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Course change: Navigating urban passenger transport toward sustainability through modal shift

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ABSTRACT
Staying within the 2 °C (preferably 1.5 °C) limit requires fast and fundamental system changes, also in urban passenger transport. Shifting car traffic to environmentally friendly transport modes is one central strategy to make urban transport more sustainable and climate friendly. However, in most cities car use remains high. Therefore, this paper analyzes what course change is needed regarding direction, scale and speed of change for urban sustainability and climate protection reasons. The paper analyzes the role of modal shift as a strategy in itself and in relation to land-use (avoid) and efficiency (improve) measures. The paper draws on insights from European frontrunning cities and explorative forecasting scenarios calculated with the sophisticated integrated land-use transport model "Ruhr Region 2050". The paper suggests that a significant reduction of urban car use is needed (*direction*) that roughly equals a fast halving of car use (*scale*), which has proven feasible under the current socio-political conditions by annual reduction rates of 0.5 to 1.5 percentage points of the trip-based modal share of car use (*speed*). Significantly reducing car use requires comprehensive and high-intensive measures that go far beyond usual practices. Modal shift measures need to play a crucial role in integrated approaches with land-use (avoid) and efficiency (improve) measures because they have the potential to significantly reduce car use and CO_2 emissions and because they can produce comparatively fast effects – which makes modal shift measures first aid approaches to achieve a fast "bending of the curve" of excessive car use and growing CO_2 emissions.

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1. Introduction

Humanity has to act in an unprecedented fast way to combat climate change. So far, human activities have already caused approximately 1.0 °C of global warming and we are heading toward 3 to 4 degrees by the end of the century if we do not increase and accelerate actions now (IPCC, 2018). Climate change as one core "planetary boundary" that delineates the environmental limits within which humanity can safely operate (Rockström et al., 2009) has already been crossed in 2015 (Steffen et al., 2015). Staying within the 1.5 °C limit is essential to prevent dangerous and irreversible threats of global warming to ecosystem and humankind (IPCC, 2018). However, the current global and German CO_2 emission reduction commitments and actions are not even sufficient to stay within the 2 °C limit (IPCC, 2018; SRU, 2019). This underlines the very urgent need for energy system changes – also in urban passenger transport. Taalas & Msyua put in a nutshell by saying: "Every bit of warming matters, every year matters, every choice matters" (IPCC, 2018, p. vi).

One central strategy to make urban passenger transport more sustainable and climate friendly is modal shift, i.e. shifting car traffic to the environmentally friendly transport modes (walking, cycling, public transport; complementary car sharing) that needs to be implemented in integrated approaches with traffic avoidance and improving transport efficiency (avoid-shift-improve) (Sims et al., 2014, p. 603). Avoiding journeys can be achieved by, for example, densifying urban settlement structures, car pooling, utilizing information and communications technology and home office. Shifting traffic can be encouraged by push and pull measures: Push measures are restrictive against car use and aim to make car driving less attractive. Pull measures improve environmentally more friendly transport modes to reduce car dependency and to make alternatives to the car more attractive (Batty et al., 2015; Creutzig et al., 2012). Improved energy efficiency can be achieved by lowering energy intensity (MJ/passenger km) (e.g., enhancing vehicle and engine performance, using lightweight materials) and by reducing carbon intensity of fuels (CO_2eq/MJ) (e.g., substituting oil-based products with natural gas, bio-methane, biofuels, electricity or hydrogen produced from low GHG sources) (Sims et al., 2014, p. 603).

Modal shift can be specifically well addressed in cities and urban areas (Zimmer et al., 2017), because cities have

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dense and mixed-use settlement structures and diversified mobility options and because modal shift measures are a classical field of action for policy makers at the local level (Müller & Reutter, 2020). Nevertheless, in most cities no major modal shift has been realized so far and the transport sector is considerably lacking behind in contributing its dutiful share to CO_2 emission reductions.

Considering the complex and very challenging task ahead of us to rapidly develop low carbon urban transport systems, there is relatively limited scientific knowledge about what this acutally means for urban modal shift strategies. While many studies have investigated the potential effect of single modal shift measures or measure combinations on reducing car use and CO_2 emissions, there are three aspects that still appear under-researched.

1. Only few studies have analyzed modal shift measures in a deliberately ambitious and target-oriented approach that address the overall direction, scale and speed of change needed to effectively reduce urban CO_2 emissions – particularly regarding analyses for a specific region and a time frame until 2050.
2. Only few studies have analyzed a deliberately wide range of different modal shift measures, their relevance compared to each other and in relation to land-use (avoid) and efficiency (improve) measures, which is due to the inability of many models to adequately simulate interdependencies between measures and measure bundles like counter, synergy and rebound effects.
3. While it is common practice to use empirical data to underpin scenario studies, real-world knowledge is not commonly used to "bridge" insights gained from scenario analyses to real-world developments to estimate what course change appears to be necessary and feasible.

This paper aims to step into this open research gap. Using the theoretical framework of transition theory, the paper analyzes the direction, scale and speed of change needed in urban modal shift strategies for climate protection and urban sustainability reasons. The paper thinks backwards from the long-term goals of urban sustainability and the very challenging "well below 2 °C limit", preferably 1.5 °C limit, to estimate the kind and scale of action needed already today (Raskin et al., 1998, 2002, 2010; Rotmans et al., 2001). The paper takes a three-step approach to provide target, transformation and system knowledge (Schneidewind, 2013) by 1. discussing the adequacy and feasibility of an ambitious modal split target (*target knowledge*); 2. developing modal shift measures that are assumed to be adequate to reach the proposed modal shift target (*transformation knowledge*); 3. estimating the modal shift and CO_2 emission reduction effects of these measures in explorative forecasting scenarios – overall and in relation to land-use (avoid) and efficiency (improve) measures (*system knowledge*).

The paper uses the highly complex integrated land-use transport (ILUT) model "Ruhr Region 2050" developed by Spiekermann & Wegener, Urban and Regional Research (S&W), which allows to analyze a deliberately wide range of different modal shift measures. The measures are analyzed in a consequently ambitious approach for the Ruhr Metropolitan Region in Germany. Furthermore, the paper integrates a considerable amount of real-world knowledge from successful frontrunning cities (past modal shift developments, existing targets, good practice measure examples) to generate a holistic 'big picture' (Köhler et al., 2019) of the dimension of change that is needed and that appears feasible under the current socio-political conditions. By this approach, the paper aims to bring together profound scientific insights from the scenario and the real world to generate scientifically robust and societally relevant (Padmanabhan, 2018) knowledge to support sustainability transitions in urban passenger transport.

Section 2 provides a literature review regarding transition research (2.1), modal shift analyses (2.2) and the use of ILUT models for sustainability purposes (2.3). Section 3 describes the "starting conditions" of the Ruhr Metropolitan Region (political background, current state of urban passenger transport). Section 4 details the methods applied in the analysis. Section 5 presents the results. Section 6 discusses the results, its strengths and limitations, outlines further research needs, reflects upon actions to be taken in the Ruhr Metropolitan Region and concludes with further reaching thoughts about a fundamental course change to come about.

2. Literature review

2.1. Transition theory

The paper uses transition theory to focus research topic and analysis. Transition research seeks to better understand the dynamics and mechanisms of sustainability transitions and to support and accelerate societal transformation processes through knowledge-based navigation support (Loorbach et al., 2017). It emerged at the end of the 1990s with origins in the Netherlands and Western Europe (Grin et al., 2010). Over the last two decades, literature on transition theory has grown rapidly (Köhler et al., 2019) and transition research is entering mainstream policy by being recognized in policy-relevant strategy documents (European Environment Agency, 2019; Turnheim et al., 2020; WBGU, 2011).

Significantly reducing car use is a challenge that can be defined as a sustainability transition of urban transport, i.e., a radical socio-technical transformation process toward a sustainable society (Grin et al., 2010). Transition theory argues that for supporting fundamental societal change processes, system, target and transformation knowledge is needed (Bierwirth et al., 2017). Target knowledge provides visions, norms and concepts of a reasonable and appropriate destination that is operationalized in indicator-based targets (Wiek et al., 2006). Transformation knowledge sheds light on what is necessary "to realize the transition from the current to the target state" (Wiek et al., 2006, p. 744). From a transition theory perspective, the development and use of a portfolio of options is essential when there is a lot of uncertainty about which option is best "to avoid the danger of getting locked into sub-optimal solutions" (Kemp et al., 2007, p. 4), which is why this paper analyzes a deliberately wide range of different modal shift measures. System knowledge includes insights on the problem situation, the functioning of the analyzed system and future knowledge of potential system developments (Kemp et al., 2007), for example through scenario analysis. The three steps of this paper aim to provide target, transformation and system knowledge to support sustainability transitions in the field of urban modal shift.

2.2. Modal shift

Modal shift targets are frequently reported in urban case studies (Buehler et al., 2017; Buehler & Pucher, 2011; Gössling, 2013), but have been less analyzed per se. Transition research considers missions and targets toward sustainability to be a "challenging but important topic that raises fundamentally political questions about defining collective priorities". However, so far the transition research community "has done less research on policy missions and targets" (Turnheim et al., 2020, p. 118).

The available options to achieve substantial modal shifts are widely known (Batty et al., 2015; Santos et al., 2010). Numerous studies have analyzed the effects of single modal shift measures on reducing car use and CO_2 emissions (see supplemental material for central results). Scenario studies that analyze the effects of modal shift measure combinations in passenger transport have been conducted for different geographical scales, different policy options (avoid, shift, improve) and different policy intensities, using different methodological approaches (Cuenot et al., 2012; Hammadou & Papaix, 2015; Hensher, 2008; Hickman & Banister, 2007; International Energy Agency, 2009; Kii et al., 2014; Potter, 2007; Zhang & Zhang, 2018). Some studies have analyzed high-intensity measures to assess their potential to reach CO_2 emission reduction targets in both backcasting and forecasting scenarios (Conti, 2018; Creutzig et al., 2012; Hickman et al., 2010; Reutter & Reutter, 2016). The studies suggest that it is extremely difficult to reach CO_2 mitigation targets in passenger transport and that radical measures are needed that go far beyond usual current practices, covering land-use (avoid), modal shift and efficiency (improve) measures in an integrated approach. While efficiency measures are understood to bring about major contributions to carbon reductions, they are likewise seen critically due to possible rebound effects, socially and environmentally unsustainable use of critical raw materials, limited renewable energy capacities to supply all energy sectors, and their limited contribution to overall urban sustainability (e.g., air pollution, noise, accidents, land usage, urban living) (Hickman & Banister, 2007). Land-use measures have the potential to shorten trip distances and reduce car dependence through dense and mixed-use settlement structures (Hammadou & Papaix, 2015; Santos et al., 2010). However, their impact is rather small and slow, because the built environment cannot be changed easily (Aditjandra, 2013; Creutzig et al., 2012; Zhang & Zhang, 2018). Research underlines the need to use more advanced and detailed transport models to analyze the potential of comprehensive policy packages and the complex interdependencies between policies (synergies, rebound effects) (Creutzig et al., 2012; Cuenot et al., 2012; Hickman et al., 2010).

2.3. Integrated land use transport (ILUT) models

ILUT models simulate the reaction of households and individuals to urban system changes, which can be influenced by the model user by entering assumed policies, e.g., land-use and transport policies (Wegener, 2014).

The first ILUT model was the spatial-interaction or gravity model implemented by Lowry (1964). The model consists of two singly constrained spatial-interaction location models, a residential location model and a service and retail location model nested into each other. Spatial-interaction location models retain the original Lowy concept of modeling the location of human activities as destinations of trips using the production-constrained spatial-interaction model. Early operational examples of this kind are MEPLAN (Echenique, 1985), TRANUS (de la Barra, 1989) and PECAS (Hunt & Abraham, 2005). These models use a multi-industry, multi-regional input-output framework to predict the location of production and consumption in the urban regions. The second group of land-use transport models predicts the opportunity for spatial interactions called accessibility. Examples of operational accessibility-based location models are IRPUD (Wegener, 1982), RURBAN (Miyamoto & Kitazume, 1989), MUSSA (Martinez, 1996), DELTA (Simmonds 1999) and UrbanSim (Waddell, 2002).

The urban models sketched so far represent the main model types existing until the end of the 1960s. From then on, the urban modeling scene has become increasingly fragmented along two dividing lines: The first divide runs between equilibrium modeling approaches and models that attempt to capture the dynamics of urban processes. The second more recent divide runs between aggregate micro-analytic approaches and new microscopic agent-based models.

The IRPUD model applied in this paper integrates all of these advances in modeling technology. Its location submodels use advanced user-group specific spatial interaction models to take account of both land market and accessibility aspects of land market competition. It considers the dynamic evolution of urban markets by dividing the future into time periods of limited duration and it considers the diversity of consumer preferences by disaggregating household preferences by individual households in the housing market. That a similar disaggregation of preferences was not performed in the labor market, land market, market for nonresidential buildings and transport market (see section 4.2) was a limitation accepted for data about user preferences and computing speed considerations.

While a reasonable number of sophisticated ILUT models has been developed and applied to real-world environments (Hunt et al., 2005; Iacono et al., 2008; Kii et al., 2016; Moeckel et al., 2018; Wegener, 2004, 2019), it is an ongoing

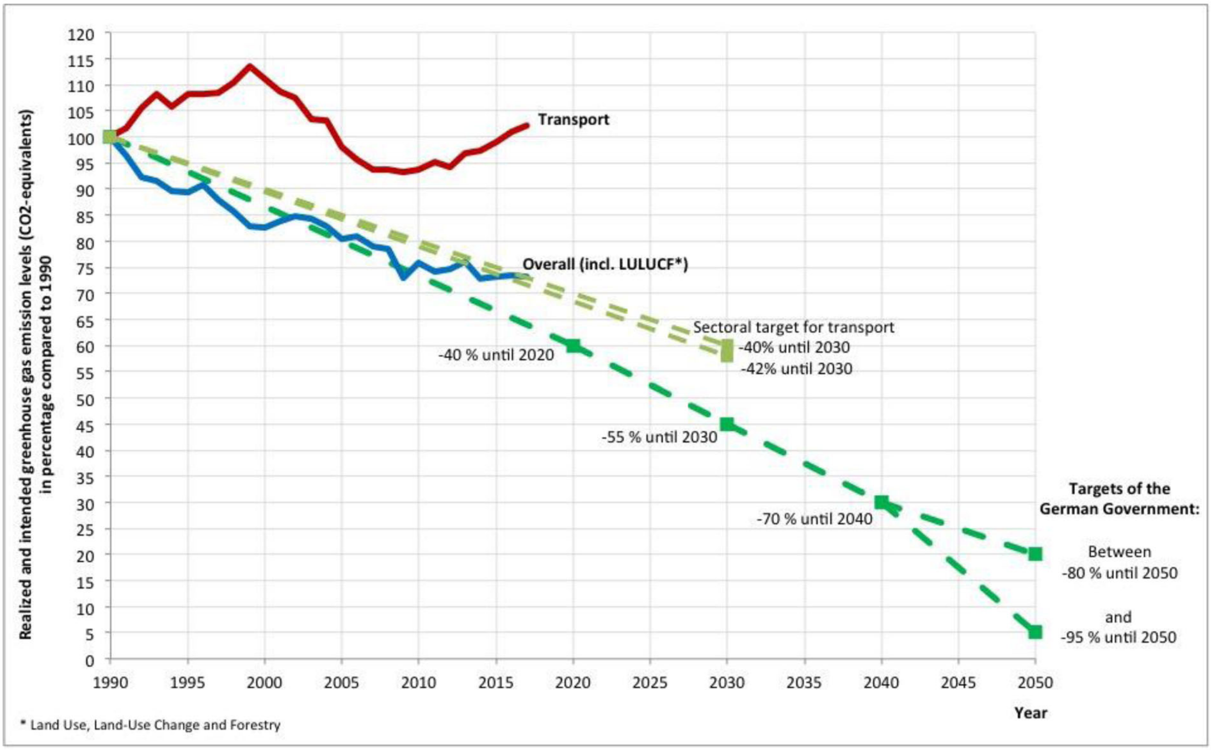


Figure 1. Overall and transport greenhouse gas emissions in Germany and mitigation targets of the German Government (1990–2050).
Source: Reutter et al. (2013, p. 8), (updated in 2019).
Sources of data: Umweltbundesamt (2019a, 2019b, 2019c); BMUB (2016).

challenge to integrate environmental aspects (Acheampong & Silva, 2015; Ford et al., 2018; Wegener, 2018). This paper represents one of the early endeavors to use an ILUT model for analyzing mitigation options in an urban area. Preceding ILUT studies that analyzed sustainability aspects of passenger transport have focused on different topics and different geographical and time scales (Aditjandra (2013): land-use in a British metropolitan region 2000–2031; Kii et al. (2014): road pricing and land-use regulations in a simplified synthetic city; Hensher (2008): pricing strategies and public transport frequency in the Sydney metropolitan area 2010–2015). This paper extends former research by analyzing a deliberately wide rage of different modal shift measures for the long time period 1990–2050 and their relation to land-use (avoid) and efficiency (improve) measures, which is possible by using the "sophisticated modeling system [of the Ruhr Area Model]" (Ford et al., 2018, p. 92).

3. Orientation: Where are we now?

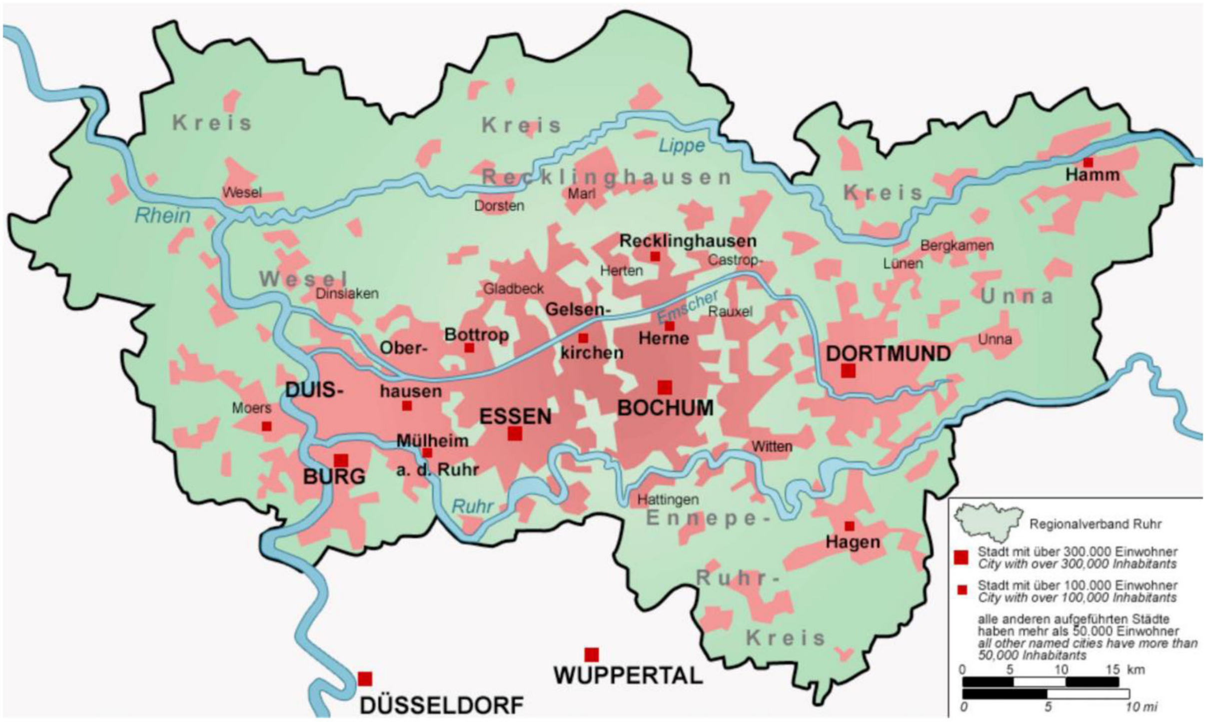
3.1. Political background: Reducing car use for climate protection

By April 2021, 191 of 197 Parties have ratified the Paris Agreement (United Nations Framework Convention on Climate Change, 2021) that aims at "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (UNFCCC, 2015, p. 3). Germany ratified in September 2016. In its Climate Action Plan, the German Federal Government reaffirms its target set in 2010 to reduce CO_2 emissions by 40% until 2020, 55% until 2030 and 80% to 95% until 2050 compared to 1990 (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit [BMUB], 2016).

The transport sector causes about one fifth of overall direct CO_2 emissions in Germany – to the largest degree caused by car traffic on roads (61%) (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit [BMU], 2019b). The specific target for the transport sector is to reduce CO_2 emissions by 42 to 40% until 2030 compared to 1990 (BMU 2016). In 2019, the overall CO_2 emission reduction targets for 2030 and 2050 and the sector-specific targets entered a national climate protection law (Bundes-Klimaschutzgesetz (KSG)).

Without taking effects of the Corona crisis into account, the German 2020 target to reduce CO_2 emissions by 40% compared to 1990 is expected to be missed by about 8 percentage points (BMU, 2019a). Whereas the overall energy-related greenhouse gas emissions of Germany were reduced by 27,7% by 2017 (BMU, 2019a), greenhouse gas emissions of the transport sector are currently higher than 1990 (+2,2% 1990–2017) (Umweltbundesamt, 2019a, p. 137) (Figure 1). This underlines that particularly in the transport sector, fast and effective counteractions are needed.

There is increasing scientific knowledge that more ambitious targets and significantly accelerated actions are needed due to the insufficient past CO_2 emission reductions and because current reduction ambitions will not even lead to stay within the 2 °C limit (IPCC, 2018; SRU, 2019). Several citizen movements claim that Germany needs to become climate neutral much sooner: by 2035 (e.g. Fridays for Future,



Source: Daniel Ullrich, 2004, CC BY-SA 3.0;

Figure 2. Urban structures of the Ruhr Metropolitan Region – all cities with more than 50,000 inhabitants.
Source: https://de.wikipedia.org/wiki/Ruhrgebiet#/media/Datei:Ruhr_area-map.png

German Zero e.V.) or even by 2025 (Extinction Rebellion) instead of 2050.

Currently, German cities and regions do not have any legally binding reduction obligations. Nevertheless, many cities have self-committed to ambitious reduction targets, for example to become climate neutral by 2030 (Tübingen) or 2035 (Gießen, Konstanz, Düsseldorf, München, Soest). In the Ruhr Region, seven of the eleven administratively independent cities join the Covenant of Mayors for Climate and Energy, which implies the objective to reduce CO_2 emissions by at least 40% until 2030 compared to 1990 and to accelerate decarbonization for 2050 (https://www.eumayors.eu/en/). Since 2019, the first German cities including one third of the 53 Ruhr Region municipalities declared their "climate emergency", i.e., they acknowledge that humanity is in a climate emergency and that more ambitious and accelerated actions need to be taken.

3.2. Starting conditions: High share of car use in the Ruhr metropolitan region

The Ruhr Metropolitan Region is one of the largest agglomeration areas in Europe. 5.1 million inhabitants (2018) live in 53 municipalities in an area of 4,439 km^2 with an average population density of 1,140 inhabitants per km^2 (www.metropoleruhr.de). Eleven administratively independent large cities form the urban center with roughly 2.5 million inhabitants. Another 42 municipalities belong to four districts in the border zones that also contain rural areas (Figure 2).

During the rise of coal production in the 19th century, settlement structures grew rapidly, particularly around mineshafts. This has led to pronounced polycentric settlement structures. Extensive destructions in World War II created favorable conditions to realize car-friendly urban structures. The working-class milieu favored this planning principle because the car was seen as a status symbol according to the motto "We have made it" (Behr & Ahaus, 2015). Although the polycentric settlement structures and a dense rail and road network principally offer favoring conditions for sustainable mobility, car use is high: 58% of all trips are made by car (year 2017) (Regionalverband Ruhr [RVR], 2018), compared to an average of 38% to 50% in major German cities and urban areas (Nobis & Kuhnimhof, 2019). A high share of car use occurs throughout the region also in big cities above 500,000 inhabitants (Dortmund, Essen, Duisburg) and above 100,000 inhabitants (Bochum, Gelsenkirchen) (see supplemental material). Overall, the Ruhr Metropolitan Region can be considered a "late-moving urban area" where no relevant modal shifts have been realized so far and where much more ambitious approaches are required – as it is the case in many other urban areas.

4. Methods

4.1. Methodological approach

The methodological approach consists of three steps (Figure 3). First, the paper discusses the ambitiousness and feasibility of an operationalized modal split target that has been introduced

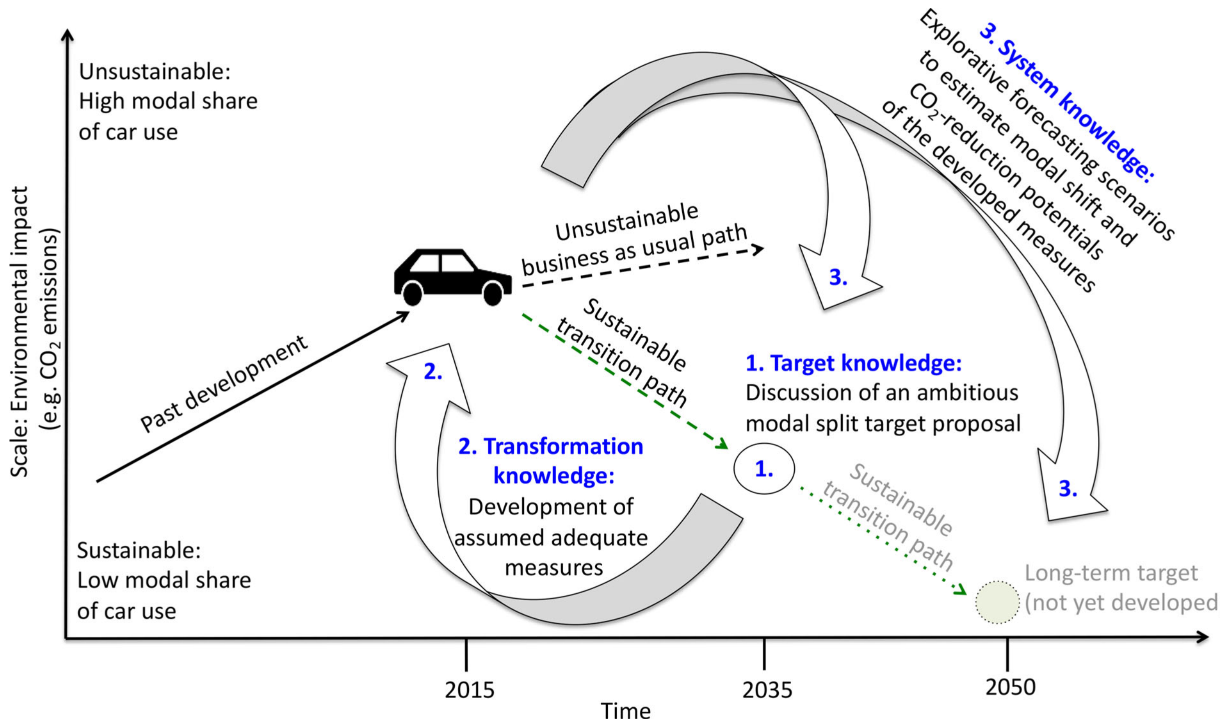


Figure 3. Methodological approach: Navigating toward sustainable urban passenger transport regarding direction, scale and speed of urban modal shift. Own figure; similar figures see Hickman & Banister (2007, p. 379) and Van Vuuren et al. (2015, p. 305) (which is also used in Geels et al., 2020).

to the mobility debate of the Ruhr Metropolitan Region for sustainability reasons but not yet been politically adopted. Targets should comply with the SMART criteria and be specific, measurable, ambitious, realistic and time-bound (Maxwell et al., 2015). The paper focuses on the question to what extend the proposed target can be considered to be "realistic" by relating it to past developments and future targets of selected real-world frontrunner cities.

Second, a purposely wide range of modal shift measures are developed that are assumed to have the potential to reach the proposed modal shift target. The measures fall within the area of responsibility of regional and local stakeholders and reinforce EU and national transport policies through a regional approach. Furthermore, land-use (avoid) and efficiency (improve) measures are developed. The measures are developed in an expert approach (Wiek et al., 2006), i.e. by discussions among the research team members based on existing data and empirical research. Each measure is substantiated by at least one European "counterpart"-city (or region) that has already successfully realized a similarly ambitious measure. The city examples are used to substantiate the scenarios and to check their plausibility. The selected frontrunning cities are also used in steps 1 and 3, where their modal split developments are analyzed.

In the third step, the paper estimates the modal shift and CO_2 emission reduction potentials of the developed single measures and measure bundles by conducting explorative forecasting scenarios with the integrated land-use transport (ILUT) model "Ruhr Region 2050" developed by S&W. The paper juxtaposes selected modal shift modeling results to already successfully realized modal shifts in the city examples to provide a holistic picture of the direction, scale and speed of urban modal shift that appears feasible if politically intended and to do a plausibility check of the scenario results. Wiek et al. argue that while "knowledge about the future is 'non-verifiable' in the conventional sense", plausibility is a quality criterion for scenarios that generate future-oriented knowledge (2013, p. 135). Plausibility means that the futures described by the scenarios can be considered to be theoretically 'occurable' ("could happen") and are not completely unthinkable (Kosow & Gaßner, 2008). So far, there is no scientific consensus on the concrete meaning or operationalization of plausibility for scenarios (Urueña, 2019). Wiek et al. (2013) propose a 'retrospective' plausibility check for constructing and evaluating future scenarios. They refer to the futurist quote "the future is already here – it's just not very evenly distributed" (Emery, 1977; as cited on p. 138) and claim that scenario elements can be deemed plausible if similar events have occurred in the past or are still occurring, at the same location or elsewhere, under similar or different conditions, or if scenarios are at least substantiated by theoretic concepts (Wiek et al., 2013).

4.2. Integrated Land use and transport model Ruhr 2050

The ILUT model "Ruhr Area 2050" covers the time period 1990 to 2050 (base year: 2015). The model is a further development of the IRPUD ILUT model that has originally been developed since 1977 for the city region of Dortmund and applied in several research projects (Beckmann et al., 2007; Fiorello et al., 2006; Lautso et al., 2004; Spiekermann & Wegener, 2005). The model analyzes the complex interactions of developments in demography, economy, land use, transport and the environment in the Ruhr Metropolitan

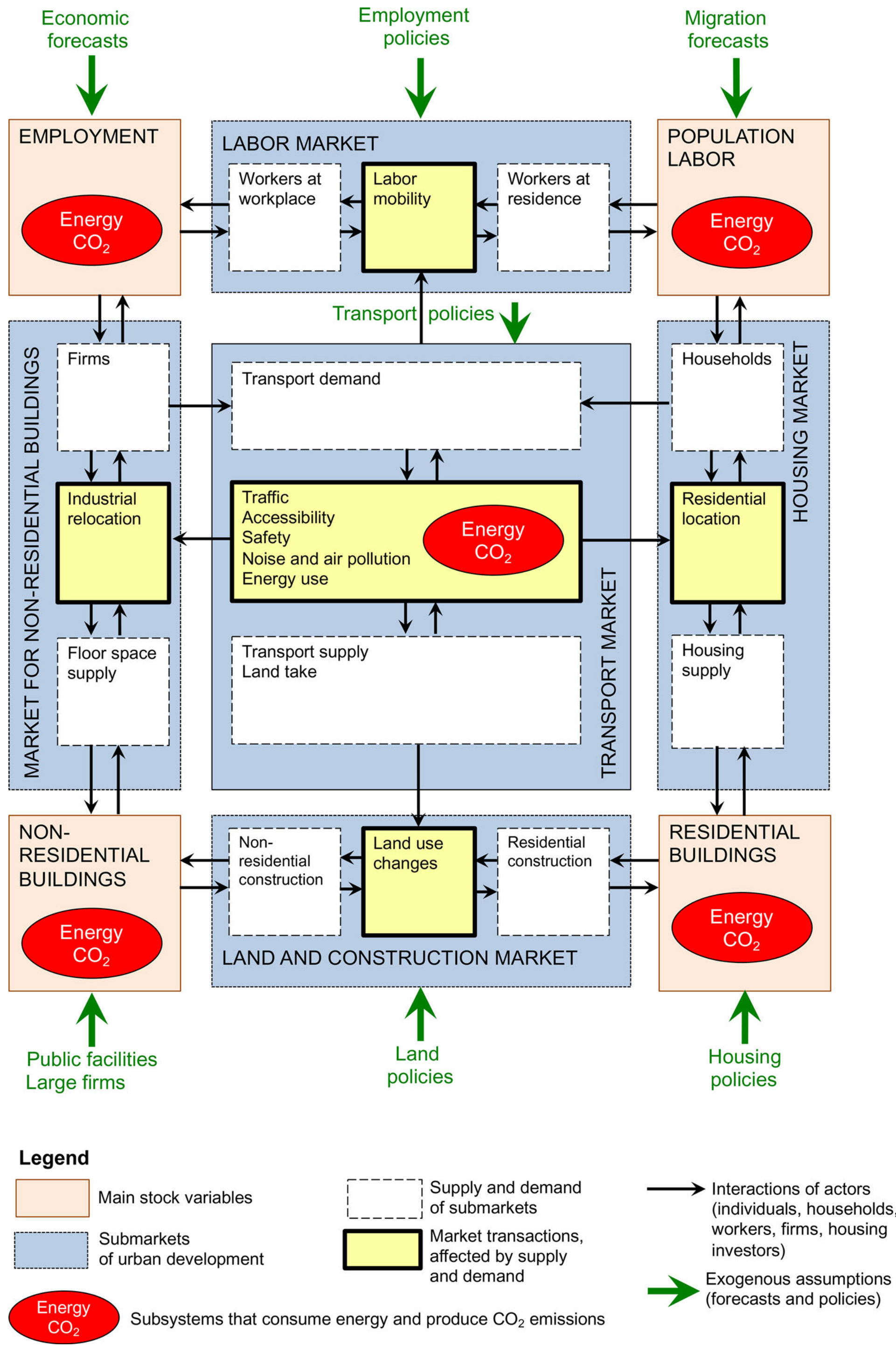


Figure 4. Subsystems of the integrated Ruhr Area model.
Source: Wegener (2018, p. 5); Schwarze et al. (2017, p. 13); color changes and slight amendments

Region from 1990 to 2050, based on large data sets and long computing times (Wegener, 2020).

All scenarios are modeled with two different assumptions about energy price developments, because energy prices impact the effectiveness of measures: moderate increases (fuel prices increase 1% per year; A-scenarios) and high increases (4% per year; B-scenarios). The business-as-usual scenarios (A-/B-BAU) show the developments that are most likely to occur if all ongoing trends and developments continue until 2050. Measures mainly come into action in 2020; some are gradually intensified at later stages.

The following sections outline the modeling methodology of the ILUT model Ruhr 2050 (for a detailed explanation see Wegener, 2018).

4.2.1. Rationale and structure of the model

The model endogeneously simulates the behavior (e.g., land-use, mobility decisions) of private actors (persons, households, companies) as a reaction to urban developments that can be exogeneously influenced by the model user through entering assumed public planning policies in the policy fields of economic promotion, housing, public facilities and transport (Schwarze et al., 2017). The model estimates the resulting effects on land use, transport and the environment in the Ruhr Metropolitan Region. The model simulates a rational behavior of private actors, which is guided by preferences and group-specific constraints (legal, economic, informational). For modeling travel behavior, three quantitative indicators are used: travel time, travel costs and a comfort factor. The comfort factor is qualitatively estimated for each transport mode and considers aspects that influence the use of a transport mode, such as physical efforts, weather dependency and subjective safety perceptions (Schwarze et al., 2017). The model assumes that individuals try to maximize the number of destinations that can be reached within their given money and travel time budgets. This leads to more and longer trips if travel is fast and cheap and less and shorter trips if environmental policies make mobility slower and more expensive.

The model subdivides the Ruhr Metropolitan Region into 687 internal zones and 134 external zones surrounding the Ruhr Area. Multimodal transport networks interconnect these zones with each other. Figure 4 is a schematic representation of the most important model components. The model consists of six interconnected submodels (transport, ageing, public programs, private construction, labor market, housing market), which are calculated in cyclical sequences. The transport model calculates four different trip purposes (work, shopping, services/social and education trips) of four socioeconomic groups for four travel modes (car, public transport, cycling, walking) in three-year-steps. Mobility decisions of individuals and households (car ownership, number of trips, travel distances, mode and route choice) react to the development of traveling time and costs, costs for owning a car, energy prices and household budgets. Equilibrium of the transport network is generated as a reaction to congestion (Wegener, 2018).

4.2.2. Model data

The model integrates four data groups: model parameters (e.g., demography, households, housing, land-use, transport, income/costs, preferences), regional data (economic and demographic development of the region), zonal data (distribution of urban structures in the base year of the simulation 1990) and regional transport network data (past and assumed future developments) (Wegener, 2018). 1987 census data is used for the base year (1990). Digital geodata is used for zonal information, e.g., regional and urban land-use maps. For the transport network, information is used from official open data city maps, OpenStreetMap and digital public transport timetables (Brosch et al., 2014).

4.2.3. Calibration and validation

The model is calibrated by using empirical structural data from the past (see section 4.2.2). Parts of the model are based on expert estimations, if no or insufficient empirical data is available, e.g., for the price development of electric cars or the number of cars that are replaced through car sharing. The extrapolation of past or present data is also necessary where data for future developments are required; these are necessarily exogenous assumptions, which significantly influence the outcomes of the scenarios. In other words, the model outputs are no forecasts that can be expected to become real with certainty, but possible futures that may appear desirable or to be avoided.

Several approaches were used to validate the model, like sensivity analyses, expert discussions among the members of the research project coming from three different research and planning institutions in the fields of geography, transport, spatial and infrastructure planning in several workshops, and comparing modeling results to real-world developments in frontrunner cities. Furthermore, preliminary and final modeling approaches and results were discussed with experts from research and practice in workshops and on conferences and widely distributed in reports and project notes. This way of validation is typical for research projects dealing with long-term developments into the future. Overall, the model adequately simulates long time periods of past developments (e.g., population trends, CO_2 emissions, modal split) compared to many other ILUT models that do not simulate past developments at all or for such a long time period.

5. Results

5.1. Target knowledge: Where do we need to head?

There is no direct link of what the "well below 2 °C" or 1.5 °C limit mean for a mid-term modal shift target. Modal shift is only one strategy besides traffic avoidance and technical improvements. Each society and each city has to agree upon its own modal shift target, based on the specific starting and framework conditions. However, for climate protection and urban sustainability reasons there is the need to substantially reduce car use, particularly in urban areas where modal shift can be particularly well addressed and where the negative impacts of car use directly impact health and quality of life (Sims et al., 2014). A modal shift target serves as a mid-term proxy (Van Vuuren et al., 2015) to navigate at an adequate speed and to an adequate scale into the right direction of sustainability and climate protection goals and to develop adequate measures to get there.

A trip-based modal split target proposal of 25% car use, 25% public transport, 25% cycling and 25% walking ('four quarters') has been developed by the Wuppertal Institute for Climate, Environment and Energy [WI] in dialogue with regional stakeholders and introduced to the mobility debate of the Ruhr Metropolitan Region in several studies for the target year 2035 (base year: 2012) (Reutter et al., 2013 & 2017) (Figure 5). The target has been proposed due to its catchiness and because it implies the thumb rule of a fast halving of urban car use (Müller & Reutter, 2017). The target has been discussed in the region since then, for example by the regional planning institution (RVR, 2014), but has not yet been politically adopted. Only the City of Essen (590,000 inhabitants) adopted a 4 × 25% target for 2035 as part of its successful application to win the "European

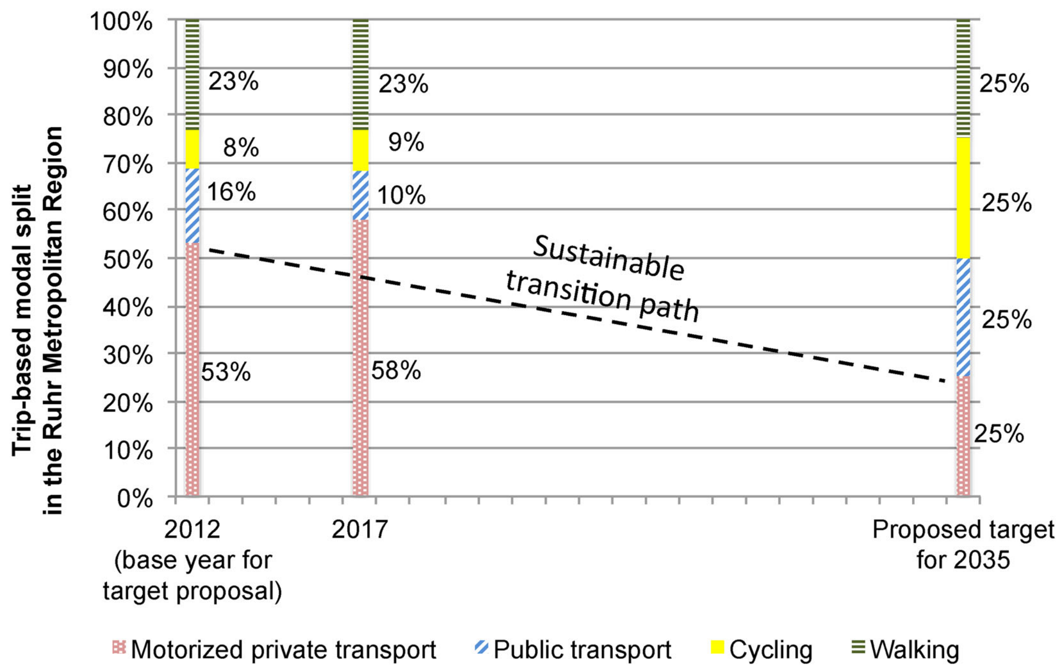


Figure 5. Scale of change needed: Current modal split in the Ruhr Metropolitan Region and proposed target for 2035. Modal split data: Grindau & Sagolla (2012); RVR (2019); Target proposal: Reutter et al. (2013, 2017), RVR (2014).

Green Capital Award 2017" of the European Commission (City of Essen, 2014) and currently works on reaching this target (City of Essen, 2019). However: according to the latest data available, the modal share of car use has continued to increase from 53% (2012) to 58% (2017) (Figure 5).

To estimate the ambitiousness and feasibility of the modal split target proposal, this section compares the proposed target to the 13 selected real-world city examples (see section 5.2) regarding the current modal share of car use (1.), existing targets (2.), and already successfully realized past reduction rates (3.):

1. Reducing car use down to a trip-based modal share of 25% can be considered to be very ambitious, as currently only four of the selected real-world cities come close to such a low share (Barcelona 24.2% (2013), Vienna 27% (2020), Vitoria-Gasteiz 24.7% (2014), Zurich 25% (2015) (see Appendix 1).
2. The proposed target implies that the trip-based modal share of car use needs to be reduced by 1.2 percentage points per year (2012–2035). Four out of the 13 selected frontrunner cities have also adopted modal split targets (Copenhagen, London, Vienna, Zurich; see Appendix 2). The targets equal quite uniformly average reduction rates of 0.7 percentage points trip-based modal share of car use, up to 1.0 percentage point in case of Vienna's target for 2030 (based on an assumed reached target in 2025). The proposed target therefore represents an ambitious target, as it implies a higher reduction rate compared to the existing targets in the selected cities.
3. All selected 13 European frontrunner-cities have successfully reduced their share of car use in the past years: By 0.3 (Karlsruhe) to 1.1 (Oslo) trip-based percentage points per year (mostly: 0.5 to 0.6), when calculating the average reduction rates based on the earliest and the latest modal split data available (see Appendix 1). This calculation allows estimating the reduction potentials over a longer time period that may also include times without any modal shifts ("long-term average").
   For eight cities, modal split data is available for a long time period, but main modal shifts have occurred during shorter time periods. In these "sharpes reduction phases", the average reduction rates range between 0.7 and 2.0 percentage points per year (see Appendix 1). Sharpest reduction rates of more than 1.2 percentage points per year have been realized by Copenhagen (2.0), Oslo (1.8) and Vitoria-Gasteiz (1.5). Such maximum reduction rates might have been realized for example under favorable political constellations or when ambitious modal shift measures were implemented – and may refer to what transition scholars call "acceleration phases" of transition processes (Loorbach et al., 2017; Rotmans et al., 2001). In acceleration phases, visible structural change takes place through developments in different societal sub-systems that reinforce and amplify each other (Raskin et al., 2002). Although the manifold reasons for stronger reduction phases remain a black box, because they are not analyzed in this paper, the identification of "sharpest reduction rates" allows estimating what maximum reduction rates appear feasible if politically intended and decisively pushed forward.

Overall, the proposed target for the Ruhr Metropolitan Region, which implies an average reduction rate of 1.2 trip-based percentage points per year, can be considered to be very ambitious, as it is higher than the long-term average reduction rates realized by the selected frontrunner cities and has proven feasible only during accelerated times of change in three of the 13 selected cities. To reach the target, considerably accelerated actions are needed in the Ruhr Metropolitan Region. This is particularly true against the background that in recent developments the modal share of car use has continued to increase, which now requires an even more radical course change with an average reduction rate of 1.8 trip-based percentage points per year. Such a reduction rate is only achievable through continuously accelerated change processes like during the "sharpest reduction phases" of Copenhagen and Oslo.

Overall, an ambitious modal shift target is justified, as the Ruhr Metropolitan Region has not yet reduced its urban share of car use, whereas other cities have already successfully done so. Given the existing formal agreements (e.g., Paris Agreement, national targets, climate emergency), the maturing knowledge about climate protection requirements (IPCC, 2018) and the narrowing time window to act timely make a fast and fundamental course change even more pressing. For a partly rural region like the Ruhr Metropolitan Region, a regional target implies that large and dense cities like Essen and Dortmund need to reduce their car modal share even below 25 per cent to compensate higher shares in rather rural areas, where it appears more difficult to reduce car dependence. London, Vienna and Zurich clearly aim for lower shares than 25 per cent.

5.2. Transformation knowledge: What are adequate options for action?

The ambitious modal shift target requires measures that go far beyond usual practices. Table 1 presents the push and pull measures developed for modeling that are assumed to have the potential to significantly reduce car use. The table also includes the land-use (avoid) and efficiency (improve) measures developed for modeling. Each measure is substantiated by a real-world city example that has already successfully implemented a similarly ambitious measure. The city examples "bridge" the scenario study to the real-world by demonstrating that ambitious transport policies, which go far beyond conventional practices, are not only scientific assumptions but, in their basic idea, have proven to be realizable socio-politically. Transition scholars use this qualitative-quantitative "bridging" of different methodological approaches to facilitate dialogue from different perspectives and to support policy formation and action (Geels et al., 2016, 2020).

5.3. System knowledge: How far do we get with these measures regarding modal shift and CO_2 emission reductions?

To estimate how far the Ruhr Metropolitan Region would get with the measures, single and combined measure scenarios (Table 2) are modeled in the ILUT "Ruhr Area Model 2050" developed by S&W.

According to the modeling, the trip-based modal share of car use starts at a high level in the baseline years 1990 (50%) and 2015 (54%) and remains at a high level until 2050 in both BAU scenarios (A: 58%; B: 53%) (Appendix 3). The transport CO_2 emissions increase from 1990 to 2015 (1.2 to 1.6 tons CO_2 per inhabitant per year [t CO_2/i/y]) and decrease only slightly until 2050 if energy prices are low (1.5 t CO_2/i/y; i.e., +25% compared to 1990) compared to a stronger reduction if energy prices are high (1.0 t CO_2/i/y, i.e., −17% compared to 1990), due to technological improvements (vehicle fuel efficiency). The developments underline the impact higher energy prices have (B scenarios), as they reduce the trip-based modal share of car use by 5 percentage points and CO_2 emissions by one third compared to A-BAU in 2050. Higher energy prices could be politically realized for example by internalizing the external costs of car driving through an ecological tax at state level (Reutter et al., 2013).

5.3.1. Single measure scenarios

Most push and pull measures reduce the trip-based modal share of car use by up to 3 percentage points and contribute to CO_2 emission reductions (Appendix 3). Most successful among the push and pull measures in reducing CO_2 emissions are the push measures "reallocation of road space" (up to −41%) and "area-wide speed limits" (up to −24%), which make car driving slower and also contribute to reduced car use. The efficiency measure "increased energy efficiency of the vehicle fleet" reduces CO_2 emissions by up to 45% compared to BAU, but increases the modal share of car use by up to 4 trip-based percentage points as a rebound effect, because car driving gets cheaper. "Promotion of electric mobility" reduces CO_2 emissions by up to 14%, but does not lead to modal shifts. The scenario "more frequent public transport services" substantially increases transport caused CO_2 emissions (up to +28%), because the extended public transport services increase CO_2 emissions more than they reduce CO_2 emissions through modal shift (Reutter et al., 2013). The pull measures that accelerate walking and cycling do not lead to relevant modal shifts or CO_2 emission reductions. In the model, the measures do attract additional pedestrians and cyclists, but only few car drivers shift to non-motorized transport modes (see discussion in section 6.1). The land use measures do not lead to any relevant changes in car use or CO_2 emissions.

5.3.2. Combined scenarios

Figures 6 and 7 present the development of the modal share of car use over the course of time for the seven combined measure scenarios (see Appendix 3 for numerical results). The land-use and energy efficiency measures (scenarios 81 and 82) have almost no effect on changing the modal share of car use or even slightly increase car use. The pull measures (scenario 84) reduce the trip-based modal share of car use by up to 5 percentage points compared to BAU. The push measures (scenario 83) have a stronger effect and reduce car use by up to 9 percentage points. The combined modeling of the push and pull measures (scenario 91) intensifies the modal shift effects, as the effects do not only add up to each other but extra percentage points can be realized

Table 1. Assumptions of the measures developed for modeling and similar real-world examples.

Measures developed and modeled for the Ruhr Metropolitan Area (numbers = scenario numbers)	Real-world examples of similar measures in selected European cities
Land use	
13 Densification at railway stations: From 2020 onwards, construction projects for housing, retail and commercial use are permitted exclusively in zones with at least one railway station. This is the case in 170 of the 687 modeling zones (Schwarze et al., 2017).	In Hammarby Sjöstadt, a brownfield redevelopment area (24,000 inhabitants) located three kilometers south of **Stockholm** city center, dense and mixed-use settlement structures were developed with diversified mobility options including an extended tram line, which have led to decreased car use and CO_2 emissions (Foletta, 2011b).
23 New housing at railway stations: Starting in 2020, public authorities construct 13,000 publicly subsidized dwellings annually to provide affordable housing. All dwellings are constructed in immediate vicinity to railway stations (same zones as in scenario 13) (Schwarze et al., 2017).	Greenwich Millennium Village, a mixed-use, hig-density brownfield redevelopment site nine kilometers from **London** city center, with high quality public transportation and low car use (Foletta, 2011a).
Energy efficiency	
32 Promotion of electric mobility: Starting in 2020, subsidies for buying an electric car are increased step-by-step up to 33% of the purchase price in 2050. Also, fast charging stations in city centers are promoted by public infrastructure investments. The share of electric cars rises in this scenario from 30% in the BAU scenario to 50% in 2050.	Through intense promotion, battery electric vehicles (BEVs) make up 54.3% of all cars sold in **Norway** in 2020 (The Guardian, 2021), compare to 6.7% in Germany (Kraftfahrtbundesamt, 2021). Norway has the goal to only sell zero-emission cars starting from 2025. In **Oslo** (670,000 inhabitants), more than 50,000 pure electric passenger cars were registered in July 2020 (Joshi, 2020). The city promotes electric car use by infrastructural measures and incentives.
33 Area-wide car sharing: The car sharing offer increases from 2 car sharing vehicles per 1,000 inhabitants in 2020 to 3 vehicles/1,000 inhabitants in 2030 and 4 vehicles/1,000 inhabitants in 2040 (compared to 0.14 car sharing vehicles/1,000 inhabitants in the City of Essen in 2013) (Bundesverband CarSharing e.V., 2013).	**City of Karlsruhe** (316,000 inhabitants): Karlsruhe is the current 'car sharing capital' of Germany with most car sharing vehicles per 1,000 inhabitants (2.15 carsharing vehicles per 1.000 inhabitants in 2015; 3.2 in 2019) – compared to most German cities with far below 1 car sharing vehicle per 1,000 inhabitants (Bundesverband CarSharing e.V., 2015, 2019). **City of Bremen** (557,000 inhabitants): The city actively promotes car sharing by providing parking spaces for car sharing vehicles in public street space that are well connected to public transport, cycling and walking ('mobil.punkte'). Bremen has reached its target to increase the number of car sharing users from 11,000 in 2016 to 20,000 in 2020 (City of Bremen, 2020).
34 Increased energy efficiency of the vehicle fleet (decreased fuel consumption): Reduction of the average fuel consumption of cars from 8 liters per 100 km in 2020 to 3 liters per 100 km in 2050 (compared to 6.7 liters in the BAU scenario), e.g., through a regional climate zone.	**City of London** (3.3 m inhabitants in Inner London): Congestion charge was introduced in 2003 and has led to reduced CO_2 emissions and air pollutants and improved efficiency of the vehicles circulating within the charging zone (TfL, 2007).
Car (push strategies)	
41 Regional toll Ruhr Region: Beginning in 2020, all private cars in the Ruhr Region have to pay a monthly fee of 75 Euro (138 Euro in 2050 due to inflation). The costs equal the assumed costs of the 'citizen ticket' and are similar to the costs of existing road toll systems in European cities (e.g. Milan 2–5 Euro/day, Stockholm 1.10–11.10 Euro/day) (Sadler Consultants Ltd., n.d.).	The **City of Stockholm** (936,000 inhabitants) introduced a city toll in 2007 that reduced traffic volumes by about 18 to 20% in the first five years of operation (Börjesson et al., 2012).
42 Reallocation of road space on main roads: In 2020, all six- and four-lane streets for cars (including highways) are reduced by two lanes. In 2030, all remaining four-lane streets are reduced by two lanes. The released road space is reallocated for more environmentally friendly modes of transport.	The **City of Vitoria-Gasteiz** (245,000 inhabitants) changed several two-lane streets to one-way streets for cars and reallocated the reduced car lanes for cycling (CIVITAS, 2014). From 2002 to 2014, the share of cycling could be increased from 1% to 13% of all trips. Until 2020, the cycling share shall be further increased to 15% (City of Vitoria-Gasteiz, 2010).
43 Area-wide speed limits: In 2020, the following speed limits are introduced: 80 km/h on motorways, 60 km/h on highways, 30 km/h on all other streets.	The **City of Munich** (1.5 m inhabitants) implemented far-reaching speed limits with 30 km/h speed limit zones on 85 to 90% of the inner-city road network (Hutter, 2019).
44 Increased parking fees: Starting in 2020, parking fees increase step-by-step so that in 2050 they are four times higher than in 2020.	The **City of Barcelona** (1.6 m inhabitants) uses its parking revenues to finance the public bike sharing system 'Bicing' (Kodransky & Hermann, 2011).
Public transport (pull strategies)	
51 Extension of public transport network: New tramlines are built by reactivating tramlines that were abolished in the past. The extended public transport network equals the tramline network that already existed in the Ruhr Region in the 1950s/1960s.	The **City of Nantes** (298,000 inhabitants) was the first city in France to reintroducing the tramway (abolished in 1958, reintroduced in 1985). Since then, the public transport network has been constantly extended, e.g. by 22% from 2000 to 2010 (offer per kilometer) (City of Nantes, 2009).
52 More frequent public transport services: Starting in 2020, the public transport service frequencies are increased step-by-step, so that in 2050 service frequencies are four times more often than in 2050.	The **City of Vienna** (1.8 m inhabitants) extended public transport services and increased service frequencies (City of Vienna, 2015) parallel to the reduced annual urban public transport ticket from 449 Euro to 365 Euro (one Euro per day) in 2012 and the continuously rising number of annual ticket holders (373,000 in 2011; 852,300 in 2019) (Wiener Stadtwerke, 2020). From 1993 to 2012, the trip-based share of public transport of the Vienna inhabitants increased from 29% to 39% (supplemental material).
53 Introduction of a 'citizen ticket': Starting in 2020, each household has to pay a monthly contribution of 75 Euro (138 Euro in 2050 due to inflation). In return, public transport use in the entire Ruhr Region is free of any extra-charge. The assumptions for the price are based on model calculations of a doctoral thesis for the introduction of a citizen ticket in the City of Wuppertal that would cost 42 to 82 Euros per month and household with/without third user financing, assuming that transport volumes increase by 10 to 30% (Waluga, 2017, p. 247).	**North Rhine-Westphalia (NRW):** Until today, no citizen ticket has ever been introduced in Germany. A comparable, solidarily financed ticket is the semester ticket for university students that has been introduced since 1991 at almost all universities in Germany. Since 2008, more than half a million university students in the Federal State of NRW, and thus also in the Ruhr Metropolitan Region, can use the public transport network of the entire federal state (17.9 mn inhabitants). Semester tickets are well accepted by the students, significantly reduce car use and CO_2 emissions and support students in their decision to abandon their car (Müller, 2016).

(continued)

Table 1. Continued.

Measures developed and modeled for the Ruhr Metropolitan Area (numbers = scenario numbers)	Real-world examples of similar measures in selected European cities
Cycling (pull strategies)	
61 System acceleration of cycling: Starting in 2020, the average cycling speed increases step-by-step so that in 2050 the average cycling speed is 30% faster than in 2020.	The **City of Copenhagen** (591,000 inhabitants) promotes system acceleration of cycling, e.g. by fast cycling routes and 'green waves' for average cycling speeds of 20 km/h (Cycling Embassy of Denmark, 2018). Cycling speed in Copenhagen could be increased from 15.3 km/h (2004) to 16.4 km/h (+7,2%) (2014) (City of Copenhagen, 2013 & 2015), compared to 10.6 km/h (2008) in Germany (Arndt & Zimmermann, 2012). Until 2025, cycling speed shall be accelerated by 15% compared to 2012 (City of Copenhagen, 2011). For 48% of the Copenhageners, the possibility for fast cycling is one of the main reasons to cycle (City of Copenhagen, 2011).
62 Fast cycling routes network: Until 2050, the currently being built fast cycling route 'Radschnellweg Ruhr' that crosses the Ruhr Region from east to west (planned length: 101 kilometers) is extended to a network of fast cycling routes that consists of four east-west routes and eight north-south routes and allows an average cycling speed of 20 km/h.	In Denmark, 28 municipalities are working together in the **Region of Copenhagen** to create a network of cycle superhighways ('Supercykelstier'). 60 routes are planned that total a length of 850 kilometers. Until 2019, 167 kilometers have been finished (Cycle Superhighways, 2019).
Walking (pull strategies)	
71 System acceleration of walking: Starting in 2020, footpaths are shortened step-by-step (e.g. by crossing aids, removal of barriers) so that in 2050 walking distances are 20% shorter and faster than in 2020.	Since 2011, the **City of Berlin** (3.5 m inhabitants) has a walking strategy that aims at creating a dense network of interconnected, direct and attractive walking connections and avoiding detours (City of Berlin, 2011). The share of walking could be increased from 25% (1998) to 31% (2013) of all trips per day (supplemental material). Since 2003, the **City of Zurich** (416,000 inhabitants) promotes walking with several separate strategies (Ott, 2006).

For measure fact sheets see Reutter et al. (2017).

Table 2. Single and combined measure scenarios.

Single measure scenarios	Combined scenarios
13 Densification at railway stations	81 Land-use
23 New housing at railway stations	
32 Electric mobility	82 Energy efficiency[a]
33 Car sharing	
34 Fuel consumption	
41 Regional toll Ruhr Region	83 Car traffic (push measures)
42 Reallocation of road space on main roads	
43 Area-wide speed limits	
44 Increased parking fees	
51 Extension of public transport network	84 Public transport/cycling/walking (pull measures)
52 More frequent public transport services	
53 Introduction of a 'citizen ticket'	
61 System acceleration of cycling	
62 Fast cycling routes network	
71 System acceleration of walking	
All measures (scenarios 81, 82, 83 and 84)	85 All measures
All push and pull measures (scenarios 83 and 84)	91 Push & pull measures
All push and pull and energy efficiency measures (scenarios 82, 83 and 84)	92 Push & pull & energy efficiency

[a]Scenario 82 also includes measure 31 "building energy". However, the measure specifically addresses CO_2 emissions of buildings and does not have an effect on transport emissions. Thus, the measure is not further considered in this paper (see Schwarze et al., 2017, for combined CO_2 emissions of buildings and transport).

(up to −19 percentage points). If land-use, efficiency and push and pull measures are modeled together (scenario 85), the highest reductions of car use can be realized (up to −21 percentage points). Whereas the land-use measures do not have an effect if modeled separately, a result in line with former research (Aditjandra, 2013), they do lead to additional reductions of car use in the long-term if modeled in combination with push and pull and energy efficiency measures (scenario 85). Overall, the scenarios demonstrate that push and pull measures can lead to considerable modal shifts and that land-use measures can intensify their effects in the long run. However, the scenarios also illustrate that even if all ambitious measures are implemented, there is still a reasonable gap of 10 (B-scenarios, higher fuel prices) to 12 percentage points (A-scenarios, lower fuel prices) to reach the proposed target of a 25% car modal share. Thus, according to the modeling, additional ambitious measures are needed to reach the proposed target.

Figures 8 and 9 show the effects on reducing CO_2 emissions across time. The land-use measures (avoid) have almost no effect on reducing CO_2 emissions (scenario 81). One explanation is that settlement structures change only very slowly and are marginal compared to existing settlement structures. In the scenarios, only 7% new housing is built from 2020 until 2050 and only little of this is affected by the land-use measures (Schwarze et al., 2017).

The push and pull measures have very different effects on CO_2 emissions: Whereas the restrictive push measures

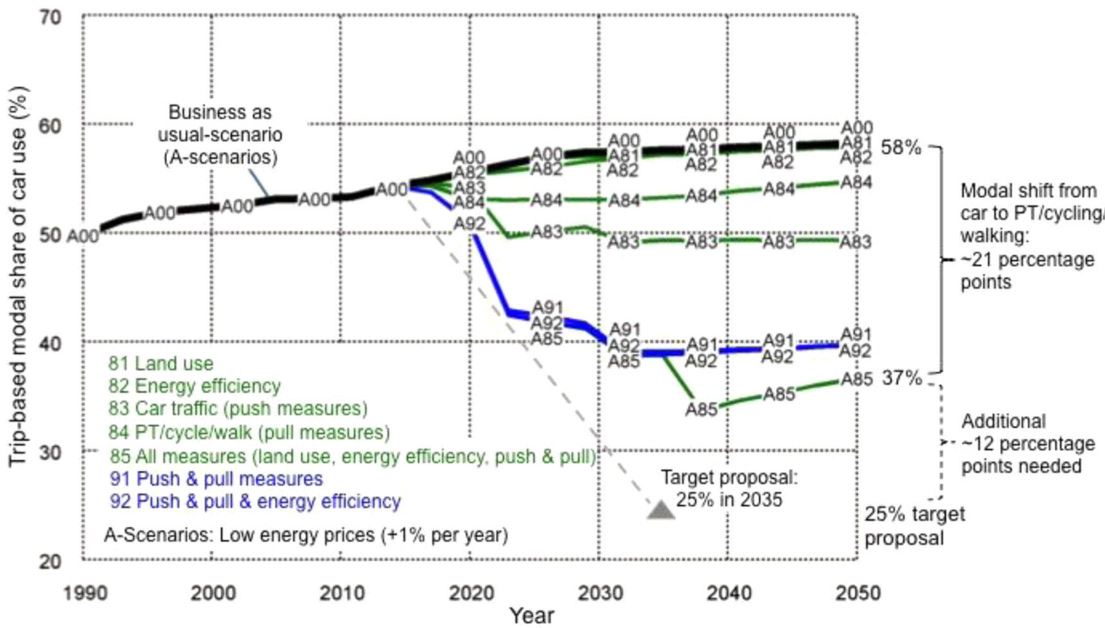


Figure 6. Modal share of car use (A-scenarios) and proposed target for 2035. Modeling: S&W; Figure: S&W amended by Müller; PT = public transport

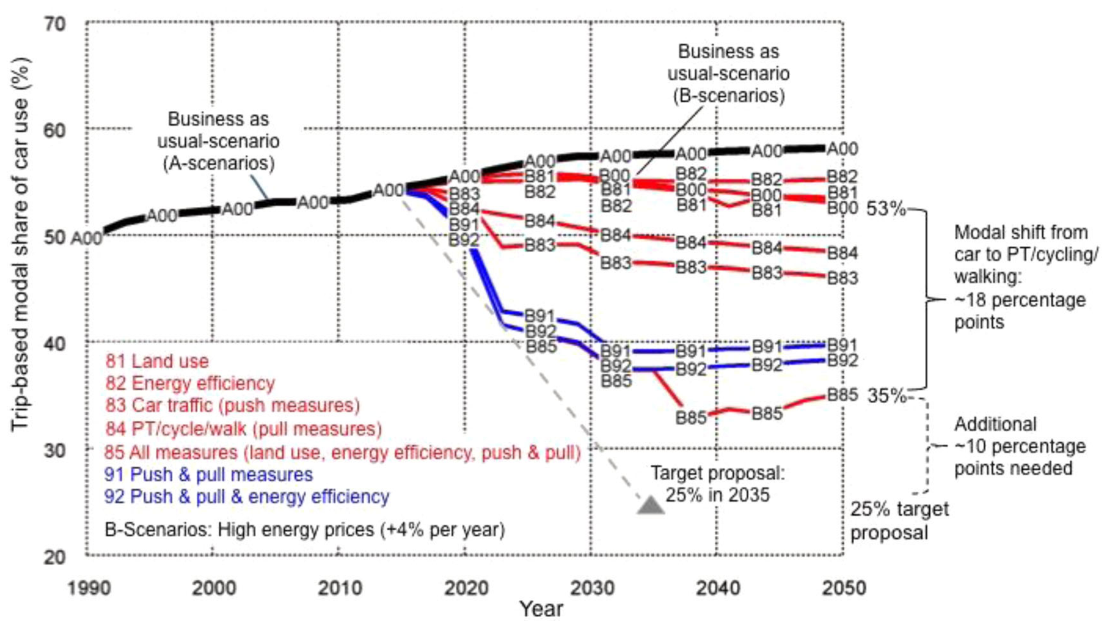


Figure 7. Modal share of car use (B-scenarios) and proposed target for 2035. Modeling: S&W; Figure: S&W amended by Müller; PT = public transport

(scenario 83) have the strongest CO_2 emission reduction effects of all combined scenarios (up to −59% compared to BAU), which are even stronger than the efficiency measures, the pull measures (scenario 84) increase CO_2 emissions (up to +29%), because extended transport services lead to increased CO_2 emissions. The walking and cycling measures show only small effects. Thus, the modeling demonstrates that push measures are very effective to achieve fast and fundamental reductions in CO_2 emissions and need to be adressed much more by policy makers. However, the practical consequence cannot be to solely implement push measures, because this would be neither politically feasible nor advisable, as mobility is a basic need that has to be made possible – by providing a diverse range of sustainable mobility options. This also includes extended public transport services, even if they increase CO_2 emissions, because they are necessary to transform the overall urban transport system to reduce car dependency. The combined push and pull measures (scenario 91) reduce CO_2 emissions by 12% [B] to 42% [A] compared to BAU and as such almost as much as the efficiency measures (–29% [B], −45% [A]), particularly if energy prices remain low (A-scenarios). If modal shift and efficiency measures are modeled together (scenario 92), CO_2 emissions can be further reduced (–40% [B] to −53% [A]).

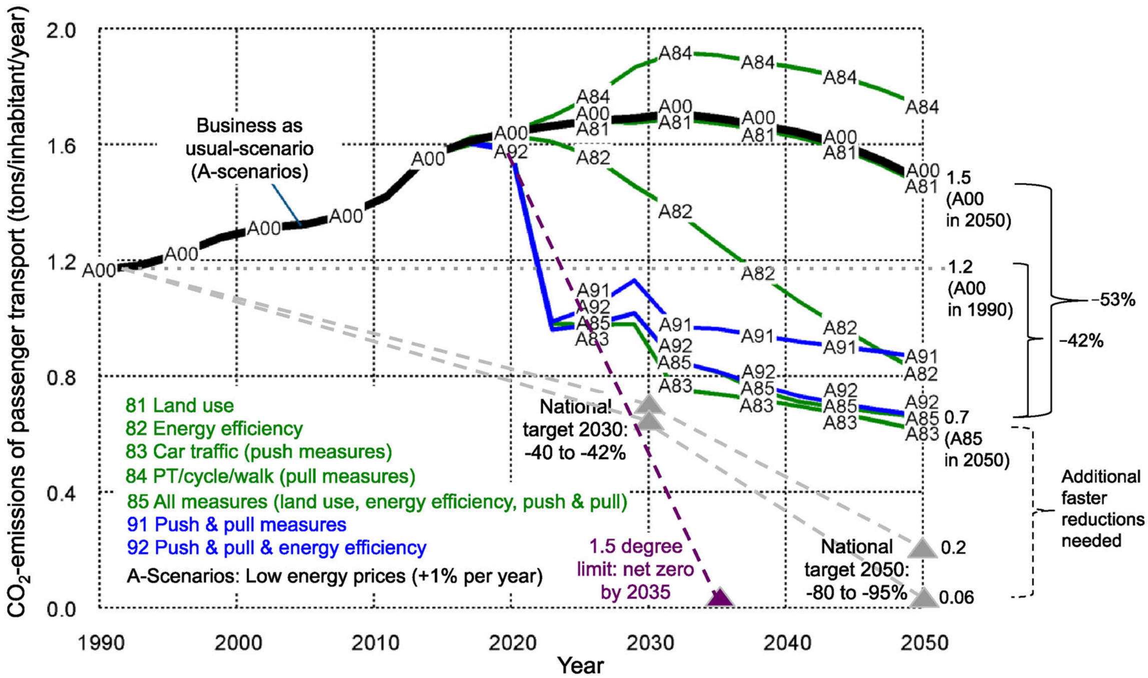


Figure 8. CO_2 emissions of passenger transport (A-scenarios), climate protection targets of the German Government and net zero target by 2035. Modeling: S&W; Figure: S&W amended by Müller; PT = public transport; net zero target by 2035 according to Fridays for Future & German Zero e.V.

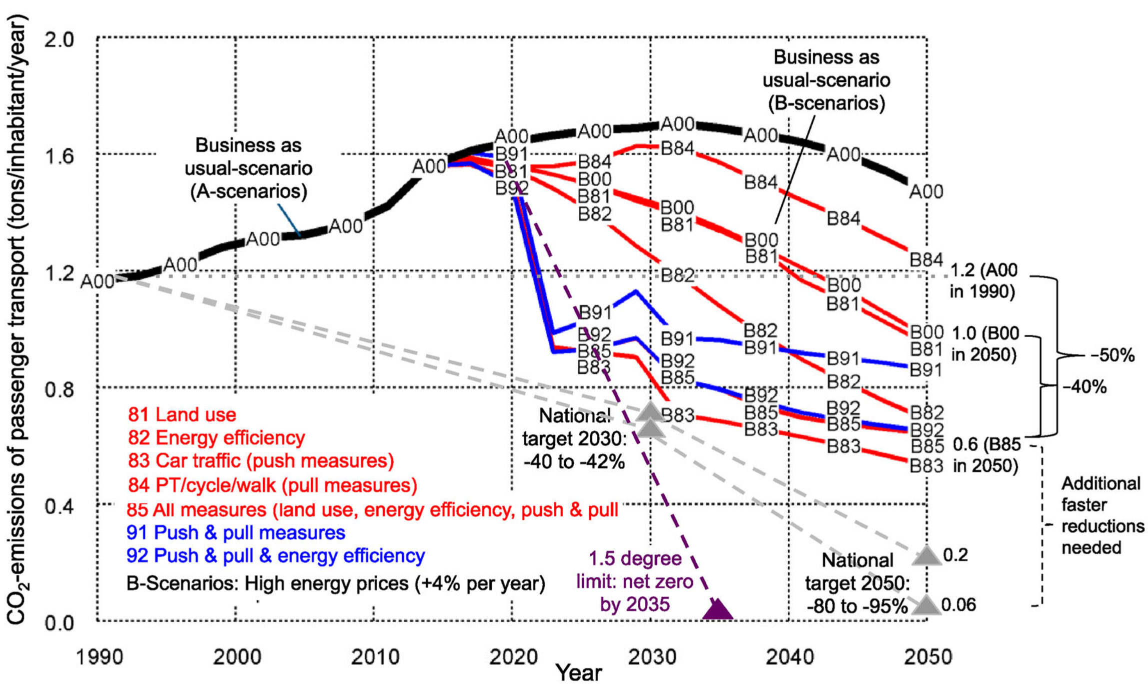


Figure 9. CO_2 emissions of passenger transport (B-scenarios), climate protection targets of the German Government and net zero target by 2035. Modeling: S&W; Figure: S&W amended by Müller; PT = public transport; net zero target by 2035 according to Fridays for Future & German Zero e.V.

Compared to 1990, the efficiency measures reduce CO_2 emissions by 31% [A] to 41% [B] – and by far do not reach climate protection targets. Modeling energy efficiency measures together with modal shift measures (scenario 92) leads to additional CO_2 emission reductions (–42% [A] to −50% [B] compared to 1990); the further inclusion of land-use measures does not lead to significant further reductions (scenario 85). Overall, even if all ambitious measures are modeled, they do not reach neither the 2030 nor the 2050 CO_2 emission reduction targets set by the German Government – and by far do not reach climate neutrality by 2035 as claimed e.g. by Fridays for Future and Germany Zero to stay within the 1.5 °C limit.

Figures 8 and 9 provide important insights on the speed of change that appears feasible: Modal shift measures – and particularly restrictive push measures – can reduce CO_2

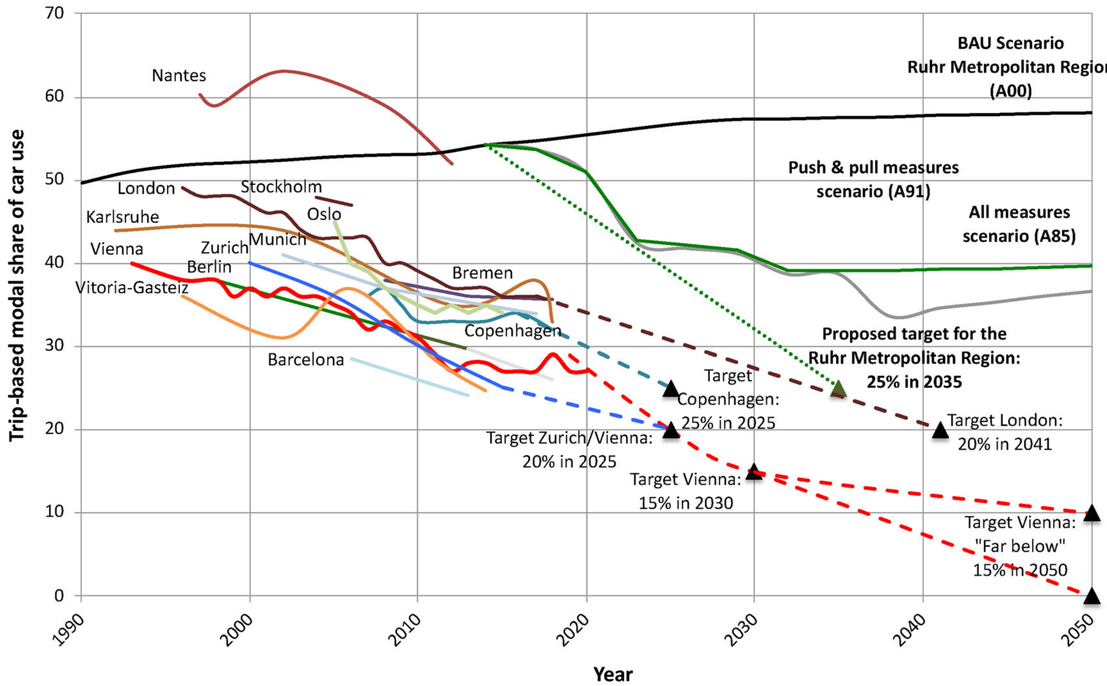


Figure 10. Potentials for reducing the modal share of car use: Indications from forecast scenarios and thirteen real-world city examples.
The rather conservative A-scenarios with only one percent fuel price increases per year and less modal shifts are used in the figure. City modal shifts represent overall developments in the cities, not the specific effects of the single measures presented in section 5.2. Data and sources: Supplemental online material.

emissions much faster than efficiency or land-use measures, i.e., the total amount of CO_2 emissions emitted across time is lower (smaller integral underneath the curve). The different reduction curves derive from a different definition of the scenarios: The push and pull measures are defined to enfold their main effects shortly after implementation in 2020 – just like for example speed limits can be implemented rather quickly. Energy efficiency measures take effect rather slowly – just like the technical upgrade of the vehicle fleet takes a rather long time. Thus, modal shift measures are important to timely "bend the curve" of excessive CO_2 emissions, as "limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO_2 since the pre-industrial period, that is, staying within a total carbon budget" (IPCC, 2018, p. 14). As such, modal shift measures represent life-saving emergency measures that need to be undertaken immediately at the accident site of the transport-co-caused climate crisis – to achieve a fast alleviation of excessive CO_2 emissions, just as vehemently claimed by citizen movements such as Fridays for Future (Neubauer et al., 2020).

5.3.3. *Synopsis: Juxtaposition of modal shift scenario results to real-world developments*

Figure 10 juxtaposes key modal shift scenario results to the overall modal split developments of the thirteen European frontrunner-cities to synthesize the main insights gained from the real-world and the scenario world regarding direction, scale and speed of modal shift that appears feasible. Figure 10 forms a quite coherent picture: The trip-based modal share of car use decreases to a similar degree in the scenarios and the real-world city examples. The figure underlines that significant modal shifts appear feasible not only in the scenario calculations but also under the actual socio-political conditions of the thirteen real-world cities. Vice versa, the real-world cities provide a plausibility check of the modal shift scenarios. The similar reduction rates suggest that the calculated modal shifts are not completely unthinkable but 'could happen'. Considering that the cities most likely have not implemented policy packages that are as radical and comprehensive as the policies modeled, the scenarios appear to represent rather low reduction rates compared to the real-world cities. This indicates that it might be more difficult to reduce the share of car use in the traditional car-oriented Ruhr Metropolitan Region compared to the role model city examples, maybe due to specific settlement and transport structures, and/or that modal shift effects may have been modeled in a rather cautious and conservative approach.

Figure 10 underlines that under the current socio-political conditions, it takes time to reduce the urban modal share of car use down to a sustainable amount. While other cities have started a long time ago to consequently pursue modal shift strategies and to reduce the share of urban car use, the Ruhr Metropolitan Region has not yet started to get on this transition path. Vienna for example set its first modal shift target as early as 1993 (25% modal share of car use by 2010) (City of Vienna, 1993) and has since then systematically and regularly monitored its modal split developments and consequently took action to readjust the implemented measures of its modal shift strategy. The paper demonstrates that there is no time to lose for actions to start: immediately and consequently – just now.

6. Discussion

This section discusses the results of this paper, its strengths and limitations and further research needs (6.1), elaborates the practical implications for the Ruhr Metropolitan Region (6.2) and concludes with further reaching thoughts about fundamental change to come about (6.3).

6.1. Course change in urban modal shift

The paper analyzed from a broad and complex perspective what course change is necessary and feasible in urban modal shift regarding direction, scale and speed of change. It estimates the role of modal shift as a strategy in itself and in relation to land-use (avoid) and efficency (improve) measures. Using transition theory as a theoretical framework, the paper has "bridged" (Geels et al., 2016, 2020) insights from a scenario study with a considerable amount of real-world knowledge to develop scientifically robust and societally relevant (Padmanabhan, 2018) target, transformation and system knowledge to support societal transformation endeavors in urban passenger transport.

Target knowledge: The target knowledge underlines that an ambitious modal split target is necessary that roughly equals a fast halving of the trip-based modal share of car use, which appears feasible under the current social-political conditions by reducing the trip-based share of urban car use by 0.5 to 1.5 percentage points per year if politically intended. Estimating a feasible reduction rate by using modal split data has limitations, as modal split data is often not directly comparable within and between cities, because data can differ due to data collection modalities (e.g., persons reached, area covered). Some researchers recently even question the overall usability of the modal split indicator for analyzing the success of urban transport policies, because reduced trip-based car shares do not necessarily represent reduced overall traffic volumes (Holz-Rau et al., 2018). The authors argue that despite these known deficiencies, the modal split indicator is nonetheless a robust and practicable proxy indicator to do a fast first sustainability check of urban passenger transport. The modal split indicator is widely used by city administrations to assess and communicate their environmental performance in urban passenger transport – and to readjust policies if modal split targets appear not to be reached. In Vienna, for example, car use increased from 2017 (27%) to 2018 (29%). This made the vice mayor reinforce a still ongoing debate if Vienna needs to implement more ambitious approaches like an urban road toll or an inner urban ban of cars from outside Vienna (Gaigg, 2019). The paper uses the "second best" modal split data as "best quickly available" data to heuristically find out about the scale and speed of modal shift that appears feasible to support policy formation and action by narrowing the extensive and complex long-term challenge down to an action-oriented year-to-year task. However, a fundamental question remains: Would reduction rates of 0.5 to 1.5 percentage points per year, as they have demonstrated to be feasible in frontrunning cities under the socio-political conditions of those past times, still be sufficient in light of the new scientific knowledge about climate protection requirements?

Transformation knowledge: This paper has analyzed a deliberately wide range of different modal shift measures that can all be considered relevant adjusting screws of urban transport planning to make passenger transport more sustainable. Most of these measures are well known and there is no need to "reinvent the wheel". In line with former research, this paper concludes that high-intensive measures are required across a wide range of different policy fields that go far beyond usual practices to get on a low carbon transition path in urban passenger transport (Brand et al., 2017; Creutzig et al., 2012; Hickman et al., 2010; Potter, 2007). The paper makes use of real-world knowledge to a much larger degree than common papers that focus on the mere, single-discipline presentation of modeling results. While many studies use empirical data to underpin scenarios, e.g., as part of the literature review (Hammadou & Papaix, 2015), this paper makes use of good practice examples from real-world frontrunner cities as a research result in itself to check plausibility of the scenarios and to provide appealing good practice input that may serve heuristic learning (Macmillen & Stead, 2014, p. 84) for transition processes. Presenting good practice real-world examples has limitations, for example because the city examples cannot be readily transferred across city-contexts (Geels et al., 2016; Gudmundsson et al., 2005) and they do not provide explaining factors for how and why they became successful, which should be further analyzed by in-depth case studies from the transition theory perspective. Nevertheless, learning from good practice examples may be of particular importance when making decisions related to the vast uncertainty of complex long-term transformation processes, because they demonstrate that there actually truly exist successfully realized measures and course changes. Furthermore, alluring good practice examples may speak to the heart of people, which is assumed to be essential for transformational learning (Singleton, 2015): it requires the combination of intellectual (academic) understanding (*head*) with emotion that can alter values and attitudes (*heart*), which may ultimately lead to a society that has the guts for action (*hands*), which may trigger further learning processes.

System knowledge: The paper reinforces former research that modal shift is a crucial strategy for sustainability and climate protection in urban passenger transport (Conti, 2018; Hickman et al., 2010). The paper extends former research by shedding light on possible counter, synergy and rebound effects, suggesting that the combined implementation of push and pull measures leads to additional reductions in the modal share of car use. The modeling suggests that modal shift measures are important options for action at local and regional level in addition to developments that can be mainly triggered from the European and national level (e.g., more efficient vehicle fleet through CO_2 emission limits for new cars and increased fuel prices through environmental fuel taxation). Modal shift measures need to be implemented in a fast, area-wide and high-intensive approach to contribute effectively to reducing CO_2 emissions by the enormous amount and speed required for climate protection. Restrictive push measures have the potential to fast and significantly reduce CO_2 emissions, which needs to be addressed much more by policy makers compared to current practices. Nevertheless, an integrated approach of push and pull measures is important to create attractive sustainable mobility options (walking, cyling, public transport, car sharing), to be politically persuasive, to gain societal acceptance and to realize synergy effects. The paper underlines the importance of modal shift measures to timely "bend the curve" (Raskin et al., 1998, 2002) of excessive CO_2 emissions, i.e., to achieve a fast reduction of overall CO_2 emitted by urban transport across time, as modal shift measures can take effect faster than land-use (avoid) measures and the technical upgrade of the vehicle fleet (improve). This is an important aspect, which so far has not received adequate attention by research and practice in relation to its relevance.

When assessing the scenario results, five aspects need to be considered.

1. The Ruhr Model might have created rather conservative estimates regarding modal shift and CO_2 emission reduction potentials, particularly regarding cycling and public transport. The low impacts of the cycling measures have been criticized as implausible during presentations (workshops, conferences). In the model, the cycling measures do contribute to an increased cycling share (see likewise Creutzig et al., 2012), but these gains are not coming from shifted car traffic. Although also empirical studies have revealed rather low impacts of cycling measures on reducing car use and CO_2 emissions (Brand et al., 2014; Neves & Brand, 2019; Pritchard et al., 2019), many cities around the world have demonstrated significantly increased levels of cycling in the last years (Pucher et al., 2010). Also, the scenario "regional toll" reduces the modal share of car use only by 3 percentage points and CO_2 emissions by 3%, whereas empirical studies have demonstrated modal shifts from car to public transport by 14 to 39% and CO_2 emission reductions by 13 to 16% (Börjesson et al., 2012; Croci, 2016). The rather slow responses of the model might be because ILUT models have originally been developed to model incremental changes rather than rapid transformations (Ford et al., 2018). According to Ford et al. (2018), the unprecedented need for a fast transformation of the built urban environment to reduce CO_2 emissions poses "substantial challenges" for the use of land-use transport models and requires further research on model adjustments. Coming studies should even further exemplify the direction, scale and speed of change needed by using ILUT models for backcasting to define policy packages that meet the requirements of the Paris Agreement or the 1.5 °C limit (Ford et al., 2018). Or put in a different way: Would usual motorized private transport still be a remaining mobility option for urban areas if climate protection is taken seriously? Ford et al. assume that "such techniques could encourage politicians and citizens that change at such unprecedented speed and scale is feasible, even if difficult" (2018, p. 87).
2. Certain aspects that could further reduce car use and CO_2 emissions were not modeled due to financial restrictions in the research project or limited compatibility with modeling logics, like extensive bicycle parking facilities, a public bike rental system or information and communication measures. Likewise, important aspects such as leisure traffic, freight transport, transport costs and environmental impacts were not considered and should be further addressed by research.
3. The use of an ILUT model does not provide insights on the dynamics and non-linear developments of socio-technical transition processes that include concurrent processes of acceleration and slowdown, when multiple changes in social, technical, political, market and environmental subsystems co-evolve. Analyzing them would require stepping into the ongoing development of socio-technical scenario analysis (Geels et al., 2020; Holtz et al., 2015).
4. Scenarios necessarily imply relevant uncertainties, particularly if complex societal sub-systems such as the urban transport system are modeled over a long time period (Ford et al., 2018). In the scenarios, some settings are based on exogenous assumptions that needed to be made if empirical data was not available or due to model requirements, which significantly influence the scenario outcomes (e.g., price development of electric cars, number of cars replaced through carsharing).
5. However, the value of scenarios is not that they predict exact futures or prescribe required measure combinations, but that they provide insight from the future into the scale of change needed today (Raskin et al., 2000; Sondeijker et al., 2006). As such, the scenarios developed in this paper are hoped to provide knowledge for a better understanding of necessary long-term developments, to create public awareness about the urgency for political action (Wegener, 2020) and to open up room for societal and political debate about sustainable future development paths.

6.2. Implications for the Ruhr metropolitan region

The paper demonstrates that climate protection and sustainable urban development mean nothing less than a complete course change from gradually reducing unsustainability to fast and fundamentally changing urban passenger transport. Even if the scenarios do not fully reach the proposed modal shift and necessary CO_2 emission reduction targets, the paper underlines an inconvenient truth: A radical course change is not only necessarry but possible – if societally wanted as a "wind of change" (Meine, 1989: song associated with the Fall of the Berlin Wall). While frontrunning cities have started long ago to consequently pursue ambitious modal shift strategies, the Ruhr Metropolitan Region is still lagging behind and no change has been realized so far. The region urgently needs to move forward to the "take-off" phase, i.e., the phase when fast and fundamental system changes toward sustainability get started (Loorbach et al., 2017; Rotmans et al., 2001). Transition theory recognizes that societal changes do not come about through technocratic governance and top-down steering toward fixed targets (Wiek et al., 2006), but through a continuous and iterative process of debating, finding consensus on desired futures and developing realizable transition paths through learning and experimenting (Köhler et al., 2019; Loorbach, 2007). The results of this paper are hoped to provide a fertile ground for societal and political debate and transformative actions to happen. Actions should include the organization of regional discussion formats for stakeholders and decision makers to mutually decide upon future development paths, the political adoption of an operationalized modal split target, the organization of learning formats among cities and the timely implementation of adequate policy packages. The wide range of different measures analyzed in this paper may provide input for the "clever mixing and skillful combination" (WBGU, 2011, p. 9) of policy approaches, which is assumed to be essential for achieving systemic structural change: well-known and innovative measures, measures that are easier and harder to implement, with quick wins and fundamental long-term transformations, restricting push measures and enabling pull measures. There cannot be one unique blueprint ("one fits all") and each city and urban society has to develop its own transition path.

Research points out that transport policies that aim to drastically reduce CO_2 emissions can have major social and economic consequences (Conti, 2018), lead to winners and losers (Köhler et al., 2019), and may be perceived by many citizens as serious restrictions of their quality of life (Wegener, 2020). Therefore, it is important to communicate the co-benefits that such measures can bring (Wegener, 2020), like less noise and air pollution, better health, less land usage, more urban green, less traffic-related injuries and deaths, monetary fuel-savings and improved urban living quality (Creutzig et al., 2012). The knowledge of this paper is hoped to provide guidance for an adequate and timely course change in urban modal shift and to assist cities and regions to transform themselves in a collective and adaptive way (Kemp et al., 2007).

6.3. Conclusions

Needless to say: The challenges ahead to fundamentally transform urban passenger transport are enormous, by no means an automatism and might even fail (Raskin et al., 1998; WBGU, 2011). There are strong lock-ins and path dependencies that prevent change to come about easily, like traffic-inducing built environments, long life-cycles of transport infrastructures and strong dependencies on car-use due to the deep embedment of the car in our societal structures (WBGU, 2011). There are powerful forces like the oil and automotive industry, capitalist structures and the political-industrial complex that work hard on preserving the status quo and counteract the need and speed of sustainability transitions (Göpel, 2016; Köhler et al., 2019).

Significantly changing the course of urban mobility to the direction, scale and speed needed might seem "unrealistic" from today's point of view and may raise concerns over public acceptability. However, a profound change is inevitable and might suddenly turn out to be feasible if emergencies and societal developments trigger an acceleration process that leads to political 'tipping points' – just like the Fukushima catastrophe in 2011 lead to a formerly unthinkable immediate nuclear phase-out by the German Federal Government driven by Germanys chancellor and her conservative government. Also, the Corona crisis may have given an impression of the dimension of change that is feasible if the world's community is at severe danger. An essential question remains: How can a fast, fundamental and enduring system change of a similar scale and speed be achieved by liberal democracies? Changing the transport system is more than the mere implementation of fossil-free solutions. Fundamental change requires both 'hard' technological innovations and 'soft' socio-cultural mindshifts - a socio-technical transformation with new forms of values, habits, policies and structures (Bierwirth et al., 2017; Loorbach et al., 2016; WBGU, 2011). This transformation requires enormous efforts by all parts of society through a joint commitment and support of citizens, civil society, science, education, business, political and administrative players (Müller & Reutter, 2017).

There are some promising 'signs of hope' at the near horizon that societal support for a fundamental course change toward climate protection and transport transition is growing – for example the Fridays for Future movement, increasing voting results for green parties in democratic elections, shifting values in institutions and society, young people using the car less and transition research entering mainstream policy. Hopefully, these developments will soon open up windows of opportunity to upscale and accelerate current reform actions toward profound sustainability transitions in urban passenger transport to come about.

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References

Acheampong, R. A., & Silva, E. A. (2015). Land use-transport interaction modeling: A review of the literature and future research directions. *The Journal of Transport and Land Use*, *8* (3), 1–28. https://doi.org/10.5198/jtlu.2015.806

Aditjandra, P. T. (2013). The impact of urban development patterns on travel behavior: Lessons learned from a British metropolitan region using macro-analysis and micro-analysis in addressing the sustainability agenda. *Research in Transportation Business & Management*, *7*, 69–80. https://doi.org/10.1016/j.rtbm.2013.03.008

Arndt, W.-H., & Zimmermann, F. (2012). *Mobilitätsverhalten in Deutschland [Mobility behavior in Germany]*. Deutsches Institut für Urbanistik.

Batty, P., Palacin, R., & González-Gil, A. (2015). Challenges and opportunities in developing urban modal shift. *Travel Behaviour and Society*, *2*(2), 109–123. https://doi.org/10.1016/j.tbs.2014.12.001

Beckmann, K. J., Brüggemann, U., Gräfe, J., Huber, F., Meiners, H., Mieth, P., Moeckel, R., Mühlhans, H., Rindsfüser, G., Schaub, H., Schrader, R., Schürmann, C., Schwarze, B., Spiekermann, K., Strauch, D., Spahn, M., Wagner, P., & Wegener, M. (2007). *ILUMASS: Integrated land-use modelling and transport system simulation*. Final Report. German Aerospace Center (DLR). http://www.spiekermann-wegener.de/pro/pdf/ILUMASS_Endbericht.pdf

Behr, F., & Ahaus, B. (2015). "Mobilität von Morgen – Bilder die (uns) bewegen" – Partizipation für Visionen zur Mobilität [Mobility of tomorrow – Pictures that move (us)]. In H.-J. Wagner & C. Sager (Ed.), *Wettbewerb "Energieeffiziente Stadt" – Kommunikation und Partizipation* (pp. 119–138). Münster: LIT Verlag.

Bierwirth, A., Augenstein, K., Baur, S., Bettin, J., Buhl, J., Friege, J., Holtz, G., Jensen, T., Kaselofsky, J., Liedke, C., Palzkill, A., Saurat, M., Schneidewind, U., Schönborn, S., Schweiger, S., Viebahn, P., & Vondung, F. (2017). *Knowledge as transformative energy. On linking models and experiments in the energy transition in buildings*. oekom. https://epub.wupperinst.org/frontdoor/index/index/docId/6658

Börjesson, M., Eliasson, J., Hugosson, M., & Brundell-Freij, K. (2012). The Stockholm congestion charges – 5 years on. Effects, acceptability and lessons learnt. *Transport Policy*, *20*, 1–12. https://doi.org/10.1016/j.tranpol.2011.11.001

Brand, C., Cluzel, C., & Anable, J. (2017). Modeling the uptake of plug-in vehicles in a heterogeneous car market using a consumer segmentation approach. *Transportation Research Part A*, *97*, 121–136. https://doi.org/10.1016/j.tra.2017.01.017.

Brand, C., Goodman, A., & Ogilvie, D. (2014). Evaluating the impacts of new walking and cycling infrastructure on carbon dioxide emissions from motrized travel: A controlled longitudinal study. *Applied Energy*, *128*, 284–295. https://doi.org/10.1016/j.apenergy.2014.04.072

Brosch, K., Huber, F., Schwarze, B., Spiekermann, K., & Wegener, M. (2014). *Integriertes Modell Ruhrgebiet 2050 – Projektbeschreibung [Integrated Ruhr Area Model 2050 – Project description]*. http://www.spiekermann-wegener.de/pro/pdf/EWR_1.1.1_Projektbeschreibung_Oktober_2014.pdf

Buehler, R., & Pucher, J. (2011). Sustainable transport in Freiburg: Lessons from Germany's environmental capital. *International Journal of Sustainable Transportation*, *5*(1), 43–70. https://doi.org/10.1080/15568311003650531

Buehler, R., Pucher, J., & Altshuler, A. (2017). Vienna's path to sustainable transport. *International Journal of Sustainable Transportation*, *11*(4), 257–271. https://doi.org/10.1080/15568318.2016.1251997

Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU). (2019a). *Klimaschutzbericht 2018 [Climate Protection Report 2189 2018]*. https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/2190Klimaschutz/klimaschutzbericht_2018_bf.pdf

Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit. (2019b). *Klimaschutz in Zahlen [Climate protection in numbers]*. Retrieved from https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/klimaschutz_zahlen_2019_broschuere_bf.pdf

Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) [Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety]. (2016). *Climate Action Plan 2050 – Principles and goals of the German government's climate policy*. https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/klimaschutzplan_2050_en_bf.pdf

Bundesverband CarSharing e.V. (2013). bcs-Städtevergleich: CarSharing-Angebote in deutschen Großstädten über 200.000 Einwohnern [bcs city comparison: car sharing in German large cities with more than 200,000 inhabitants].

Bundesverband CarSharing e.V. (2015, June 10). *CarSharing-Städteranking 2015 [Car sharing city ranking 2015]*. Press release. https://carsharing.de/sites/default/files/uploads/pm_staedteranking_2015.pdf

Bundesverband CarSharing e.V. (2019). *CarSharing-Städteranking 2019 [Car sharing city ranking 2019]*. http://carsharing.info/sites/default/files/uploads/tabelle_staedteranking_2019_0.pdf

City of Berlin. (2011*). Fußverkehrsstrategie für Berlin [Walking strategy for Berlin*]. Senatsverwaltung für Stadtentwicklung Berlin, Bereich Kommunikation. https://www.berlin.de/sen/uvk/verkehr/verkehrsplanung/fussverkehr/mobilitaetsgesetz/fussverkehrsstrategie/

City of Bremen. (2020). *Bremen unter den weltweiten Top10 der Carsharing-Städte – Internationale "2020 Carshare City Awards" verliehen [Bremen among world wide top10 car sharing cities – international '2020 carshare city awards' awarded]*. Bremen. https://www.senatspressestelle.bremen.de/detail.php?gsid=bremen146.c.337243.de&asl=bremen02.c.732.de

City of Copenhagen. (2011). *Good, better, best – The city of Copenhagen's bicycle strategy 2011-2025.* Technical and Environmental Administration Traffic Department. http://kk.sites.itera.dk/apps/kk_pub2/pdf/823_Bg65v7UH2t.pdf

City of Copenhagen. (2013). *Copenhagen - City of cyclists. Bicycle Account (2012).* Technical and Environmental Administration, Traffic Department. https://kk.sites.itera.dk/apps/kk_pub2/pdf/1034_pN9YE5rO1u.pdf

City of Copenhagen. (2015). *Co-create Copenhagen*. Technical and Environmental Administration. https://kk.sites.itera.dk/apps/kk_pub2/pdf/1534_0TdC5G2XZr.pdf

City of Essen. (2014). *Section 02: Local transport. Application to become European Green Capital 2017*. http://ec.europa.eu/environment/europeangreencapital/winning-cities/2017-essen/essen-2017-application/

City of Essen. (2019, September 25). *Modal-Split 2035: Handlungskonzept im Rat diskutiert [Modal split 2035: action plan discussed* in council]. https://www.essen.de/meldungen/pressemeldung_1326741.de.html

City of Nantes. (2009). *Chap 2 – Local transport. Application for European Green Capital 2013*. http://ec.europa.eu/environment/europeangreencapital/wp-content/uploads/2011/05/EGCNantesUKChap2-F.pdf

City of Vienna. (1993). *Verkehrskonzept Wien – Leitlinien [Traffic concept Vienna - Guidelines]*. Magistrat der Stadt Wien, Magistratsabteilung 18. https://www.wien.gv.at/stadtentwicklung/studien/pdf/b006549.pdf

City of Vienna. (2015). *Wie finanziert sich der Öffentliche Verkehr in Wien? [How is public transport in Vienna financed?]* Article of 13 April 2015. Magistrat der Stadt Wien. https://wien1x1.at/site/wie-finanziert-sich-der-oeffentliche-verkehr-in-wien/#02

City of Vitoria-Gasteiz. (2010). *Application for European Green Capital Award 2012-2013 – Vitoria-Gasteiz*. http://ec.europa.eu/environment/europeangreencapital/wp-content/uploads/2011/04/European-Green-Capital-Award-2012-13-nuevo-estandar.pdf

CIVITAS. (2014). *CIVITAS study tour in Vitoria-Gasteiz, Spain, 19 & 20 June 2014*. http://www.civitas.eu/sites/default/files/civitas_study_tour_vitoria-gasteiz_june_2014_measure_description_0.pdf

Conti, B. (2018). Modal shift and interurban mobility: Environmentally positive, socially regressive. *Journal of Transport Geography*, *69*, 234–241. https://doi.org/10.1016/j.jtrangeo.2018.05.007

Creutzig, F., Mühlhoff, R., & Römer, J. (2012). Decarbonizing urban transport in European cities: Four cases show high co-benefits. *Environmental Research Letters*, *7*(4), 044042. https://doi.org/10.1088/1748-9326/7/4/044042

Croci, E. (2016). *Urban road pricing: A comparative study on the experiences of London, Stockholm and Milan*. Transportation Research Procedia, 6th Transport Research Arena, Warsaw, Poland, April 18–21 (pp. 253–262). https://doi.org/10.1016/j.trpro.2016.05.062

Cuenot, F., Fulton, L., & Staub, J. (2012). The prospect for modal shifts in passenger transport worldwide and impacts on energy use and CO_2. *Energy Policy*, *41*, 98–106. https://doi.org/10.1016/j.enpol.2010.07.017

Cycle Superhighways. (2019). *Cycle superhighway bicycle account 2019*. https://supercykelstier.dk/wp-content/uploads/2016/03/Cycle-Superhighway-5Bicycle-Account-2020.pdf

Cycling Embassy of Denmark. (2018). *ITS solutions for cyclists*. https://cyclingsolutions.info/its-solutions-for-cyclists/

de la Barra, T. (1989). *Integrated land use and transport modelling*. University Press.

Echenique, M. H. (1985). The use of integrated land use transportation planning models: The cases of Sao Paulo, Brazil and Spain. In F. M. Bilbao (Ed.), *The practice of transportation planning* (pp. 263–286). Elsevier.

Emery, F. (1977). *Futures we are in*. Martinus Nijhoff. (as cited in Wiek, 2013, p. 138).

European Environment Agency. (2019). *Sustainability transitions: Policy and practice* (EEA Report, No 09/2019). Publications Office of the European Union. https://www.eea.europa.eu/publications/sustainability-transitions-policy-and-practice

Fiorello, D., Huismans, G., López, E., Marques, C., Steenberghen, T., Wegener, M., & Zografos, K. G. (2006). *Transport strategies under the scarcity of energy supply*. In A. Monzon and A. Nuijten (Eds.), STEPs Final Report. Buck Consultants International. http://www.spiekermann-wegener.de/pro/pdf/STEPs_Final_Report.pdf

Foletta, N. (2011a). Greenwich Millenium Village – London, United Kingdom. In N. Foletta & S. Field (Eds.), *Europe's vibrant new low car(bon) communities* (pp. 8–17). Institute for Transportation & Development Policy. https://3gozaa3xxbpb499ejp30lxc8-wpengine.netdna-ssl.com/wp-content/uploads/2014/07/15.-092611_ITDP_NED_Desktop_Print.pdf

Foletta, N. (2011b). Hammarby Sjöstadt. In N. Foletta & S. Field (Eds.), *Europe's vibrant new low car(bon) communities* (pp. 30–45). Institute for Transportation & Development Policy. https://3gozaa3xxbpb499ejp30lxc8-wpengine.netdna-ssl.com/wp-content/uploads/2014/07/15.-092611_ITDP_NED_Desktop_Print.pdf

Ford, A., Blythe, P., Dawson, R., & Barr, S. (2018). Land-use transport models for climate change mitigation and adaptation planning. *Journal of Transport and Land Use*, *11*(1), 83–101. https://doi.org/10.5198/jtlu.2018.1209

Gaigg, V. (2019, February 13). Steigender Autoanteil in Wien löst Diskussion über Fahrverbote in City aus [Increasing modal share of car use in Vienna triggers discussion about vehicle bans in city]. *Der Standard*. https://www.derstandard.at/story/2000097951392/erneut-rekorde-bei-wiener-oeffis-aber-auch-auto-anteil-in

Geels, F. W., Berkhout, F., & Van Vuuren, D. P. (2016). Bridging analytical approaches for low-carbon transitions. *Nature Climate Change*, *6*(6), 576–583. https://doi.org/10.1038/nclimate2980

Geels, F. W., McMeekin, A., & Pfluger, B. (2020). Socio-technical scenarios as a methodological tool to explore social and political feasibility in low-carbon transitions: Bridging computer models and the multi-level perspective in UK electricity generation (2010-2050). *Technological Forecasting & Social Change*, *151*, 119258. https://doi.org/10.1016/j.techfore.2018.04.001

German Advisory Council on Global Change (WBGU). (2011). *World in transition – A social contract for sustainability*. WBGU. https://www.wbgu.de/en/publications/publication/world-in-transition-a-social-contract-for-sustainability

Göpel, M. (2016). *The great mindshift. How a new economic paradigm and sustainability transformations go hand in hand*. Springer Open. https://www.springer.com/de/book/9783319437651

Gössling, S. (2013). Urban transport transitions: Copenhagen, City of Cyclists. *Journal of Transport Geography*, *33*, 196–206. https://doi.org/10.1016/j.jtrangeo.2013.10.013

Grin, J., Rotmans, J., & Schot, J. (2010). Introduction: From persistent problems to system innovations and transitions. In J. Grin, J. Rotmans, & J. Schot (Eds.), *Transitions to sustainable development. New directions in the study of long term transformative change* (pp. 1–8). New York, NY: Routledge.

Grindau, G. H., & Sagolla, W. (2012). Nahverkehr [Local transport]. In E. Kratzsch, S. Raskob, M. Lürwer, & U. Carow (Eds.), *Memorandum zur Bewerbung der Metropole Ruhr als „Grüne Hauptstadt Europas "[Memorandum of the Ruhr Metropolitan Regions's application as "European Green Capital"]* (pp. 64–65). Bochum, Essen, Dortmund: Cities of Bochum, Essen, Dortmund, Regionalverband Ruhr. https://rathaus.dortmund.de/dosys/gremrech2.nsf/0/580A531843D9D883C12579B8004BE9CA/$FILE/Memorandum_Gruene_Hauptstadt_Europas.pdf.pdf

Gudmundsson, H., Wyatt, A., & Gordon, L. (2005). Benchmarking and sustainable transport policy: Learning from the BEST network. *Transport Reviews*, *25*(6), 669–690. https://doi.org/10.1080/01441640500414824

Hammadou, H., & Papaix, C. (2015). Policy packages for modal shift and CO_2 reduction in Lille, France. *Transportation Research Part D: Transport and Environment*, *38*, 105–116. https://doi.org/10.1016/j.trd.2015.04.008

Hensher, D. A. (2008). Climate change, enhanced greenhouse gas emissions and passenger transport – What can we do to make a difference? *Transportation Research Part D: Transport and Environment*, *13*(2), 95–111. https://doi.org/10.1016/j.trd.2007.12.003

Hickman, R., Ashiru, O., & Banister, D. (2010). Transport and climate cahnge: Simulating the options for carbon reduction in London. *Transport Policy*, *17*(2), 110–125. https://doi.org/10.1016/j.tranpol.2009.12.002

Hickman, R., & Banister, D. (2007). Looking over the horizon: Transport and reduced CO_2 emissions in the UK by 2030. *Transport Policy*, *14*(5), 377–387. https://doi.org/10.1016/j.tranpol.2007.04.005

Holtz, G., Alkemade, F., de Haan, F., Köhler, J., Trutnevyte, E., Luthe, T., Halbe, J., Papachristos, G., Emile Chappin, E., Kwakkel, J., & Ruutu, S. (2015). Prospects of modelling societal transitions: Position paper of an emerging communiy. *Environmental Innovation and Societal Transitions*, *17*, 41–58. https://doi.org/10.1016/j.eist.2015.05.006

Holz-Rau, C., Zimermann, K., & Follmer, R. (2018). Der Modal Split als Verwirrspiel [Confusing modal split]. *Straßenverkehrstechnik*, *62*(8), 539–550.

Hunt, J. D., & Abraham, J. E. (2005). Design and implementation of PECAS: A generalised system for the allocation of economic production, exchange and consumption quantities. In M. E. H. Lee-Gosselin & S. T. Doherty (Eds.), *Integrated land-use and transportation models: Behavioural foundations* (pp. 253–274). Elsevier.

Hunt, J. D., Kriger, D. S., & Miller, E. J. (2005). Current operational urban land-use-transport modelling frameworks: A review. *Transport Reviews*, *25*(3), 329–376. https://doi.org/10.1080/0144164052000336470

Hutter, D. (2019). *München wird zur Tempo-30-Zone [Munich becomes tempo-30-zone].* Süddeutsche Zeitung of 14 July 2019. https://www.sueddeutsche.de/muenchen/muenchen-verkehr-tempo-30-zonen-1.4523896

Iacono, M., Levinson, D., & El-Geneidy, A. (2008). Models of transportation and land use change: A guide to the territory. *Journal of Planning Literature*, *22*(4), 323–340. https://doi.org/10.1177/0885412207314010

International Energy Agency. (2009). Transport energy and CO_2: Moving towards sustainability. OECD Publishing. https://doi.org/10.1787/9789264073173-en

Intergovernmental Panel on Climate (IPCC). (2018). Summary for policymakers. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield (Eds.), *Global warming of 1.5 °C. An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_Low_Res.pdf

Joshi, K. (2020). *Oslo city hits new milestone – Most electric vehicles per capita.* https://thedriven.io/2020/07/07/oslo-city-hits-new-milestone-most-electric-vehicles-per-capita/

Kemp, R., Loorbach, D., & Rotmans, J. (2007). Transition management as a model for managing processes of co-evolution towards sustainable development. *International Journal of Sustainable Development & World Ecology*, *14*(1), 15–78. https://doi.org/10.1080/13504500709469709

Kii, M., Akimoto, K., & Doi, K. (2014). Measuring the impact of urban policies on transportation energy saving using a land use-transport model. *IATSS Research*, *37*(2), 98–109. https://doi.org/10.1016/j.iatssr.2014.03.002

Kii, M., Nakanishi, H., Nakamura, K., & Doi, K. (2016). Transportation and spatial development: An overview and a future direction. *Transport Policy*, *49*, 148–158. https://doi.org/10.1016/j.tranpol.2016.04.015

Kodransky, M., & Hermann, G. (2011). Europe's parking U-turn: From accomodation to regulation. Institute for Transportation & Development Policy (ITDP). https://www.itdp.org/wp-content/uploads/2014/07/Europes_Parking_U-Turn_ITDP.pdf

Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M. S., … Wells, P. (2019). An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions*, *31*, 1–32. https://doi.org/10.1016/j.eist.2019.01.004

Kosow, H., & Gaßner, R. (2008). *Methoden der Zukunfts- und Szenarioanalyse. Überblick, Bewertung und Auswahlkriterien [Methods of future and scenario analysis. Overview, assessment and selection criteria].* Institute for Futures Studies and Technology Assessment. https://www.izt.de/fileadmin/downloads/pdf/IZT_WB103.pdf

Kraftfahrtbundesamt. (2021). *Jahresbilanz - Neuzulassungen 2020 [Annual balance of new admissions 2020].* https://www.kba.de/DE/Statistik/Fahrzeuge/Neuzulassungen/jahresbilanz/jahresbilanz_inhalt.html

Lautso, L., Spiekermann, K., Wegener, M., Sheppard, I., Steadman, P., Martino, A., Domingo, R., & Gayda, S. (2004). *PROPOLIS: Planning and research of policies for land use and transport for increasing urban sustainability.* PROPOLIS Final Report. LT Consultants. http://www.spiekermann-wegener.de/pro/pdf/PROPOLIS_Final_Report.pdf

Loorbach, D., Frantzeskaki, N., & Avelino, F. (2017). Sustainability transitions research: Transforming science and practice for societal change. *Annual Review of Environment and Resources*, *42*(1), 599–626. https://doi.org/10.1146/annurev-environ-102014-021340

Loorbach, D., & Shiroyama, H. (2016). The challenge of sustainable urban development and transforming cities. In D. Loorbach, H. Shiroyama, J. Fujino, & S. Mizuguchi (Eds.), *Governance of urban sustainability transitions. European and Asian experiences* (pp. 3–12). Theory and Practice of Urban Sustainability Transitions. Springer. https://doi.org/10.1007/978-4-431-55426-4

Loorbach, D. A. (2007). *Transition management. New mode of governacne for sustainable development* [Phd thesis]. Erasmus Universiteit Rottermdam.

Macmillen, J., & Stead, D. (2014). Learning heuristic or political rhetoric? Sustainable mobility and the functions of best practice. *Transport Policy*, *35*, 79–87. https://doi.org/10.1016/j.tranpol.2014.05.017

Martinez, F. J. (1996). MUSSA: Land use model for Santiago City. *Transportation Research Record: Journal of the Transportation Research Board*, *1552*(1), 126–134. https://doi.org/10.1177/0361198196155200118

Maxwell, S. L., Milner-Gulland, E. J., Jones, J. P. G., Knight, A. T., Bunnefeld, N., Nuno, A., Bal, P., Earle, S., Watson, J. E. M., & Rhodes, J. R. ((2015). Being smart about SMART environmental targets. *Science*, *347*(6226), 1075–1076. https://doi.org/10.1126/science.aaa1451

Meine, K. (1989). Wind of change [Recorded by Scorpions]. On *Crazy World* [CD].: Los Angeles, CA & Hilversum: Mercury Records (1990). Retrieved from https://www.youtube.com/watch?v=n4RjJKxsamQ

Miyamoto, K., & Kitazume, K. (1989). A land use model based on random utility/rent-bidding analysis (RURBAN). *Selected Proceedings of the Fifth World Conference on Transport Research (4)* (pp. 107–121). Yokohama, Japan.

Moeckel, R., Moreno Chou, A. T., Garcia, C. L., & Okrah, M. B. (2018). Trends in integrated land-use/transport modeling: An evaluation of the stat of the art. *Journal of Transport and Land Use*, *11*(1), 463–476. https://doi.org/10.5198/jtlu.2018.1205

Müller, M. (2016). Semester tickets for university students in Germany: A success story for 25 years. *World Transport Policy and Practice*, *21*(4), 7–18.

Müller, M., & Reutter, O. (2017). Vision development towards a sustainable North Rhine-Westphalia 2030 in a science-practice-dialogue. *Sustainability*, *9*(7), 1111. https://doi.org/10.3390/su9071111

Müller, M., & Reutter, O. (2020). Benchmark: Climate and environemtally friendly urban passenger transport – The concepts of the European Green Capitals 2010-2020. *World Transport Policy and Practice*, *26*(2), 21–43.

Neubauer, L., Thunberg, G., von der Heyden, A. d. W., & Charlier, A. (2020, July 16). *Face the climate emergency. Open letter and demands to EU and global leaders.* https://climateemergencyeu.org

Neves, A., & Brand, C. (2019). Assessing the potential for carbon emissions savings from replacing short car trips with walking and cycling using a mixed GPS-travel diary approach. *Transportation Research Part A*, *123*, 130–146. https://doi.org/10.1016/j.tra.2018.08.022

Nobis, C., & Kuhnimhof, T. (2019). *Mobilität in Deutschland – MiD Ergebnisbericht [Mobility in Germany – MiD final report].* A study of infas, DLR, IVT, infas 360 on behalf of Federal Ministry of Transport and Digital Infrastructure. https://www.mobilitaet-in-deutschland.de

Ott, R. (2006). Umsetzung der Zürcher Mobilitätsstrategie [Implementation of the Zürcher mobility strategy]. City of Zurich, Tiefbauamt (Ed.), Zurich. Retrieved from https://docplayer.org/39254283-Umsetzung-der-zuercher-mobilitaetsstrategie.html

Padmanabhan, M. (2018). Introduction – Transdisciplinarity for sustainability. In M. Padmanabhan (Ed.), *Transdisciplinary research and sustaianbility: Collaboration, innovation and transformation* (pp. 1–32).Routledge Studies in Environment, Culture, and Society.

Potter, S. (2007). Exploring approaches towards a sustainable transport system. *International Journal of Sustainable Transportation*, *1*(2), 115–131. https://doi.org/10.1080/15568310601091999

Pritchard, R., Bucher, D., & Frøyen, Y. (2019). Does now bicycle infrastructure result in new or rerouted bicyclists? A longitudinal GPS study in Oslo. *Journal of Transport Geography*, *77*, 113–125. https://doi.org/10.1016/j.jtrangeo.2019.05.005

Pucher, J., Dill, J., & Handy, S. (2010). Infrastructure, programs, and policies to increase bicycling: An international review. *Preventive Medicine*, *50*, S106–S125. https://doi.org/10.1016/j.ypmed.2009.07.028

Raskin, P., Banuri, T., Gallopín, G., Gutman, P., Hammond, A., Kates, R., & Swart, R. (2002). *Great transition – The promis and lure of the times ahead.* Global Scenario Group, Stockholm Environment Institute. https://www.researchgate.net/publication/273698260_The_Great_Transition_The_Promise_and_Lure_of_Times_Ahead

Raskin, P. D., Electris, C., & Rosen, R. A. (2010). The centurey ahead: Searching for sustainability. *Sustainability*, *2*(8), 2626–2651.10.3390/su2082626. https://doi.org/10.3390/su2082626

Raskin, P. D., Gallopin, G., Gutman, P., Hammond, A., & Swart, R. (1998). Bending the curve: Toward global sustainability. Global Scenario Group, Stockholm Environment Institute. https://www.sei.org/publications/bending-curve-toward-global-sustainability/

Reutter, O., Müller, M., Esken, A., Fekkak, M., Gröne, M.-C., Richard, J., Treude, M. (2017). *Die Lage der Umwelt in der Metropole Ruhr – dargestellt anhand von 15 Umweltindikatoren [The state of the environment in the Ruhr Metropolitan Region - presented using 15 environmental indicators*]. Wuppertal Institute in cooperation with Planungsbüro Richter-Richard, in: Regionalverband Ruhr (Ed.): Bericht zur Lage der Umwelt in der Metropole Ruhr [Report about the state of the environment in the Ruhr Metropolitan Region]. https://shop.rvr.ruhr/media/pdf/18/b3/22/Umweltbericht-Ruhr-2017.pdf

Reutter, O., Berlo, K., Bierwirth, A., Boehler-Baedeker, S., Brinkmann, C., Fekkak, M., Friedrichowitz, C., Friege, J., Grimmer, K., Jansen, U., Kaselofsky, J., Klement, J., Lechtenböhmer, S., Lucas, R., Müller, M., Nanning, S., Rohne, H., Schäfer-Sparenberg, C., Schepelmenn, P., Schulz, S., Wagner, O. (2013). Metropole Ruhr - Grüne Hauptstadt Europas [Ruhr Metropolitan Region - European Green Capital]. In cooperation with Planungsbüro Richter-Richard. Wuppertal: Wuppertal Institute. http://wupperinst.org/uploads/tx_wupperinst/Metropole_Ruhr_Endbericht.pdf

Reutter, O., & Reutter, U. (2016). Climate protection in urban transport – Six scenario studies in Germany: More climate protection, fever carbon dioxide emissions, less car traffic. *Journal of Traffic and Transportation Engineering*, *4*, 75–85. https://doi.org/10.17265/2328-2142/2016.02.002

Regionalverband Ruhr [RVR]. (2014). *Perspektiven für die räumliche Entwicklung der Metropole Ruhr [Perspectives for spatial developments in the Ruhr Metropolitan Region].* https://www.rvr.ruhr/fileadmin/user_upload/01_RVR_Home/02_Themen/Regionalplanung_Entwicklung/Regionaler_Diskurs/2013_Entwurf_Perspektiven.pdf

Regionalverband Ruhr [RVR]. (2018, September 12). *RVR legt regionale Ergebnisse der deutschlandweiten Mobilitätsstudie vor* [RVR presents regional results of the German-wide mobility study]. Press release [online].

Regionalverband Ruhr [RVR]. (2019). *Regionales Mobilitätsentwicklungskonzept für die Metropole Ruhr (Entwurf)* [Regional *mobility concept for the Metropolitan Ruhr Region (draft)].* Report developed by Planersocietät, Gertz Gutsche Rümenapp, Goudappel Coffeng b.v., Spiekermann & Wegener (S&W) Stadt- und Regionalforschung, HTC – Hanseatic Transport Consultancy. Author. https://www.rvr.ruhr/fileadmin/user_upload/01_RVR_Home/02_Themen/Mobilitaet/Mobilitaetskonzepte/Entwurf_Endbericht_Regionales_Mobilitaetsentwicklungskonzept.pdf

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanzak, R., Svedin, U., … Foley, J. (2009). Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society*, *14*(2), 32. https://doi.org/10.5751/ES-03180-140232

Rotmans, J., Kemp, R., & van Asselt, M. (2001). More evolution than revolution: Transition management in public policy. *Foresight*, *3*(1), 15–31. https://doi.org/10.1108/14636680110803003

Sachverständigenrat für Umweltfragen (SRU). (2019). *Für die Umsetzung ambitionierter Klimapolitik und Klimaschutzmaßnahmen [For implementing ambitious climate policies and climate protection measures].* Open letter of 16 September 2019. https://www.umweltrat.de/SharedDocs/Downloads/DE/04_Stellungnahmen/2016_2020/2019_09_Brief_Klimakabinett.pdf?__blob=publicationFile&v=5

Sadler Consultants Ltd. (n.d.). *Urban access regulations in Europe.* European Commission. http://www.urbanaccessregulations.eu

Santos, G., Behrendt, H., & Teytelboym, A. (2010). Part II: Policy instruments for sustainable road transport. *Research in Transportation Economics*, *28*(1), 46–91. https://doi.org/10.1016/j.retrec.2010.03.002

Schneidewind, U. (2013). Gesellschaftliche Veränderungsprozesse verstehen und gestalten [Transformative literacy. Understanding and shaping societal transformations]. *Gaia - Ecological Perspectives for Science and Society*, *22*(2), 82–86. https://doi.org/10.14512/gaia.22.2.5

Schwarze, B., Spiekermann, K., Wegener, M., Huber, F., Brosch, K., Reutter, O., & Müller, M. (2017). *Cities and climate change: Ruhr area 2050 – Integrated Ruhr area model and regional modal shift.* http://www.spiekermann-wegener.de/pro/pdf/EWR_Ruhr_Area_260717.pdf

Scorpions. (1990). *Wind of change. Song released on 6 November 1990 on the album "Crazy World".* https://www.youtube.com/watch?v=n4RjJKxsamQ.

Simmonds, D. C. (1999). The design of the DELTA land-use modelling package. *Environment and Planning B: Planning and Design*, *26*(5), 665–684. https://doi.org/10.1068/b260665

Sims, R., R., Schaeffer, F., Creutzig, X., Cruz-Núñez, M. D. D., Dimitriu, M. J., Figueroa Meza, L., Fulton, S., Kobayashi, O., Lah, A., McKinnon, P., Newman, M., Ouyang, J. J., Schauer, D., Sperling, G. & Tiwari. (2014). Transport. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, & J. C. Minx (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* (pp. 599–670). Cambridge University Press. https://www.ipcc.ch/report/ar5/wg3/

Singleton, J. (2015). Head, heart and hands model for transformative learning: Place as context for changing sustainability values. *Journal of Sustainability Education*, *9*, 1–16. http://www.jsedimensions.org/wordpress/wp-content/uploads/2015/03/PDF-Singleton-JSE-March-2015-Love-Issue.pdf.

Sondeijker, S., Geurts, J., Rotmans, J., & Tukker, A. (2006). Imagining sustainability: The added value of transition scenarios in transition management. *Foresight*, *8*(5), 15–30. https://doi.org/10.1108/14636680610703063

Spiekermann, K., & Wegener, M. (2005). *Räumliche Szenarien für das östliche Ruhrgebiet [Spatial scenarios for the Eastern Ruhr Area].* Final Report. Institut für Landes-und Stadtentwicklungsforschung und Bauwesen des Landes Nordrhein-Westfalen (ILS NRW). http://www.spiekermann-wegener.de/pro/pdf/ILS_Raumszenarien.pdf

Steffen, W., Richardson, K., Rockström, J., Cornell, S., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855. https://doi.org/10.1126/science.1259855

The Guardian. (2021). *Electric cars rise to record 54% market share in Norway.* https://www.theguardian.com/environment/2021/jan/05/electric-cars-record-market-share-norway.

Transport for London (TfL). (2007). *Impacts monitoring.* Fifth Annual Report, July 2008. http://content.tfl.gov.uk/fifth-annual-impacts-monitoring-report-2007-07-07.pdf

Turnheim, B., Asquith, M., & Geels, F. W. (2020). Making sustainability transitions research policy-relevant: Challenges at the science-policy interface. *Environmental Innovation and Societal Transitions*, *34*, 116–120. https://doi.org/10.1016/j.eist.2019.12.009

Umweltbundesamt. (2019a). *Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem Kyoto-*

Protokoll. Nationaler Inventarbericht Zum Deutschen Treibhausgasinventar, 2018 1990 – 2017 [Reporting under the climate framework convention of the *United Nations and the Kyoto Protocol. National inventory report, greenhouse gas inventory 1990-2017].* Dessau-Roßlau: Umweltbundesamt.

Umweltbundesam. (2019b). *Daten der deutschen Berichterstattung atmosphärischer Emissionen - Treibhausgase 1990-2017 [Data of German reporting on atmospheric emissions – greenhouse gases 1990-2017].* Dessau-Roßlau: Umweltbundesamt.

Umweltbundesamt. (2019c). *Nationale Trendtabellen für die deutsche Berichterstattung atmosphärischer Emissionen 1990 – 2017 [National trend tables for German reporting on atmospheric emissions 1990-2017].* Dessau-Roßlau: Umweltbundesamt.

United Nations Framework Convention on Climate Change (UNFCCC). (2015). *Paris agreement*. United Nations. http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

United Nations Framework Convention on Climate Change (UNFCCC). (2021). *Paris agreement – Status of ratification.* https://unfccc.int/process/the-paris-agreement/status-of-ratification

Ullrich, D. (2004). Karte der Siedlungsstruktur des Ruhrgebiets [Map of settlement structures of the Ruhr Area]. Retrieved from https://de.wikipedia.org/wiki/Ruhrgebiet#/media/Datei:Ruhr_area-map.png

Urueña, S. (2019). Understanding "plausibility": A relational approach to the anticipatory heuristics of future scenarios. *Futures*, *111*, 15–25. https://doi.org/10.1016/j.futures.2019.05.002

Van Vuuren, D. P., Kok, M., Lucas, P. L., Prins, A. G., Alkemade, R., Van den Berg, M., Bouwman, L., Van der Esch, S., Jeuken, M., Kram, T., & Stehfest, E. (2015). Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, *98*, 303–323. https://doi.org/10.1016/j.techfore.2015.03.005

Waddell, P. (2002). UrbanSim: Modeling urban development for land use, transportation and environmental planning. *Journal of the American Planning Association*, *68*(3), 297–314. https://doi.org/10.1080/01944360208976274

Waluga, G. (2017). *Das Bürgerticket für den öffentlichen Personennahverkehr. Nutzen – Kosten – Klimaschutz [The citizen ticket for public transport. Benefits, costs, climate protection], Wuppertaler Schriften zur Forschung für eine nachhaltige Entwicklung, Band 9*. Munich: oekom. https://epub.wupperinst.org/frontdoor/deliver/index/docId/6751/file/WSFN9_Waluga.pdf

Wegener, M. (1982). Modeling urban decline: A multilevel economic-demographic model of the Dortmund region. *International Regional Science Review*, *7*(2), 217–241. https://doi.org/10.1177/016001768200700207

Wegener, M. (2004). Overview of land-use transport models. In D. A. Hensher & K. Button (Eds.), *Handbook of transport geography and spatial systems* (Vol. 5, pp. 127–146). Pergamon/Elsevier Science.

Wegener, M. (2014). Land-use transport interaction models. In M. Fischer & P. Nijkamp (Eds.), *Handbook of regional science* (pp. 741–758). Springer.

Wegener, M. (2018). *The IRPUD Model* (Working Paper 18/01). Spiekermann & Wegener Urban and Regional Research. http://www.spiekermann-wegener.de/mod/pdf/AP1801.pdf

Wegener, M. (2020). Chapter 9: Are urban land-use transport interaction models planning support systems? In S. Geertman & J. Stillwell (Eds.), *Handbook of planning suport science* (pp. 153–160). Edward Elgar Publishing. https://doi.org/10.4337/9781788971089.00017

Wiek, A., Binder, C., & Scholz, R. W. (2006). Functions of scenarios in transition processes. *Futures*, *38*(7), 740–766. https://doi.org/10.1016/j.futures.2005.12.003

Wiek, A., Keeler, L. W., Schweizer, V., & Lang, D. J. (2013). Plausibility indications in future scenarios. *International Journal of Foresight and Innovation Policy*, *9*(2/3/4), 133–147. https://doi.org/10.1504/IJFIP.2013.058611

Wiener Stadtwerke. (2020). *Geschäftsbericht 2019 [Annual Report 2019].* https://www.wienerstadtwerke.at/eportal3/ep/contentView.do/pageTypeId/71283/programId/3600056/contentTypeId/1001/channelId/-49476/contentId/5001347

Wuppertal Institute for Climate, Environment and Energy. (2013). *Metropole Ruhr – Grüne Hauptstadt Europas [Ruhr Metropolitan Region – European Green Capital].* (In cooperation with Reutter, O., Berlo, K., Bierwirth, A., Boehler-Baedeker, S., Brinkmann, C., Fekkak, M., Friedrichowitz, C., Friege, J., Grimmer, K., Jansen, U., Kaselofsky, J., Klement, J., Lechtenböhmer, S., Lucas, R., Müller, M Nanning, S., Rohne, H., Schäfer-Sparenberg, C., Schepelmenn, P., Schulz, S., Wagner, O.). http://wupperinst.org/uploads/tx_wupperinst/Metropole_Ruhr_Endbericht.pdf

Wuppertal Institute for Climate, Environment and Energy. (2017). *Die Lage der Umwelt in der Metropole Ruhr – dargestellt anhand von 15 Umweltindikatoren [The state of the environment in the Ruhr Metropolitan Region – presented using 15 environmental indicators].* (In cooperation with Planungsbüro Richter-Richard. Reutter, O., Müller, M., Esken, A., Fekkak, M., Gröne, M.-C., Richard, J., Treude, M., in: Regionalverband Ruhr (Ed.): Bericht zur Lage der Umwelt in der Metropole Ruhr) [Report about the state of the environment in the Ruhr Metropolitan Region]. https://shop.rvr.ruhr/media/pdf/18/b3/22/Umweltbericht-Ruhr-2017.pdf

Zhang, W., & Zhang, M. (2018). Incorporating land use and pricing policies for reducing car dependence: Analytical framework and empirical evidence. *Urban Studies*, *55*(13), 3012–3033. https://doi.org/10.1177/0042098017720150

Zimmer, W., Blanck, R., Cyganski, R., Peter, M., Wolfermann, A., & Mocanu, T. (2017). *Renewbility: Options for a decarbonisation of the transport sector up to 2050. ECEEE Summer Study Proceedings.* https://www.researchgate.net/profile/Rita_Cyganski/publication/318317352_Renewbility_options_for_a_decarbonisation_of_the_transport_sector_up_to_2050/links/59634541a6fdccc9b152bcee/Renewbility-options-for-a-decarbonisation-of-the-transport-sector-up-to-2050.pdf

Appendix 1: Realized past reduction rates of the modal share of car use in the thirteen real-world city examples – overall and during accelerated times of change

City (inhabitants)	Trip-based modal share of car use (%) Earliest data available		Latest data available		Time interval in years	Development of modal share of car use In total (percentage points)	On average (percentage points per year)
Barcelona (1.6 m)	2006	28.5	2013	24.2	7	−4.3	−0.6
Berlin (3.8 m)	1998	38	2018	26	20	−12	−0.6
Bremen (569,000)	2008	40,4	2018	35,6	10	−2,4	−0.5
Copenhagen (632,000) *Long-term average*	2007	36	2018	32	11	−4	−0.4
Copenhagen *sharpest reduction phase*	*2008*	*37*	*2010*	*33*	*2*	*−4*	*−2.0*
Karlsruhe (306,000) *Long-term average*	1982	44	2018	33	35	−6	−0.3
Karlsruhe *sharpest reduction phase*	*2002*	*44*	*2012*	*35*	*10*	*−9*	*−0.9*
London (8.9 m Greater London, 3.3 m Inner London) *Long-term average*	1996	49	2017	36	21	−13	−0.6
London *sharpest reduction phase*	*1999*	*48*	*2008*	*40*	*9*	*−8*	*−0.9*
Munich (1.5 m)	2002	41	2017	34	15	−7	−0.5
Munich *sharpest reduction phase*	*2002*	*41*	*2008*	*37*	*6*	*−4*	*−0.7*
Nantes (309,000) *Long-term average*	1997	60.3	2012	52	15	−8.3	−0.6
Nantes *sharpest reduction phase*	*2002*	*63.1*	*2012*	*52*	*10*	*−11.1*	*−1.1*
Oslo (693,000) *Long-term average*	2005	45	2015	34	10	−11	−1.1
Oslo sharpest reduction phase	*2005*	*45*	*2011*	*34*	*6*	*−11*	*−1.8*
Stockholm (950,000)	2004	48	2006	47	2	−1	−0.5
Vienna (1.9 m) *Long-term average*	1993	40	2020	27	27	−13	−0.5
Vienna sharpest reduction phase	*2002*	*37*	*2012*	*27*	*10*	*−10*	*−1.0*
Vitoria-Gasteiz (250,000) *Long-term average*	1996	36	2014	24.7	18	−11.3	−0.6
Vitoria-Gasteiz *sharpest reduction phase*	*2006*	*36.9*	*2014*	*24.7*	*8*	*−12.2*	*−1.5*
Zurich (434,000)	2000	40	2015	25	15	−15	−1.0

Sources and additional modal split data: Supplemental online material.
The italics emphasize when city modal split data is additionally analyzed regarding “sharpest reduction phases” (as compared to only “long-term averages”).

Appendix 2: Targets to reduce the modal share of car use

City	Starting point[a]	Trip-based modal share target of car use	Time interval in years	Reduction of modal share of car use: Overall (percentage points)	Reduction of modal share of car use: Average per year (percentage points, rounded)
Ruhr Metropolitan Region (target proposal based on 2012 data)	53% in 2012	25% by 2035	23	−28	−1.2
Copenhagen (target of 2015)	33% in 2014	25% by 2025	11	−8	−0.7
London (target of 2017)	36.5% in 2016	20% by 2041	25	−16.5	−0.7
Vienna[b] (target of 2014)	28% in 2014	20% by 2025	11	−8	−0.7
	20% in 2025 (assumed)	15% by 2030	5	−5	−1.0
Zurich (target of 2012)	30% in 2010	20% by 2025	15	−10	−0.7

[a]The starting point is the modal share of car use in the year closest to the year the target is adopted (or proposed in case of the Ruhr Metropolitan Region).
[b]Further target of the City of Vienna: "far below 15%" by 2050. Sources and additional data: Supplemental online material.

Appendix 3: Modeling results of the transport measures in the ILUT "Ruhr Area Model 2050"

		Trip-based modal share of motorized private transport (in %)		**CO_2 emissions of transport (tons/inhabitant/year)**	
1990		∼50		∼1.2	
2015		∼54		∼1.6	
		A-scenarios	B-scenarios	A-scenarios	B-scenarios
Business as usual (BAU) 2050		∼58	∼53	∼1.5	∼1.0
Measure scenarios		Approximate impacts of measures compared to the BAU scenarios 2050 (in percentage points)		Approximate impacts of measures compared to the BAU scenarios 2050 (in %)	
Land use	13 Densification at railway stations	0	0	0%	0%
	23 New housing at railway stations	0	0	−1%	−1%
Efficiency	32 Promotion of electric mobility	0	0	−14%	−14%
	33 Area-wide car sharing	−1.5	−1	−1%	+1%
	34 Increased energy efficiency of the vehicle fleet	+2.5	+4	−45%	−29%
Car (push)	41 Regional toll Ruhr Metropolitan Region	−3	−3	−3%	−3%
	42 Reallocation of road space	−2	−1	−41%	−26%
	43 Area-wide speed limits	−1.5	−2	−24%	−16%
	44 Increased parking fees	0	0	−1%	−1%
Public transport (pull)	51 Extension of public transport network	−0.2	−0.2	0%	0%
	52 More frequent public transport services	−2	−2.2	+19%	+28%
	53 Introduction of a 'citizen ticket'	−1.5	−2	−1%	−1%
Cycling (pull)	61 System acceleration of cycling	0	0	0%	0%
	62 Fast cycling routes network	0	0	0%	0%
Walking (pull)	71 System acceleration of walking	−0.8	−1	−1%	0%
Combined scenarios	81 Land-use	0	+0.5	−1%	−2%
	82 Efficiency measures	0	+2	−45%	−29%
	83 Push measures (car)	−9	−7	−59%	−45%
	84 Pull measures (public transport, cycling, walking)	−3.5	−4.8	+19%	+29%
	85 All measures	−21	−18	−53%	−40%
	91 Push & pull measures	−19	−13	−42%	−12%
	92 Push & pull & energy efficiency	−19	−15	−53%	−40%

Own numerical reporting of the graphic modeling results of S&W in Reutter et al. (2013); A-scenarios: 1% fuel price increase per year; B-scenarios: 4% fuel price increase per year.