trips [billion] | 2040 | 0.77 | 0.33 | 1.21 | 5.09 | 7.39 |
| **Scenario 2: Focus active mobility** | Modal Split (trips) | 2040 | 25% | 8% | 16% | 52% | 100% |
| | PKT [billion km] | 2040 | 3.90 | 1.61 | 21.78 | 60.17 | 87.46 |
| | VKT [billion km] | 2040 | - | - | - | 46.10 | 46.10 |
| | Trips [billion] | 2040 | 1.82 | 0.57 | 1.16 | 3.81 | 7.37 |
| **Scenario 3: Focus car pooling** | Modal Split (trips) | 2040 | 11% | 4% | 14% | 71% | 100% |
| | PKT [billion km] | 2040 | 1.68 | 0.83 | 15.79 | 107.54 | 125.84 |
| | VKT [billion km] | 2040 | - | - | - | 68.31 | 68.31 |
| | Trips [billion] | 2040 | 0.85 | 0.30 | 1.02 | 5.27 | 7.43 |
| **Scenario 4: Goodbye private car** | Modal Split (trips) | 2040 | 21% | 6% | 16% | 57% | 100% |
| | PKT [billion km] | 2040 | 3.14 | 1.14 | 19.99 | 75.41 | 99.69 |
| | VKT [billion km] | 2040 | - | - | - | 48.08 | 48.08 |
| | Trips [billion] | 2040 | 1.49 | 0.43 | 1.10 | 4.05 | 7.07 |
| **Scenario 5: Utopia** | Modal Split (trips) | 2040 | 23% | 7% | 20% | 50% | 100% |
| | PKT [billion km] | 2040 | 3.25 | 1.24 | 25.98 | 49.90 | 80.38 |
| | VKT [billion km] | 2040 | - | - | - | 32.09 | 32.09 |
| | Trips [billion] | 2040 | 1.55 | 0.47 | 1.31 | 3.26 | 6.59 |

## 5.5 Discussion

The results show that making PT more attractive alone ("pull" or "carrots"-measures) is by far not sufficient to substantially reduce car use (and reach Austria's climate goals). Making PT more attractive, like in Scenario 1 - *All regions aboard*, does not only reduce the relative attractiveness of the mode car but also that of the active modes. Thus, reducing the share of active mobility, while the share of private car in the modal split as well as the annual pkm/a show only minor changes.

Scenario 2 - *Focus active mobility* shows a large change in the modal split for private car and PT as well as in their VKT/a and pkm/a, although hardly any restrictive measures against private car are implemented. This demonstrates the high potential of promoting active mobility, but is

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also related to the underlying development of vehicle fleets (e.g. lower share of e-cars). Promoting active mobility has the side effect to make PT use more attractive by making walking and cycling access and egress routes to and from PT stations more attractive. However, simultaneously making PT more attractive also creates competition between the climate and environmentally friendly transport modes.

The results of Scenario 3 - *Focus carpooling* show rebound effects due to the increased occupancy rate. The use of car-pooling makes journeys by car less expensive for individuals and thus more attractive again (see also causal chain in Section 4.4.4). Likewise, rebound effects are evident in the increase in the share of e-cars. Without countermeasures (such as km-based road pricing for all vehicles), this encourages the use of private cars. In Scenario 4 - *Goodbye private car*, a similar development in the modal split and car mileage can be achieved as in Scenario 2 - *Focus on active mobility*, although this requires additional massive investments in PT and restrictive measures for car use. Nevertheless, Scenario 4 could be more desirable in providing mobility services for people who are not capable of walking or cycling larger distances.

### 5.5.1 Limitations

Every model comes with limitations that need to be accounted for when interpreting the results. Although the MARS model has proven to produce realistic simulation results in the past, there are several limitations that should be considered. First and foremost, a computer model always is an abstraction of reality and can only incorporate a limited number of entities. In terms of the Sustainable Mobility Guarantee and its effects as described in Chapter 4, only a limited number of impacts can be included in the MARS model due to its structure and uncertainties.

- No spatial details – high level of aggregation for measures (120 zones = administrative districts of Austria)
- Many uncertainties for parameters that are not part of the SMG scenarios (e.g. development of motorization, share of e-cars, fuel price, etc.)
- Development of freight transport and influence on passenger mobility
- For many parameters/assumptions no empirical data available
  - Data for calibration from 2013/14 (no newer national survey available)
  - More data needed for: travel behaviour of demand responsive services, car-pooling, MaaS, cycling infrastructure (cycling rates very „inert" in MARS)

Excluded due to the structure of the model or due to limited empirical data are for example possible effects on the motorization rate due to the existence of an SMG (as described in Section 4.4.4). The motorization rate is an external input in MARS, possible effects are not modeled internally but tried to account for by using different scenarios for the development of motorization rates with the limiting effect that endogenous feedback cannot be modeled.

Effects of the COVID-19 pandemic are not included in the model. Analyses showed that car traffic quickly bounced back to normal levels (Frey et al., 2024); in Vienna, cycling and walking rates stayed higher and public transport lower than before the pandemic (Wiener Linien, 2021).

For some parameters, there is not yet sufficient empirical data on their impact on travel behavior available to provide a reliable basis for modeling. Therefore, some measures were only estimated as percentage factors. Empirical data on behavior influence would be needed especially for effects of DRT, carpooling, MaaS, and the expansion of bicycle and walking infrastructure.

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### 5.5.2 Fuel prices

Fuel prices in Austria have increased dramatically following the Russian invasion in Ukraine in February 2022. The price for diesel have increased from EUR 1.38/l in January 2022 by 51 % to a maximum of EUR 2.09/l in July 2022 and dropped to EUR 1.59/l in December 2023.[13]

Electricity prices have also increased sharply in 2022 and 2023. The Austrian Electrcity Price Index (ÖSPI) rose from 164,62 in January 2022 to 649,10 in Decembre 2022 and to the maximum of 729,68 in February 2023 after falling again to 274,15 in January 2024[14]. Starting in December 2022, the Austrian government introduced a price cap for electricity, so that households pay maximum EUR 0.10/kWh net for a basic quota of 2,900 kWh per year[15].

Although prices were increased that much, short-term mobility behaviour of people in Austria seems to not have changed significantly. The 2022 “NowCast” assessment of the Environment Agency Austria (Heinfellner et al., 2023) shows a decrease in vehicle fuel sold in Austria. However, this is mainly due to less exports (less vehicles from outside refuelling in Austria due to lower prices) and a rather small decrease in freight transport of -0.2 % compared to 2021. On the other hand, VKT by car in Austria have increased by 2.7 %.

The only variation concerning the cost of driving a car in the simulations was made with the introduction of nationwide road pricing (for all cars on all roads) of up to EUR 0.5/km in the year 2040 (“RES_2”). Results of this parameter are shown in Figure 5.14 and 5.15. The model shows a considerable effect of less VKT by car due to rising cost of driving. Short-term developments in reality might not reflect the long-term behaviour of people. This aspect should be considered carefully and long-term developments monitored in order to draw conclusions on effects of fuel price on the mobility behaviour.

### 5.5.3 Restrictive measures for car use

In the current scenarios, only the adjustment of speed limits and road pricing were considered as “push” measures. There are many other measures that could be implemented instead or additionally. Frey et al. (2023) propose an increase of the mineral oil tax (MöSt) and motor-related insurance taxes, the introduction of congestion charges in cities, the redistribution of public space in cities (in favour of active mobility and PT), driving bans or traffic organization measures in local areas and further measures to internalize “external costs” such as an increase of $CO_2$ pricing and car parking charges. The introduction of these measures or a different policy mix could further increase the effectiveness of the Sustainable Mobility Guarantee with respect to climate targets.

Due to the model basis, some aspects cannot be mapped. These include the operating times and the distinction between school days and non-school days. Since MARS only simulates a classic working day and only differentiates between the two time periods peak and off-peak, the effects of these parameters cannot be analysed directly. For the simulation, it was assumed that it is a working day with school and the corresponding assumptions were made.

### 5.5.4 New mobility services

It is argued that wide-ranging PT in rural areas is only feasible with the use of “new mobility services” such as demand response transport (DRT) or sharing services (Herget et al., 2021;

[13] BMK (2023). Treibstoffpreise aktuell. URL: https://www.bmk.gv.at/themen/energie/preise/aktuelle_preise.html, accessed 29.12.2023

[14] Austrian Energy Agency 2023. Österreichischer Strompreisindex (ÖSPI) URL: https://www.energyagency.at/fakten/strompreisindex, accessed 29.12.2023

[15] Stromkostenzuschussgesetz SKZG (2827/A), BGBl. I Nr. 156/2022

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OECD-ITF, 2021), which might show different usage practices than traditional PT (with fixed schedule and stations). In MARS, DRT is not considered as a separate means of transport, but is simulated together with the existing public transport. Due to the spatial aggregation level of MARS and the time and resource constraints of the thesis, a separate consideration was out of scope. The assumption was made for the model that the mode choice does not significantly depend on whether the access route and waiting time apply to a classic scheduled bus or a demand-responsive vehicle, as only aggregated values at district level are included in the simulation anyway. The same applies to car pooling and vehicle sharing, which are not mapped as separate modes of transport. Instead, in those scenarios that promote pooling, an increased occupancy rate of private cars is assumed. Currently, there are several pilot projects that assess the introduction of innovative DRT services in rural areas in Austria, but empirical results regarding mode choice are still scarce. In a meta-review Javaid et al. (2020) found that such new shared mobility modes can reduce the use of private cars, but are often reducing public transport use as well. For future research, however, it is desirable to implement the distinction between on-demand transport and classic scheduled public transport as well as pooling in models in order to better analyse possible effects. For this, empirical data on the choice of means of transport with the corresponding offer is needed, which could be obtained in research-supported pilot projects of implementation.

### 5.5.5 Active mobility

There is only limited empirical evidence on the relation between measures and effects in mode choice concerning active mobility. A systematic literature review by Campos Ferreira et al. (2022) analysed the factors influencing perception of different factors by pedestrians and cyclists. Negative impact can be attributed to traffic speed and density and the fear of being hit in terms of safety. Crime is the major security concern and bad weather, high air and sound pollution as well as slopes decrease comfort perception. Insufficient lighting impacts the perception of all three factors negatively: safety, security and comfort.

Several negative influences can be reduced by reducing the speed and volume of car traffic (safety concern of being hit and air and sound pollution) and therefore restrictive measures for car use can be seen as “win-win” measures for the implementation of a Sustainable Mobility Guarantee, reducing car use and providing better conditions for active mobility. The provision of safe infrastructure in the form of separated cycle paths and routes in low traffic zones can add to that. Concerns of cyclists in terms of theft and vandalism should be countered by providing bike parking facilities that are surveilled or lockable, especially at train stations. Perceptions of comfort can be impacted positively by providing infrastructure that reduces slopes and shields from poor weather conditions such as rainy, cold or hot weather. This includes wind barriers and canopies, trees lining paths and showers and changing rooms at destinations such as the work place. (Campos Ferreira et al., 2022)

Knoflacher (2007) and Peperna (1982) showed that pedestrians accept up to 70 % longer walking distances in car-free street designs than in car-oriented streets. A study on pop-up cycle paths during the COVID-19 crisis offered new insights. Kraus and Koch (2021) found a correlation of the increase in cycling (number of cyclists at cycle counting stations) between 11 % and 48 % due to the construction of temporary cycling infrastructure - adjusted for factors such as placement of counting stations, availability of public transport, population density, propensity for “green lifestyle”, topography and weather. Although Vienna installed pop-up cycle lanes only on a very small scale and for a short period of time (Frey et al., 2024), the number of people

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cycling during the COVID-19 pandemic increased between 2019 and 2020 by 12 % at the city's counting stations[16].

Empirical evidence on active mobility use for the case study of the Austrian province Upper Austria can be found in Hackl et al. (2019). They show that mixed-use and density of the settlement structure as well as adequate infrastructure influence walking and cycling positively. They also show, that attitudinal variables of the population have a strong influence on cycling. Measures should therefore include several different types, addressing safety, security and comfort as well as attitude (e.g. through campaigns).

In the MARS-UBA model used for this study, the cycling shows particular "inertia", which means it does not react sensitively to measures, except for increasing only the attractiveness of cycling. This could also be related to the available calibration data. Modal share of cycling has been historically low in Austria. The calibration data of the latest nationwide mobility survey shows a cycling share of only 6.6% of trips on weekdays (Follmer, Gruschwitz, Kleudgen, et al., 2016). More research - especially in the Austrian context - is necessary to further explore these aspects empirically. In terms of modelling, new approaches in MARS could be explored by modifying the mode choice, e.g. in dependence of population groups. Similarly to the car mode only being available for people with a driving license, it could be possible to model population according to the possibility of using the bike as a transport mode.

### 5.5.6 Conclusion

The scenarios show that a mix of measures promoting active mobility and public transport combined with restrictive measures for car use yield the largest mode shift towards PT and active modes. The most relevant insights are:

- Promoting active mobility shows benefits in reducing car usage and increases PT usage since walking and cycling are feeder modes
- Promoting PT reduces walking and cycling and has not much effect on the use of private cars, if not combined with restrictive measures
- An increased share of e-cars reduces costs of driving and promotes car usage
- Spatial planning measures reducing trip distance are necessary to curb overall energy intensity of travel

I would like to emphasize that the simulations are estimates of possible effects in different scenarios and not precise forecasts of future development. As with all models, the results reflect assumptions made and cannot provide any information on the actual course of developments in the future. For this reason, the scenarios were defined as broadly and differently as possible, to estimate a realistic range of effects. Although there are several limitations, the simulations present a first estimation of the possible impact on travel behaviour of differently designed Sustainable Mobility Guarantees on a national level in Austria. The analysis presents a basis for evaluating policy effects that can inform political decisions for selecting a policy mix that is fit to meet political objectives. Additionally, the simulations help to identify future research needs.

[16] https://www.fahrradwien.at/radfahren-in-zahlen/radzahlen-2020/, accessed 08.01.2024

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# Chapter 6

# Cost-benefit analysis

In this chapter, I first explain the logic and criticism of cost-benefit analyses (CBA) with focus on the transport sector in Section 6.1. Then I present the CBA approach chosen in this thesis, including a discussion on travel time valuation (Section 6.2). In Section 6.3, the cost calculation is explained and in Section 6.4 the benefit calculation. Results of the base case calculation are shown in Section 6.5 while results of the sensitivity analysis are presented in Section 6.6. This is followed by a discussion in Section 6.7 and conclusions in the final section.

## 6.1 Introduction to CBA

Social cost-benefit analyses (CBA) (sometimes also called benefit-cost analyses) are applied widely by economists and engineers to assess projects and policies, especially infrastructure projects such as road or railway constructions (Mackie et al., 2014; Van Wee, 2012). CBAs are usually performed before detailed planning (ex-ante) to help decision-making, often to compare different projects, project variations (such as different routes of a new road) or to prioritize infrastructure projects due to limited public budgets.

The costs of building new infrastructure or introducing a new policy are compared to benefits, in monetary values to enable the comparison. The method is rooted in Welfare Economics where micro-economic techniques are used to measure well-being at the aggregate level (Hickman & Dean, 2017). It is based on a utilitarian approach, comparing policy options from the perspective of utility with the notion of rational individuals who make decisions based on known costs and benefits (Van Wee, 2012). Mackie et al. (2014) give an extensive overview on CBA practices for transport project appraisal in Europe, USA, Australia and New Zealand. Their findings indicate that methodologies and valuation techniques are broadly similar across these countries and all of the studied nations embed CBA within a broader assessment framework that includes non-monetized benefits, for example with an additional multi-criteria analysis (MCA). The authors conclude that CBA can be a useful tool to overcome cognitive, structural and process-related limitations and biases in decision-making. Despite broad criticism and limitations of the method (see below), CBAs are deemed particularly useful to compare schemes within national transport programs. (Mackie et al., 2014)

### 6.1.1 Criticism and limitations of CBA

Criticism of the method addresses many different aspects. Van Wee (2012) summarizes and discusses the limitations of CBA for transport projects and policies from an ethical perspective. The criticisms include that utilitarianism is limited in its application and is not useful for all purposes of interest in CBAs. Another critique addresses the issue that some effects are difficult to monetize and the fact that distributional effects are ignored in standards CBAs. It is also debated that only humans matter and animals or other living organisms don't. Van Wee (2012)

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also discusses questions of power: the process of selecting, defining and designing parameters and options that are assessed in the CBA and bias the outcome.

Hickman and Dean (2017) discuss specific issues of CBAs in transport appraisals in the UK. They argue that CBAs are incomplete on the cost and benefit side and that there are several problematic issues including the limits of quantification, the weight given to time savings, discounting, distributional effects, accuracy of projections and poor achievements of CBA results compared to policy goals. They specifically mention shortcomings of CBA in light of 'important policy goals' on climate change, social equity and developing attractive urban areas.

Although some proponents of CBA argue that all relevant costs and benefits are considered, the decision of what is deemed 'relevant' and 'good' includes normative assumptions and the aspects studied in a CBA always reflect only a part of the economic, social and ecological systems we are embedded in (Gössling et al., 2019; Hickman & Dean, 2017). An overview of impacts that are considered or not in standard CBA in the UK is shown in Table 6.1, based on Hickman and Dean (2017).

**Tab. 6.1:** Impacts of cost-benefit analysis in the UK transport sector, based on Hickman and Dean (2017)

| Impacts that are quantified and monetized | Impacts that can be monetized (but are not reported in standard CBA in the UK) | Impacts deemed not feasible to monetize |
|---|---|---|
| - Commuting and other uses | - Regeneration | - Security |
| - Accidents | - Wider impacts | - Access to services |
| - Physical activity | - Option and non-use values | - Affordability |
| - Noise & air quality | - Landscape | - Severance |
| - Journey quality | - Reliability impact on commuting and other users | - Townscape |
| - Greenhouse gases | | - Historic environment |
| - Business users and private sector providers | - Reliability impact on business users | - Biodiversity |
| | | - Water environment |

Regarding monetization, CBAs face criticism because assigning monetary values to intangible values such as social impacts, ecosystem services or human life can be arbitrary and vary widely based on culture and assumptions made. Additionally, environmental resources are treated as substitutable by any other resource, reduced to a single monetary value. Environmentalists and critical economist scholars have long pointed out such shortcomings of neoclassical environmental economics (Stern, 1997). Some resources such as biodiversity or endangered species, a stable climate and cultural heritage sites are irreplaceable. It is a valid concern that CBAs therefore cannot capture the actual societal value of some resources and are not able to consider long-term effects and tipping points in climate and biodiversity (see also Section 1.1).

Another criticism concerns redistributional effects and equity. The benefits in a CBA are computed on an aggregated level for the whole society and do not show who profits from it and who might be disadvantaged. Although there are approaches to differentiate between beneficiaries and cost-bearers, they usually have no impact on the outcome of the CBA (Lucas et al., 2015). Martens and Di Ciommo (2017) looked into equity effects in CBA and give an overview of the literature. They argue that projects serving the majority population perform better than comparable projects serving disadvantaged groups of the population. They further compared

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two approaches using travel time savings and accessibility and conclude that both are insufficient to address all equity effects.

Emberger et al. (2008) compared different types of CBAs with target-based appraisal approaches and found that they are incompatible. The monetary approach of standard CBAs does not reflect the targets set in the case studies. Therefore a CBA is deemed inappropriate for assessing whether a transport project is achieving political goals. A number of other scholars point out similar limitations and the incompleteness of CBA regarding economic, ecological and social aspects (e.g. Hickman & Dean, 2017; Marleau Donais et al., 2019; Metz, 2008).

To account for uncertainties and non-monetary indicators, CBAs are often combined with a multi-criteria analysis (MCA) (also called multi-criteria decision analysis MCDA) (Gühnemann et al., 2012; Hickman & Dean, 2017; Marleau Donais et al., 2019). Such analyses can capture non-monetary values but are also limited to potential biases of the users applying the method. In CBAs and MCAs, weights are sometimes applied to reflect preferences. On the one hand, this can serve to balance out biases, for example in case of participatory approaches where different types of stakeholders are included in the decision making process. On the other hand, using weights could also lead to even stronger biases of the appraisal results. Personal attitudes and values of decision makers who assign weights can influence the outcome, for example such as weighting economic factors more than environmental factors, following current paradigms and mental models as described in Chapter 4. In the case study of appraisal methods for the National Secondary Road Network in Ireland described by Gühnemann et al. (2012), the Irish National Road Authority Board weighted 'economy' with 35 %, 'integration' with 35 % and 'environment', 'safety' and 'accessibility' with only 10 % each.

Hickman and Dean (2017) suggest a strengthened participatory MCA as an alternative approach for transport project appraisal. They point out the political dimension of decision-making and argue that it requires debate. They propose a discursive, participatory approach allowing impacts to be assessed against multiple criteria and wider actor views to be reflected in the process. A similar argument is made by Dekker et al. (2019) who propose a participatory approach combined with a new econometric framework. The approach includes a web-tool used by a representative sample of citizens to select public sector projects within a certain budget constraint. The projects are presented with reference to a range of social impacts, described in qualitative and quantitative terms. Results from the survey are used to estimate a direct utility function that can be included in the social welfare function to inform policy makers on the ranking.

## 6.2 CBA Framework in this thesis

I acknowledge the criticism of the method and the limitations of CBA in transport project appraisal, nonetheless I regard CBA a useful method to analyze the SMG scenarios in this thesis for the following practical reason: CBA is such a commonly used tool in practice for evaluating transport projects and policies by public authorities, that is seems valuable to "translate" a new concept (the Sustainable Mobility Guarantee) into this framework in order to "speak the language" of decision-makers when explaining the costs and benefits of such a guarantee. Furthermore, a CBA of the SMG concept (bearing in mind the limitations mentioned above) could help to formulate well-founded criticism on the aspects that might be less suitable for such an assessment.

To account for the shortcomings inherent in the CBA methodology, it is common practice to couple it with an MCA, allowing for the incorporation of non-monetary indicators and a broader range of perspectives. An MCA would be a suitable approach for analysing the SMG concept, as it could capture diverse social and environmental factors that are difficult to quantify in monetary terms. However, an effective MCA ideally involves a participatory process, including

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various stakeholders to ensure a balanced and representative evaluation. Due to the significant resources required for such a process, and given the constraints of this thesis, a participatory MCA is beyond its scope.

The CBA approach in this thesis adapts the standard approaches by critically discussing user benefits estimated as travel time savings and putting more focus on aspects that are often treated as 'externalities' such as environmental impacts, accidents and health effects. In the sensitivity analysis, the range of impact of changing critical parameters is shown. This offers a broadened view and allows for more precise discussion of current practices. The CBA is seen as an assessment tool to discover the key parameters in creating cost-effective implementation scenarios. But the decision, if and how an SMG is realized ultimately remains political.

The CBA in this thesis has three objectives: (1) to identify the scale of financial investment needed to implement an SMG, (2) to show the benefits that such an investment could yield and (3) to assess the efficiency of investment for different scenarios.

The methodological guideline for conducting the CBA is the "Guide to Cost-Benefit Analysis of Investment Projects. Economic appraisal tool for Cohesion Policy 2014-2020" of the European Commission (2014), which served as a rough framework that was adapted to the needs of the research, as described in the following. While changes in travel time are not considered in the base case calculations of the CBA (see Section 6.2.3 for discussion), the benefit side is amended with option and non-use value and health benefits of active mobility. Preliminary results of the CBA have been presented and discussed at the $17^{th}$ International Conference on Travel Behavior Research (IATBR) in Vienna in July 2024 (Laa, 2024). The feedback from peers was incorporated into the final approach and calculations.

As described in the following, there is a lack of data regarding the identification of costs and large uncertainties regarding costs and benefits. A more detailed CBA approach that would analyze each parameter in more detail is out of scope of this thesis. Therefore, the CBA must be understood as a first approximation of an economic assessment of the SMG concept.

### 6.2.1 System boundaries

The system boundaries are corresponding to the political sphere, data availability and model boundaries used in the travel behavior analysis in Chapter 5. Spatial boundaries are the territory of the State of Austria. Of course, the Austrian economy is not separate from neighboring countries, the EU and global developments and environmental impacts can have global effects. However, compromises have to be made to make the analysis feasible but limitations arising from the chosen system boundaries should be kept in mind when interpreting the results.

The time frame considered in CBAs is usually chosen with respect to operational life of infrastructure and corresponding to discount rates (Mackie et al., 2014). Reflecting usual lifetime of transport infrastructure, I chose an appraisal period of 40 years, with measures being incrementally implemented from 2021 until 2040, when the SMG is in full effect. Benefits and costs are calculated for every year based on simulation results (see Chapter 5) for the model period from 2021 until 2040. After that, benefits are assumed to be constant at the value in the final simulation year (2040) and costs are assumed to be constant at the value of operating and maintenance costs in the final simulation year.

### 6.2.2 Costs

On the cost side, initial investments, operating and maintenance costs are considered. Initial investment costs include financing of additional bus stops, additional railway lines and infrastructure for active mobility. Operating and maintenance costs include bus and train services

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(and new vehicles) as well as DRT services. Maintenance cost of infrastructure and other costs such as for MaaS services and communication activities are considered as well. First results of a cost estimate for a Sustainable Mobility Guarantee have been published by Shibayama and Laa (2024). These estimates are the basis for the cost estimate in this thesis.

For estimating the necessary investment, many uncertainties exist, such as missing data on the gap between current services and PT services for an SMG and different options of providing the quality level of services (e.g. railway, bus services and DRT). The calculation of costs is therefore only a first estimation. I assume a different mix of services as well as different service quality levels for the scenarios, as described in Section 6.3.

Tax related costs, changes in PT ticket prices and road pricing are not considered in the CBA. Such costs are usually excluded because they are transfer payments shifting money between individuals and the public sector without affecting overall societal welfare.

### 6.2.3 Travel time valuation

The valuation of travel time is included in standard CBAs in travel time savings and sometimes in congestion cost. A standard case would be a new proposed road that would make travel between two destinations faster and - in theory - lead to saving time that could be used for other purposes. In infrastructure appraisal, travel time savings (i.e. reduced travel time by car for roads or by PT for railways or bus lines) usually account for a majority of the benefits, often representing more than 70 % of all benefits (European Commission, 2014; Mackie et al., 2014). The high valuation of travel time savings and the consideration of travel time savings in general are subject to large criticism (e.g. Hickman & Dean, 2017). In the following, I explain the basis for travel time valuation and then discuss the different types of criticism, concluded by the approach I chose regarding travel time valuation for the CBA in this thesis.

Individuals value time differently. The same individual might value time spent doing different activities differently. Traveling is mostly interpreted as something negative that needs to be minimized, although it is argued that some forms of travel might have a positive utility or that there is a desired travel time budget and only when it is exceeded, traveling is seen as a disutility (Mokhtarian & Chen, 2004). But there are also differences in the perceived value of time for different transport modes. Time spent in a car is valued differently than time spent in PT, on a bike or walking. And these values might be different for each person, reflecting individual preferences. Different perceptions of the value of time can be shown with stated preference surveys, where respondents choose between hypothetical choices of routes and modes involving different costs or with revealed preference approaches, based on observed travel choices involving different costs (Metz, 2008).

In CBAs, the Value of Travel Time Savings (VTTS) is sometimes used, representing the marginal willingness-to-pay for reducing travel time. VTTS for PT shows usually lower values than for driving a car. Hartwig et al. (2024) give an overview of estimates in literature showing the range of values for VTTS of EUR 3.90/h - EUR 13.61/h for PT and EUR 4.63/h - EUR 28.14/h for car drivers. The PT/car ratio is generally less than zero and seems to decline with time. This is explained with increasing availability of information and communication technology (ICT) which facilitates multitasking while traveling with PT.

Then, there is the approach to value time economically. Time spent traveling cannot be used for working (or only to a limited extent) and is therefore valued on the basis of economically productive time. Most countries studied by Mackie et al. (2014) base business travel time savings on the “cost savings” approach with the values representing wage plus non-wage employment costs. It has been debated that ’saved’ business travel time might not be converted to working

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but rather to leisure time. The Hensher approach (Hensher, 1977) takes this into account and usually gives lower valuations than the cost savings method.

Usually, values for travel time savings differ between type of trip (business, commuting, leisure) and transport mode. In the review by Mackie et al. (2014), all countries differentiated the value of travel time savings by trip purpose and most also by mode. In Sweden, trip length is also influencing the value of travel time with values differing for trips longer or shorter than 100 km.

Despite the ubiquitous practice of considering travel time savings as described above, the way in which travel time savings are calculated and also the fact that they are even considered in CBAs is criticized. One critique refers to the scale of travel time savings with small increments (e.g. only few seconds or minutes saved per individual) being aggregated to large total travel time savings (Emberger, 2004; Hickman & Dean, 2017; Marohn, 2021). It is argued that such small units of time cannot be used for other activities. Some appraisal guidelines try to reflect this in discounting small travel time savings. Germany, for example, applies a 30 % discount to road travel time savings below 5 minutes (Mackie et al., 2014).

Emberger et al. (2008) showed that the standard CBA approach in the UK is inconsistent with local targets regarding accidents and time savings. In the assessed CBAs, travel time savings are secured at the expense of accident cost increases. This means the standard approach to travel time savings might not be in line with targets that have been set politically such as the resolution of a city to reduce traffic accidents. The authors argue that monetary values could be adapted to reflect such targets.

A more profound critique regards the phenomenon of stable “travel time budgets” that has been discussed since the late 1970s (e.g. Hupkes, 1982; Schafer, 2000; Zahavi & Talvitie, 1980) with the average time allocated to transport per person showing stability over time with an average of 1.1 - 1.3 hours per day. In a more recent review, Mokhtarian and Chen (2004) find that on a disaggregated level, travel time expenditures of individuals show differing patterns that can be explained in part by measurable characteristics, however, on the aggregate level travel time budgets seem stable. Therefore, some scholars argue, if the time spent travelling remains stable on an aggregate level, travel time savings should not be considered in transport project appraisal. Metz (2008) discusses this as the “myth of travel time savings”. He argues that the utility of new infrastructure is not travel time savings but rather improved accessibility, however, with diminishing marginal utility with increased access to services. Metz (2008) suggests to conduct research on willingness-to-pay for access instead of considering agglomeration benefits of access, as it is sometimes done in CBA. In a report for the World Bank, Cervero (2011) discusses problems with the use of travel time savings with empirical evidence showing that improvements to roads and PT - which in theory would have reduced travel time - have not resulted in a reduction of time per day that people devote to travel. Rather, they increase the number and length of trips. Over time, induced traffic can also diminish the effects of time savings.

For Austria, considering the last three national travel surveys (Follmer, Gruschwitz, Kleudgen, et al., 2016; Hiess et al., 2007), the trend shows a slight increase of average time spent travelling per day, from 67 min/day in 1983 to 70 min/day in 1990, which is the same value that has been observed for the latest survey in 2013/14. The average distance travelled, however, has increased continuously from 21.8 km/day in 1983 to 28.4 km/day in 1995 to 34.4 km/day in 2013/14.

But the issue is not only with individuals choosing to travel longer distances with increased speed but also changes in land use leading to destinations being farther away in the long term. The extension of road networks has been shown to lead to urban sprawl, rendering trip lengths longer (Baing, 2010; EEA, 2006; Litman, 2013; Mattioli et al., 2020; Newman & Kenworthy, 2015).

Mokhtarian and Chen (2004) summarize the problematic as a paradox in transport planning:

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> *"[...] the TTB [travel time budget] idea appears [...] to clash with one of the most fundamental tenets of conventional travel behavior theory: that travel time is a disutility to be minimized. The travel time minimization principle underlies a great deal of policy-making as well as virtually all regional travel demand forecasting models, and is used to justify monetizing the benefits of transportation improvements on the basis (primarily) of travel time savings."* (Mokhtarian & Chen, 2004)

As a solution to the paradox, they provide the viewpoint that individuals still increase their overall utility when they are using 'saved' travel time to visit more destinations or ones that are farther away but are more attractive. As Cervero (2011) puts it, the prospect of travel time savings influences decisions of individuals in the short term on when, where and by which mode people travel, but over time new routes become part of established patterns of daily activity. Therefore, he argues, benefits of new transport infrastructure should be viewed not in terms of travel time savings but an improvement of accessibility.

So while some argue for adapting monetary values of travel time savings (Emberger et al., 2008), some (such as Cervero, 2011; Metz, 2008) argue for new indicators reflecting accessibility as an extension to or instead of travel time savings, and some argue that travel time savings can still be used, as a proxy for accessibility and even a conservative estimate of overall welfare gains (e.g. Van Wee & Rietveld, 2008). Even though standard CBAs put a focus on travel time savings and the fact that accessibility as well as spatial development are generally seen as something good (increasing welfare), it has been shown that such developments are also linked to a range of negative effects (see Chapter 1).

All of the above leads to the question of normative decisions about which effects are desirable and which impacts should be included in a CBA. As discussed e.g. by Hickman and Dean (2017), Gössling et al. (2019) and Nyborg (2014), CBAs are always incomplete, are based on controversial value judgments and can be biased by ideological orientations of actors involved in the analysis. By stating the selection of criteria and assumptions explicitly, however, CBAs for transport projects can contribute to transparency and consistency in decision-making.

Coming back to the question of considering travel time savings and valuation of travel time for the CBA in this thesis, the introduction of an SMG as proposed in this study is different from standard CBAs. I do not assess one project that only adds infrastructure to the existing transport network but a set of measures. Some of these measures decrease travel time for individuals who use PT, cycling or walking due to new infrastructure or services improving accessibility for these modes. On the one hand, some of the measures allow for shorter distances and better access to services due to spatial planning for denser settlement structures. Additionally, some measures deliberately impact travel by car, making it slower (through lower speed limits), more expensive and less convenient, in order to reduce car use, mainly for environmental reasons. In standard CBA this would be seen as a disutility. It is difficult to unravel these overlaying effects regarding travel time and accessibility. There are no standard procedures on how to account for mode shift and how to evaluate changes in access to services. Or how to deal with mode shift effects reducing car traffic and therefore congestion for those still driving by car. The EC guidebook on CBA states: "*When calculating time costs for passengers diverted from other routes or means of transport, practice across Europe varies and yet there is no consensus on the correct approach to take.*" (European Commission, 2014, p. 93).

While I acknowledge the differing valuation of time on the individual level, I argue that travel time savings should not be used as a parameter on which to base public investment decisions for long-term projects on, due to the diminishing effects over time with stable travel time budgets and induced demand. I therefore chose an approach that does not include travel time valuations, neither on the side of increased trip duration for car trips, nor for travel time savings for PT

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and active modes or regarding congestion costs. The SMG is a policy with the goal to reduce environmental harm in the transport sector while providing accessibility through sustainable modes of transport. So the main purpose is to provide a sustainable *option* for traveling. To account for this, instead of using travel time valuations, I assume option and non-use values for new PT services. The stated objectives should inform the choice of criteria against which the scenarios are assessed. While all CBAs remain incomplete, I argue that the most relevant criteria for an assessment that serve the purposes of this study are included in the CBA approach chosen. In the sensitivity analysis, the (negative) travel time savings for car trips are calculated to show the dimensions of the travel time changes.

Future research could look into the effects on travel time, mode shift and accessibility in more detail in order to comply with standard CBA approaches and provide comparability. For practical implementation of an SMG, I recommend to assess different options in a broader appraisal process in a participatory manner, e.g. as proposed by Hickman and Dean (2017) or Dekker et al. (2019).

### 6.2.4 Benefits

On the benefit side, the most relevant difference to standard CBA approaches is the non-consideration of travel time savings (i.e. changes in travel time), as discussed above. The following impacts are considered:

- Option and non-use value
- Vehicle operating cost savings
- Accident costs
- Air pollution costs
- Noise costs
- GHG emission costs / climate change damage
- Air pollution costs of well-to-tank emissions
- Health effects of active mobility

Option and non-use values are based on a review by Laird et al. (2009). The analysis of "external costs" was guided by three references, as explained in the following. The quantification of average external costs of accidents, air pollution, noise and well-to-tank emissions is based on the "Handbook on the external costs of transport" (European Commission, 2019). Monetary values for GHG emission costs are based on the "Methodenkonvention 3.1 zur Ermittlung von Umweltkosten" of the German environment agency (Matthey & Bünger, 2020). The quantification of vehicle operating costs is based on the assumptions made in MARS. The monetary values for health effects of active mobility refer to the analysis "The Social Cost of Automobility, Cycling and Walking in the European Union" by Gössling et al. (2019). Details for all benefit assumptions are described in Section 6.4.

### 6.2.5 Indexing and Discount rates

The analysis is carried out in constant (real) prices, with prices fixed in the base year 2021. This is in line with the CBA guide of the European Commission (2014). Because costs and benefits arise over the lifetime of a project, it is considered necessary to convert monetary values in the future to a net present value (NPV) through discounting. Discounting can be performed

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separately for the cost analysis and benefit analysis or even for each parameter or with the same discount rate applied to all costs and benefits. Discount rates reflect the time value of money. Regarding investment costs, this can be based on the viewpoint that wealth can be invested to generate profits and current resources therefore have a greater value than future resources, also including inflation (Litman, 2011). Such a Financial Discount Rate (FDR) is typically reflecting return on capital that could be earned in an alternative investment.

Changes in value regarding benefits are usually reflected by Social Discount Rates (SDR) or Social Opportunity Cost of Capital (SOCC), rooted in different ideas. It is argued that people in general prefer the present to the future, consumption levels are expected to rise, leading to a lower marginal utility of additional consumption; future consumption levels are uncertain and better technology will make it easier to deal with impacts in the future. (Harrison, 2010; Litman, 2011; Quiggin, 2006)

Discount rates and evaluation periods applied in practice for CBAs of transport projects vary widely. Countries have different recommendations and guidelines on discounting. For example, in the United States, the discount rate is 7 % and evaluation periods depend on the lifetime of projects (usually 25-30 years), while in the UK, discount rates vary between 2.5 % and 3.5 % and the default evaluation period is 60 years (Marleau Donais et al., 2019). Litman (2011) recommends about 6 % discount rate for lower-risk projects and 8.6 % for higher-risk projects.

The Guide to Cost-Benefit Analysis of Investment Projects of the European Commission (European Commission, 2014) uses different discount rates in the financial analysis and in the economic analysis. The FDR in the financial analysis is recommended with 4 %. In the economic analysis, the Social Discount Rate (SDR) is applied and recommended with 5 % for Cohesion states and 3 % for other member states of the European Union. The reference periods for the financial analysis differ by sector. Regarding transport projects they are assumed with 30 years for railway projects, 25-30 years for roads and for urban transport projects.

The practice of discounting benefits is criticised because future generations are usually valued less than current generations. This is questioned especially in the discourse surrounding climate change impacts with proponents arguing for low discount rates or a discount rate of zero (Hickman & Dean, 2017; Litman, 2011; Philibert, 2006; Quiggin, 2006). For some, it is even envisageable to use negative discount rates under the assumption that environmental resources will become more scarce every year (Fleurbaey & Zuber, 2013).

Indicators for CBA performance in this thesis are calculated with different discount rates to show the effect that this choice has on the results. Considered discount rates are 0 %, 3 % and 5 %. For the indicator formulas, see Section 6.2.6.

### 6.2.6 Indicators

The analysis will be based on the indicators of Benefit-Cost Ratio (BCR), Net Present Value (NPV) and Internal Rate of Return (IRR), calculated according to the formulas presented in the following.

#### Benefit-cost ratio (BCR)

BCR is the ratio of the present value of benefits to the present value of costs. A BCR larger than 1 indicates that benefits exceed costs.

$$BCR = \sum_{t=0}^{T} \frac{(B_t)}{(1+i)^t} / \frac{(C_t)}{(1+i)^t} \tag{6.1}$$

where:

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$BCR$ = Benefit-cost ratio
$B_t$ = Benefits
$C_t$ = Costs
$i$ = Discount rate
$t$ = Year
$t...T$ = Year 0 (beginning of the planning period) until the end year T

### Net present value (NPV)

NPV represents the difference between the present value of a project's benefits and its costs over its entire lifespan. A positive NPV indicates that a project is expected to generate more benefits than costs. The measurement unit of NPV is a monetary value.

$$NPV = \sum_{t=0}^{T} \frac{(B_t - C_t)}{(1+i)^t} \tag{6.2}$$

where:

$NPV$ = Net present value (present value of net benefits)
$B_t$ = Benefits
$C_t$ = Costs
$i$ = Discount rate
$t$ = Year
$t...T$ = Year 0 (beginning of the planning period) until the end year T

### Internal rate of return (IRR)

The IRR can be interpreted as the annual earnings rate of a project, representing the discount rate for which the NPV is zero. To find the IRR, the NPV equation is solved for the interest rate (r), see below. IRR is usually measured in percentage. If the IRR is larger than the required discount rate, a project can be considered feasible. While the NPV provides an absolute value that can be less meaningful when comparing projects of varying size, the IRR provides a percentage-based comparison.

$$NPV = \sum_{t=0}^{T} \frac{(B_t - C_t)}{(1+r)^t} = 0 \tag{6.3}$$

where:

$r$ = IRR - internal rate of return
$NPV$ = Net present value
$B_t$ = Benefits
$C_t$ = Costs
$t$ = Year
$t...T$ = Year 0 (beginning of the planning period) until the end year T

To solve for the IRR, the Microsoft Excel formula `=IRR(values,[guess])` was used with the annual (non-discounted) net benefits as the input array for values and no guess. Excel calculates IRR using an iterative method, starting with an initial guess and repeatedly adjusting the value until the result is accurate to within 0.00001 percent. In one of the sensitivity calculations (Section 6.6.4, Scenario 3), Excel returned a `NUM`-error for the IRR, even with providing a guess. In that case, the IRR was found manually with iterating discount rates.

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## 6.3 Costs of implementing an SMG in Austria

### 6.3.1 Public transport

#### 6.3.1.1 Initial investments

Initial investments have to be made for new PT routes such as new railway lines and new bus lines. Unfortunately, there is a large data gap regarding the existing transport network and future necessities to provide better quality as defined in the SMG scenarios, due to two issues. The first issue is related to the model structure of MARS, which does not include routing, which is why quality improvements of PT are implemented implicitly. This means that there is no information about where exactly a new train or bus station will be, but only the information, that people living within certain zones will have a reduced walking distance to the PT stop. Secondly, there are different options of providing the quality level of services for an SMG, which differ largely between railways, bus services and DRT services. The calculation of investments for new PT lines is therefore to be understood as an initial approximation with many uncertainties and more research needs with regard to these issues. For the CBA, I assume a different mix of services (rail, bus, DRT) as well as different service quality levels for the scenarios. Costs for bus and rail infrastructure are described in the following. For DRT services, only operating costs are considered.

The planning, environmental assessment and construction of new railway lines takes much longer than implementing new bus routes. In Austria, railway infrastructure development is programmed for six-year periods. The current master plan for Austrian railway infrastructure development (BMK & ÖBB Infra, 2023) outlines the projects and investment for the years 2023 - 2028 with a total investment of bnEUR 19 (about bnEUR 3 per year). Most projects included in the master plan are not new lines but modernization or upgrading of existing lines. Moreover, the costs associated with building railway lines are influenced by various factors, such as the topography (e.g., whether tunnels are necessary) and the type of railway and construction (e.g., heavy rail, metro, tram, or whether rigid construction or sleepers are used). Construction costs range between EUR 20 million per km for urban tramways (pers. communication with Wiener Linien, 2021) and EUR 120 million per km for large-scale tunnel projects (BBT-SE, 2021).

To account for the long lead times in railway construction, I chose to consider only new bus lines for the first ten years of the cost calculation (2021-2030) with a cost of $\text{EUR}_{2021}$ 10,000 for a new bus stop (K. Plank et al., 2022). To estimate additional bus stops in the year 2040, I use multiplication factors of current stations: 2.5 x for Scenarios 1 - 3 (which show different levels of DRT services), and 4 x for Scenario 4 and 5. K. Plank et al. (2022) contacted regional and urban PT authorities and estimate that there are currently about 55,000 bus stops in Austria. Regarding new railway lines, I assume an investment cost of $\text{mEUR}_{2021}$ 300 per year (for the years 2031-2040) for new railway lines in the Scenarios 1-3 (with the assumption that 10% of usual yearly ÖBB construction costs serve the SMG) and $\text{bnEUR}_{2021}$ 1.5 per year for the scenarios 4-5 (representing 50 % of usual construction costs).

#### 6.3.1.2 Operating and maintenance costs

Besides initial investment costs, the ongoing expenses for PT will be higher when implementing an SMG. Such costs include maintenance of infrastructure, vehicle operating costs, energy costs, train and bus drivers and other staff. For the CBA, operating and maintenance costs for buses, including the cost of additional vehicles are based on K. Plank et al. (2022) (based on the value that the regional public transport authority VOR (*Verkehrsverbund Ostregion*) is using in their calculations) with $\text{EUR}_{2021}$ 3.50 per vkm. Operating costs for trains are assumed with $\text{EUR}_{2021}$ 11

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per vkm based on Schönfelder and Streicher (2021, p. 21). Converting the MARS results for PT in person-km to vehicle-km for trains and buses is performed based on the analysis of Schönfelder and Streicher (2021). The scheduled km (vkm) of PT in 2018 (Schönfelder & Streicher, 2021, p. 25) are used as a basis and increased proportionally per year with the change of person-km travelled according to the MARS simulation results.

Costs of DRT services are based on the analysis of Schönfelder and Streicher (2021, p. 17) which follows the approaches of Sommer et al. (2016) and Mehlert and Zietz (2014). The calculation assumes a commercial, on-demand service without fixed schedules or routes with local taxi companies conducting the trips. For each of the five SMG scenarios, the number of inhabitants that should be served by DRT and the operating hours are defined. Costs per kilometer are derived from taxi tariffs in Austria and a flat rate for general costs of $mEUR_{2021}$ 2 per year is added to each scenario. Tab. 6.2 shows the assumptions and total cost per year for the service to be in full effect in 2040.

**Tab. 6.2:** DRT operating costs for each SMG scenario based on Schönfelder and Streicher (2021)

| | Sc 1 | Sc 2 | Sc 3 | Sc 4 | Sc 5 |
|---|---|---|---|---|---|
| Served inhabitants [million inh.] | 1.15 | 0.47 | 0.58 | 0.23 | 0.23 |
| Operating hours p.a. | 5,110 | 5,110 | 5,840 | 6,205 | 8,760 |
| Passengers [million passengers/a] | 4.70 | 1.90 | 2.70 | 1.10 | 1.60 |
| Operating cost [$mEUR_{2021}$/a] | 54 | 22 | 31 | 21 | 30 |
| General cost [$mEUR_{2021}$/a] | 2 | 2 | 2 | 2 | 2 |
| Total cost [$mEUR_{2021}$/a] | 56 | 24 | 33 | 23 | 32 |

### 6.3.2 Active mobility

Regarding active mobility, there too exists a lack of data regarding existing infrastructure and necessities corresponding to the quality levels modeled in MARS. However, it is possible to soundly estimate investment needs based on literature, as described in the following.

#### 6.3.2.1 Cycling investment

For cycling, the estimation is based on a study by PLANOPTIMO and Verracon (2022), commissioned by the BMK, aiming to estimate the total necessary investment to increase modal share of cycling significantly by 2030. Results show that a total investment between EUR 5.57-6.95 billion is needed, including investment for infrastructure (cycling paths and parking facilities), subsidies for bike sharing facilities, facilitating bike transport on trains, communication (e.g., promotion campaigns), subsidies for individuals and companies, research investment, educational expenses and additional personnel. Over a 20-year period, this investment amounts to EUR 34-43 per person per year, which aligns with international spending in countries with high cycling rates, such as the Netherlands, where approximately EUR 30 per person per year has been consistently invested over the past 40 years (APPGCW, 2020).

For the calculation of additional cycling paths, PLANOPTIMO and Verracon (2022) used a combination of existing cycling plans of the nine Austrian provinces and a GIS analysis to estimate the necessary kilometers of cycling paths to bridge the difference between existing infrastructure and the envisioned comprehensive network. Regarding the cost, the provinces provided average cost per km of cycling path and the study authors added estimated costs of mEUR 2 for special facilities such as bridges or underpasses every 25 km. This leads to an average cost of EUR 440,000 per km for a total of 7,737 km of new regional cycling paths, plus actual planned investments in Vienna and Vorarlberg of mEUR 44.6 and mEUR 417.8, respectively.

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The study (PLANOPTIMO & Verracon, 2022) developed three scenarios showing differences in local cycling networks in urban areas, while inter-communal networks are not differentiated. These scenarios were used to correspond to the SMG scenarios in this study. The total value of $bnEUR_{2021}$ 5.57 is used in Scenario 3, while Scenarios 2, 4 and 6 use the higher end of the range with $bnEUR_{2021}$ 6.95.

#### 6.3.2.2 Walking investment

Investment for walking infrastructure encompasses walking master plans, sidewalk extensions, pedestrianized streets, pedestrian crossings and additional seating in public space. I estimated EUR 2 per person and year for the scenario with lower measures for active mobility (Scenario 3), and EUR 3 per person and year in the upper scenarios (Scenario 2, 4 and 5), for a population of 8.9 million. Estimates are based on the investment in walking infrastructure co-funded by the "klimaaktiv mobil" scheme of BMK. In the year 2022, the total investment of "klimaaktiv mobil" was 15.9 million euros (BMK, 2023b), translating to EUR 1.76 per person. "klimaaktiv mobil" is funding projects that go beyond maintenance of infrastructure and have to adhere to quality standards such as minimum widths of infrastructure.

#### 6.3.2.3 Maintenance cost

Maintenance cost of infrastructure for active mobility is considered negligible. According to Gössling et al. (2019), infrastructure maintenance for walking and cycling is each less than $EUR_{2017}$ 0.001/pkm on average for EU countries.

### 6.3.3 Other costs

The implementation should be accompanied by participatory processes, communication campaigns to inform the population, promote the SMG for higher acceptance and other accompanying measures such as extra enforcement of speed limits and MaaS applications. Such costs are estimated to be within the range of single-digit millions and are assumed as a flat rate of $mEUR_{2021}$ 5 per year in each scenario.

## 6.4 Benefits of implementing an SMG in Austria

### 6.4.1 Option value and non-use value

Although option values and non-use values are not commonly used in CBAs at the moment, it is argued that transport projects provide not only benefits for users of the new infrastructure or service but there is also an inherent value for people to have the option of using it (Hickman & Dean, 2017; Laird et al., 2009). I follow this approach to account for better accessibility through new infrastructure and services in the CBA. Due to the rather novel concept, however, literature on the topic is still limited. Laird et al. (2009) reviewed five studies on option and non-use values for different bus and rail projects. Table 6.3 shows an overview of the study results with values converted to $EUR_{2021}$ for Austria based on Statistik Austria (2022b) and OECD (2024).

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**Tab. 6.3:** Option and non-use values for rail and bus services, based on Laird et al. (2009)

| | **Study 1** | **Study 2** | **Study 3** | **Study 4** | **Study 5** |
|---|---|---|---|---|---|
| **Mode** | Bus | Rail | Bus | Rail | Rail |
| **Population unit** | Mixture of household (HH) and individual values | Probably HH values | Probably HH values | Individual values | HH |
| **Alternative public transport service available** | No | Existing bus service and alternative rail line/train station | No | No | Half hourly bus service |
| **Value p.a. $GBP_{2002}$** | 36 | 36 | 58 | 139 | 190 |
| **Value HH/a converted to $EUR_{2021}$ (Austria)** | 77 | 193 | 110 | 107 | 354 |

Converted to $EUR_{2021}$ for Austria, the values show a wide range between EUR 77-354 per household and year with the smallest value for a bus project and the highest for a railway with a half hourly bus service as an existing alternative. There clearly needs to be more research conducted to analyze option and non-use values more precisely and with comparable methods.

In order to make valid statements about the use value, option and non-use value of an SMG, it would be necessary to conduct surveys on the topic. Unfortunately, this is out of scope of this thesis. However, in order to include the aspects of option and non-use values in the CBA, I include assumed values in line with the results from literature. For Scenarios 1, 2 and 3, I assume values on the lower end of the range from Laird et al. (2009), for Scenario 4, a mean value of $EUR_{2021}$ 216 per year and household and the highest value for Scenario 5. The number of households that are affected are also differentiated in the scenarios, with assumptions based on the current coverage with PT, following the PTSQL framework. The analysis by Shibayama et al. (2022) shows that on working days during the school year, 15.4 % of the inhabitants in Austria live in areas that are not served by PT according to the quality levels. With an assumed population of 8.9 million and 2.18 people per household, this represents about 628,700 households. For Scenarios 1, 2 and 3, it is assumed that 90 % of those households (approx. 566,000) are served by the SMG in such a way, that the option value is applicable to them. 62.4 % of the population are outside of the PTSQ levels A-C, which can be considered as already having good quality PT services. For Scenario 5 - *Utopia*, it is assumed that 100 % of the inhabitants outside PTSQ levels A-C profit from the SMG in such a way, that the option value is applicable to them. This translates to a total of 2,548,000 households (with assumed 2.18 people per household). For Scenario 4 - *Goodbye private car*, this number is reduced to only 80 % of the inhabitants outside of PTSQ levels A-C, representing about 2,038,000 households. These values are assumed for the year 2040, when the SMG is in full effect and yearly values before that are increased linearly.

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**Tab. 6.4:** Option and non-use values for the SMG scenarios

| Option and non-use values - year 2040 | | | |
|---|---|---|---|
| **Scenario** | **Value [EUR/HH/a]** | **No. of households** | **Total value [mEUR/a]** |
| 1 - *All regions aboard* | 77 | 566,000 | 43.6 |
| 2 - *Focus active mobility* | 77 | 566,000 | 43.6 |
| 3 - *Focus car pooling* | 77 | 566,000 | 43.6 |
| 4 - *Goodbye private car* | 216 | 2,038,000 | 440.2 |
| 5 - *Utopia* | 354 | 2,548,000 | 902.0 |

### 6.4.2 Vehicle operating costs

Vehicle operating cost savings are included in the CBA approach by the European Commission (2014). Due to reduced vehicle-km driven by car, the private costs for vehicle operation are reduced. Gössling et al. (2019) give average vehicle operating costs for the modes car, cycling and walking, however, it is not clear which cost factors for cars are included in the values. While the article states that the costs for car travel include fuel, oil and tyre wear, maintenance and depreciation, parking fees, road tolls as well as financing, insurance, registration fees and taxes, the costs are described differently in the supplementary material. There, estimates of the German ADAC including *"depreciation, oil and tire wear, inspections and maintenance, oil and fuel costs"* and values from Denmark (without citation), including the same aspects, are named. Average values for the EU are assumed to be lower with $EUR_{2017}$ 0.25/pkm because vehicles are on average smaller than in Germany. Consideration of parking fees and road tolls for public roads as well as taxes are not in line with the assumptions of the CBA in this thesis. Furthermore, in generalized cost calculations, usually only the *perceived* operating costs are considered.

Therefore, I chose an approach based on the vehicle operating cost assumptions in MARS, as described in Section 5.2.4. The average fuel prices vary in the scenarios depending on the fleet composition (considering fossil fuels and electricity prices). The net prices start for all scenarios at EUR 0.141/vkm in the year 2020 and range between EUR 0.065/vkm (in the external scenario "Transition_2040_3" with full electrification) and EUR 0.186/vkm (in the external scenario "WEM19") in the year 2040. I assume that reduced vehicle-km will be entirely due to less travel with ICE cars and use the 2021 value of EUR 0.143/vkm as the estimate for net fuel costs. Other perceived costs considered in MARS are assumed with EUR 0.084/km. The values are added up for the assumed vehicle operating costs of cars in the CBA. As recommended by European Commission (2014), the Rule of Half is applied, assuming mode change for reduced vehicle-km. This means that only 50 % of the benefits in comparison to the BAU are counted in the CBA. Operating costs for cycling and walking are not considered. Tab. 6.5 shows the assumed value.

**Tab. 6.5:** Vehicle operating costs based on assumptions in MARS, converted to the price basis of 2021 based on Statistik Austria (2022b)

| Vehicle operating costs | | |
|---|---|---|
| **Car** | 22.70 | [$EUR\text{-}cent_{2021}$/vkm] |

### 6.4.3 Accident costs

Values for accident costs are based on a guide by the European Commission (2019). They define accident costs as *"the social costs of traffic accidents that are not covered by risk oriented insurance*

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*premiums"* (p. 38) and include five components: human costs, medical costs, administrative costs, production losses and material damages. The largest part of accident costs is made up by the Value of Statistical Life (VSL) assumed with EUR 3.6 million for the EU28, where consumption loss needs to be deducted. The other components are based on the estimates of the SafetyCube project (Wijnen et al., 2017). The full methodology can be viewed in European Commission (2019, p. 41ff.).

The handbook includes the average costs in EUR-cent per vehicle-kilometer differentiated for passenger cars, motorcycles, buses and rail for EU countries (European Commission, 2019, p. 45, Table 8). For calculating the benefit, the change in vehicle-kilometers travelled by private motorized vehicles is assumed to be split into 97.6 % passenger car traffic and 2.4 % motorcycle traffic (based on the ratio of person-km travelled on working days in Follmer, Gruschwitz, Kiatipis, et al. (2016) of *"MIV"* and *"sonstige"*). The respective values in each year are multiplied with the average costs per vkm according to the European Commission (2019). A similar approach was chosen for PT. The results of the MARS model do not differentiate between bus and rail travel. The changes in person-kilometer travelled with PT are assumed to be split into 47.85 % bus traffic and 52.15 % rail traffic (based on the ratio of person-km travelled on working days in Follmer, Gruschwitz, Kiatipis, et al. (2016) of *"Eisenbahn"* and *"sonstiger öffentlicher Verkehr"*). The resulting values are multiplied with the average costs per pkm for buses and trains according to European Commission (2019). Table 6.6 shows the final values for accidents assumed in the CBA.

**Tab. 6.6:** Accident costs based on European Commission (2019), converted to the price basis of 2021 based on Statistik Austria (2022b)

| Accident costs | | |
|---|---|---|
| **Car** | 7.93 | EUR-cent$_{2021}$/vkm |
| **Motorcycle** | 14.65 | EUR-cent$_{2021}$/vkm |
| **Bus** | 1.10 | EUR-cent$_{2021}$/pkm |
| **Train** | 0.33 | EUR-cent$_{2021}$/pkm |

### 6.4.4 Air pollution costs

The assumptions for air pollution are also based on the guide of the European Commission (2019). The impacts considered include health effects, crop losses, material and building damage and biodiversity loss. Cost factors are based on damage costs quantified in the NEEDS-project with several adjustments. For a detailed description of the analysis, see European Commission (2019, p. 51ff.). Average costs per person-kilometer and vehicle-kilometer are shown in a table for different modes, including passenger cars, motorcycle, bus, coach, train electric, train diesel (European Commission, 2019, p. 57, Table 16). For calculating the benefit, the average for passenger cars (with ICE) was chosen, with the (simplifying) assumption that all of the vehicle-km that are reduced in the scenarios relate to ICE cars. I further assumed average values for PT by bus (using the mean of bus and coach values) and by train (using the mean of high speed passenger train, electric passenger train and diesel passenger trains). Given the large share of railway electrification in Austria, the value for air pollution costs by trains is probably overestimated, leading to a net reduction of benefits in the scenarios meaning that this is a rather conservative estimate. Assumptions for vkm and pkm travelled by motorcycles and bus/rail are the same as for accident costs (see above). In Tab. 6.7, the final values with price basis 2021 are shown.

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**Tab. 6.7:** Air pollution costs based on European Commission (2019), converted to the price basis of 2021 based on Statistik Austria (2022b)

| Air pollution costs | | |
|---|---|---|
| **Car** | 0.78 | EUR-cent$_{2021}$/vkm |
| **Motorcycle** | 1.23 | EUR-cent$_{2021}$/vkm |
| **Bus** | 0.82 | EUR-cent$_{2021}$/pkm |
| **Train** | 0.30 | EUR-cent$_{2021}$/pkm |

### 6.4.5 Noise costs

Monetary values for noise costs are based on the recommended values in the EC Handbook on external costs of transport (European Commission, 2019). The values include effects of annoyance, calculated using a willingness-to-pay approach and health costs of noise, based on an environmental burden of disease method. The methodology is explained in detail in European Commission (2019, p. 93ff.). Average costs for different land-based modes are shown in Table 35 in (European Commission, 2019, p. 97). The calculation for the CBA is similar to the one for air pollution costs. It was assumed that all reduced vehicle-km in the scenarios relate to ICE cars and average values for PT by bus (mean of bus and coach values) and by train (mean of high speed passenger train, electric passenger train and diesel passenger trains). The assumptions of traffic volumes of motorcycles and bus/rail are the same as for accident costs and air pollution costs (see above). In Tab. 6.8, the final values with price basis 2021 are shown.

**Tab. 6.8:** Noise costs based on European Commission (2019), converted to the price basis of 2021 based on Statistik Austria (2022b)

| Noise costs | | |
|---|---|---|
| **Car** | 0.99 | EUR-cent$_{2021}$/vkm |
| **Motorcycle** | 10.36 | EUR-cent$_{2021}$/vkm |
| **Bus** | 0.33 | EUR-cent$_{2021}$/pkm |
| **Train** | 0.92 | EUR-cent$_{2021}$/pkm |

Only noise effects due to changes in road and rail traffic levels are considered in the analysis. Some scenarios include the introduction of lower speed limits on roads, which would also lead to reduced traffic noise. Benefits due to noise reduction are therefore probably underestimated. However, urbanization effects might lead to more people being exposed to traffic noise, which is not taken into account. Further simplifications are made with regard to time of day and absolute traffic volume.

### 6.4.6 GHG emissions - climate change damage

Costs of GHG emissions have been historically underestimated regarding the damage that climate change causes and estimates of the "social cost of carbon" have increased considerably over time (Kikstra et al., 2021; Tol, 2023). In method guides for transport CBAs and literature regarding the cost of GHG emissions, there is a wide range of unit costs for monetizing GHG emissions. I present some of the most relevant and explain the assumptions used in the analysis.

In the CBA guide of the EC (European Commission, 2014), the evaluation of GHG emissions is based on the Carbon Footprint Methodology of the European Investment Bank and unit costs from the 2013 guide "The Economic Appraisal of Investment Projects at the EIB" (EIB, 2013). Unit costs of GHG emissions are presented as values in three scenarios (high, central and low)

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with a price basis of 2010 and annual adders for the years 2011 to 2030. It is recommended to use the values from the central scenario starting from EUR 25/t$CO_2$e in 2010 with an annual adder of 1 Euro. A new guide (EIB, 2023) has been published in 2023, with much higher costs, based on the EIB Climate Bank Roadmap (EIB, 2020). The unit costs are presented from 2020 to 2050 in values with a price basis 2016. They range from $EUR_{2016}$ 80/t$CO_2$e in 2020 to $EUR_{2016}$ 524/t$CO_2$e in 2040 and up to $EUR_{2016}$ 800/t$CO_2$e in 2050. The approach followed by the EIB Climate Bank Roadmap (EIB, 2020, outlined in Annex 5) is based on the shadow cost of carbon, referring to the cost required to drive the economy to meet the 1.5°C temperature target. They argue that this is the correct conceptual basis to account for changes in emissions resulting from projects that are assessed in CBAs.

The standardized CBA according to the Austrian guideline RVS 02.01.22 (FSV, 2010) considers climate costs with EUR 50/t$CO_2$e (price basis 2009), indexed with the CPI to 2016 (Statistik Austria, 2022b) this would be only $EUR_{2016}$ 56.8/t$CO_2$e. The method guide for the CBA for the assessment of the "Zielnetz 2040", the target railway network in Austria (V. Plank et al., 2022), follows the EU values for the "InvestEU" fund, which are based on the shadow prices of the EIB (2020).

The German Environment Agency (Matthey & Bünger, 2020) recommends a unit cost of $EUR_{2020}$ 195/t$CO_2$e for the year 2020 with a discount rate of 1 % and $EUR_{2020}$ 680/t$CO_2$e with a discount rate of 0 % and an increase of the costs to $EUR_{2020}$ 250/t$CO_2$e in 2050 in the case of 1 % discount rate and $EUR_{2020}$ 765/t$CO_2$e in 2050 with 0 % discount rate. The values are based on the damage cost approach by Anthoff (2007) and values are at the lower bound of GHG-emission damage cost estimates (Matthey & Bünger, 2020). The recommended value of $EUR_{2020}$/ 195t$CO_2$e for the year 2020 is close to the average value derived in the $5^{th}$ IPCC assessment report (IPCC, 2014, p. 691) as an average of all studies with 1 % discount rate, which would be $EUR_{2020}$ 182/t$CO_2$e adapted to German price base in 2020 (Matthey & Bünger, 2020).

For the analysis in this thesis, the costs for GHG emissions are based on the recommendations of Matthey and Bünger (2020), however, using the costs with 0 % discount rate, in line with the assumptions regarding discounting for other benefits. This means that damage caused today and in the future will be weighted the same. With a discount rate of 1 %, damages occurring in 30 years time will be valued only with 74 % and damages in 60 years with only 55 %. For a discussion about discount rates see Section 6.2.5. In the sensitivity analysis, I vary the GHG emission costs to show the effects on results.

The GHG emissions considered in the CBA only represent the GHG emissions that can be attributed to reduced vehicle-km travelled by car. This means that the reduced $CO_2$ emissions due to electrification of the car fleet are not considered. It is assumed that all reduced vehicle-km are related to ICE cars. Emission factors are based on values from the Austrian Environment Agency (Fritz et al., 2023; Umweltbundesamt, 2024). They include production-related emissions, based on the lifetime mileage of vehicles, as well as upstream emissions from fuel supply. The average emission factor for ICE cars is assumed with 260 g$CO_2$e/vkm (based on Fritz et al., 2023). PT emission factors are indicated with 55.2 g$CO_2$e/pkm for buses and 11.1 g$CO_2$e/pkm for passenger trains (Umweltbundesamt, 2024). It is to be expected that the fleet of PT vehicles will be fully electrified until 2040 (in line with EU regulations). This is not considered in the CBA calculation and therefore results underestimate the benefits accordingly. Emissions from the construction of new railway lines, however, are not considered either but could play a significant role in GHG emissions in implementation scenarios that include many new railway routes.

The final assumed monetary values for GHG-emission costs are shown in Table 6.9 for cars and in Table 6.10 for PT. Values for years between 2021 and 2040 are linearly interpolated.

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**Tab. 6.9:** Costs of GHG emissions based on Matthey and Bünger (2020), converted to the price basis of 2021 based on Statistik Austria (2022b), for cars

| | Emission factor | **Costs of GHG emissions** | |
|---|---|---|---|
| | $gCO_2e/vkm$ | $EUR_{2021}/tCO2e$ | $EUR\text{-}cent_{2021}/vkm$ |
| **Car 2021** | 260 | 699 | 18.17 |
| **Car 2040** | 260 | 753 | 19.58 |

**Tab. 6.10:** Costs of GHG emissions based on Matthey and Bünger (2020), converted to the price basis of 2021 based on Statistik Austria (2022b), for PT

| | Emission factor | **Costs of GHG emissions** | |
|---|---|---|---|
| | $gCO_2e/pkm$ | $EUR_{2021}/tCO2e$ | $EUR\text{-}cent_{2021}/pkm$ |
| **Bus 2021** | 55.2 | 699 | 3.86 |
| **Bus 2040** | 55.2 | 753 | 4.22 |
| **Train 2021** | 11.1 | 699 | 0.78 |
| **Train 2040** | 11.1 | 753 | 0.85 |

Not included are possible lower emissions due to reduced speed limits. If Austria is not meeting its national climate targets as agreed in the European Climate Law (Regulation (EU) 2021/1119), it might be necessary to purchase $CO_2$ certificates. Such payments are also not included in the CBA. Overall, the costs of greenhouse gas emissions are likely underestimated due to the use of several conservative assumptions. At this point, I would like to emphasize again that the full impact of greenhouse gas emissions may also extend beyond what can be captured in monetary terms, especially when considering the potential effects of climate tipping points.

### 6.4.7 Air pollution costs of well-to-tank emissions

The production of energy used in transport includes steps such as the extraction of energy sources, processing, transport and transmission, building of energy plants and other infrastructure. All of these lead to emissions of air pollutants and GHGs and other externalities such as land use and environmental risk. The approach of European Commission (2019) includes "well-to-tank" emissions, representing costs associated with the emission of GHGs and air pollutants related to extraction, processing, transport and transmission. To avoid double-counting, the GHG emissions of energy production are subtracted. The GHG emissions are already included in the emission factors of vehicles, as described in Section 6.4.6. To account for air pollution impacts, only the share that can be attributed to air pollution are considered. For road transport, they amount to 38 % of the values shown in European Commission (2019, p. 126, Table 50). Table 6.11 shows these values that have been used in the CBA.

**Tab. 6.11:** Air pollution costs of well-to-tank emissions based on European Commission (2019), converted to the price basis of 2021 based on Statistik Austria (2022b)

| **Costs of well-to-tank emissions** | | |
|---|---|---|
| **Car** | 0.26 | $EUR\text{-}cent_{2021}/vkm$ |
| **Motorcycle** | 0.22 | $EUR\text{-}cent_{2021}/vkm$ |
| **Bus** | 0.07 | $EUR\text{-}cent_{2021}/pkm$ |
| **Train** | 0.17 | $EUR\text{-}cent_{2021}/pkm$ |

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### 6.4.8 Health benefits of active mobility

The monetary values of health benefits of active mobility are based on Gössling et al. (2019). In the cited study, the authors collect different social costs of the transport modes car, cycling and walking for use in CBAs. They provide average values per passenger-kilometer for the EU average, divided in external and private costs. Values for health benefits of active mobility are based on the extensive work that has been carried out in Denmark for cycling (Center for Transport Analytics, 2017), with benefits of walking estimated conservatively with values twice as high as the ones for cycling.

For the CBA in this thesis, external and private effects presented by Gössling et al. (2019) are summarized to one unit cost for walking and cycling each. The combined effects of health benefits and prolonged life (which is a personal benefit but an external cost due to extended pension payments), converted to the price base of 2021, are shown in the values in Tab. 6.12.

**Tab. 6.12:** Costs due to health effects of active mobility, based on Gössling et al. (2019), converted to the price basis of 2021 based on Statistik Austria (2022b)

| **Costs of health effects active mobility** | | |
|---|---|---|
| **Health effects cycling** | -69.07 | EUR-cent$_{2021}$/pkm |
| **Health effects walking** | -138.14 | EUR-cent$_{2021}$/pkm |

The difference of person-km traveled in each scenario simulation year with the BAU are multiplied with the values to calculate the benefit or cost for each year. Depending on the scenario, the impact might be positive or negative in correspondence to increased or decreased levels of walking and cycling. The output walking and cycling volumes from the MARS simulations only consider trips where active modes are the main mode of transport. The person-kilometer walking or cycling to a PT stop are not considered and therefore, health benefits from active mobility are expected to be underestimated in the CBA. In the sensitivity analysis, the effect of walking as a feeder to PT is roughly estimated (see Section 6.6.6).

## 6.5 Base case results

This section presents the results of the base case calculation, in contrast to the results of the sensitivity analysis in Section 6.6.

### 6.5.1 CBA Scenario 1 - All regions aboard

The CBA indicators for Scenario 1 are shown in Tab. 6.13. Fig. 6.1 shows the yearly costs and benefits and Fig. 6.2 the total costs and benefits (without discounting) for each criterion in the scenario.

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**Tab. 6.13:** NPV, BCR and IRR of Scenario 1 - *All regions aboard*

| | Discount rate | |
|---|---|---|
| **NPV [mEUR$_{2021}$]** | 0 % | 46,066 |
| | 3 % | 21,566 |
| | 5 % | 13,624 |
| **BCR** | 0 % | 2.20 |
| | 3 % | 2.08 |
| | 5 % | 2.00 |
| **IRR** | | 46.5 % |

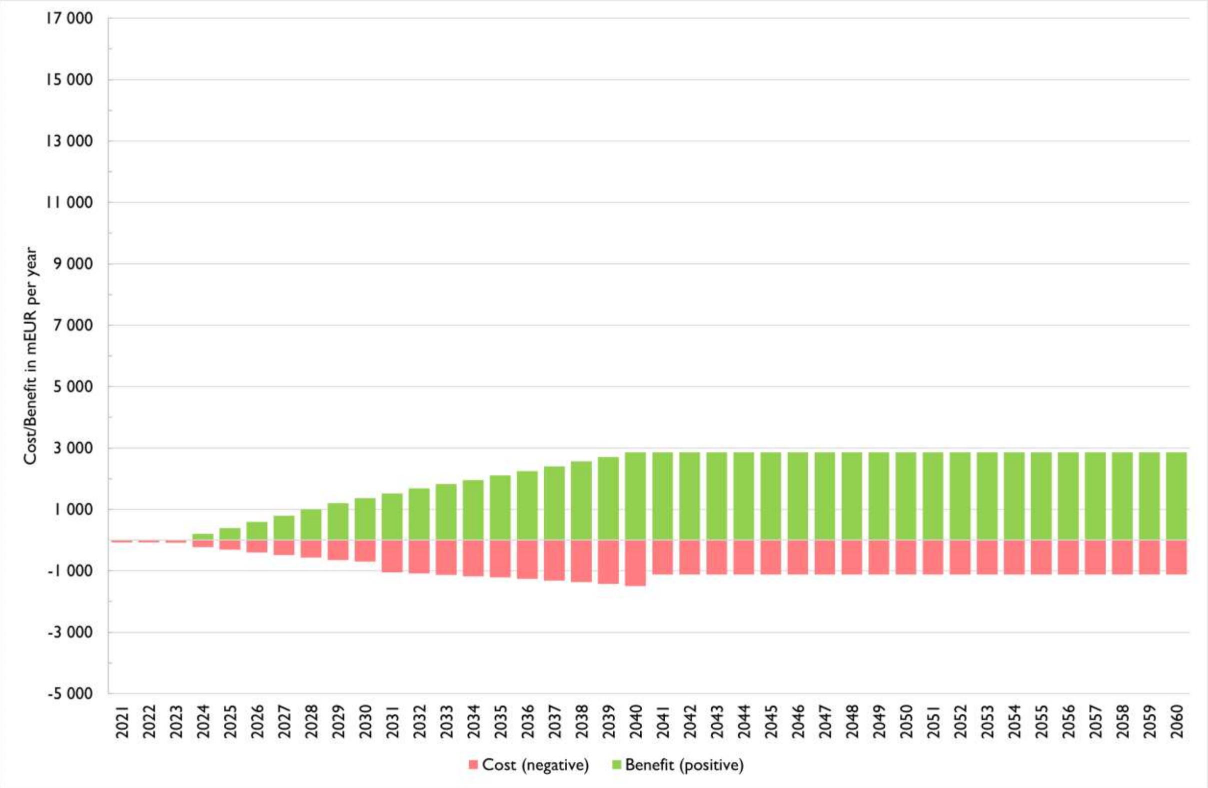


**Fig. 6.1:** Scenario 1 - costs and benefits per year (0 % discount rate)

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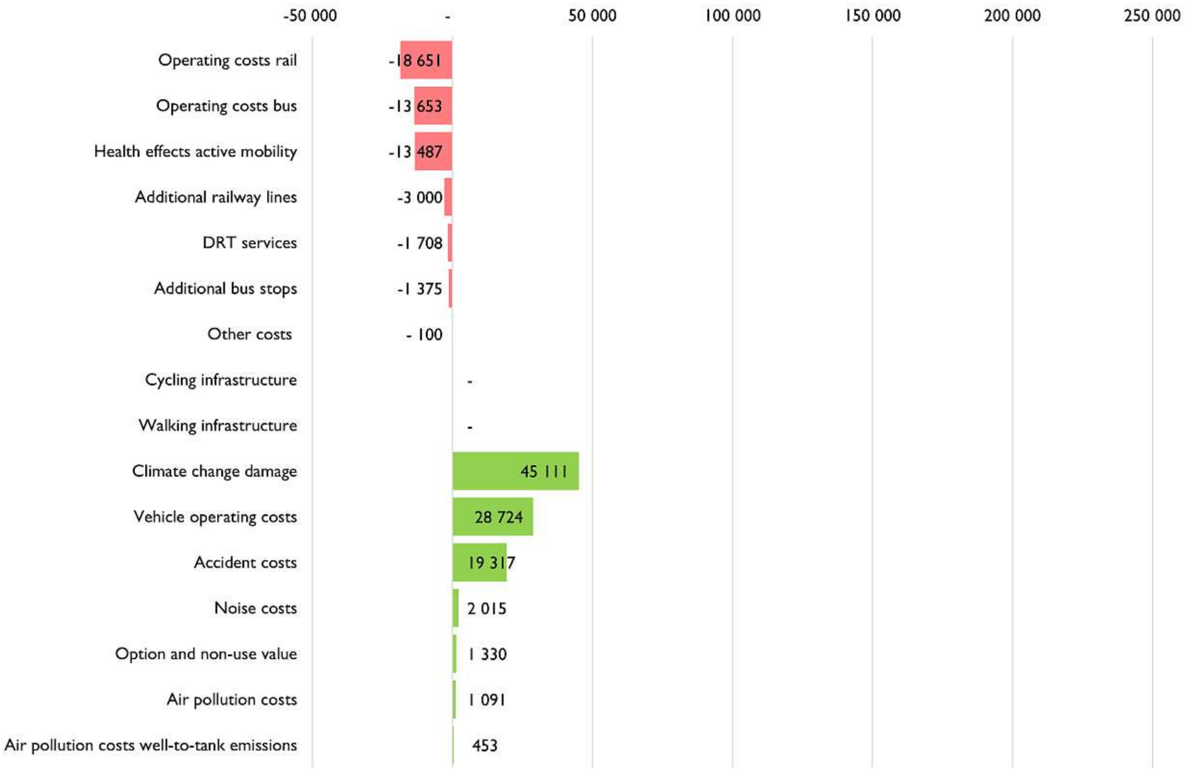


**Fig. 6.2:** Scenario 1 - total costs and benefits in million euros (2021 prices, 0 % discount rate)

The indicators of Scenario 1 show that it is well performing compared to the BAU and better than Scenario 3, except for the IRR. The NPV is $\text{mEUR}_{2021}$ 13,000-46,000. The BCR is at least 2.00 for all discount rates in the scenario and the IRR is about 47 %. It should be noted that the health 'benefits' of active mobility are the third largest cost factor with a total of more than $\text{bnEUR}_{2021}$ 13 for the 40-year appraisal period. This is due to reduced volumes of walking and cycling. The highest cost can be attributed to operating costs for PT, with rail operations amounting to almost $\text{bnEUR}_{2021}$ 18.7 and $\text{bnEUR}_{2021}$ 13.7 for buses. The largest contributions to benefits are made by avoided climate change damage ($\text{bnEUR}_{2021}$ 45.1), reduced vehicle operating costs for private cars ($\text{bnEUR}_{2021}$ 28.7) and reduced accident costs ($\text{bnEUR}_{2021}$ 19). The total costs (without discounting) amount to about $\text{bnEUR}_{2021}$ 52, which are balanced out by benefits even without considering the largest benefit of reduced climate change damage.

### 6.5.2 CBA Scenario 2 - Focus active mobility

NPV, BCR and IRR for Scenario 2 are shown in Tab. 6.14. The yearly costs and benefits can be viewed in Fig. 6.3, while the total costs and benefits (without discounting) per criteria are shown in Fig. 6.4.

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**Tab. 6.14:** NPV, BCR and IRR of Scenario 2 - *Focus active mobility*

| | Discount rate | |
|---|---|---|
| **NPV** [**mEUR**$_{2021}$] | 0 % | 244,813 |
| | 3 % | 120,429 |
| | 5 % | 79,277 |
| **BCR** | 0 % | 4.55 |
| | 3 % | 4.22 |
| | 5 % | 4.01 |
| **IRR** | | 654.5 % |

The BCR for Scenario 2 lies between 4.01 (with 5 % discount rate) and 4.55 (without discounting), which are the second highest values of all scenarios. The NPV is ca. mEUR$_{2021}$ 80,000-245,000 and slightly lower than in Scenario 4, however, Scenario 2 shows the highest IRR of all scenarios with more than 650 %. The highest cost in Scenario 2 can be attributed to rail operating costs with bnEUR$_{2021}$ 32.5, followed by bus operating costs with about bnEUR$_{2021}$ 23.7 and then costs for new cycling infrastructure with bnEUR$_{2021}$ 6.95. All other costs lie below bnEUR$_{2021}$ 3. By far the largest benefits can be attributed to avoided climate change damage (bnEUR$_{2021}$ 154.8), reduced vehicle operating costs (bnEUR$_{2021}$ 90.6) and accident costs (bnEUR$_{2021}$ 62.4). This is followed far behind by noise costs with about bnEUR$_{2021}$ 7.8. The total costs (without discounting) amount to about bnEUR$_{2021}$ 71, which is lower than the second largest single benefit of decreased vehicle operating costs.

Even though the scenario has a focus on active mobility, the total health benefits of cycling and walking are negative (with a total value of ca. bnEUR$_{2021}$ 2.2 for the appraisal period). As discussed in Section 5.5.5 cycling rates are very stable in MARS. In the majority of the analyzed years, person-km travelled in cycling are lower in Scenario 2 than in the BAU. Therefore there are negative health effects. Even though walking rates are higher in Scenario 2 than in the BAU throughout the appraisal period, the overall effect is still negative. As mentioned before, due to modelling limitations, the access and egress parts of a trip made by PT, which can be done by walking, cycling or with a car, is not included in the km travelled by each mode. Therefore, the volume of active mobility is probably higher. Further research should investigate the effects of an SMG (or the respective measures) on actual cycling rates and its benefits.

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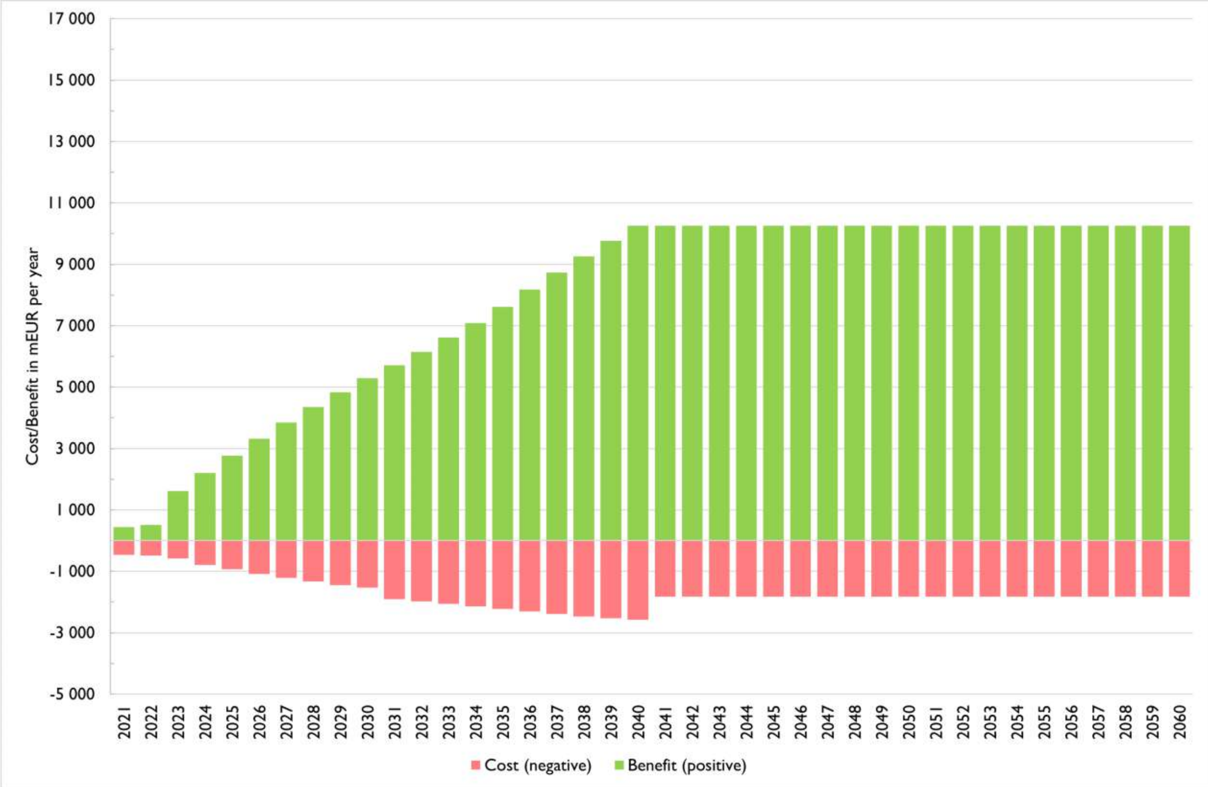


**Fig. 6.3:** Scenario 2 - costs and benefits per year (0 % discount rate)

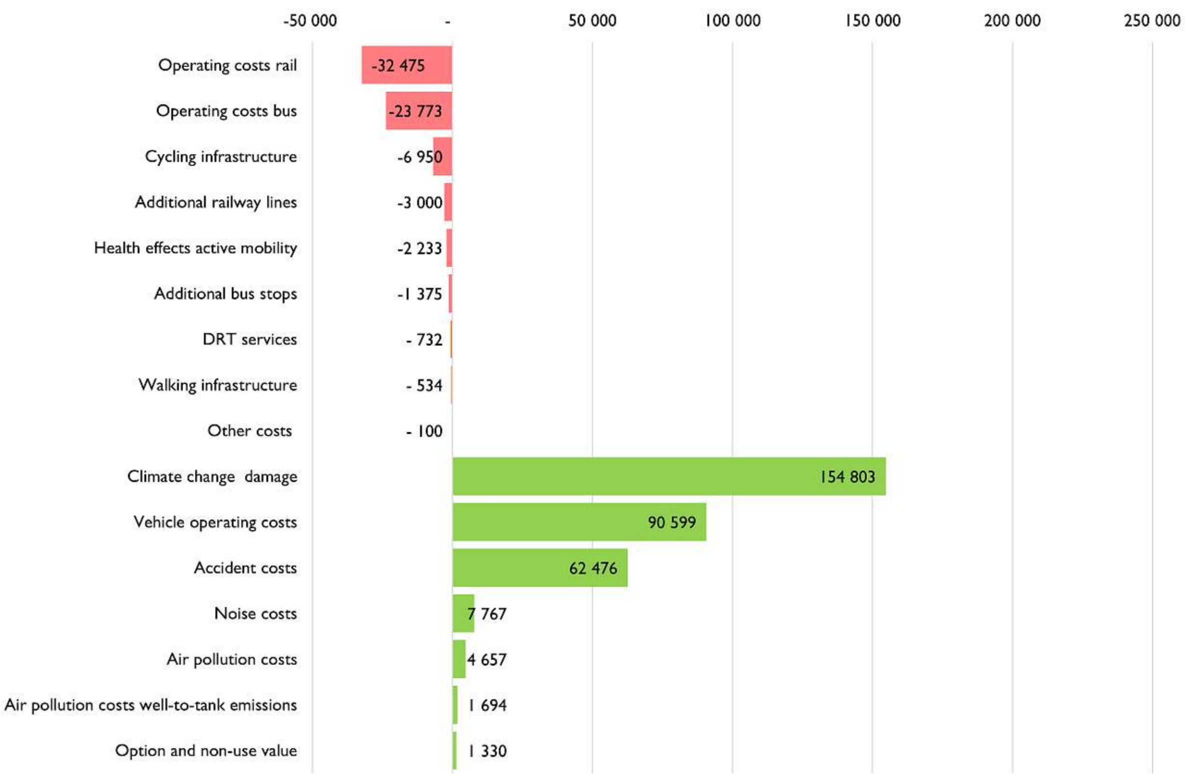


**Fig. 6.4:** Scenario 2 - total costs and benefits in million euros (2021 prices, 0 % discount rate)

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### 6.5.3 CBA Scenario 3 - Focus car pooling

Results for the CBA of Scenario 3 are shwon in Tab. 6.15, Fig. 6.5 and Fig. 6.6.

**Tab. 6.15:** NPV, BCR and IRR of Scenario 3 - *Focus car pooling*

| | Discount rate | |
|---|---|---|
| **NPV [mEUR$_{2021}$]** | 0 % | 22,650 |
| | 3 % | 15,432 |
| | 5 % | 12,299 |
| **BCR** | 0 % | 1.76 |
| | 3 % | 1.89 |
| | 5 % | 1.96 |
| **IRR** | | 140.5 % |

Scenario 3 performs worst of all scenarios in terms of both BCR and NPV. The BCR in Scenario 3 is the lowest of all scenarios, but remains greater than 1 across all discount rates. Notably, it is the only scenario where the BCR increases with higher discount rates. The lower BCR at 0 % and 3 % results from discounted costs increasing relatively more in later stages, while the benefits are higher in earlier stages. A higher discount rate therefore improves the ratio by reducing the weight of future costs. The NPV, ranging between mEUR$_{2021}$ 12,300 - 22,650, is slightly lower than in Scenario 1. The IRR is larger than in Scenario 1 with 140.5 %, due to comparably small investment size with early high returns.

The highest cost factor are the negative health effects of active mobility with about bnEUR$_{2021}$ 17.3, followed by the operating costs of PT (bnEUR$_{2021}$ 10.5 for rail and for bnEUR$_{2021}$ 7.7 bus). Costs for cycling infrastructure amount to bnEUR$_{2021}$ 5.57 and other costs are each bnEUR$_{2021}$ 3 or below. As with the other scenarios, largest benefits are mostly due to avoided climate change damage (bnEUR$_{2021}$ 34.5), reduced vehicle operating costs (bnEUR$_{2021}$ 20.4) and accident costs (bnEUR$_{2021}$ 13.7). The total costs (without discounting) amount to about bnEUR$_{2021}$ 47, which are balanced out by the two largest benefits of reduced climate change damage and vehicle operating costs. In contrast to other scenarios, the costs are not balanced out by benefits without considering reduced climate change damage (benefits amount to bnEUR$_{2021}$ 72 with considering climate change damage and bnEUR$_{2021}$ 38 without).

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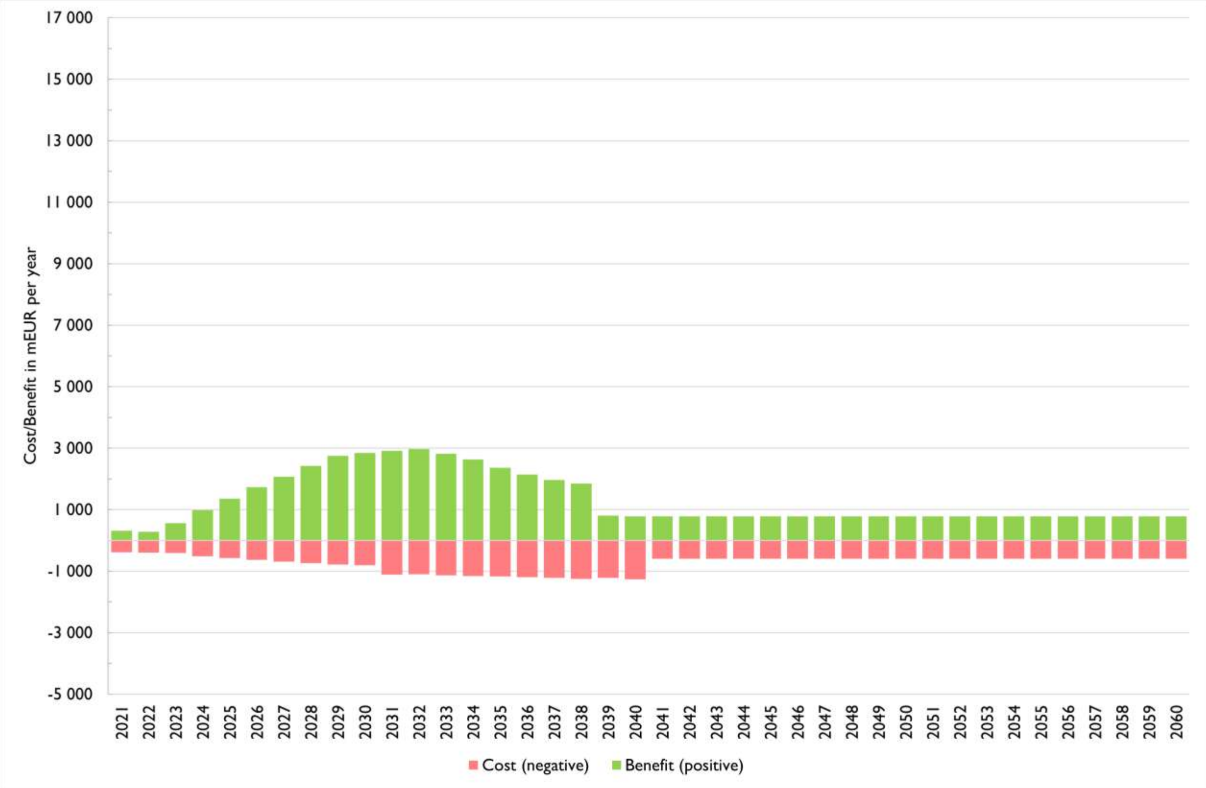


**Fig. 6.5:** Scenario 3 - costs and benefits per year (0 % discount rate)


**Fig. 6.6:** Scenario 3 - total costs and benefits in million euros (2021 prices, 0 % discount rate)

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### 6.5.4 CBA Scenario 4 - Goodbye private car

Tab. 6.16 shows an overview of the CBA indicators for Scenario 4. The yearly costs and benefits are shown in Fig. 6.7 and the total costs and benefits in Fig. 6.8.

**Tab. 6.16:** NPV, BCR and IRR of Scenario 4 - *Goodbye private car*

| | Discount rate | |
|---|---|---|
| **NPV [mEUR$_{2021}$]** | 0 % | 250,819 |
| | 3 % | 128,205 |
| | 5 % | 87,026 |
| **BCR** | 0 % | 4.50 |
| | 3 % | 4.13 |
| | 5 % | 3.93 |
| **IRR** | | 277.1 % |

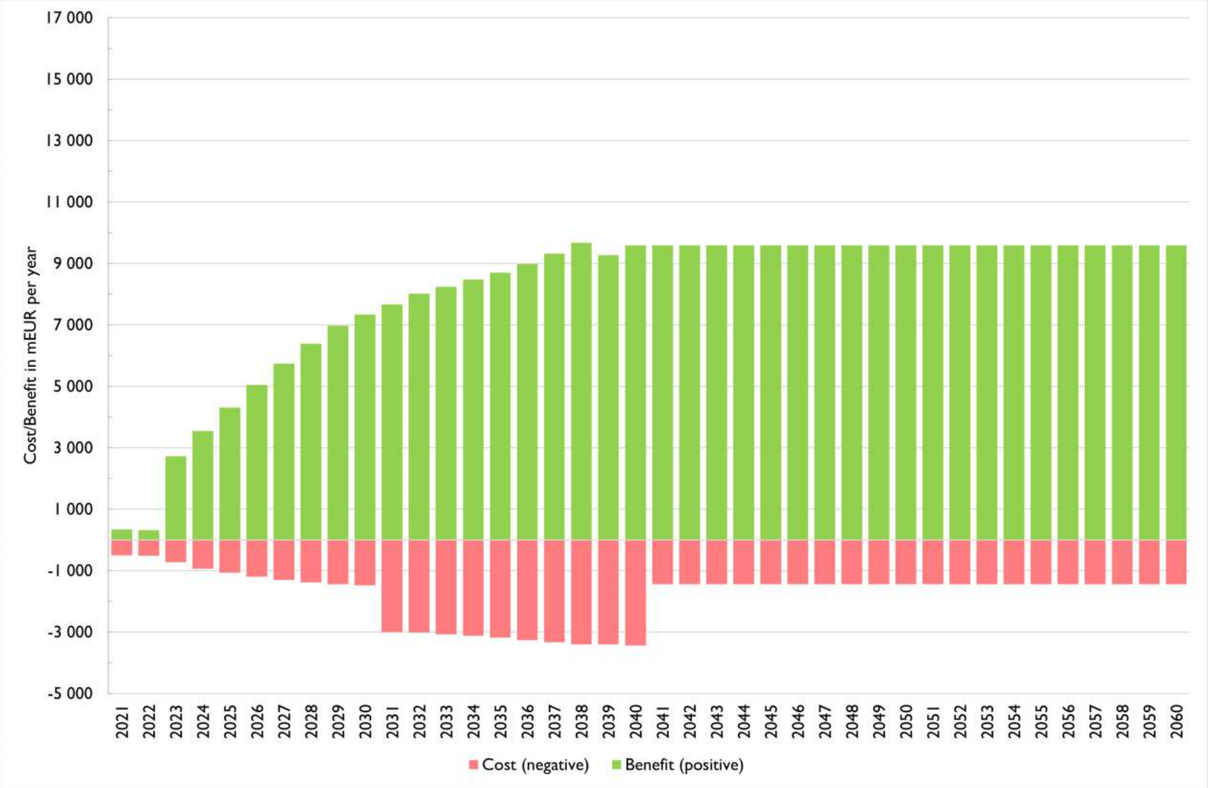


**Fig. 6.7:** Scenario 4 - costs and benefits per year (0 % discount rate)

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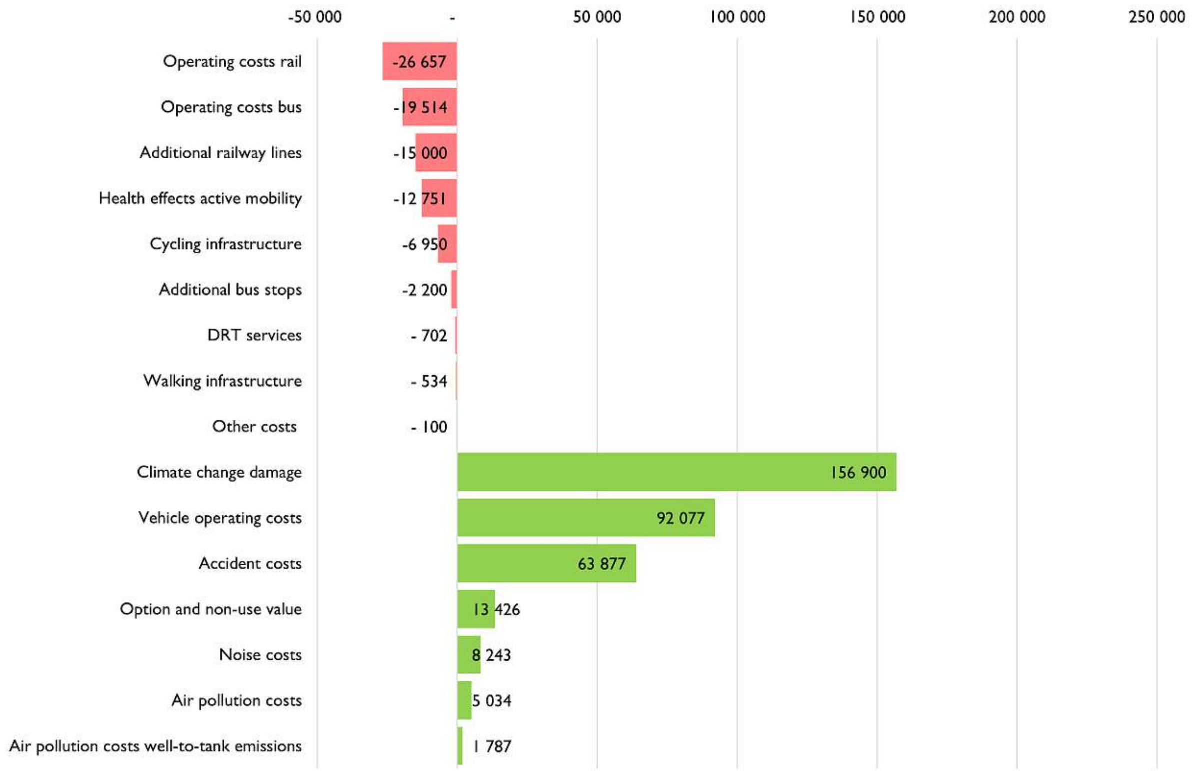


**Fig. 6.8:** Scenario 4 - total costs and benefits in million euros (2021 prices, 0 % discount rate)

The BCR for Scenario 4 ranges from 3.93 to 4.50 (see Tab. 6.16), which is slightly lower than in Scenario 2. NPV is the second highest of the scenarios with $\text{mEUR}_{2021}$ 87,000-251,000. The IRR of Scenario 4 is the third largest with about 277 %.

Following the same pattern as most other scenarios, the two parameters with the highest total costs are operating costs for rail and buses (with $\text{bnEUR}_{2021}$ 26.6 and $\text{bnEUR}_{2021}$ 19.5, respectively). In contrast to other scenarios, however, this is followed closely by costs for additional railway lines with $\text{bnEUR}_{2021}$ 15 and health effects of active mobility (with $\text{bnEUR}_{2021}$ 12.75) and by costs of cycling infrastructure with $\text{bnEUR}_{2021}$ 6.95. All other costs are lower than $\text{bnEUR}_{2021}$ 3.

The largest benefits are mostly due to avoided climate change damage ($\text{bnEUR}_{2021}$ 156.9), reduced vehicle operating costs ($\text{bnEUR}_{2021}$ 92.1) and accident costs ($\text{bnEUR}_{2021}$ 63.9). The option and non-use value amount to $\text{bnEUR}_{2021}$ 13.4. The total costs (without discounting) amount to about $\text{bnEUR}_{2021}$ 84, which is lower than the second largest single benefit of decreased vehicle operating costs.

### 6.5.5 CBA Scenario 5 - Utopia

CBA results for Scenario 5 are shown in Tab. 6.17, Fig. 6.9 and Fig. 6.10.

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**Tab. 6.17:** NPV, BCR and IRR of Scenario 5 - *Utopia*

| | Discount rate | |
|---|---|---|
| **NPV [mEUR$_{2021}$]** | 0 % | 405,169 |
| | 3 % | 201,909 |
| | 5 % | 134,371 |
| **BCR** | 0 % | 4.76 |
| | 3 % | 4.45 |
| | 5 % | 4.26 |
| **IRR** | | 317.1 % |

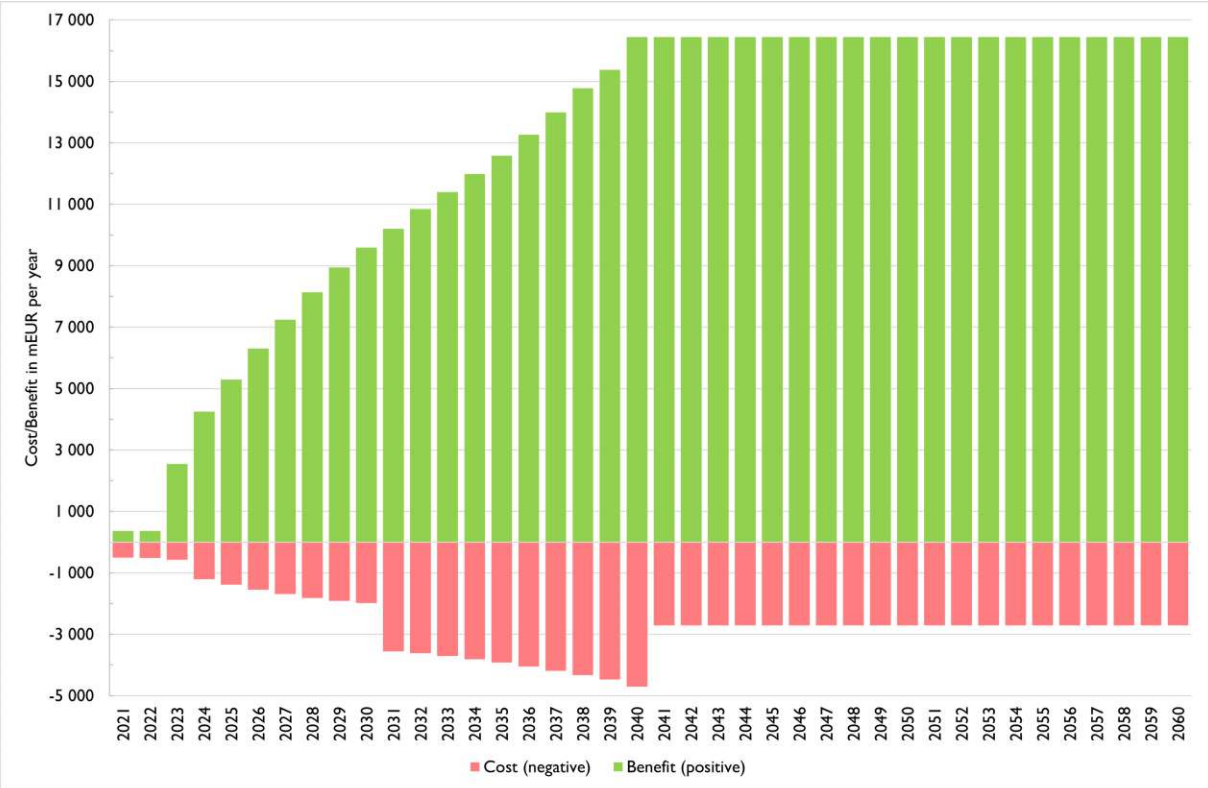


**Fig. 6.9:** Scenario 5 - costs and benefits per year (0 % discount rate)

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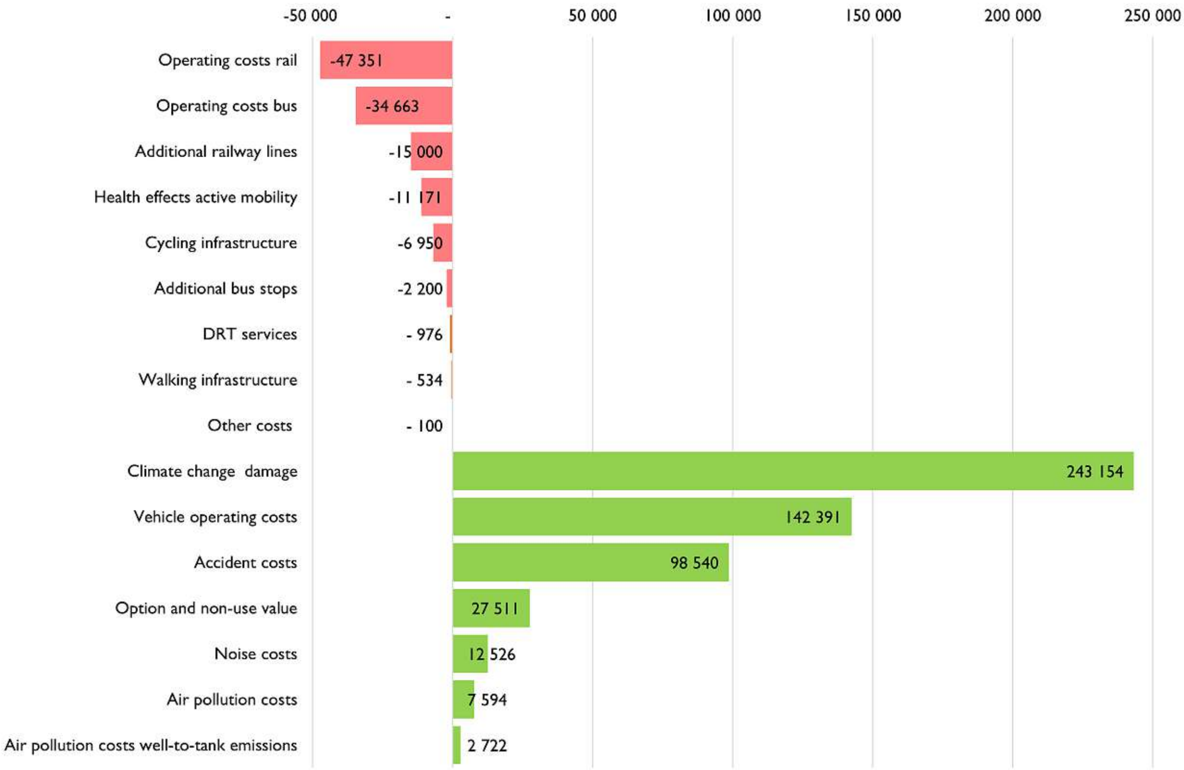


**Fig. 6.10:** Scenario 5 - total costs and benefits in million euros (2021 prices, 0 % discount rate)

NPV and BCR in Scenario 5 are the highest of all scenarios. NPV ranges between $\text{mEUR}_{2021}$ 134,000 - 405,000 and BCR between 4.26 and 4.76. The IRR is the second highest with more than 300 % (see Tab. 6.16). The costs and benefits follow almost the same pattern as in Scenario 4. Operating costs for rail and buses (with $\text{bnEUR}_{2021}$ 47.4 and $\text{bnEUR}_{2021}$ 34.7, respectively) are the largest, followed by costs of additional railway lines with about $\text{bnEUR}_{2021}$ 15. Health effects of active mobility are considerably large with $\text{bnEUR}_{2021}$ 11.2, before costs of additional cycling infrastructure ($\text{bnEUR}_{2021}$ 6.95).

By far the largest benefits can be attributed to avoided climate change damage ($\text{bnEUR}_{2021}$ 243.2), reduced vehicle operating costs ($\text{bnEUR}_{2021}$ 142.4) and accident costs ($\text{bnEUR}_{2021}$ 98.5). They are followed by option and non-use value ($\text{bnEUR}_{2021}$ 27.5) and reduced noise costs ($\text{bnEUR}_{2021}$ 12.5). The total costs (without discounting) amount to about $\text{bnEUR}_{2021}$ 117, which is lower than the second largest single benefit of decreased vehicle operating costs.

### 6.5.6 Comparison of all scenarios - base case

An overview of the results of all scenarios is shown in Tab. 6.18. Scenario 5 shows the largest NPV and BCR, followed by Scenario 4 and 2. Scenario 2 shows the largest IRR of all alternatives, indicating a great efficiency per invested Euro, while the total investment is rather small compared to Scenario 4 and 5. All three of the scenarios have a BCR of at least 3.9 for all discount rates and an NPV larger than $\text{mEUR}_{2021}$ 200,000 (with a discount rate of 0 %). Scenario 1 shows BCRs larger than 2 for all discount rates considered and an NPV between ca. $\text{mEUR}_{2021}$ 13,000 and $\text{mEUR}_{2021}$ 46,000. Scenario 3 performs worst in terms of NPV and BCR but still with a positive NPV for all discount rates and BCR larger than 1.5. The IRR with 140.5 % is higher than in Scenario 1 with 46.5 %.

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**Tab. 6.18:** Overview of NPV, BCR and IRR for all scenarios - base case

| | 1 All regions aboard | 2 Focus active mobility | 3 Focus car pooling | 4 Goodbye car | 5 Utopia |
|---|---|---|---|---|---|
| **Total cost** [$mEUR_{2021}$] | 38 488 | 68 938 | 29 633 | 71 656 | 107 773 |
| **Total benefit** [$mEUR_{2021}$] | 84 554 | 313 751 | 52 283 | 322 475 | 512 942 |
| **Net present value (NPV)** [$mEUR_{2021}$] | | | | | |
| 0% | 46 066 | 244 813 | 22 650 | 250 819 | 405 169 |
| 3% | 21 566 | 120 429 | 15 432 | 128 205 | 201 909 |
| 5% | 13 624 | 79 277 | 12 299 | 87 026 | 134 371 |
| **Benefit-cost ratio (BCR)** | | | | | |
| 0% | 2.20 | 4.55 | 1.76 | 4.50 | 4.76 |
| 3% | 2.08 | 4.22 | 1.89 | 4.13 | 4.45 |
| 5% | 2.00 | 4.01 | 1.96 | 3.93 | 4.26 |
| **Internal rate of return (IRR)** | 46.5% | 654.5% | 140.5% | 277.1% | 317.1% |

In Scenarios 2, 4, and 5, the total costs are lower than the single benefit derived from the reduced vehicle operating expenses. This indicates that these scenarios would yield a positive outcome based solely on operational cost savings. Even without factoring in the benefits associated with reduced GHG emissions, ecological improvements, or accident reductions, the implementation of an SMG demonstrates a positive economic impact.

In Scenario 1, the aggregated benefits, excluding the effects of reduced climate change impacts, exceed the total costs, while in Scenario 3, this balance is missed. These findings suggest that the introduction of an SMG could be in most cases economically justified solely on the basis of vehicle operating cost savings for individuals. Furthermore, several scenarios are projected to deliver substantial additional benefits through reductions in accident costs and environmental pollution, even if the theoretical economic value of mitigating GHG emissions cannot be fully quantified due to the accelerating impacts of climate change.

## 6.6 Sensitivity analysis

For the sensitivity analysis, seven different calculations were performed. I first tested changes in different parameters of the CBA: a more conservative value for GHG emissions costs, benefits without the highest benefit factor of vehicle operating costs for private cars and without the option and non-use value; and then the first three aspects put together in one calculation. Another analysis was performed to see how much higher the costs could be in order to still yield a BCR larger than 1 in each scenario. Then, the health effects of including walking trips to and from PT stops were estimated. And finally, I assessed the effect that considering travel time savings would have. In the following, the assumptions are described in more detail and results of the sensitivity analysis are presented.

### 6.6.1 Varying the cost of GHG emissions

For the base case calculations, the cost of GHG emissions was assumed with the values recommended by Matthey and Bünger (2020) which amount to EUR 699/t$CO_2$e in the year 2021 and EUR 753/t$CO_2$e in the year 2040 (2021 prices). In the sensitivity calculation, the lower costs recommended by the EIB (2020) are used. Converted to the price basis of 2021, they amount to EUR 113/t$CO_2$e in 2021 and EUR 577/t$CO_2$e in the year 2040. The values converted to the price basis of 2021 are shown in Tab. 6.19 and 6.20.

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**Tab. 6.19:** Costs of GHG emissions based on EIB (2020) for cars

| | Emission factor | Costs of GHG emissions | |
|---|---|---|---|
| | $gCO_2e$/vkm | $EUR_{2021}$/tCO2e | EUR-$cent_{2021}$/vkm |
| **Car 2021** | 260 | 113 | 2.93 |
| **Car 2040** | 260 | 577 | 15.01 |

**Tab. 6.20:** Costs of GHG emissions based on EIB (2020), for PT

| | Emission factor | Costs of GHG emissions | |
|---|---|---|---|
| | $gCO_2e$/pkm | $EUR_{2021}$/tCO2e | EUR-$cent_{2021}$/pkm |
| **Bus 2021** | 55.2 | 113 | 0.62 |
| **Bus 2040** | 55.2 | 577 | 3.19 |
| **Train 2021** | 11.1 | 113 | 0.12 |
| **Train 2040** | 11.1 | 577 | 0.64 |

The results of NPV, BCR and IRR for all scenarios are shown in Tab 6.21. Regarding the indicators, all scenarios perform worse than in the base case calculation, however, NPV and BCR don't change drastically. The IRR in Scenario 2 is significantly lower and only the third highest after Scenario 5 and Scenario 4. Overall, the lower cost for $CO_2$ does not change the conclusions that Scenario 2, 4 and 5 perform best, Scenario 3 performs worst in terms of BCR and NPV and Scenario 1 in terms of IRR. All Scenarios still perform better than the BAU.

**Tab. 6.21:** Overview of results - sensitivity of GHG emissions cost

| | 1 All regions aboard | 2 Focus active mobility | 3 Focus car pooling | 4 Goodbye car | 5 Utopia |
|---|---|---|---|---|---|
| **Total cost** [$mEUR_{2021}$] | 38 488 | 68 938 | 29 633 | 71 656 | 107 773 |
| **Total benefit** [$mEUR_{2021}$] | 71 266 | 268 419 | 39 615 | 272 782 | 440 199 |
| **Net present value (NPV)** [$mEUR_{2021}$] | | | | | |
| 0% | 32 779 | 199 481 | 9 982 | 201 126 | 332 426 |
| 3% | 14 391 | 94 938 | 6 989 | 98 745 | 160 508 |
| 5% | 8 600 | 60 867 | 5 609 | 65 045 | 104 249 |
| **Benefit-cost ratio (BCR)** | | | | | |
| 0% | 1.85 | 3.89 | 1.34 | 3.81 | 4.08 |
| 3% | 1.72 | 3.54 | 1.40 | 3.41 | 3.74 |
| 5% | 1.63 | 3.31 | 1.44 | 3.19 | 3.53 |
| **Internal rate of return (IRR)** | 25.2% | 120.4% | 54.4% | 140.1% | 162.1% |

### 6.6.2 Benefits without vehicle operating costs for cars

Reduced vehicle operating costs are the second largest factor of benefits in all scenarios. Since they are not always considered in CBAs, I tested the results for all scenarios without considering any vehicle operating costs of private cars. Results are shown in Tab. 6.22.

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**Tab. 6.22:** Overview of results - sensitivity of vehicle operating costs for cars

| | 1 All regions aboard | 2 Focus active mobility | 3 Focus car pooling | 4 Goodbye car | 5 Utopia |
|---|---|---|---|---|---|
| **Total cost** [mEUR$_{2021}$] | 38 488 | 68 938 | 29 633 | 71 656 | 107 773 |
| **Total benefit** [mEUR$_{2021}$] | 55 830 | 223 152 | 31 894 | 230 398 | 370 551 |
| **Net present value (NPV)** [mEUR$_{2021}$] | | | | | |
| 0% | 17 342 | 154 213 | 2 261 | 158 741 | 262 778 |
| 3% | 7 354 | 74 539 | 3 279 | 79 549 | 129 149 |
| 5% | 4 255 | 48 413 | 3 241 | 53 296 | 85 115 |
| **Benefit-Cost Ratio (BCR)** | | | | | |
| 0% | 1.45 | 3.24 | 1.08 | 3.22 | 3.44 |
| 3% | 1.37 | 2.99 | 1.19 | 2.94 | 3.20 |
| 5% | 1.31 | 2.84 | 1.25 | 2.79 | 3.07 |
| **Internal rate of return (IRR)** | 18.9% | 148.0% | 59.7% | 157.9% | 182.0% |

Results are similar to the sensitivity results of lower $CO_2$ costs; all scenarios show slightly weaker results than the base case calculations but perform better than the BAU. The ranking of scenarios does not change except for the IRR of Scenario 2, which is only the third highest.

### 6.6.3 Benefits without option and non-use value

In this analysis, the option and non-use value is not considered at all and has been set to zero in the calculation. Results are shown in Tab. 6.23.

**Tab. 6.23:** Overview of results - sensitivity of option and non-use value

| | 1 All regions aboard | 2 Focus active mobility | 3 Focus car pooling | 4 Goodbye car | 5 Utopia |
|---|---|---|---|---|---|
| **Total cost** [mEUR$_{2021}$] | 38 488 | 68 938 | 29 633 | 71 656 | 107 773 |
| **Total benefit** [mEUR$_{2021}$] | 83 224 | 312 421 | 50 953 | 309 049 | 485 431 |
| **Net present value (NPV)** [mEUR$_{2021}$] | | | | | |
| 0% | 44 736 | 243 483 | 21 320 | 237 392 | 377 658 |
| 3% | 20 898 | 119 761 | 14 764 | 121 461 | 188 089 |
| 5% | 13 177 | 78 831 | 11 852 | 82 516 | 125 130 |
| **Benefit-cost ratio (BCR)** | | | | | |
| 0% | 2.16 | 4.53 | 1.72 | 4.31 | 4.50 |
| 3% | 2.04 | 4.20 | 1.85 | 3.96 | 4.21 |
| 5% | 1.97 | 3.99 | 1.93 | 3.78 | 4.04 |
| **Internal rate of return (IRR)** | 44.4% | 615.1% | 136.3% | 248.1% | 251.7% |

The omission of option and non-use values shows the largest changes for results of Scenarios 4 and 5, as was predictable, given that these scenarios were assumed with the highest values in this regard. Nevertheless, Scenarios 4 and 5 have only slightly lower result values for all three indicators. Scenario 2 still shows the highest IRR, but in this case also the second highest NPV with a discount rate of 0 % (higher than Scenario 4) and slightly larger but almost even BCR values to Scenario 5.

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### 6.6.4 Combination of lower GHG emission costs, no vehicle operating costs and no option and non-use value

In another calculation, the three parameters that have been tested individually above are combined, which means that the results shown in Tab. 6.24 do not consider vehicle operating costs as well as option and non-use values and use the lower costs or GHG emissions based on EIB (2020).

**Tab. 6.24:** Overview of results - sensitivity of GHG emission costs, vehicle operating costs and option and non-use value

| | 1 All regions aboard | 2 Focus active mobility | 3 Focus car pooling | 4 Goodbye car | 5 Utopia |
|---|---|---|---|---|---|
| **Total cost** [$mEUR_{2021}$] | 38 488 | 68 938 | 29 633 | 71 656 | 107 773 |
| **Total benefit** [$mEUR_{2021}$] | 41 212 | 176 490 | 17 897 | 167 279 | 270 297 |
| **Net present value (NPV)** [$mEUR_{2021}$] | | | | | |
| 0% | 2 725 | 107 551 | - 11 736 | 95 623 | 162 524 |
| 3% | - 489 | 48 380 | - 5 832 | 43 344 | 73 929 |
| 5% | - 1 215 | 29 556 | - 3 896 | 26 805 | 45 753 |
| **Benefit-cost ratio (BCR)** | | | | | |
| 0% | 1.07 | 2.56 | 0.60 | 2.33 | 2.51 |
| 3% | 0.98 | 2.29 | 0.66 | 2.06 | 2.26 |
| 5% | 0.91 | 2.12 | 0.70 | 1.90 | 2.11 |
| **Internal rate of return (IRR)** | 2.2% | 33.5% | -200.6% | 45.0% | 50.1% |

Results show that the BCR in Scenario 1 and Scenario 3 are falling below 1 for some of the assumed discount rates and the NPV is negative in these cases. IRR for Scenario 3 is also negative. Scenarios 2, 4 and 5 perform much worse than in the base case calculations but still show BCR of 1.9 or more, NPVs between $mEUR_{2021}$ 26,800 - 162,524 and an IRR larger than 30 %.

### 6.6.5 Possible cost increase

The calculation of costs in the base case is based on uncertain assumptions. To analyze sensitivity to cost changes, I calculated the possible increase of overall costs that would still yield a BCR of 1, which means that the total benefits are as large as the total costs (for a discount rate of 0 %). The percentages of possible increases have been calculated for all scenarios, as shown in Tab. 6.25.

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**Tab. 6.25:** Overview of results - sensitivity of cost increase

| | 1 All regions aboard | 2 Focus active mobility | 3 Focus car pooling | 4 Goodbye car | 5 Utopia |
|---|---|---|---|---|---|
| **Cost base case** [mEUR$_{2021}$] | 38 488 | 68 938 | 29 633 | 71 656 | 107 773 |
| **Increase of total cost** [%] | **119.7** | **355.1** | **76.4** | **350.0** | **375.9** |
| **Total cost** [mEUR$_{2021}$] | 84 554 | 313 751 | 52 283 | 322 475 | 512 942 |
| **Total benefit** [mEUR$_{2021}$] | 84 554 | 313 751 | 52 283 | 322 475 | 512 942 |
| **Net present Value (NPV)** [mEUR2021] | | | | | |
| **0%** | - | - | - | - | - |
| **Benefit-Cost Ratio (BCR)** | | | | | |
| **0%** | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

The analysis of possible cost increase shows that for Scenario 1 and 3, the total cost can increase around 120 % and 76 %, respectively, in order to still show a positive balance (with an assumed discount rate of 0 %). Scenario 2, 4 and 5 show the large margin of possible higher costs of implementation that would still yield a BCR larger than 1. The overall costs could increase 350 % in Scenario 4; 355 % in Scenario 2 and 376 % in Scenario 5.

### 6.6.6 Health effects of PT walking access and egress

In order to account for positive health effects due to walking to and from public transport stations, an approximation was estimated. For the additional person-km walking, an average distance to and from the PT station with 250 m was assumed, therefore 0.5 km was multiplied with the difference in the number of PT trips between the BAU and the scenarios. The additional walking kilometers were added to the health benefits of walking. Results are shown in Tab. 6.26.

**Tab. 6.26:** Overview of results - sensitivity of health effects of walking as feeder to PT

| | 1 All regions aboard | 2 Focus active mobility | 3 Focus car pooling | 4 Goodbye car | 5 Utopia |
|---|---|---|---|---|---|
| **Total cost** [mEUR$_{2021}$] | 38 488 | 68 938 | 29 633 | 71 656 | 107 773 |
| **Total benefit** [mEUR$_{2021}$] | 84 604 | 313 801 | 52 295 | 322 508 | 513 016 |
| **Net present value (NPV)** [mEUR$_{2021}$] | | | | | |
| 0% | 46 116 | 244 862 | 22 662 | 250 852 | 405 243 |
| 3% | 21 591 | 120 456 | 15 439 | 128 224 | 201 947 |
| 5% | 13 640 | 79 296 | 12 304 | 87 039 | 134 397 |
| **Benefit-cost ratio (BCR)** | | | | | |
| 0% | 2.20 | 4.55 | 1.76 | 4.50 | 4.76 |
| 3% | 2.08 | 4.22 | 1.89 | 4.13 | 4.45 |
| 5% | 2.00 | 4.01 | 1.96 | 3.93 | 4.26 |
| **Internal rate of return (IRR)** | 46.6% | 656.1% | 140.6% | 277.2% | 317.2% |

Results change only very little compared to the base case calculations. Although there is a certain effect reducing the negative health impact, it is not enough to balance out the reduced pkm in walking and cycling. In Scenario 2, for example, the average yearly change of pkm walking compared with BAU (2021-2040) is -500 million pkm. The assumption of walking 0.5 pkm for each additional PT trip (with an average of 1.1 billion trips per year more in Scenario 2

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than in the BAU) leads to a total average of only 55 million pkm walking with the net effect of -445 million pkm walking.

### 6.6.7 Travel time savings

Changes in travel time in the scenarios affect all modes. Travel time for cars is either not changed at all compared to Scenario 0 - *Business as usual* (in Scenario 1) or increased due to lower speed limits and/or changes in walking and cycling which affect the number of parking places for cars and therefore the distance and time walking to or from a parking place. Travel time by PT is reduced in all of the scenarios due to higher frequency of train and bus services and smaller distances to and from PT stops. Travel time for active modes is reduced in the scenarios due to new infrastructure that creates shorter distances or allows for faster walking or cycling. Therefore, travel time savings of PT and active modes would be a benefit, if considered in the CBA.

The calculation of travel time savings for PT and active modes in MARS is complex due to the model structure that computes a large set of subscripts for each PT trip. Each PT trip has one access and one egress part which both can be performed with three different modes (car, walking, cycling) and in four different distance classes.[1] Therefore, only the effects on travel time for car trips are assessed. Travel time for cars is increasing in some scenarios and therefore creates costs (i.e. negative benefits). The calculation is therefore conservative because only costs due to longer travel times by car are considered and no travel time savings.

To calculate changes in car travel time, the number of trips and travel time for each scenario and each O-D pair was exported from MARS as csv-documents and imported to R Studio, where the calculation of travel time savings was performed. The data and code can be provided by the author on request. The calculation follows the Rule of Half approach to calculate the consumer surplus (European Commission, 2014, p. 89), as described in this equation:

$$B_{ij} = \frac{1}{2} \cdot (T_{0ij} + T_{Xij}) \cdot (t_{0ij} - t_{Xij}) \tag{6.4}$$

where:

$B_{ij}$ = Benefit of travel time savings for the O-D pair $ij$
$T_{0ij}$ = Number of trips from $i$ to $j$ in Scenario 0
$T_{Xij}$ = Number of trips from $i$ to $j$ in Scenario X
$t_{0ij}$ = Monetized travel time for trips from $i$ to $j$ in Scenario 0
$t_{Xij}$ = Monetized travel time for trips from $i$ to $j$ in Scenario X

The calculation was performed for each O-D pair and then aggregated for each time step to get the total benefit from travel time savings per year for the time frame 2021-2040. The values for the period 2041-2060 are assumed with the constant values of 2040. The monetary value for travel time savings is based on V. Plank et al. (2022) (the CBA for the Austrian railway network) and amounts to $EUR_{2021}$ 13.46/h converted to the price basis of 2021 (Statistik Austria, 2022b). It is an average value considering different types of trips that is applied for travel time savings by rail and car. Results of total values for the time frame 2021-2040 with a discount rate of 0 % are shown in Tab. 6.27.

[1] Attempts to export the disaggregated data to perform the analysis in Excel or with R resulted in software crashes, while the attempt to aggregate the entities directly in MARS using Vensim failed with unclear error messages in the software.

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**Tab. 6.27:** Benefits of travel time savings (TTS) for car trips

| | Sc1 | Sc 2 | Sc 3 | Sc 4 | Sc 5 |
|---|---|---|---|---|---|
| **TTS Benefits** [$mEUR_{2021}$] | 0.0 | -120.7 | -37.3 | -171.7 | - 160.1 |

The results for Scenario 1 - *All regions aboard* are 0 because it includes no measures that restrict car use or affect its speed. Scenario 3 shows the second lowest value with a cost of $mEUR_{2021}$ 37.3, which is lower than the smallest cost parameter "Other costs" with $mEUR_{2021}$ 100 (Fig. 6.6). Scenario 3 does not include lower speed limits, the effects in the model are due to measures for active mobility that are assumed to increase the walking time to car parking places. Effects in Scenario 2 are due to measures in active mobility as well as a lower speed limit of 30 km/h in urban areas. With a total cost of $mEUR_{2021}$ 120.7, it represents the second lowest cost parameter, after costs for walking infrastructure ($mEUR_{2021}$ 534) and before "Other costs" with $mEUR_{2021}$ 100. The largest effect can be seen in Scenario 4 with a maximum yearly cost of $mEUR_{2021}$ 5.1 in 2040. The total amount of cost of travel time savings for the assessment period is $mEUR_{2021}$ 171.7, which represents the second lowest cost parameter for this scenario, too. Results for Scenario 5 are slightly lower, since travel times are affected in the same way as in Scenario 4, but overall less trips are made by car.

**Tab. 6.28:** Overview of NPV and BCR for all scenarios - sensitivity of considering travel time savings for car trips

| | 1 All regions aboard | 2 Focus active mobility | 3 Focus car pooling | 4 Goodbye car | 5 Utopia |
|---|---|---|---|---|---|
| **Total cost** [$mEUR_{2021}$] | 38 488 | 69 059 | 29 670 | 71 828 | 107 934 |
| **Total benefit** [$mEUR_{2021}$] | 84 554 | 313 751 | 52 283 | 322 475 | 512 942 |
| **Net present value (NPV)** [$mEUR_{2021}$] | | | | | |
| 0% | 46 066 | 244 692 | 22 613 | 250 647 | 405 009 |
| 3% | 21 566 | 120 366 | 15 414 | 128 114 | 201 823 |
| 5% | 13 624 | 79 234 | 12 287 | 86 962 | 134 311 |
| **Benefit-cost ratio (BCR)** | | | | | |
| 0% | 2.20 | 4.54 | 1.76 | 4.49 | 4.75 |
| 3% | 2.08 | 4.21 | 1.89 | 4.12 | 4.44 |
| 5% | 2.00 | 4.00 | 1.96 | 3.92 | 4.26 |
| **Internal rate of return (IRR)** | 46.5% | 654.0% | 140.5% | 276.9% | 316.9% |

Results of the CBA for this sensitivity testing are shown in Tab. 6.28. Obviously, there are no changes in Scenario 1, but the effect on other scenarios is also very small with the largest being a decrease of the NPV of $mEUR_{2021}$ 160 in Scenario 5, a decrease of the IRR of 0.5 %-points to 654.0 % in Scenario 2 and changes of up to 0.01 in the BCR.

### 6.6.8 Conclusion of sensitivity analysis

The sensitivity analysis has shown that there are no large differences in the results regarding the performance of the scenarios with varied parameters. Only in the case of combining three worst case scenarios (lower costs of GHG emissions, no vehicle operating costs and no option and non-use value), the Scenarios 1 and 3 perform worse than the BAU. The scenarios performing best within the framework chosen for the CBA in this thesis are Scenario 5 - *Utopia*, Scenario 2 - *Focus active mobility* and Scenario 4 - *Goodbye private car*, which show robust positive

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results that perform better than the BAU in all the tested parameters. However, the scenarios should be judged also along other criteria. Concerning Scenario 2, I already mentioned that the external scenario assumptions are not in line with national decarbonization objectives in Austria. Even though the scenario performs good in the CBA, it is not compatible with carbon neutrality in the transport sector until the year 2040 due to low share of electric vehicles in the fleet. Scenario 5 - *Utopia*, on the other hand, could be problematic for financing reasons. Since the CBA considers private and public costs, changes in PT ticket fares, road pricing and taxes are not considered. However, they could have a large influence on what is deemed financially feasible from the perspective of public policies. Scenario 5, for example, includes PT free of charge, which means that subsidies for PT will increase dramatically. This might be difficult to achieve with limited public budgets.

## 6.7 Discussion

### 6.7.1 Suitability and limitations of the CBA framework

First of all I would like to point out that the results of the CBA have to be interpreted cautiously. As discussed before, multiple simplifications have been made in order for the CBA to stay within the scope of this thesis. Additionally, as discussed in Chapter 5, the results from MARS simulations also have to be critically interpreted, e.g. regarding the levels of cycling. As mentioned in Section 5.5.5 the share of cycling in the simulations is relatively low when combining measures to make cycling more attractive with policies impacting walking and PT. Overall, the cumulative vehicle-kilometers traveled by bike are lower in all SMG scenarios than in the BAU. Regarding the CBA, this means that there is a negative effect on health due to lower cycling rates. Another important assumption is the development of e-car shares. As already discussed, some of the scenarios include full electrification of the car fleet until 2040, while others do not. However, overall climate targets of Austria (with carbon neutrality in 2040) cannot be met without replacing (almost) all vehicles with alternative propulsion technologies. This means that the results of the CBA can only serve as a basis for further research and discussion.

Some aspects that are of interest with regard to the SMG concept cannot be assessed with a CBA. The SMG is seen as a policy that combines social and ecological objectives, which means that it aims to address justice and equity aspects. Such aspects, e.g. regarding distributional effects are not part of the standard CBA approaches in transport. Likewise, some ecological aspects can't be satisfactorily assessed with a CBA. As explained in the planetary boundaries framework (Fanning et al., 2021; Rockstrom et al., 2009), there are several boundaries that humanity should not trespass in order to keep the planet livable. This is reflected only in a very limited way in the CBA framework. Further analysis should be conducted to look into the role of transport on each of these boundaries and compatibility of transport policy with staying within these boundaries.

In conclusion, CBAs offer the possibility to explore certain impacts and compare different scenarios of a transport policy within a framework that is always incomplete. The method enables an assessment of the SMG scenarios in this thesis that provide interesting insights and can be used for further debate. However, I recommend to base decisions on practical implementation on more extended assessments and a participatory approach.

### 6.7.2 Key parameters of the CBA

The largest cost factors in the CBA are operating costs for PT and costs for the construction of new railway lines. On the benefit side, the largest impacts are attributed to reduced GHG

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emissions, vehicle operating costs and accident costs, followed in some scenarios by option and non-use value. Like vehicle operating costs and accident costs, other 'external' costs are also multiplied with the change in vehicle-kilometers traveled. This means that keeping vkm low has a positive impact on several of the benefit criteria considered. Health benefits of active mobility are somewhat special. While they could yield considerable benefits with higher levels of cycling and walking, in the SMG scenarios, the overall effect is negative due to decreased cycling volumes. Out of these characteristics, certain key parameters and leverage points for the economic efficiency of the implementation of an SMG (and similar transport policies) can be derived. By searching for an optimal mix of rail, bus and DRT services, costs for PT can be kept low. While the enhancement of active mobility is comparably low-cost and can act as a catalyst for PT use, policy implementation should be monitored closely in order to avoid shifting from walking and cycling to PT trips. To keep vehicle operating costs and 'externalities' as low as possible, car traffic has to be reduced. In scenarios with full electrification, this is only possible when including restrictive measures for car use in the policy mix.

### 6.7.3 User benefits, option values and non-use values

The assessments of user benefits, option values and non-use values should be investigated in more detail. This was out of scope of the thesis, but there are many aspects that should be discussed further. Future research should also look more into the "guarantee" aspect of an SMG and could assess willingness-to-pay for the concept. Empirical data could be collected for example with stated preference surveys, as described in the review analysis by Laird et al. (2009) of option values and non-use values of rail and bus.

### 6.7.4 Financial resources

With the government being guarantor, it is necessary to allocate public budget to finance investments in the creation of a Sustainable Mobility Guarantee. Looking at current public budgets and subsidies in Austria, the necessary investment could be conceivable by reallocation within current budgets in the transport sector.

#### Environmentally harmful subsidies in transport

In a study by Kletzan-Slamanig et al. (2022) the amount of environmentally harmful subsidies in Austria has been estimated. They range between bnEUR 4.1 and bnEUR 5.7 per year of which 60 % of subsidies address the transport sector, including commuter allowances (*"Pendlerpauschale"*), reduced fuel tax for diesel and tax advantages for company cars used by employees. By theoretically reallocating these subsidies to the creation of an SMG, a considerable share of the estimated financing needs could be covered. The yearly operating costs for the SMG scenarios, which range between $\text{bnEUR}_{2021}$ 1.1 - 2.7, could be covered entirely with the subsidies of the transport sector.

#### Financial organization of transport in Austria

In Austria, transport financing is complex due to federalism, fragmented competences and organization based on regional public transport authorities (*"Verkehrsverbünde"*). Such complexities are described well in Mitterer et al. (2017), showing back-and-forth transfers between state, provinces, public transport authorities and municipalities. The responsibilities regarding funding of an SMG were also one of the most discussed topics in the expert workshops (see Section 3.2).

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Regarding the national transport networks, there are specific organisations for railways and highways. The ASFINAG (*Autobahnen- und Schnellstraßen-Finanzierungs-Aktiengesellschaft*) plans, finances, builds, maintains and collects tolls for federal highways. It is an outsourced company that generates its income independently through road pricing (flat rate vignettes for federal highways), while the state is liable for the debt. The state of Austria owns 100 % of the shares of ASFINAG under the responsibility of the BMK. Due to the ASFINAG law (*ASFINAG-Gesetz*, BGBl. Nr. 591/1982), which states that all profits have to be reinvested in maintenance and building of new highway infrastructure, it is currently not possible to redirect revenue from road pricing on federal roads to other types of infrastructure. Theoretically, this could be changed in order to finance an SMG. The ÖBB (Austrian Railways/*Österreichische Bundesbahnen*), on the other hand, are organized as a holding with several companies for passenger transport (ÖBB-Personenverkehr AG), cargo transport (Rail Cargo Austria AG) and infrastructure (ÖBB-Infrastruktur AG). The shares of the parent company are held 100 % by the state of Austria and are administered by the BMK. Operations and building of new infrastructure is not covered by sold tickets and infrastructure usage fees. Therefore, the government assigns money from the public budget to ÖBB.

Subsidies for ÖBB are regulated in the Federal Railway Law (*Bundesbahngesetz*, BGBl. Nr. 825/1992). The government and national parliament usually agree on a 6-year plan (the *Rahmenplan*) for financing the construction of new and maintenance of existing infrastructure. The plan is extended every year for one year. Inflation is considered with a fixed valorizaton of 2.5 % p.a.[2]. This gives ÖBB security in planning ahead but does not allow for short-term changes in infrastructure planning. In the past legislative period, the budget for ÖBB was significantly higher than in the years before. While the budget between the years 2007 and 2018 ranged from bnEUR 1.9-2.5 per year (BMVIT & ÖBB Infra, 2007, 2008, 2009, 2011, 2012, 2013, 2014, 2016, 2017, 2018), the plan for 2024 - 2029 considers bnEUR 21.1, thus about bnEUR 3.5 per year (BMK & ÖBB Infra, 2024). A linear increase considering 2.5 % since 2018 would have resulted in only bnEUR 2.8 per year on average for the period 2024 - 2029. The higher levels of financing for public railway lines probably need to be upheld, if not increased, should the SMG be implemented.

As mentioned above, ASFINAG - the publicly owned company responsible for highways in Austria - is organized in a way that road pricing profits are reinvested for construction and maintenance of highways without the use of public budgets. In Austria, competences for road construction are divided among the state, provinces and municipalities. Municipalities are responsible for the local streets within their territory that have been transferred to the municipality by the provinces while the provinces are responsible for all roads that are not part of the highway network. The financial means for maintenance and construction of new roads in the responsibility of provinces and municipalities have to be paid by the public budgets. ASFINAG plans the construction of new highways, which are discussed to be environmentally harmful and not fit to reach sustainability goals. The transport ministry commissioned an analysis of all new federal road projects and dismissed some of them (Banko et al., 2022). This includes the S1 highway (also referred to as *Lobauautobahn* with the controversial tunnel *Lobautunnel*), a ring road project for the capital city Vienna which has been projected to cost bnEUR 1.9[3] and the S34 highway next to St. Pölten, the capital of the province Lower Austria, projected to cost mEUR 208[4]. In theory, the budget that will not be used for constructing new roads could be available to fund alternatives such as public transport and infrastructure for active mobility.

[2]https://www.bmk.gv.at/themen/verkehrsplanung/ausbauplan/plan_oebb.html

[3]https://kurier.at/chronik/wien/zwei-jahrzehnte-kampf-um-den-lobautunnel-vor-dem-aus/401823913, accessed 28.06.2024

[4]www.asfinag.at/bauen-erhalten/bauprojekte/s-34, accessed 28.06.2024

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However, the mentioned road projects could be taken up again by a new government, and the current legal structure does not allow for cross-financing between transport modes.

#### New funding instruments

New instruments might be another source for funding an SMG and in the sense of a “push and pull” approach might be needed (e.g. as road pricing) to reduce car use. Such instruments could be pricing for car parking, elevated taxes on fossil fuel or $CO_2$ or road pricing, which eventually generate additional revenues for financing. Some of the SMG scenarios (Scenario 4 and 5) incorporate road pricing up to EUR 0.50 per km for all types of cars on all roads. The introduction of such high prices might not be politically feasible, but would generate large additional revenue for the state. In the year 2040 when the SMG is in full effect, this would yield a revenue of bnEUR 16 per year in Scenario 5. The revenues are not included in the CBA but the instrument might be used to finance the implementation of an SMG.

### 6.7.5 Wider economic impacts

So called ’wider economic impacts’ are usually not included in CBAs but are relevant for the overall economic effect of transport policy. Such impacts include effects on the number of jobs and value creation. Lower levels of car use and lower motorization rates probably lead to less cars being sold, which might pose a problem for the car industry and supplier companies and in the following for state revenues and economic security of workers (Mattioli et al., 2020). It is therefore argued that there is the need for a social-ecological transformation of the automotive industry, which requires strategic decisions and state interventions (Pichler et al., 2021). However, with a change to more sustainable transport modes, there might also be positive effects on employment due to the need for more people working in the production of vehicles for PT, in the bicycle industry, driving buses and trains, as well as in construction, modification and maintenance of infrastructure and vehicles. A study for Germany (Candeias & Krull, 2022) found that there could be an overall positive effect on the number of jobs with a social-ecological transformation in the transport sector.

Transitioning towards sustainable transport in Austria could enhance domestic value creation by reducing dependence on imported fossil fuels and foreign-manufactured vehicles. Austria’s rail industry is already a significant contributor to the national economy, employing over 27,000 people and generating more than bnEUR 1.6 in direct value (Austrian Rail Industry, 2023). The industry also plays a key role in innovation, with Austria leading Europe in per capita research and development spending on rail vehicle technology. Additionally, Austria is a top global exporter of rail vehicles.

## 6.8 Conclusion

The CBA shows that the introduction of an SMG in Austria could yield significant benefits that outweigh the costs in several scenarios. Based on the analysis here, I argue that it is financially feasible to implement a Sustainable Mobility Guarantee. Initial investments for SMG implementation range between $\text{bnEUR}_{2021}$ 4.4 and $\text{bnEUR}_{2021}$ 24.7, while operating and maintenance costs amount to $\text{bnEUR}_{2021}$ 1.1 - 2.7 per year. By restructuring financial transfers, reducing counterproductive subsidies and using new funding instruments, the funding needs for implementation could be achieved. The costs are balanced out by considerable benefits in reduced harm for humans and the environment as well as reduced costs for vehicle operation of private cars. Comparing the SMG scenarios, Scenario 5 - *Utopia* leads to the largest NPV and

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highest BCR, followed by Scenario 2 and Scenario 4. The three of them lie within similar ranges, although Scenario 2 is not compatible with overall climate goals in Austria. Scenario 1 and 3 show negative NPV and BCR lower than 1 in some cases tested in the sensitivity analysis and show much lower NPV and BCR than the other scenarios in the base case results. The economic efficiency of introducing an SMG can be further influenced by tweaking the relevant parameters, e.g. higher share of DRT and limiting new railway lines, promoting active mobility as well as combination with restrictive measures for car use. Further analyses should be conducted as one part of democratic procedures to find an optimal implementation design.

Results of the CBA can furthermore help to design economically effective policies for sustainable transport and the CBA approach developed in the course of this thesis could also be applied to assess transport policies outside of the context of an SMG.

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# Chapter 7

# Conclusion

In this chapter, I first summarize and reflect on the results and the research process (Section 7.1), followed by answers to research questions. Next, Section 7.3 discusses suggestions for future research, followed by Section 7.4 with policy recommendations. The chapter is concluded with a Section on final conclusions.

## 7.1 Summary and reflection of research process

The research is centered on the concept of a Sustainable Mobility Guarantee (SMG), defined as a policy framework to ensure comprehensive, accessible, and sustainable transport options for daily journeys. This guarantee emphasizes public transport (including regular and Demand-Responsive Transit), cycling, and walking, with complimentary shared mobility while deliberately excluding private cars, virtual mobility, and freight transport. The SMG is designed to improve sustainable mobility options while reducing the dependency on private cars, with interim measures such as carpooling considered to facilitate the transition.

Key findings suggest that the SMG could significantly influence transport planning and mobility behaviour, although its success depends on broader systemic changes. Both qualitative and quantitative methods were used to explore various scenarios. The literature review highlights varying approaches to mobility guarantees, often narrowly focused on single modes such as carpooling or public transport, with implementation through contracts, pilot projects, or legal frameworks. In contrast, this study defines a Sustainable Mobility Guarantee (SMG) as a more holistic approach combining social and ecological objectives. The SMG aims to provide reliable, accessible, and non-discriminatory mobility services while promoting sustainable travel behaviour. With a focus on both urban and rural contexts, it proposes differentiated service standards and infrastructure development, positioning itself as an alternative between specific guarantees and broad legal rights.

The qualitative analysis highlights that while an SMG can foster change, its impact remains limited without broader systemic efforts. The Leverage Points framework suggests that SMG implementation mostly targets lower leverage points (with limited impact), which may shift transport planning away from a car-centric perspective but are insufficient for transformative change without engaging higher leverage points. This raises a critical concern: by primarily addressing lower leverage points, research risks reinforcing incremental improvements with limited impact rather than driving systemic transformation. The use of Causal Loop Diagrams (CLD) helped identify system behaviours and rebound effects, such as increased car use due to carpooling, shifting trips from active modes to public transport or land use changes driven by better public transport (PT). Effective SMG strategies should counter these tendencies.

Simulation results with the strategic transport model MARS show that the impact of an SMG in reducing car traffic is rather limited without combining the additional infrastructure and services of the SMG with restrictive measures for car use. The two scenarios with the largest scope of an SMG (Scenario 4 - *Goodybe private car* and Scenario 5 - *Utopia*) are coupled with

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lower speed limits and road pricing. They can significantly reduce car use while enhancing public transport and walking. Scenario 1 - *All regions aboard* and Scenario 3 - *Focus carpooling* with a lower scope of SMG, however, show only limited results with regard to changes in travel behaviour. Scenario 2 - *Focus active mobility* performs similarly to Scenario 4 with respect to reducing car use and improving public transport, while offering significantly fewer PT services. This is mainly due to different assumptions in the uptake of electric cars.

Finally, the Cost-Benefit Analysis (CBA) reveals that Scenario 5 - *Utopia* offers the highest Net Present Value (NPV) and Benefit-Cost Ratio (BCR), followed by Scenario 2 and Scenario 4. Scenario 2 shows the largest IRR (Internal Rate of Return) of all alternatives. Scenario 1 and 3 show significantly lower results in the CBA. Performance in terms of economic, social and environmental indicators could be further optimized by combining different measures and assessing the ideal mix of conventional PT with DRT and sharing services.

The study also acknowledges several limitations. Simulations with MARS show valid system behaviour and deliver plausible results with regard to mode choice and development of mobility behaviour, although the model has its own limitations such as high-level aggregation, uncertainties in parameter estimation, and limited empirical data. Additionally, aspects such as the interplay between the SMG and spatial planning as well as comfort of PT services are important for comprehensive assessment but are not included in the analysis. The research identifies potential rebound effects, such as increased car use due to enhanced carpooling or land use changes, which could result from improved accessibility by sustainable modes in rural areas. The CBA results must be interpreted cautiously due to simplifications and exclusion of certain social and ecological factors.

In conclusion, while the SMG could play a crucial role in advancing sustainable transport, it should be integrated with other measures required to address the broader social-ecological transformation. The thesis introduces several new contributions to the field of sustainable transport. Firstly, it establishes a clear and comprehensive framework for the SMG as a tool for the social-ecological transformation of the transport sector. This adds clarity to existing debates around sustainable mobility. Secondly, by using MARS simulations, it provides evidence on the impact of policy mixes and emphasizes that an SMG is most effective when combined with restrictions on private car use. Thirdly, the work advances the understanding of the economic feasibility of sustainable transport policies through a Cost-Benefit Analysis (CBA). This sheds light on the economic, social, and environmental trade-offs associated with current trends and different SMG scenarios.

## 7.2 Answers to research questions

The research questions formulated in Section,1.5 have been answered in the previous chapters and will be summarized here.

### Which different definitions of mobility guarantees or related concepts exist?

In the literature review (see also Section 3.1), various definitions of mobility guarantees and related concepts were explored, revealing that these guarantees can range from specific, narrowly defined services - such as the “guaranteed ride home” programs - to broader, more comprehensive legal frameworks, such as the right to sustainable mobility enshrined in laws. These definitions often vary by geographic scope and the level of authority responsible, and are implemented through a mix of contracts, legal regulations, and pilot programs. While specific guarantees focus on individual modes of transport or specific routes, broader legal approaches aim to integrate multiple modes and address social, economic, and environmental objectives. The

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varying approaches are typically shaped by the policy and legal context, with a growing trend toward integrating sustainability into mobility guarantees, particularly in European contexts.

### What are the key components of an SMG?

Based on the findings of the literature review on existing concepts and the requirements determined in the stakeholder workshops, the key components of an SMG as understood in this thesis have been defined. A Sustainable Mobility Guarantee (SMG) could be structured around three key components: legal frameworks, service provision, and sustainability. Legally, it would involve regulations for planning and maintaining transport infrastructure, ensuring quality standards for roads, railways, and active mobility facilities such as cycling lanes and pedestrian pathways. It would also include guidelines for public transport services, specifying minimum service levels such as frequency, coverage, and accessibility, with a focus on integrating various transport modes and platforms. In terms of services, the SMG would ensure comprehensive and equitable access to public transport, including both fixed-route services and flexible options such as Demand-Responsive Transport (DRT). It would support the development of open and non-discriminatory digital mobility platforms, providing transparent information and facilitating seamless connections between different transport modes. The framework emphasizes sustainability by promoting travel options that are environmentally friendly while ensuring accessibility to reduce car dependence for the society. This distinguishes the SMG from other approaches, which may focus more narrowly on service provision without integrating broader sustainability objectives.

### What different scenarios can be developed for an SMG introduction, focusing on design aspects, implementation scales, and external uncertainties?

To address different approaches to implement an SMG, five distinct scenarios were defined, ranging from minimal to extensive implementations. Scenario 0 - *Business as Usual (BAU)*, represents the current state of trends and prognoses without any SMG. Scenario 1 - *All Regions Aboard* proposes basic improvements in public transport services, especially in rural areas, serving as a lower-intensity approach. Scenario 2 - *Focus Active Mobility* enhances public transport moderately while placing significant emphasis on walking and cycling infrastructure. Scenario 3 - *Focus Carpooling* similarly upgrades public transport but also promotes carpooling as a complement to services in less well-served areas. Scenario 4 - *Goodbye Private Car* aims for comprehensive public transport availability and incorporates strong measures to discourage private car use. Finally, Scenario 5 - *Utopia* represents an idealized scenario with 24/7 free public transport and strong policies to eliminate private car use. These scenarios vary in design and implementation intensity, providing a spectrum of potential impacts and adjustments based on the extent of SMG adoption.

### What potential impacts would an SMG have on transport planning and the patterns of travel behaviour?

This question was answered based on the Multi-Level Perspective (MLP), "Leverage points in Systems" framework and Causal Loop Diagrams (CLDs), as described in Chapter 5. An SMG would primarily impact lower "leverage points" in the transport system, such as specific service provisions and infrastructure improvements. While these adjustments can lead to local improvements in accessibility and influence travel behaviour by making sustainable options more attractive, their capacity to drive broader systemic change in the sense of a social-ecological transformation in the transport planning field is limited. An SMG could play a supportive role, helping to shift mental models - especially those of transport planners and decision-makers -

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from car-centric approaches to more sustainable views. But it must be accompanied by strategic changes that address changes on a higher level. Furthermore, implementing an SMG could also generate rebound effects, such as increased rural migration due to better transport provision or a rise in car use linked to enhanced carpooling services. To maximize the effectiveness of an SMG and mitigate these potential rebound effects, it should be integrated within a broader framework of systemic changes that address both higher and lower leverage points.

### How would the implementation of an SMG affect travel behaviour in Austria, including changes in modal split and vehicle kilometers, across different scenarios?

The quantitative simulation results for different SMG scenarios highlight varying impacts on travel behaviour in Austria. Scenario 1 shows only minimal changes in the modal split and overall travel behaviour compared to the BAU Scenario. Scenario 2, which emphasizes active mobility, results in a significant reduction in car use and a shift towards public transport and active modes. However, Scenario 2 assumes a less advanced development of electric vehicles compared to Scenarios 4 and 5 and is therefore not in line with Austrian targets for $CO_2$-emissions reductions. Scenario 3, which promotes carpooling, paradoxically increases person kilometers traveled by car due to higher car occupancy rates despite a reduction in vehicle kilometers traveled. Scenario 4, featuring extensive public transport improvements coupled with restrictions on private car use, leads to a considerable reduction in both vehicle kilometers traveled and private car usage while boosting public transport. Scenario 5, with 24/7 free public transport and stronger measures restricting private car use, demonstrates the extreme potential impacts on travel behaviour but may be less feasible to implement in practice. Overall, a combination of enhanced active mobility and restrictive measures on private car use yields the most significant shifts in travel behaviour, with different scenarios highlighting the role of external factors such as the electrification of the vehicle fleet.

### How effective is the Cost-Benefit Analysis (CBA) framework in evaluating the SMG, and what are the limitations of this method?

CBA is a widely used tool for assessing transport policy and infrastructure projects. The method provides a structured framework to quantify costs and benefits, though it is essential to acknowledge its inherent biases and gaps. The traditional CBA framework faces several criticisms which impact its effectiveness in evaluating concepts such as the SMG. Key criticisms include the limitations of utilitarianism and the inability to fully account for distributional effects, non-monetizable impacts, and long-term environmental consequences. Since its introduction, the method has been adapted and is often combined with a multi-criteria analysis (MCA) to account for aspects that can't be monetized. For evaluating the SMG, adapting the CBA framework to include non-traditional benefits and performing sensitivity analyses helps to address and discuss some of these issues. For practical implementation, I recommend to assess different SMG policy options in a broader appraisal process including MCA and public participation.

### What are the key parameters of the CBA, the Net Present Value (NPV), Benefit-Cost Ratio (BCR) and Internal Rate of Return (IRR) for each SMG scenario?

The CBA of the SMG scenarios show that Scenario 5 has the highest BCR between 4.26 and 4.78 (for different discount rates) and the largest NPV (ca. $\text{bnEUR}_{2021}$ 134 - 405), while Scenario 2 shows the highest IRR with 655 %. The largest cost factors are operating costs for railway and buses in all scenarios. However, benefits are significantly higher, mainly due to reductions in climate change damage and savings of vehicle operating and accident costs. Scenario 1 and Scenario 3 have lower NPV, BCR and IRR, indicating less favorable economic performances. It is crucial to note that while active mobility offers significant benefits, its effectiveness in the SMG scenarios is compromised by decreased cycling volumes, which could undermine the potential health gains. Effective implementation should therefore focus on balancing high costs with substantial benefits, optimizing public transport, active mobility, and integrating restrictive measures for car use to maximize economic efficiency.

Although not included in the analysis, introducing an SMG could also yield substantial wider economic benefits. These could include increased job creation and enhanced domestic value within the public transport industry and infrastructure sectors.

## 7.3 Directions for future research

Based on the findings and limitations of this study, several avenues for future research emerge, as described in the following.

### Modelling mode choice

To improve the accuracy and reliability of transportation models like MARS, there is a need for enhanced data collection and model refinement. The existing model faces limitations due to the high level of data aggregation and outdated calibration data. Investing in updated data collection efforts and incorporating more recent and detailed data can provide a clearer picture of transportation behaviour and infrastructure impacts. More precise and current data is needed particularly for cycling and new mobility services. Research should focus on capturing detailed data from effects of new cycling infrastructure - including bike lanes and secure parking - on mode choice. Incorporating factors such as e-bikes and different population cycling capabilities could also help create more reliable results.

Future research should explore the integration of new mobility services, such as demand-responsive transport (DRT) and vehicle-sharing, into highly aggregated national transport models such as MARS. These services probably lead to different usage patterns compared to traditional public transport, and their inclusion could significantly alter predictions about public and private transport use. Given that the current MARS model does not fully account for these new mobility services, further empirical research is needed to understand their impact on user preferences and overall transportation dynamics. This involves evaluating ongoing pilot projects, gathering data on user behaviour with new mobility options, and enhancing transportation models to incorporate these services as distinct modes of transport.

Another important research avenue is the evaluation of various restrictive measures for car use, such as congestion charges, increased taxes, and other policy interventions. These measures could potentially play a significant role in reducing car usage and achieving climate targets. Currently, the scenarios considered in this thesis include only a limited set of restrictive measures, and a broader exploration of additional measures is warranted. Research should involve simulations that incorporate a variety of restrictive measures and analyze their effects on car usage. Pricing mechanisms could be tested progressively (e.g. higher costs for households with more income) and results analyzed across population groups to assess distributional effects. Additionally, studying case studies from cities where such measures have been implemented can provide valuable insights into their effectiveness and inform the development of more comprehensive policy strategies.

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### Relationship with land use

The interaction of transportation and land use with regard to an SMG has only been discussed qualitatively in this thesis. Further research should look into possible rebound effects of an SMG on long-term land use development for managing unintended consequences. Another relevant aspect is the interplay of locally available services - e.g. such as grocery stores, medical services and restaurants - and mobility options. Investigating how the availability of essential services within various distances from residential areas impacts community well-being and economic vitality could offer valuable insights. This could involve empirical studies that assess the effectiveness of different levels of service provision in fostering local economies and reducing dependency on extensive travel.

### Political aspects and practical implementation

Building on the findings of this research, exploring the political dimensions of implementing an SMG (or other sustainable transport concepts) could offer valuable insights. A key area for further investigation is the identification and analysis of vested interests that may hinder progress. This could involve mapping stakeholders and understanding their economic dependencies and power dynamics within the current transport system. By examining how these interests shape policy decisions, researchers can better identify barriers to change and develop strategies to overcome them. Additionally, understanding the political context is crucial for effective advocacy. Analyzing policymakers' motivations and constraints, along with leveraging existing power structures, can provide strategies to influence policy decisions in favour of sustainable transport.

Public engagement and participatory approaches are also seen as critical. Future research could investigate how involving communities in decision-making impacts policy acceptance and effectiveness. Evaluating different engagement strategies could contribute to designing policies that are more inclusive and successful.

### Economic and social equity analysis

As described in the CBA chapter, the estimation of costs for implementing an SMG is only a rough estimate. More detailed analyses of the gap between status quo of infrastructure and services and the desired quality for an SMG should be conducted in order to create more sound cost estimates.

The applicability and precision of the Cost-Benefit Analysis (CBA) framework could be enhanced by incorporating additional parameters, such as option values and the treatment of travel time and external costs. Future research should assess option and non-use values of the SMG concept, for example through stated preference surveys. The complexities of considering travel time savings in CBAs of policy packages such as the SMG equally deserve a more thorough analysis.

Addressing the limitations of the CBA in evaluating social equity and environmental sustainability is crucial. Further research could focus on integrating justice and equity considerations into transport policy assessments, as well as evaluating how transport policies align with planetary boundaries and environmental thresholds.

Further investigation is needed into the distributional impacts of SMG policies, particularly regarding their effects on different socioeconomic groups and regions. Research should assess whether these policies contribute to or mitigate existing inequalities in access to transport services and how they affect various demographics, including low-income communities and rural populations.

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## 7.4 Policy recommendations

Policy recommendations address various levels of governance and should be differentiated for the case study and other geographic contexts. In Austria, the findings suggest that policy-makers on all levels should cooperate to establish a robust and integrated regulatory framework if they want to support the SMG. Drawing from the findings of this research, it is evident that at the national level, prioritizing investments in optimizing public transport services is crucial. While infrastructure and operational costs for public transport can be substantial, reduced vehicle operating and accident costs as well as further benefits outweigh these expenses. A considerable share of the funding needed for an SMG could be sourced from reallocating environmentally harmful subsidies (see Section 6.7.4).

Regional authorities and the transport associations can play a crucial role in organizing PT services that are in line with quality criteria defined by an SMG. Local authorities should focus on enhancing cycling and walking infrastructure, with the understanding that health benefits from active mobility can be significant if adequately supported. However, it is important to be aware of the potential shift in travel behaviour from active modes to public transport, as observed in some scenarios. Local governance can also play a key role in implementing restrictive measures to manage and reduce car use, such as speed limits and congestion pricing, to mitigate rebound effects. Regardless of implementing the specific SMG approach as discussed in this thesis, the research shows that measures for sustainable mobility offer large social and economic benefits. Decision makers do not have to "wait" for a refined SMG-concept but can already start to implement elements of the SMG and individual measures to support sustainable mobility.

This research underscores the importance of including data-driven insights and stakeholder collaboration in policy design to balance economic viability with ecological benefits. Supporting periodic surveys of mobility behaviour and funding of updating transport models to reflect current trends and help monitoring developments can further enhance policy effectiveness.

For other countries, adapting these recommendations requires considering local contexts and transportation needs. While the core principles of investing in public transport, enhancing active mobility infrastructure, and reducing car use remain applicable, each country should tailor its approach based on its specific geographic, economic, and social conditions.

## 7.5 Final conclusions

This thesis demonstrates the potential of a Sustainable Mobility Guarantee (SMG) as an effective policy framework to promote accessible and sustainable transport - a critical step in addressing some of the most pressing social and ecological challenges of our time. By focusing on reducing car dependence and enhancing PT as well as active mobility, the SMG contributes to a more equitable and environmentally responsible transport system.

Economically, the largest benefit of the SMG comes from the reduction in greenhouse gas (GHG) emissions, which plays a pivotal role in its overall value. However, even without considering these emission reductions, the SMG demonstrates a positive economic outcome, as its benefits significantly outweigh the associated costs. Additional major benefits are lower vehicle operating costs, lower accident costs and reduced environmental pollution.

However, realizing the full potential of the SMG requires coordinated efforts across all levels of governance. National investments in high-quality public transport, reallocating environmentally harmful subsidies, and fostering demand-responsive services are essential steps. Local authorities must enhance walking and cycling infrastructure while introducing measures to manage car use, such as speed limits or congestion pricing.

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The SMG aligns with the broader goals of a social-ecological transformation, contributing to a sustainable and resilient mobility system that addresses both environmental challenges and social needs. It could ensure affordable and sustainable mobility options and serve as a basis for policies aimed at curbing excessive car use. This thesis underscores that policymakers do not need to wait for a fully refined SMG framework to begin implementation. Incremental measures supporting public transport, walking and cycling as well as car use reduction can already deliver substantial societal benefits. By taking decisive action now, decision-makers can set the foundation for a comprehensive and transformative framework for a socially just and sustainable transport system.

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