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RESEARCH

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Modelling policy scenarios: refocussing the model-policy logic for the case of German passenger transport

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Abstract

Background National energy and climate scenarios are typically simulated or optimised using sectoral or energy system models, which include a large number of model settings and scenario assumptions. However, their realisation is contingent upon framework conditions and policy settings, which are often included in accompanying narrative scenarios. This paper therefore proposes refocussing the model-policy logic towards directly modelling policy effects. Applying this approach to the case of German passenger transport, I focus on demand-side policies and use open-source databases and models to develop a module for the translation of policies into model parameters.

Results Separate model runs were used to test a ceteris paribus policy reference scenario for 2035, the marginal impacts of modelled single policy effects, and a joint policy package scenario. Relative to the reference, demand-side policies show significant impacts: an annual reduction of 355 bn person-kilometres (30%) and a reduction of car-owning households from 95 to 90% in rural areas and from 76 to 64% in urban areas. The resulting mode shift decreases car-driven kilometres by 400 bn and increases public transport by 45 bn per year. This may reduce GHG emissions by an additional 30 Mt (or 33%) relative to the reference in 2035.

Conclusions Transport demand policies can significantly mitigate GHG, calling for a stronger policy focus beyond the much-studied shift to electric vehicles. While further research and model development are needed, the feasibility of policy scenario modelling increases its utility for policy-making.

Keywords Transport demand policy, Passenger transport, Policy modelling, Emission mitigation, Avoid shift improve

Introduction

Background

Despite the climate targets of the Paris Agreement [1] and recent advances in scientific understanding of climate change and its mitigation [2–4], political action has failed to adequately curb emissions. As a result, the remaining carbon budgets to reach climate targets [5] are now running low, such that industrialised countries must decarbonise all sectors by 2050 at the latest. The transport sector presents a special challenge globally, given the incompatibility of its current path with climate targets. This sector has seen the highest recent increases in final energy demand, which almost doubled from 65EJ in 1990 to 120EJ in 2019 [6], as well as the highest CO_2 increases, which rose from 4.6Gt/a in 1990 to 8.2 Gt/a in 2019 [7]. In high-income countries like Germany, transport emissions rose by 5% between 1995 and 2020 [8], making transport the only sector to experience an emission increase in recent decades. A policy framework

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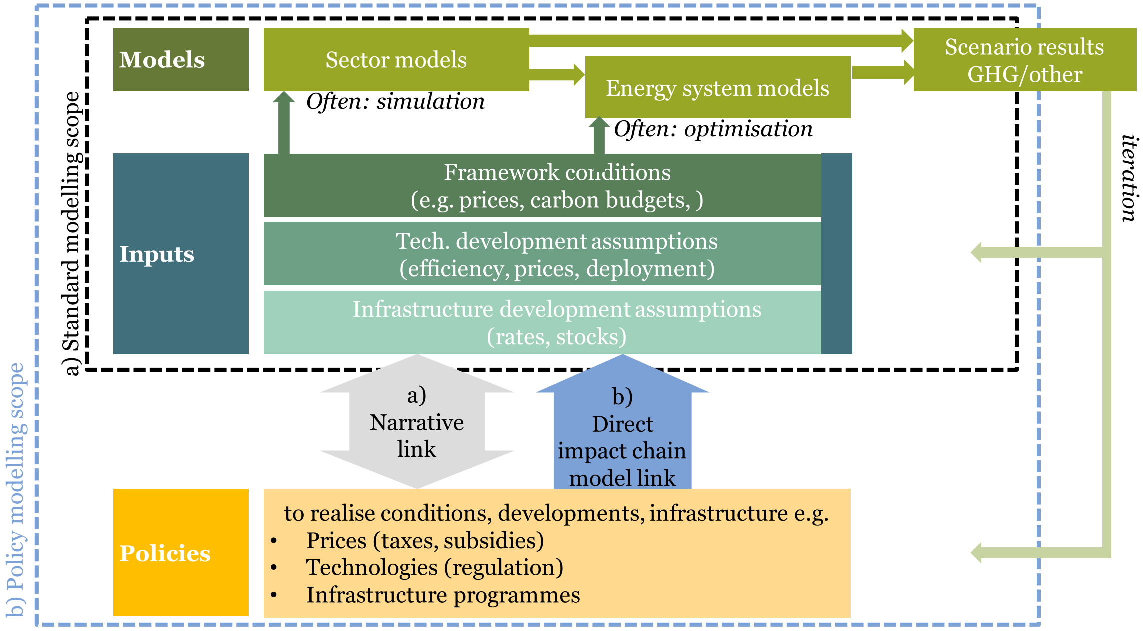

Fig. 1 Role of policies in energy and decarbonisation scenario modelling: scope of **a** standard and **b** policy modelling

conducive to transport decarbonisation is thus key to achieving climate targets.

Germany is the largest European economy and also the largest greenhouse gas (GHG) emitter, with a 2045 net zero-emission target in the enacted climate law [9], plus interim sectoral targets. There are numerous scenarios and underlying models (see [10–12]), as well as many different proposed energy transition policies and databases (see [13, 14] for an overview). In general, both planned and enacted policies [15] and research have tended to focus on technical options, but demand-side options are considered to have high mitigation potential [16, 17]. This leaves a research gap in scenarios, especially concerning the types of policies that may realise this potential.

Use of models in policy-making

In the field of energy transitions, modelling tools play a crucial role in decision-making: they are used to inform policy-making by laying out possible future pathways (ex ante evaluations), facilitate the ex post assessment of implemented policies, and justify policy decisions [18]. Model-based scenario studies can help clarify complex systems and interactions, anticipate the effects of virtual experiments, illustrate potential futures [19], and identify “big points” and “key points” [20] in the parameters that lead to substantial changes in the defined scenarios, including through systematic sensitivity analysis [21, 22]. This approach provides policy-makers with insights into the specific areas and target indicators for those policies needed to effect change.

For most national energy and decarbonisation scenario modelling, the applied techno-economic sectoral or energy system models vary key exogenous input parameters, often through sub-scenarios. For example, they may vary energy efficiency ambition levels, the degree of lifestyle change, levels of acceptance, and/or the depth of policy action. The literature is extensive, offering examples from the broader transport sector [23–25] and the German context [26–29]; for a review of the “Big Five” scenarios, see Luderer et al. [11]. In many scenarios, parameter variations are typically embedded in accompanying storylines or narratives that cover social and environmental factors [30] as well as policy frameworks. Some key parameter changes are directly linked to policy instruments. Carbon pricing when set as a tax, or technology shares when directly regulated, e.g. through phase-outs, are examples of such instruments. Other parameters are exogenously set as assumptions within the respective narrative scenario context. In this idealised standard approach, policies expected to be necessary are iteratively derived or formulated while the scenario narrative is being developed [30]. This process is shown as stylised approach a) in Fig. 1.

Research gap and proposed approach

The likeliness of presented scenarios (for the German case see [10–12]) hinges on the materialisation of specific parameter changes—which, in turn, are influenced by existing political framework conditions. The narrative scenario’s dependency on existing policy frameworks is

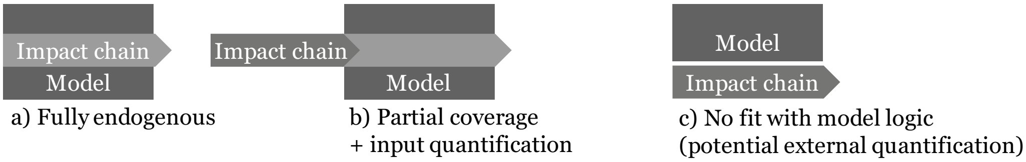

Fig. 2 Options of (policy) impact chain integration in models. Source: Based on [15]

a feature of stylised standard energy scenario modelling, which uses connected narrative scenarios. The direct derivation of scenarios from policy settings (approach b in Fig. 1) constitutes at least a partial research gap not closed by many models. To address this gap, this paper extends the scope of the model to include explicit policy quantification and applies this method to the case of German passenger transport. Using both direct and indirect methods, I model policy impacts on parameters and make assumptions transparent. Since implementing demand-side policies and measures for transportation are key to reaching climate targets, and as the modelling of transport demand pathways is understudied in comparison to technology choice and fuel switch, the paper focuses on demand-side policies.

The research question is whether, how, and to what extent demand-side policies can be directly modelled by assessing the potential impacts of policy packages on German passenger transport, yielding insights of relevance to policy-making.

The proposed approach requires applied models that can integrate policy effects. Whether and to what degree this is possible depends on two factors: (1) the ability to operationalise policies into quantifiable parameters for model integration and (2) the scope and architecture of the specific model.

Energy system models (ESM) typically do not represent demand sectors like transportation, buildings or industry, or do so only at a general level. Thus, they cannot accurately represent sectoral policies. For sector policy modelling, specialised models are needed that can cover identified policy impact chains within the model or through annex calculations [15]. Figure 2 shows three options: (a) the policy's impact logic aligns with the model's and thus can be directly represented in the model, as happens when developing a new rail or bicycle infrastructure that alters available networks; (b) the policy impacts certain parameters that are used as exogenous inputs to models, which requires partial pre-modelling of the policy impact chain, as when taxation instruments interact to alter variable costs; or (c) impact chains cannot be integrated because they fall outside the model's logic; in that case, full side-quantification would be needed. Examples of cases requiring a simulation model include demand-related policies; policies related to technology or vehicle fleet require additional models. In addition, some policies cannot be quantified at all and therefore must be excluded from a policy modelling approach. Examples may include certain changes to the legal framework that are undeniably necessary—for example, to alter long-term infrastructure planning—but that affect logics that lie outside the scope of transport models.

To implement the proposed approach, I build on open-source models and data. Section "Methods" , introduces the used methods and materials, including the policy database and the transport model, and outlines the modules necessary for incorporating demand-side policies and defining policy scenarios. Section "Results" presents the results of modelled policy impacts, which are discussed in Sect. "Discussion" alongside the limitations and further development needs of the model. Section "Conclusions" concludes.

Methods

Transport policy collection and categorisation

As a first step, I generated a transport policy database by collecting individual policy instruments from sources listed in Table 1. This policy collection is part of the Energy Sufficiency Policy Database and follows the same methodology [13]. However, it also covers policies that aim not only to avoid, but also improve and shift modes of transport.

The resulting policy database includes single policy instruments categorised by policy strategy, measure and activity induced, instrument type as per the reporting categories listed in [36], estimated time-to-impact, and sufficiency type [37]. A complete version of 140 collected transport policies, including those intended to improve transport, is provided as a tab in the supplementary material with additional policy categorisations. However, this database is not entirely used for this article and is thus only briefly outlined in Appendix A.

Prioritisation and model logic

To select the policies to be implemented in the model, an "initial sifting" [38] was conducted to filter out policies not aligned to the objectives, problems and opportunities of the policy (decarbonisation of the transport sector), as well as those outside of the sector scope (passenger transport) and/or that lacked sufficient detail.

Table 1 Main sources represented in the transport policy database

Source	Geographical coverage	Sectoral coverage	References
27 EU National Energy and Climate Plans	EU	All	27 national documents [31]
Massnahmen fuer ein 1,5-Grad- Gesetzespaket	Germany	All	[32]
A radical transformation of mobility in Europe: Exploring the decarbonisation of the transport sector by 2040	EU	Transport	[33]
Behavioural Climate Change Mitigation Options and Their Appropriate Inclusion in Quantitative Longer Term Policy Scenarios	EU	All (excl. industry)	[34]
Klimaneutrales Deutschland	Germany	All	[27]
Modelling road transport emissions in Germany—Current day situation and scenarios for 2040	Germany	Road transport	[35]

To prioritise policies for model implementation, I used the approach proposed by Climact and NCI [33] to assess three characteristics of each policy entry: (1) maturity, i.e. the policy's implementation phase (in planning or implemented, in how many constituencies, and for how long); (2) replicability (extent to which the identified policy can be replicated in theory, and whether it has been replicated in practice), and (3) expected impact (potential to mitigate emissions). Appendix A includes details on the coding and procedure. The coding was reviewed by two external transport researchers whose detailed feedback was included in the coding revision. The average of the above indicators yields a combined traffic light priority indicator.

Finally, I assessed the feasibility of representing each policy from the prioritised list within the target model. This step is specific to the target model(s) under consideration, as it depends on model architecture and scope. For instance, a model may or may not directly represent specific policies, require additional model development, or need auxiliary quantifications (Fig. 2). For the case of transport modelling, bottom-up transport simulation, as well as agent-based and aggregated transport models can represent policies that change prices or infrastructures. Policies that pursue "avoidance" strategies will require explicit transport demand modelling and mobility infrastructures, and policies aimed at technology choice or car ownership will need modelling capacities for those issues. For this study, I evaluated the feasibility of incorporating these policies into the macroscopic transport model *quetzal_germany* as a representative model in the field. Importantly, model-specific differences can lead to different feasibility outcomes for other models. For example, if the framework allows modelling vehicle technology choices, policies addressing technologies can be included. This is not the case for this work, which uses exogenous results from other studies [27] for vehicle fleet development.

Applied transport model: quetzal_germany

Transportation modelling applies two main approaches: microscopic and macroscopic. Microscopic models typically simulate individual mobility decisions and movements along transport infrastructures with high spatial and temporal resolution. Macroscopic models address the total volumes of traffic flows across various modes of transport and transport infrastructures. They typically follow a classic four-step (often consecutive) modelling approach [39] that addresses: (1) trip generation (modelling of trip volumes and origins); (2) trip distribution (modelling of destinations of trips); (3) mode choice (of available transportation modes); and (4) traffic assignment (the matching of modelled trips by modes on transport infrastructures, like roads and railways).

For this study, focused on the case of Germany, I use the open-source macroscopic transport model *quetzal_germany* [40]. This aggregated transport model, written in Python and implemented through Jupyter Notebooks, estimates intra-zone traffic based on external data and simulates traffic between 2225 zones within Germany.[1] The model is segmented into the following demand segments: commuting, business, education, grocery shopping or medical executions, leisure, and accompanying trips; each of which is also segmented by car availability within households. The main data sources used to calibrate and validate the model are the Federal Transport Infrastructure Plan 2030 (VP2030, [42]) and the national mobility survey (MiD2017 [43]). The mode choice step is designed as a random utility theory-based Nested Logit model for each segment, with land and air transport alternatives. The road network model is based on OpenStreetMap (OSM) data and, for public transport, on

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[1] The share of endogenously modelled inter-zonal passenger transport volume amounts to approx. 86%, the remainder to intra-zonal volumes estimated from each zone's population density and the number of attractions relevant to each demand segment [41].

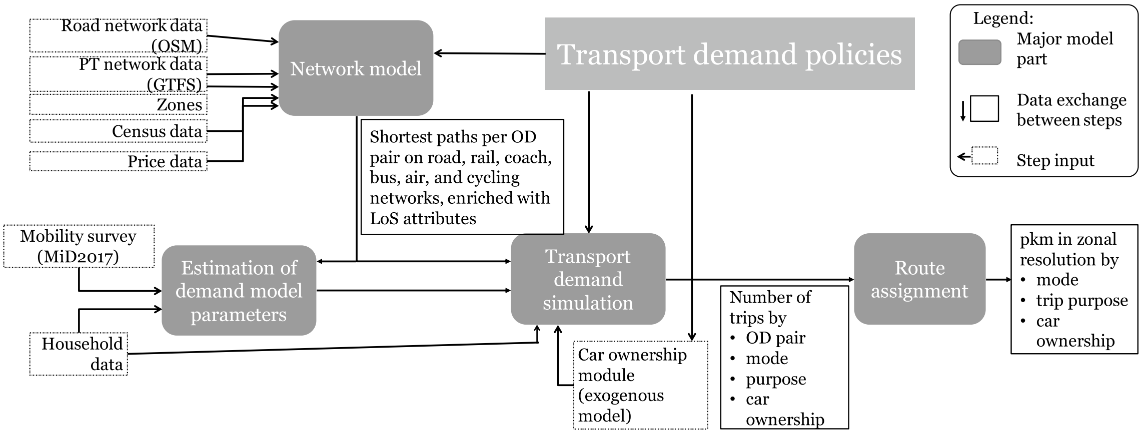


Fig. 3 Modelling avoid and shift policies in quetzal_germany

General Transit Feed Specification (GTFS) [44] timetable data. Emissions calculations are based on TREMOD/HBEFA data [45]. Model results yield that for business trips, travel price has no impact on mode decisions, and that for commuting, price elasticity is double the average. Mode choice for trips of both purposes is more time-sensitive on longer distances, while trips for shopping and education are less time-sensitive on shorter distances [46]. For detailed elasticity estimates by trip purposes see the "input" folder in the github repository [40]. Model outputs have been validated based on 2017 MiD empirical data and show only marginal deviations from validation data in terms of modal split [for details see Table 3 in 46]. Data sources, model design, specification and the calibration/validation of the model are outlined in detail in the literature [46]; Fig. 3 displays major model parts and interactions.

This work focuses on modelling demand-side policies aligned with *avoid* and *shift* strategies, but incorporates technical *improve* measures (efficiency and drive-train switch) in the reference/background assumptions. The initial assessment of modelling feasibility revealed that many mode *shift* policies could be modelled with the 2022 version (v1.1.0) [47] of the mode choice module, but that several policies, especially *avoid* strategies, needed additional model features that are now included in the latest version (v2.1.0) [40]. These features include an endogenous trip generation and distribution module [41], a railway expansion module, and a module for car ownership choice modelling [48].

Car ownership (CO) rates are key, because the model is fully segmented by CO due to the differing mobility choices of households with or without access to a car. Initially, CO rates were determined based on exogenous statistical data [43]. However, a dedicated representative survey in Germany [49] analysing the determinants of car ownership [50] led to the development of an openly available module for endogenously modelled car ownership levels [48]. Due to limitations of its underlying dataset, the model can only link to a limited number of the selected policies. The model is segmented by three urbanisation categories (rural/suburban/urban; for details see [48, 50]).

Policy representation in the model

Avoid and *shift* policies alter numerous input parameters at different stages of the modelling process. For *mode shift* policies, the main leverage points alter prices, availability and frequency of different modes, which are then processed during the mode choice modelling step. The same parameters, together with specific local points of interest (POI) or regulations (e.g. regarding working from home), alter the transport demand and destinations—and thus the number and distance of trips—modelled in the transport demand module. Other parameters, like the availability of a local public transport infrastructure have an influence on car ownership, and are modelled in a dedicated module. Car ownership levels determine subsequent transport demand and choice steps, which are segmented accordingly. Figure 3 outlines the modelling steps and key leverage points of demand-side policies.

To make variations in the input parameter as a function of policies, the model input parameters file includes a *policy tab*, which gives access to the shortlist of policies to be modelled. For every policy instrument, the model represents that policy's impact on input parameters. Depending on the impact chain type (see "Introduction" section), policies can either directly or indirectly influence a certain parameter. Either they directly link to the *parameters* tab, or indirectly influence the parameter via auxiliary impact chain calculations (for example, when influencing prices, policies may have cumulative impacts or preclude others). Auxiliary calculations are included in the XLS for full transparency; these either follow mathematical logic or include the relevant source studies.

For scenario definition, every policy has one of two features: either a checkbox for activating or deactivating the policy, or an input field for setting a value. Statistical baseline values (for 2022) are shown for orientation. Leaving an input field blank defaults to this baseline setting. Table 2 shows the list of policies, their input type, baseline values and policy ID. The latter references the ID in the energy sufficiency policy database [13] for more detailed descriptions. The latest version of parameters.xls, which also includes background assumptions (e.g. on fuel prices, fleet efficiency and technology propulsion), is available from github [40] in the github-branch "policy".

Policy scenarios

This study models a total of 28 scenarios: one *base* scenario (calibrated for the base year 2017), one reference scenario (*ref_35*), based on assumptions about future landscape developments, such as changes in global fuel prices and propulsion technology diffusion based on[27]; and 25 individual policy scenarios. Each policy scenario alters only one policy, in accordance with the settings in Table 2 relative to *ref_35*, and in some cases combines several sub-settings (e.g. those for speed limit) into one scenario. Marginal policy effect scenarios are identified by their specific policy codes. In addition, the *policy_35* scenario combines all previously modelled individual policies except those that overlap with others. The latter are excluded from the joint policy package and marked with the superscript "d" in Table 2.

Results

The impact end-point indicator [60] for this work is GHG mitigation, measured in Mt CO_2eq. Prior to this, I present results for each sub-scenario for the impact midpoints car availability and passenger kilometres, as these are key drivers of emissions.

Car availability

In its current version, *quetzal_germany* can endogenously model CO—a key determinant in subsequent modelling steps—by categorising the population based on car availability. Here, the model results are presented; a model link was only possible for three of the policies listed due to data limitations, other policies thus show no impact.

My findings (Fig. 4) indicate that the roll-out of on-demand local public transport (*inf_2*) has the greatest impact on CO, followed by enhancements in the frequency and quality of public transportation (*inf_1*). This is due to the strong link between poor PT quality and the decision to own a car (as modelled in [50]). In addition, the availability of a remote work option (*reg_4*) has a small impact on car ownership. Interestingly, these effects are consistently stronger in urban areas than elsewhere, since the higher PT frequency and denser PT availability in urban areas enable people to live car-free. In the policy package (*policy_35*) scenario, household car availability drops from 76 to 64% in urban areas and from 94 to 90% in rural areas. Grey markers in Fig. 4) indicate respective policy impacts on CO were not possible to model due to the underlying dataset that did not allow to establish respective policy impact chains.

Appendix B, which gives more detailed outputs on the number of cars per household, shows that this number drops substantially in the *policy_35* scenario.

Passenger kilometres

Overall, the scenarios show that the modelled policies had a significant impact on passenger kilometres (pkm). Figure 5 presents the absolute pkm outcomes; Fig. 6 shows the differences in pkms relative to the 2035 reference scenario (*ref_35*). Between 2017 (*base_17*) and 2035 (*ref_35*), the total pkm increased only marginally. By contrast, in the scenario combining individual policies (*policy_35*) they decreased by 30%, amounting to an overall reduction of 355 bn pkm. This reduction is accompanied by a modal shift in the direction of public transport (PT), with car pkm decreasing by about 400 bn and public transport pkm increasing by about 45 bn.

A more detailed look at the individual policies modelled (see Table 2 for characterisations) shows differences in the sizes and directions of impacts. The availability of a remote work option (*reg_4*)—set in this scenario as an additional 50% days of remote work—shows the strongest impact on pkm, thus reducing commuting kms for all modes. However, the model does not consider substitutive or rebound trips of remote workers. For two other policies, which introduce on-demand local public transport (*inf_2*) and a full road tax charge of 9ct/km (*tax_12*), the modelling indicates a high impact on reducing car pkm. These and all other policies aimed at reducing car usage (e.g. parking price increases) also serve to increase public transport km, leading to a mode shift. Pull-policies that aim to increase public transport by decreasing prices (*pt_5* to 365€/y or *pt_6* to free) also increase pkm.

A number of policies have no significant modelled impact. These include a high EU-ETS carbon price of 250€ (*tax_9*), stricter speed limits (*lim_1-3*), reducing public transport VAT to 0% (*pt_1*), free educational transport (*pt_7*), and support for stationary car sharing (*inf_6*).

The highest impacts on passenger kms is observed for those policies that also impact car availability. This is

Table 2 List of policies and settings for modelling

Policy	Unit	Input type	pol_35	2017	2022	Ref stats	Ref pol[a]	Code
Taxes/charges								
Energy tax (gasoline)	€/l	Input field	ref[b]	0,6545	0,6545	[51]	GZ (222/265-6)	tax_1
Energy tax (diesel)	€/l	Input field	ref[b]	0,4704	0,4704	[51]	GZ (222/265-6)	tax_2
Energy tax (electricity)	€/kWh	Input field	ref[b]	0,0205	0,0205	[52]	256	tax_3
Electricity network charge	€/kWh	Input field	ref[b]	0,0748	0,081	[53, 54]		tax_4
VAT fossil	%	Input field	ref[b]	19	19			tax_5
VAT electricity	%	Input field	ref[b]	19	19			tax_6
EEG Umlage	€/kWh	Input field	0	0,0688	0,0372	[53, 54]		tax_7
Carbon price non-ETS	€/t	Input field	400	0	30	law (BEHG)	266	tax_8
Carbon price ETS	€/t	Input field	250	8	89	[55]		tax_9
Road charge (all roads)	€/km	Input field	0,09	0	0	n.a.	234	tax_12
Parking								
Parking costs (urban, suburb, rural)	€/trip	Input field	15, 5, 0	5, 0, 0	5, 0, 0	[56]	202, 203	prk_1-3
Limit non-resident parking space (urban)	%	Input field	3			n.a.	206	prk_4
Road speed limitl[c]								
Highways/motorways	km/h	Input field	120	n.a.	n.a.	law (StVO)	GZ (228)	lim_1
Primary/secondary roads (B, L, etc.)	km/h	Input field	80	100	100	law (StVO)	GZ (228)	lim_2
City/built-up areas	km/h	Input field	30	50	50	law (StVO)	GZ (228)	lim_3
Public trans. pricing between zones								
VAT PT tickets (all)	%	Input field	0	19	7	[57]	253	pt_1l[d]
Short distance								
Local PT price (urban, suburban, rural)	€/trip	Input field	2.5, 3, 3	3.4		[58]	252, 256	pt_2-4l[d]
365€/a ticket		tickbox	on	n.a.	n.a.	n.a.	n.a.	pt_5l[d]
Free local public transport		tickbox	on	n.a.	n.a.	n.a.	n.a.	pt_6
Free education public transport		tickbox	on				236	pt_7l[d]
Long distance								
Price reduction/ticket subsidy	%	Input field	0	n.a.	n.a.	n.a.	252, 254	pt_8
BahnCard 50 for all		tickbox	on	n.a.	n.a.	n.a.	255	pt_9
Infrastructure and service investment								
Implement Deutschlandtakt		tickbox	on					inf_1
Local public tra. availability (on-demand)		tickbox	on	n.a.	n.a.	n.a.	249	inf_2
Reactivation of closed rail lines according	prio. 1,2,3	Input field		n.a.	n.a.	n.a.	245, 246	inf_3_run-rail
Long-distance rail average speed	km/h	Input field	150			[59]	247, 257	inf_4
Build bicycle highways between zones	4 categor.	Input field	3	n.a.	n.a.	n.a.	196, 215	inf_5
Stationary carsharing (suburban/rural)		tickbox	on	n.a.	n.a.	n.a.	tbd	inf_6
Regulatory framework								
Ban of domestic flights up to	km	Input field	2000	n.a.	n.a.	n.a.	228	reg_1
Share of people living in car-free zone in all cities with urbanisation=1:	%	Input field	30	n.a.	n.a.	n.a.	231	reg_2
Changes to travel regulation: Share of business trips replaced by telemeetings	%	Input field	50	n.a.	n.a.	n.a.	194	reg_3
Add. days worked from home (right HO)	% add. days	Input field	50	n.a.	n.a.	n.a.	192, 195, 200	reg_4
Incentives for local shops, edu. and recreational facilities (rural): add. POIs	%	Input field	33	n.a.	n.a.	n.a.	200	reg_5

[a] Refers to policy ID in the energy sufficiency database [13]. GZ refers to the page number in GermanZero [32]

[b] No change in policy scenario (same as ref_35)

[c] Max. limits per road category (specific OSM-based links can have lower limits)

[d] Overlapping with others, excluded from policy package and sum

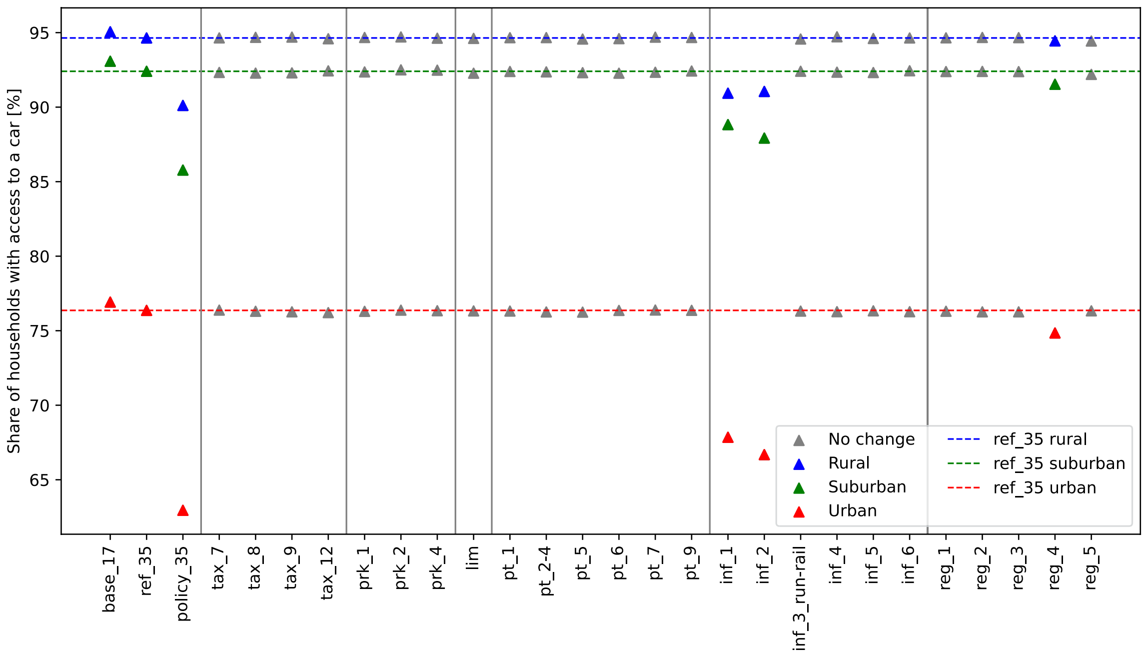


Fig. 4 Car availability (share of households) by scenario and urbanisation type

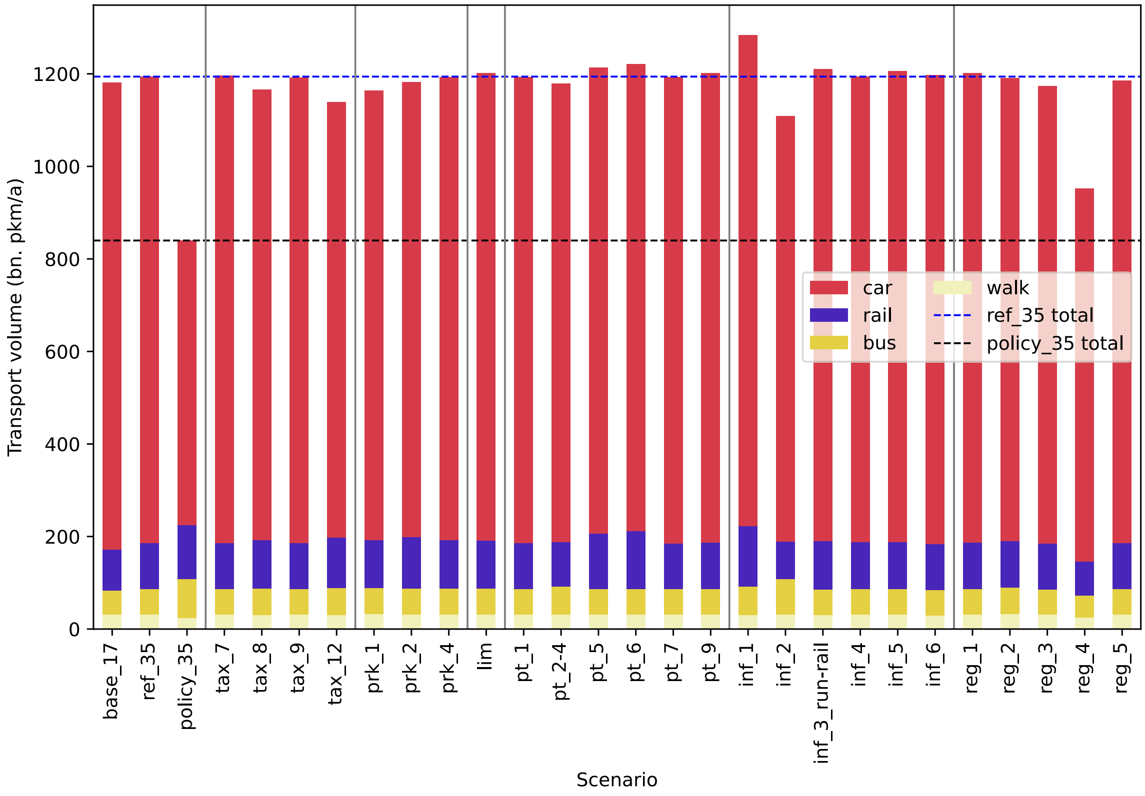


Fig. 5 Annual passenger kilometres (bn. pkm/a) per scenario and mode

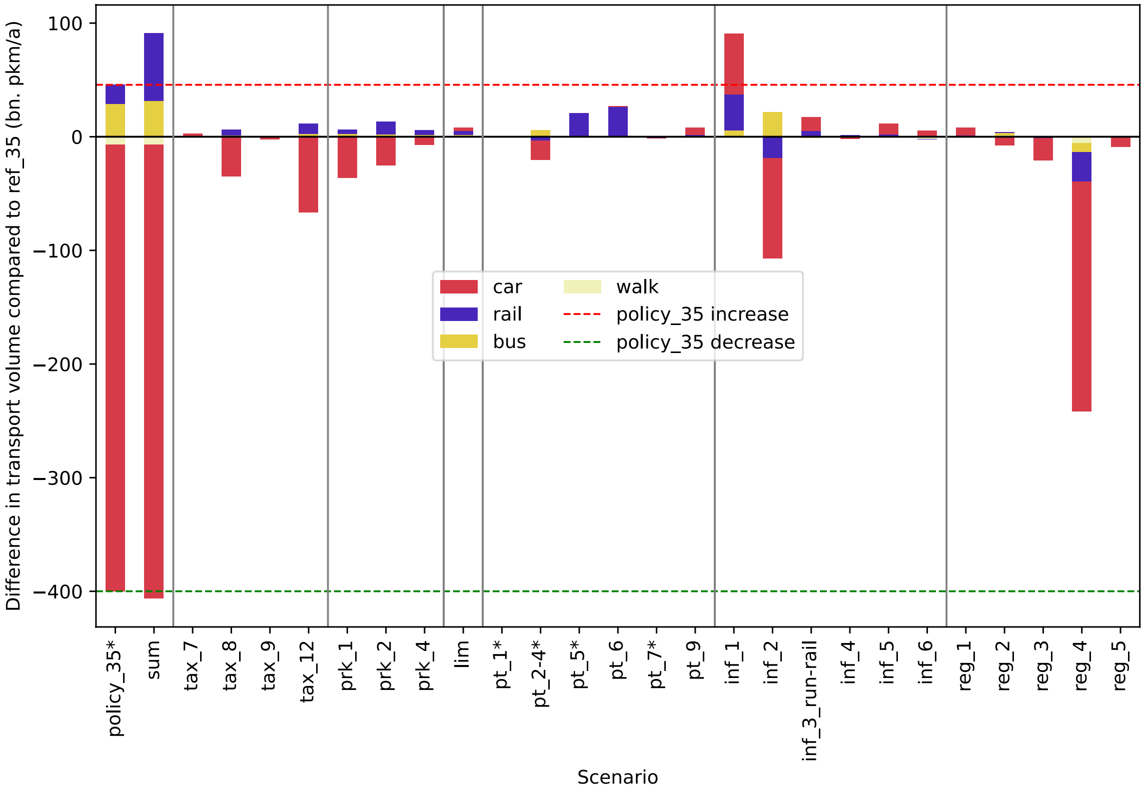


Fig. 6 Difference vs. *ref_35* in passenger kilometres (bn. pkm/a) per scenario and mode. Note: Total pkm of *ref_35*: 1194 bn. pkm. * = policy overlapping with others and thus excluded from the joint policy package and sum

because the model is segmented by car availability, and car-free households both have a lower transport demand and do not use cars. This effect partially adds to quetzal-internal mode choice and transport demand effects.

Policies effecting only minor adjustments in the model parameters or those with parameters of limited explanatory power have negligible modelled impacts. For example, increasing EU-ETS carbon prices from 100€ (2022) to 250€ (2035) may seem significant, but its effect is limited—as electricity prices are only a fraction of the total variable costs for electric vehicles (EVs). In addition, EVs constitute only 50% of the 2035 model fleet [27], such that the impact on the total weighted average variable car costs is only marginal, making EU-ETS pricing a policy of limited effect in this context.

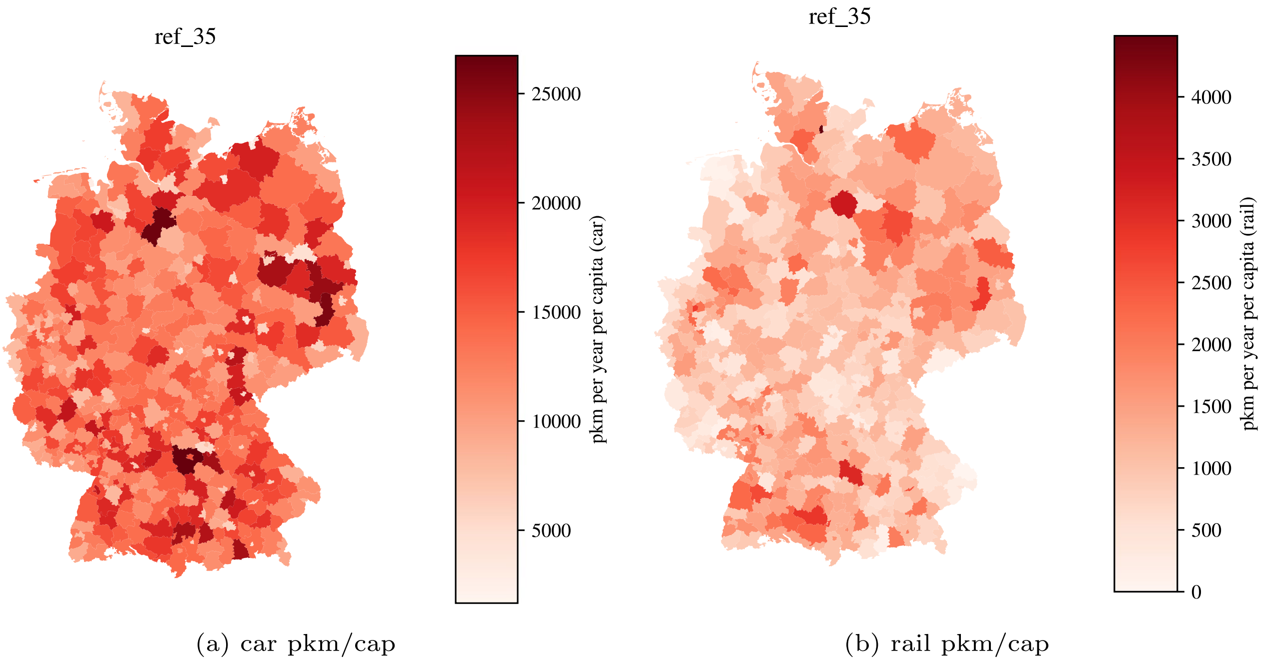
The only policy that leads to a substantial *increase* in pkm, including car pkm, is a nationwide increase in the frequency and connectivity of public transport ("Deutschlandtakt", *inf_1*). This initially surprising outcome stems from the model's architecture: an improved transportation system boosts overall transport demand. In subsequent modelling steps, high shares of car use are still modelled, leading to an increase of pkm.

The aggregate effect of all individually modelled policy impacts is slightly higher than that for the joint policy package, especially for the additional public transport travels (see "sum" in Fig. 6). This does not support often-expected policy synergy effects.

Spatial disaggregation of transport demand

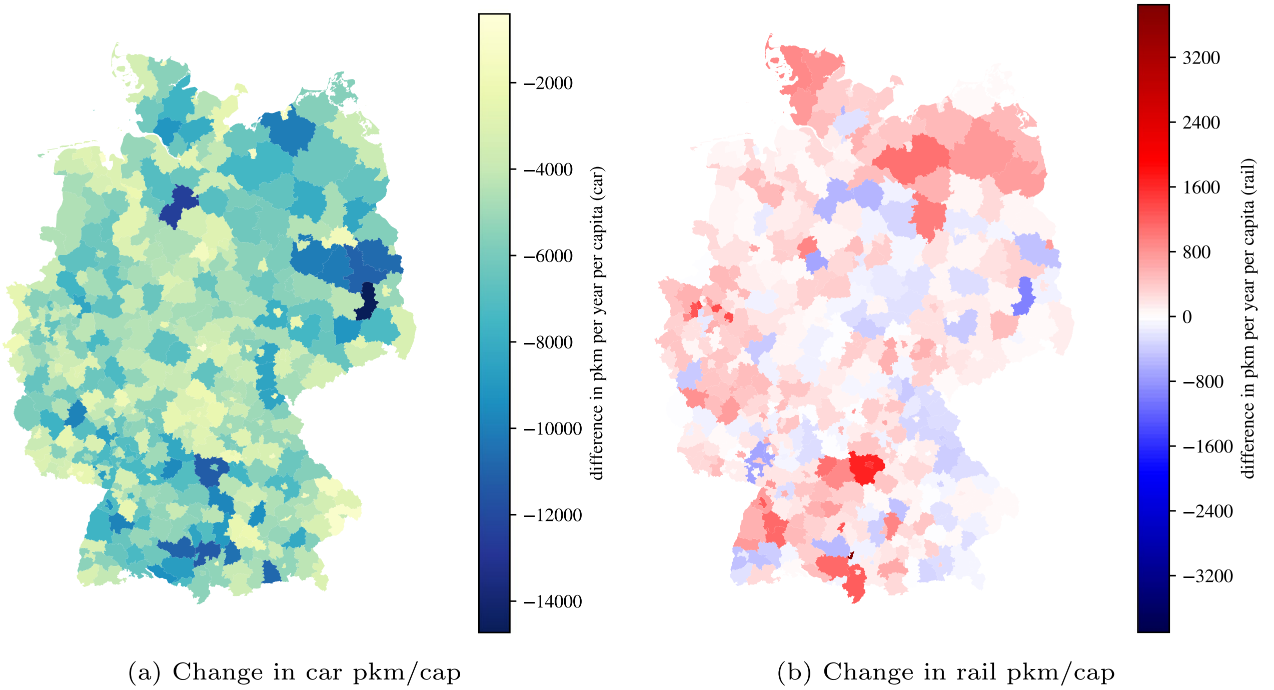
Policy impacts are not evenly distributed across the modelled geographical territory; rather, they depend on regional characteristics. Already in the reference scenario (*ref_35*), the intensity of transport demand, measured in pkm/capita, is inversely related to population density (car ownership rates, mode split, trip distances) and additionally related to commuting patterns (see Fig. 7).

Car use decreases in all model regions. Especially in regions with high car transport demands in the *ref_35* scenario yield the highest reductions in car pkm in the *policy_35* scenario, while more urbanised regions show lower reductions in car transport demand (Fig. 8a). The significant reduction in pkm in some regions, averaging up to 14726 pkm/cap, can only be understood as the modelled consequence of a package implementation of all policies, including those that increase remote working time (i.e. decrease commuting) and implement



(a) car pkm/cap (b) rail pkm/cap

Fig. 7 Transport demand intensity in pkm/cap by NUTS3 region in *ref_35* scenario



(a) Change in car pkm/cap (b) Change in rail pkm/cap

Fig. 8 Change in pkm/cap by NUTS3 region in scenarios ref_35 vs policy_35

a full on-demand roll-out, among other measures. For rail transport demand, patterns are similar but more diverse. Some regions with high car transport intensity in the *ref_35* scenario show a strong mode shift towards rail, thus increasing rail intensity. This is the case for large areas of rural southern and northeastern Germany. Conversely, in regions with moderate to high car intensities in the reference scenario, total transport demand

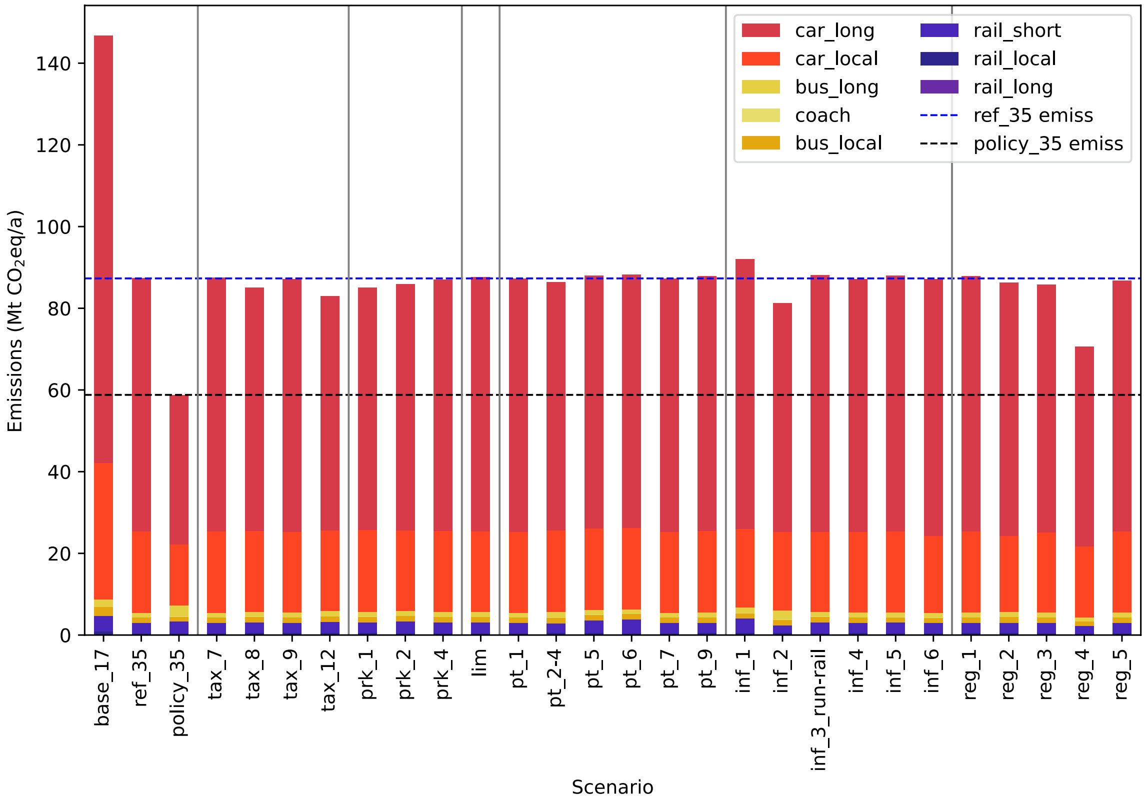


Fig. 9 GHG emissions per scenario and mode (Mt CO_2eq/a)

reductions in the policy scenario are so high that rail transport demand also decreases. This is the case, for example, in Eastern Bavaria or the suburban regions around Hamburg, Hannover, the Middle Rhine Valley near Mannheim, the Freiburg region, and rural eastern Germany (Fig. 8b).

GHG emissions

Greenhouse gas (GHG) emissions calculations use a simplified emissions module, applying emission factors per mode [46] to results of pkm per mode. In essence, emission results are a function of pkm results, emission factors, and exogenous settings regarding the vehicle stock in the scenario year. Emission factors are taken from the literature [45] and vehicle stock projections for 2035 for Germany from existing scenarios [27].[2]

In the *ref_35* scenario, GHG emissions from passenger transport drop by about 40% from 145 to 88 Mt CO_2eq due to an ambitious drive-train switch in the vehicle fleet (from 0.8% BEV and PHEV in the base year to 53.7% in 2035), along with an additional increase in renewable shares in electricity. In the policy package scenario (*policy_35*), these can be further reduced by 30 Mt (33%) to about 58 Mt CO_2eq, amounting to a 60% reduction relative to 2017. This is primarily due to reduced car use and partially due to a shift towards bus and rail. Figure 9 shows total modelled emissions by scenario and mode; differences from the *ref_35* scenario are detailed in Appendix B for better visibility.

Discussion

The results of this study show that integrating policies into the modelling framework is achievable. Single policies yielded highly variable effect sizes, partially due to the model type and data limitations. Furthermore, the policy modelling approach offers several insights. First, some single policies—economic (taxation), infrastructural (higher frequency and local on-demand services), and employment-related (increasing remote working days to reduce commuting trips)—have especially strong effects on transport demand and mode split. Second, transport demand elasticity is relatively low for most single policies. To manifest visible effects in the model for single policies, very stringent values would be necessary (e.g. electricity tax, EU-ETS prices, VAT on PT tickets). Third, the combined effect of all policies has however

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[2] Additional auxiliary calculation sources are included in the supplementary material parameters.xls.

significant potential to influence transport demand and emissions. Although not every policy impact chain is fully or adequately represented, the collective package of stringent policies can significantly contribute to achieving climate targets.

As with all models, those used in this study do not perfectly mirror reality [61]. However, the modelled policy impacts—derived from variations in input parameters based on policy impact chains, and grounded in estimations and calibrations from empirical data—do provide a solid foundation. This section discusses the reliability of modelled policy impacts for the specific case of transport demand-side policies and the quetzal_germany model.

There are a number of possible biases that likely lead to discrepancies between modelled outcomes and real-world impacts. Key among these is the reliance on empirical data from 2017 for estimating and calibrating preferences, which are subsequently used for all other scenarios. In reality, preferences change over time, leading to different elasticities and thus to different policy impacts. More specifically, a consistently changing transport policy framework will alter preference structures, probably leading to higher marginal impacts and synergy effects for the policy package. A possible outcome has been shown in a transport scenario that alters the immensely car-biased preferences [41]. As preferences are contingent on framework conditions, a link that the current model cannot yet represent, this scenario only presents the direct effects of policies with fixed preferences. This underscores the need for an endogenisation of preferences [62] in the future, potentially also by modelling peer-comparison and network effects [50].

Another general issue concerns the model's current implementation of impact chains. This implementation is extensive for pricing policies targeting a single common parameter (fossil fuel or public transport prices), but for other policies the potential interlinkages between impact chains, while possible in theory, are still missing in the model. As an example, car-free zones may not only reduce transport in that specific area; they may also affect residents outside the car-free zone due to peer-network-effects or restrictions on city centre access to public transport, suggesting that current modelling may substantially underestimate effects. These potential policy interactions require further study that will advance the development of policy models.

As a limiting factor, individual policy impact chains may be incomplete or oversimplified. One example is how the model treats increased remote working days. Here, the model considers reduced commuting but overlooks potential rebound effects, like substitutive trips or changes in consumption [63]. Additionally, improving the public transport system may yield biased results for mode pkms. As detailed in the "Methods" section, the modelling process begins by representing total trip volumes, then distances and destinations, and finally mode choice. Improving public transport reduces average travel time or costs, leading to higher volumes. However, the subsequent mode choice model, assuming constant preferences, still predicts high shares of car mode and an increase in car pkm. Apparently, price elasticities in interzonal trips are relatively low (result probably dominated by especially low-elastic business trips and much higher time-elasticities). This is aggravated by the limitation of the CO module that cannot process changes to public transport pricing. This effect may thus be substantially underestimated and needs further study.

Another challenge is the difficulty of including policies that are incompatible with the current model scope, such as taxation on car ownership or acquisition. This is another reason why the results presented give a rather conservative estimate of the total potential of demand-side policies.

The findings of this study are based on a model that draws on German transport survey data and is thus specific to the German context. While a certain validity for similar (i.e., Central European) contexts can be expected, for different contexts the model would need to be set up and calibrated accordingly. Because the modelling framework is a fully open one, this is possible as long as national survey data are available.

In the future, modelling additional aspects of the transport system may maximise the benefits for informing policy-making. Through simplified quantification, external effects such as air quality, noise or accidents could be covered, also in spatial distribution. Other factors, such as required investments in infrastructure or rolling stock, would require model development. In order to evaluate overall mobility system performance, overarching indicators (e.g., on accessibility or welfare distribution) could be developed and linked to model parameters.

Finally, this work focuses on demand-side policy. Future model developments or integrations into other models could allow to model policies that influence technology choice and fuel switch, impacting on vehicle fleets and emissions.

Conclusions

This study has suggested refocussing the model logics: instead of using scenario parameters to inform policy narratives, it explicitly models the impacts of policies with the resultant scenarios. Unlike most previous German passenger transport scenario studies, which often assume reductions in transport demand and mode split changes or model them as outcomes of other assumed conditions, this study demonstrates the feasibility of direct policy modelling. When applied to the case of German transport demand, this approach still has several shortcomings. As discussed in the previous section, individual policy impact chains may be imperfectly represented and may include biases; preferences are estimated and calibrated on data from 2017 and are assumed to stay constant, while in reality they are likely to change; and the lack of endogenisation may substantially underestimate the overall impacts and synergy effects of the policies modelled. Nevertheless, the modelled impacts derive from parameter variations following policy impact chain logics and are based on estimations from empirical data. Given these considerations, they are likely conservative, possibly underestimating the full impact of a comprehensive policy package.

The approach is validated as fundamentally viable. Even if specific policy implementations hinge on the model's capabilities, this scope can be expanded through additional model developments or auxiliary quantifications. For the German case, coverage was already possible for a large number of demand-side policies, yielding significant results: relative to the reference scenario in 2035, household car availability falls by 4 to 12 percentage points depending on urbanisation degree, total passenger kms are reduced by about 30% or 355 bn pkm, car use drops strongly while rail use increases (with geographically varying patterns), and transport GHG emissions fall by 33% or 30 Mt CO_2eq. Considering the inclusion of outcomes from future modelling of additional policies and interaction effects, the demand-side effects promise to be even higher.

This study shows the feasibility of constructing policy-backed scenarios, stressing the need for the enactment of policy frameworks to achieve certain GHG mitigation scenarios. This approach substantially increases the utility of scenarios to policy-making, not only on the local or national levels, but also globally. Although these conclusions derive from a model that was specifically calibrated for Germany, they can also inform other constituencies—and the fully open-source approach is applicable to any other case. The modelled scenario reveals that in addition to technological advancements in drive-train electrification, demand-side strategies for the *avoid* and *shift* strategies have a decisive potential for decarbonising the transport sector.

Appendix A: Transport policy database categorisations

Categorisations included in the supplementary material cover

- ASI-framework [66, 67]: (1) *Avoid/Reduce* policies aim to reduce travel needs and trips/trip lengths, thus improving transport system efficiency; (2) *Shift* policies seek to effect a mode shift from the most energy consuming modes of transport (like car and air travel), to more environmentally friendly modes (non-motorised transport or public transport), thereby improving trip efficiency; while (3) *Improve* policies seek to maximise vehicle energy efficiency and alternative energy use, thus improving vehicle and fuel efficiency.
- Instrument type [4, 37]: (1) economic (e.g. taxes, tradable certificates, market reform), (2) fiscal (e.g., subsidies and grants, tax exemptions and public expenditures for infrastructure), (3) voluntary agreements, 4) regulation (laws, standards and product identification), (5) information, (6) education (institutional), 7) research and development, 8) other (e.g., plans) and 9) not specified
- Push and pull: In a 1978 concept, push measures were defined as governmental R &D agencies that support or develop energy conserving technologies, while being careful not to displace private investment. "Policy pull" measures were defined as those that changed financial incentive structures through taxation or requirements [68]. In the more recent transport literature, the terms are adapted: "car use can be made less attractive by 'push' measures, or the use of alternatives may be stimulated by 'pull' measures. Push measures restrict people's freedom of choice; pull measures do not" [69]. In political science literature, pull measures promote the desired environmentally friendly behaviour and are regarded as non-coercive [70, 71], push measures are considered more coercive, and more likely to enforce behaviour change [72–74].
- Governance level: For situating a policy in its polity context, developing and analysing policy mixes, the governance level (local, national, international) is a structuring factor. The analytical concept of multilevel governance (MLG) was developed in the 1990 s [75, 76]. In subsequent studies, it was debated whether to include [77] or exclude [78] non-state actors. For our policy-based approach, only state actors can sensibly be assessed. Policies are categorised according to the government level at which they prompt changes to the institutional setting or procedures: EU, national, regional, or local.
- Traffic light prioritisation [33]: This combines three subindicators (maturity, replicability and impact), each with 3 possible values. Codings are specified as follows:

Table 3 Overview of pre-assessment indicator values

Indicator	Value = 1	Value = 2	Value = 3
Maturity	Formulated as idea/ intention	Some implementation examples with limited information, or at least concretely formulated and planned policies	Clear formulation and examples available
Replicability, deliverability, feasibility	Difficult to replicate/ unlikely to be feasible in area of study	Potential replicability, but barriers hindering feasibility (e.g. political, financial)	No substantial barriers for replicability in area of scope
Expected impact	Low expected impact	Medium expected impact	High expected impact
Traffic light indicator (average of above)	Low priority	Medium priority	High priority

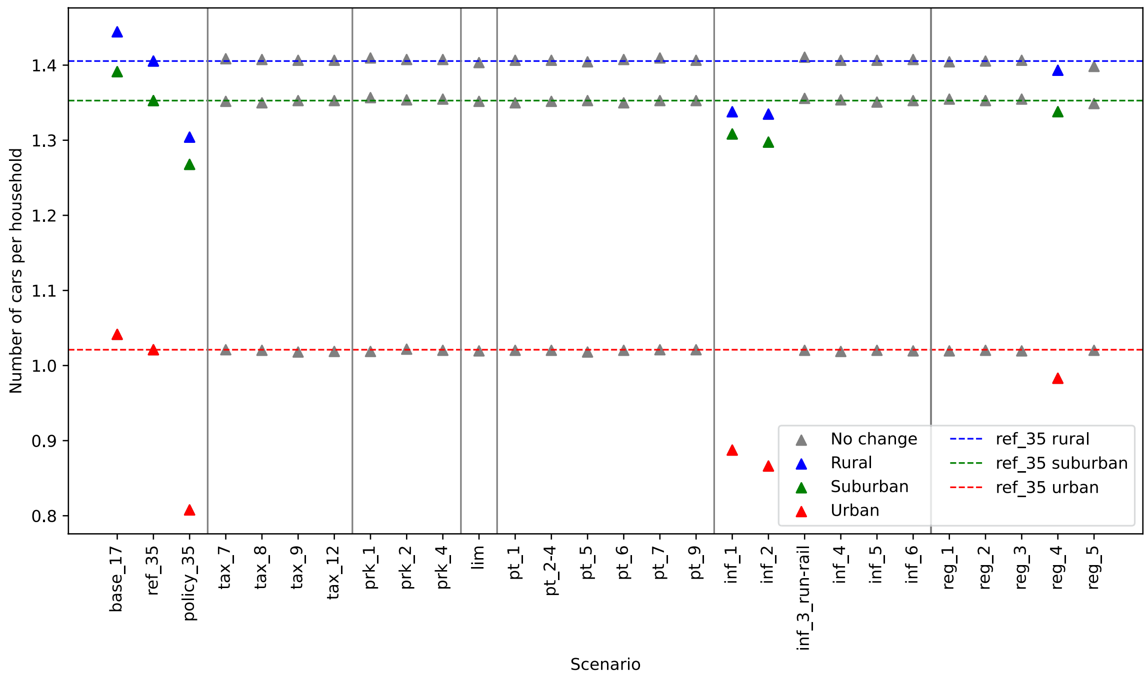

Fig. 10 Nr. of cars per household, by urbanisation, scenario and mode

Maturity: 1= the intention/formulated idea of an unimplemented policy; 2 = an example of implementation, but with limited information or with very specifically formulated policy goals and actions; 3 = a broadly implemented and clearly formulated policy, which has been implemented and evaluations

Replicability, deliverability, feasibility: This indicator aims to assess the feasibility of implementing a policy in the area of interest. [33] use a replicability indicator, which "assesses the extent to which the identified policy could be replicated in theory and whether it has been replicated in practice", which we apply to the case of Germany on a 1 = poor to 3 = high scale.

Expected impact: This assessment refers to a policy's potential expected relevant impact, if the policy is consistently and ambitiously implemented [33]. The assessment is informed by impact assessments for instruments, where readily available, and research findings, as synthesised in [79]. The expected impact on GHG emissions is rated on a 1–3 scale.

Combined traffic light priority indicator: [33] propose combining the three previous dimensions with equal weighting. The result is again rated on a 1–3 scale, represented by the authors as a traffic light score from 1=red to 3=green. I follow this approach to generate a combined traffic light indicator (see Table 3).

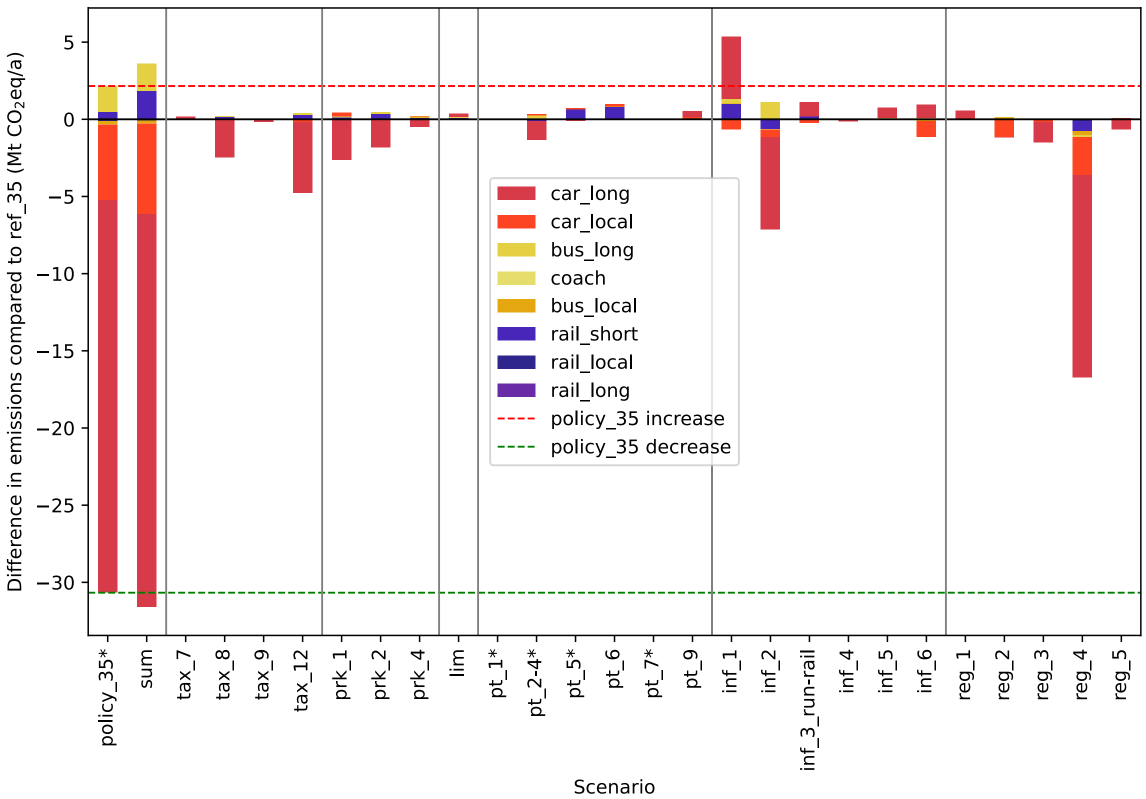

Fig. 11 Difference vs. *ref_35* in GHG emissions per scenario and mode. Total GHG emissions of *ref_35*: 87 Mt CO$_2$eq. * policy overlapping with others and thus excluded from the joint policy package and sum

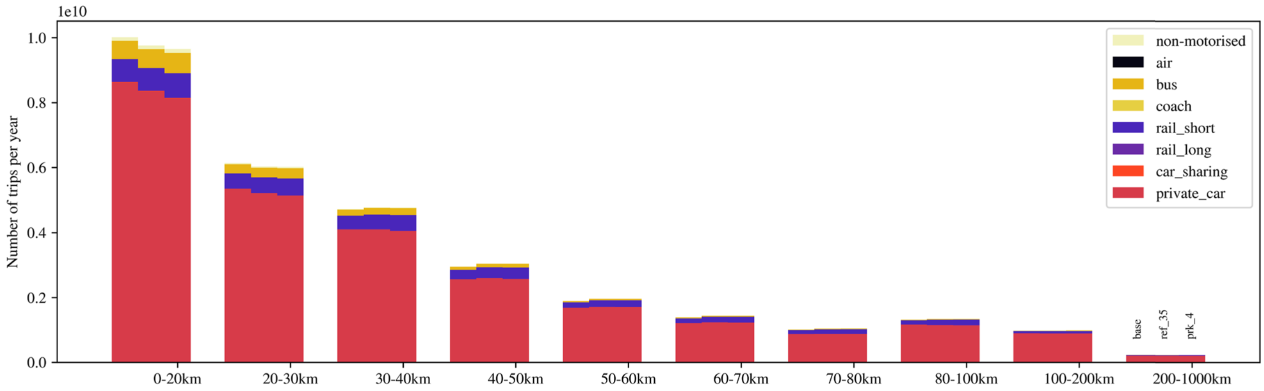

Fig. 12 Modal split of trips by distance classes for the scenarios *base_17* (base), *ref_35* and *prk_4* disaggregated by distances

Appendix B: Additional results

This annex section presents selected additional model results complementing the results section . Figure 10 shows the nr. of cars per household, as averages per rural, suburban and urban households. The general picture and explication is essentially the same as Fig. 4.

Figure 11 shows the absolute differences between GHG emissions of various policy scenarios relative to the reference scenario (*ref_35*). We observe the same patterns as with differences in pkm (Fig. 6), as GHG emissions are a linear transformation of pkm.

Figure 12 shows the distribution of the number of trips and their mode split by distance classes: the greatest number of trips occurs over short distances (inner-zonal), with the number decreasing as the distance increases. The policy scenario, here exemplary for *prk_4*, especially decreases short-distance trips.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13705-024-00467-y.

Supplementary file 1.

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Author contributions

This manuscript is the work of the single author. F. Wiese and M. Arnz commented on the first draft and the work was only possible due to the collaboration of all colleagues mentioned in the acknowledgements.

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Availability of data and materials

All data are made accessible to the extent possible on open repositories [49, 64], referenced and hyperlinks included in the bibliography.

Code availability

All code used in the various models and modules that form part of this work [40, 48, 50, 65] is referenced and links to open repositories included in the bibliography.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The author declares that he has no competing of interest.

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