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Quantifying the impact of travel time duration and valuation on modal shift in Swiss passenger transportation

Sandro Luh [a], Ramachandran Kannan [a,*], Russell McKenna [a,b], Thomas J. Schmidt [c,d], Tom Kober [a]

[a] Paul Scherrer Institute, Laboratory for Energy Systems Analysis, Forschungsstrasse 111, 5232 Villigen PSI, Switzerland
[b] ETH Zurich, Chair of Energy Systems Analysis, Dpt. of Mechanical and Process Engineering, Raemistrasse 101, 8092 Zurich, Switzerland
[c] Paul Scherrer Institute, Electrochemistry Laboratory, Forschungsstrasse 111, 5232 Villigen PSI, Switzerland
[d] ETH Zurich, Laboratory of Physical Chemistry, Dpt. of Chemistry and Applied Biosciences, Raemistrasse 101, 8092 Zurich, Switzerland

HIGHLIGHTS

- Non-monetary aspects relevant for modal shift incorporated in the Swiss TIMES model.
- Multi-objective optimization to quantify net-zero impacts of non-monetary aspects.
- Travel speed measures induce a 5–10% demand uptake of public transport.
- Weighing travel time less makes electric cars more critical for decarbonization.
- Secondary energy system effects are quantified & policy implications are drawn.

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ABSTRACT

Decarbonizing the passenger transportation sector is critical for climate change mitigation. Existing studies on net-zero scenarios using Energy System Optimization Models (ESOM) often overlook non-monetary aspects of consumers' mobility choices but primarily focus on cost aspects. This study incorporates consumers' travel time duration and valuation, and an endogenous modal shift option into the Swiss TIMES Energy system Model (STEM). STEM is applied in a multi-objective optimization framework to quantify the impacts of faster Public Transport (PT) and slower car speeds on modal shifts in the transport sector's transformation. Similarly, we assess scenarios where consumers weigh travel time less, reflecting improved travel productivity. The results show that speed variations on medium- and long-distance trips, which can be interpreted as policies for highway speed limits and more efficient PT, can induce modal shifts towards 5–10% higher PT demand. Its implied secondary effects across the energy system include a reduced need for electrification of heavy-duty trucks by 11% and a decrease in hydrogen demand in road transportation by 34% by 2050. If travelers weigh costs over travel time, PT becomes less competitive against cars. Thus, electric vehicles (EVs) need to play a more dominant role in decarbonization, with a demand increase of 13% in 2040 (+9.2 billion passenger kilometer (bpkm)) and 6% in 2050 (+5.0 bpkm), along with the need for additional 45,000 public chargers of 22 kW size. Policy implications include the emphasis on improved PT speeds, speed limits on highways, needs to achieve more widespread EV adoption, and the need for balancing travelers' decision factors when aiming for reduced transport CO_2 emissions.

Abbreviations: FPT-SC, Faster Public Transport and Slowed down Cars scenario; BEV, Battery Electric Vehicle; CPSE, Cross-Price Substitution Elasticities; EFF, Fuel efficiency; EMOO, Elastic Multi-Objective Optimization baseline scenario; EV, Electric Vehicle; FCEV, Fuel Cell Electric Vehicle; ICEV, Internal Combustion Engine Vehicle; IPCC, Intergovernmental Panel on Climate Change; km, kilometer; LoS, Level-of-Service; OPE, Own-Price Elasticity; OR, Occupancy Rate; MOO, Multi-objective optimization; PHEV, Plugin Hybrid Electric Vehicle; pkm, passenger kilometer; pp, percentage points; PT, Public Transport; RTTV, Reduced Travel Time Valuation scenario; STEM, Swiss TIMES Energy system Model; TIMES, The Integrated MARKAL-EFOM System; TTB, Travel Time Budget; vkm, vehicle kilometer; VTTS, Value of Travel Time Savings.

* Corresponding author.
E-mail addresses: Sandro.Luh@psi.ch (S. Luh), Kannan.Ramachandran@psi.ch (R. Kannan), Russell.McKenna@psi.ch (R. McKenna), Thomasjustus.Schmidt@psi.ch (T.J. Schmidt), Tom.Kober@psi.ch (T. Kober).

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1. Introduction

With most countries pledging to mitigate climate change [1], decarbonizing transportation is critical [2]. However, the passenger transport sector provides a key challenge, as non-monetary aspects are particularly relevant to consumers' mobility choices [3]. A recent IPCC report underscores the significance of travel time and costs on consumers' modal choice decisions, i.e., the shift between cars, trains, buses, and other transportation modes [2,4–7]. Energy System Optimization Models (ESOMs) commonly quantify how transformative pathways towards net-zero greenhouse gas emissions could be achieved [8–10]. ESOMs reflect future mobility technologies and look at them from an energy-systemic perspective, but they mostly assess cost-optimal (least-cost) pathways [11,12]. However, critics argue that this single-criterion objective function neglects the important dimension of non-monetary factors, such as travel-time, −comfort, and -convenience, which play an important role in real-world decision-making [12–15]. Furthermore, our literature review (Section 2) reveals that most ESOMs still neglect non-monetary aspects (beyond their neglection in the objective function). Those that consider them lack in integrating their modal shift implications in a holistic approach that represents various consumer segments and trip types and contains cross-sectoral flexibility options by considering a whole national energy system in detail.

This work acknowledges the importance of non-monetary parameters for assessing long-term energy system scenarios. Accordingly, this study enhances the existing Swiss TIMES Energy system Model (STEM) by incorporating non-monetary parameters, focusing on integrating consumers' travel time[1] duration and travel time valuation in STEM's passenger transport module. This study focuses on motorized land-based passenger transportation. Specifically, this work assesses how a stronger shift to PT could be achieved and how this could potentially release pressure from other decarbonization measures. This paper articulates current policy discussions on the potential impacts of car speed limits in cities [16–18] and highways [19,20] from an energy-systemic perspective. For this, we assess the impacts of consumers' travel time duration and travel time valuation on modal shifts, aiming to shed light on the following research questions regarding a net-zero energy system by 2050:

RQ1: What are the impacts of measures for faster PT and slowed down car speeds for modal shifts and the transformation of the transport system?
RQ2: What could be the implications for the transport system transformation if travel time becomes a less relevant factor for mobility choices, e.g., due to higher productivity while traveling?
RQ3: What are the distinguishing impacts of travel time duration and valuation variations by consumer segments and trip types?

The remainder of this work is structured as follows: Section 2 outlines the importance of travel time, modal shift, and Multi-Objective Optimization (MOO) and discusses the state-of-the-art for reflecting such aspects in ESOMs and how this work goes beyond that. Section 3 describes how such aspects are integrated into STEM. Section 4 presents the application of the advanced STEM in the Swiss context and discusses potential systemic mobility- and energy implications for the transformation towards net-zero in light of consumers' travel time duration and valuation. The limitations of this study and potential avenues for future work are presented in Section 5 with the conclusions in Section 6.

[1] Other aspects, such as the physical availability of alternative modes, comfort, and convenience are some of the other important aspects that consumers consider besides costs, are also important [3] but outside the scope of this work. The physical availability of transport modes is indirectly reflected in our analysis as transport mode demands of specific consumer segments and trip types can deviate only in a relative amount compared to today's demands (Section 3.1). Comfort can be considered by the applied model but is outside the scope of this analysis focused on travel time. Convenience, however, is a highly subjective parameter and therefore not well suited for an aggregated reflection in ESOMs.

2. Literature overview

Section 2.1 discusses important concepts, while Section 2.2 examines the state-of-the-art for reflecting those in the passenger transport sector of ESOMs.

2.1. Travel time, modal shift, and cross-price substitution elasticities

A wide range of literature underlines that travel time is a crucial factor in consumers' modal choice [21–24], which is particularly relevant in the Swiss context [3]. The Swiss mobility survey shows that travelers are about four times more likely to make their modal choice decision based on travel time than travel costs [3]. Faster PT leads to higher competitiveness and modal shares of PT, particularly in areas with increased road congestion [24]. The average consumer travels a fixed proportion of their daily time, known as Travel Time Budget (TTB) that varies across socio-demographic groups and influences the modal choice [25]. Historical TTBs tend to be stable over time even though mobility demand increased, implying that faster travel modes cover longer distances trips [25]. However, driving automation and improved-productivity during travel could lead to deviations from historically observed TTBs in the future, i.e., increased travel time durations [26]. Furthermore, economic theory commonly uses the monetary Value of Travel Time Savings (VTTS) [21,27] to define the marginal opportunity costs per time or activity, such as switching modes. The VTTS can vary by income, trip distance, transport mode, and similar [21]. For Switzerland, the VTTS is regularly determined [28] based on the national mobility survey [3]. If improved productivity while traveling may decrease the VTTS requires further research [26].

Consumers' travel time is closely linked to the potential for modal shift, i.e., the shift from one transport mode to another. Modal shift is an important measure for decarbonizing transportation [2], and researchers often study transport elasticities to better understand its opportunities and the factors influencing mobility behavior [29]. For instance, Cross-Price Substitution Elasticities (CPSEs) are an important measure to reflect the percentage change in demand for mode A when mode B's costs change by 1% [30]. However, while elasticities are an important instrument for modeling demand variations, the real-world applicability of elasticities is uncertain as many aspects play a role, such as rebound effects [31], the time horizon [32], and trip-specific and socioeconomic differences [29]. Various studies confirm that car drivers generally have lower CPSEs and are less price-responsive than PT users [33,34], limiting the potential impacts of financial incentives for achieving modal shifts towards PT [35]. To effectively achieve modal shift to PT, it is crucial to consider both CPSEs and travel time, particularly in the Swiss context, where high incomes and low price-sensitivities among car drivers prevail [28].

However, many studies show that travel time reductions and shifts to more sustainable modes could induce potentially negative rebound effects [36,37], as people may feel that their modal choices contribute to climate change mitigation and thus tend to act sustainably worse in other domains [38]. An indirect rebound could be that consumers use their saved travel time or costs for other activities, increasing their total environmental impact [37]. Furthermore, information and communication technologies [39] and autonomous cars [40] could induce direct rebound effects in mobility demands and indirect rebound effects regarding energy use in other energy system sectors [41].Policy discussions on travel time evolve around various measures for reducing road travel speeds. While few countries have introduced stricter highway speed limits to reduce greenhouse gas emissions [19,20], many cities across the globe recently reduced road speed limits from ∼50 km/

h to ~30 km/h for safety, air pollution, health, and noise reasons [42–47]. In Switzerland, road speed limits for cities are widely discussed and introduced in the context of noise reduction [16–18]. Although increasing road congestion can impede travel speeds and encourage modal shifts to PT [35], many individuals prefer to endure congestion due to their high value placed on personal car mobility [48]. Solutions to mitigate road congestion include improved PT systems [49] and priority for PT on roads, especially in congested urban areas [50], as these can lead to PT time savings and modal shifts [48].

Although car transport is expected to remain dominant in Europe, the PT share is projected to increase, mainly due to shifts from cars to trains [35]. Switzerland, with its high PT share of 26% (2019[2]) compared to the European Union's average of 17% [51], still has potential for further growth in PT's modal split [52]. Given the importance of modal shifts in decarbonizing transportation and the unique Swiss context, more research is needed to explore the interaction between travel time, CPSEs, and potential policy measures from a systemic energy perspective to better inform decision-making.

2.2. Reflecting modal shift-related non-monetary aspects in ESOMs

Several ESOM modelers started considering some aspects discussed in Section 2.1 in transportation sector modeling (see Table 1). However, many ESOMs still focus extensively on techno-economic aspects. While some studies consider travel time or endogenous modal choice, most ESOMs still merely optimize for costs (Table 1), despite the widely recognized importance of reflecting non-monetary parameters in ESOMs [12–15,53]. Appendix B summarizes how each approach in Table 1 considers those aspects. Notably, the systemic implications for the wider energy system remained under-investigated in those approaches.

MOO could overcome this limitation by assessing the tradeoff between multiple objectives, such as costs and travel time, but it is yet uncommonly applied in ESOMs [11]. MOO can be valuable when several decision parameters cannot be brought to the same denominator, e.g., when it is challenging to monetize certain aspects. Various studies with MOOs in ESOMs focus the energy supply and residential sector for studying tradeoffs between costs, CO_2 emissions, self-sufficiency, and similar [53,63–66], or on environmental impacts [67]. Finke & Bertsch [63] provide a literature-based assessment of MOO in ESOMs, but according to their review and our best knowledge, no ESOM applies MOO to assess tradeoffs of non-monetary aspects in the transport sector.

Some studies assess the role of modal shift by exogenously specifying mode-specific demand storylines [68–72], whereas in our assessment, it is implemented endogenously. Others apply model coupling in which they consider modal choice aspects and travel time in an exogenous transport simulation model, which determines the modal shares as an input to an ESOM [73,74]. However, such model coupling approaches typically ignore the reciprocal inter dependencies between transport and energy systems, which can be understood more thoroughly by endogenous modal shift dynamics within ESOMs [58]. This work aims to benefit from the advantages of the endogenous approach as outlined in Appendix C.6.

3. Methodology: enhanced STEM passenger transport module

We use STEM for this work since this is a cutting-edge ESOM that focuses on Switzerland. STEM contains a variety of sector coupling options, allowing it to assess cross-sectoral implications and potential lock-in effects for the transformation of the entire Swiss energy system. Furthermore, the STEM passenger transport module is well-developed, reflecting with a high level of techno-economic details a large variety of current and future transport modes, vehicle technologies, fuel supply chains, charging infrastructure options, consumer segments, and trips types, making it well-suited to assess various aspects of our analysis [75,76]. At the same time, the STEM can deal with high computational complexity.[3] STEM can provide valuable insights for decision makers on how to achieve an energy system transformation towards net-zero CO_2 emissions, making it an ideal tool for this work. The key features of STEM are outlined in Box 1.

We enhanced STEM's [77–79] passenger transportation module [75,76,80,81] to enable endogenous modal shift (Section 3.1). Fig. 2 visualizes the updated demand structure of STEM's passenger transport sector and its multi-objective optimization approach. Section 3.2 describes how we go beyond cost-optimization by integrating consumers' travel time for driving, fueling, and charging and considering their travel time valuation for mobility choices in a MOO. Supplementary methods are presented in Appendix C, such as summaries of consumer segments (C.1) and how this work addresses several methodological shortcomings of other studies (C.6).

3.1. Modal shift option with elastic demands

Table 2 summarizes which transport modes compete on the trip-type specific demands, distinguishing short-distance (S; ≤ 10 km), medium-distance (M; > 10 km and ≤ 80 km), and two long-distance (L; > 80 km) trips, as introduced in [76]. Fig. 3 shows how modes compete to fulfill these consumer- and trip-specific demands. Appendix C.2 presents the demands, Occupancy Rates (ORs), and trip type shares for different modes, consumers, and trip types. Appendix C.3 outlines the technical concept for enabling modal shift while preserving the overall pkm demand.

For modeling consumers' mobility demand response to cost changes, we design and implement CPSE for each transport mode, consumer segment, and trip type. However, CPSE data availability at these levels is limited. Thus, we use an approach for determining mode-specific own-price elasticities (OPEs) similar to Salvucci et al. [61]. For this, we determine, based on the Swiss mobility survey [3], the distance- and income-specific OPEs for each consumer segment and trip type according to a stated preference survey's non-purpose-specific model with interaction terms between trip distance and trip costs $\lambda_{Distance,Costs,i}$ and household income and trip costs $\lambda_{Income,Costs,i}$ [28]. The methodology and rationale for calculating the OPEs is based on various literature sources, including Mackie et al. [82], and subsequent Swiss-specific applications, such as Axhausen et al. [83,84], Hess et al. [85,86], Weis et al. [87], Fröhlich et al. [88], and Widmer et al. [89]. Concretely, we apply a formula to calculate the $OPE_{i,Costs}$ of each transport mode i based on distance-specific modal shares (P_i) and costs (C_i), in-line with its application by the Swiss Federal Office for Spatial Development [28]:

$$OPE_{i,Costs} = \beta_{Costs} * \left(\frac{Distance}{20}\right)^{\lambda_{Distance,Costs,i}} * \left(\frac{Income}{7000}\right)^{\lambda_{Income,Costs,i}} * (1 - P_i) * C_i \quad (1)$$

Such elasticities are based on fuel- and ticket cost changes for cars and PT, respectively. This aligns with our assumption that modal shift towards PT implies that consumers keep having cars but drive less with them. Though real-world transport mode elasticities depend on many more parameters [29], our approach considers various important parameters impacting such elasticities, i.e., household income, trip distance, distance-specific trip costs, and distance-specific modal shares. To our knowledge, no other study considered transport elasticities in bottom-up ESOMs with such a high level of disaggregation among

[2] The PT share is for 2019 (before the COVID-19 pandemic), since the pandemic strongly impacted the modal split, but the latest trends are indicating that transport levels are returning to pre-COVID-19 levels.

[3] The applied model contains 16 million equations with 25 million variables. The model was solved with a high-performance computing cluster, requiring about 22 h to solve one elastic scenario variant.

Table 1
List of bottom-up ESOMs with travel time or endogenous modal shift options in the transport sector.

Model name	Demand segregation			Modal shift options			Travel time duration / Modal speed				TTB	Travel infrastructure investments[2]	MOO function	Intra-annual time resolution of mobility demands	Whole energy system model	Source
	Consumer segments	Trip types	EV charging infrastructure options[1]	OPE demands	CPSE demands	Aggregated mobility demand across modes	Driving	Car fueling	EV charging	other Level-of-Services						
STEM (Swiss TIMES Energy systems Model)	Yes	Yes (distance range classes)	Yes	Yes (mode-, consumer-, and trip-specific)	Yes (mode-, consumer-, and trip-specific)	Yes (consumer- and trip-specific)	Yes (mode- and trip-specific speeds)	Yes	Yes (charger-specific)	–	Yes (consumer-specific)	–	Yes	288 time slices: • four seasons • three weekdays • 24 h per day	Yes	This work
- (test model)	–	Yes (distance range classes)	–	–	–	Yes	Yes	–	–	Yes	Yes	Yes (infrastructure investments increase speed of a transport mode)	–	–	–	[54–56]
ESME (Energy Systems Modeling Environment)	–	No	–	Yes	–	–	–	–	–	–	–	–	–	–	Yes	[32]
ESME (Energy Systems Modeling Environment)	Yes (by geographical regions)	Yes (urban vs. rural)	–	–	–	Yes	Yes	–	–	–	Yes	Yes, but they do not improve the travel time of the transport mode	–	–	Yes	[57]
TIMES-DKMS (Danish TIMES with Modal Shift)	–	Yes (distance-range classes)	–	–	–	Yes (trip-specific)	Yes (mode- and trip-specific speeds)	–	–	–	Yes	Yes	–	–	Yes	[58]
TIMES-DKEMS (Danish TIMES with Elastic Modal Shift)	–	Yes (distance range classes)	–	- (“*Null*” [59])	Yes (unitary for all modes and trip types and over time horizon)	Yes	–	–	–	–	–	–	–	–	- (only transport)	[59]
MoCho-TIMES (Modal Choice in TIMES)	Yes	–	–	–	–	–	Yes (via Value of Time to calculate intangible costs)	–	–	yes (via Value of Time to calculate intangible costs)	Yes	Yes	–	–	- (only transport)	[60]
TIMES-Nordic EMS (TIMES-Nordic Elastic Modal Shift)	–	Yes (distance-range classes)	–	Yes	Yes (trip-specific)	Yes (trip-specific)	–	–	–	–	–	–	–	32 time slices: • four seasons	Yes	[61]

(*continued on next page*)

Table 1 (*continued*)

Model name	Demand segregation		Modal shift options				Travel time duration / Modal speed				TTB	Travel infrastructure investments[2]	MOO function	Intra-annual time resolution of mobility demands	Whole energy system model	Source
	Consumer segments	Trip types	EV charging infrastructure options[1]	OPE demands	CPSE demands	Aggregated mobility demand across modes	Driving	Car fueling	EV charging	other Level-of-Services						
NATEM Quebec (Quebec North American TIMES-type optimization model)	–	–	–	Yes	Yes	Yes	–	–	–	–	–	–	–	• two weekdays • daily variation 16 time slices: • four seasons • four daily periods	Yes	[62]

Note. [1] The consideration of various EV charging infrastructure options has relevance for reflecting consumers' time duration (Section 3.2).
[2] Travel infrastructure investments refer to investments in new rail lines, bus services, roads, and similar.
[3] Dashes (–) mean that the aspect was not considered in the respective model.

consumers, trip types, and transport modes.

The available OPE data [28] distinguishes cars and PT. To distinguish the OPEs of individual PT modes in Switzerland, we adjust the Swiss average PT OPE with mode-specific factors that reflect such distinction (mode-specific OPEs compared to overarching PT OPEs) in international studies [61]. Table 3 shows the calculated OPEs. To reflect the long-term focus of STEM, we adjusted the calculated values by a factor of three, in-line with suggestions by literature to account for consumers' increased chances to factor in cost changes when making long-term decisions [29]. In-line with literature findings, our estimates reflect relatively low price-elasticities for car users and higher price-elasticities for PT users [2,33,34].

3.2. Going beyond cost optimization

While ESOMs are often optimized solely for costs [12–15], we reflect non-monetary parameters relevant to the consumer's mode choice. Specifically, we implement the travel time[4] duration and travel time valuation into STEM's passenger transport module:

1. **Driving[5,6] (car and PT):** driving (or commuting) time duration is determined based on the consumer- (***j***), trip- (***k***), and mode- (***i***) specific demand trajectories $\boldsymbol{DM_{i,j,k}}$ [*pkm*], as well as their driving speed $\boldsymbol{S_{i,j,k}^{Drive}}$ [*vkm/h*] (Appendix C.4) and occupancy rate $\boldsymbol{OR_{i,j,k}^{Drive}}$ [*pkm/vkm*] according to the Swiss mobility survey [3] (Appendix Table C.2–1 and Appendix Table C.2–2) of the vehicle in year ***t***:

$$\boldsymbol{TIME_{i,j,k}^{Drive}(t) = \frac{1}{S_{i,j,k}^{Drive}(t)*OR_{i,j,k}^{Drive}(t)}*DM_{i,j,k}(t)*\delta_{i,j}^{Drive}} \tag{2}$$

where $\boldsymbol{\delta_{i,j}^{Drive}}$ is a calibration factor.

2. **Fueling (cars):** fueling time accounts for the de-tour to drive towards a fuel station, the fueling and payment process, and returning to the initial route. We approximate 7 min for the average time at a fuel station and 3 min for the de-tour into each direction, i.e., in total 13 min per fueling event [91]. The frequency of such fueling events depends on the car-type- (***ct***) and engine-size- (***es***) specific distance range ***R*** [*vkm*] [92], approximating that refueling occurs on average after driving 70% of its range [93,94]. Further, the time duration depends on the car's fuel efficiency ***EFF*** [*vkm/MJ*] and the annual Fuel consumption ***FC***. By considering such factors for each car, the annual fueling duration is calculated:

$$\boldsymbol{TIME_{i=car,j,ct,es}^{Fueling}(t) = 13*\frac{EFF_{ct,es}(t)}{R_{ct,es}(t)*70\%}*FC_{i=car,j,ct,es}(t)*\delta_{i=car,j}^{Fueling}} \tag{3}$$

3. **Charging (electric cars):** We assume that the consumers actively allocate time only at rapid chargers, and there we account only for the time allocated to the actual charging process. In contrast, the consumers' time is unaffected by other charging options (e.g., at

[4] From a TIMES modeling perspective, the travel time is implemented as a commodity, serving as an auxiliary input to various mobility Level-of-Services (LoS).

[5] Our methodology considers the expert feedback provided in [54]: we implemented the amount of driving time as a function of the process'output commodity, i.e. the amount of driven kilometers. In this way, we respect the differences in travel speed and OR on different trip types. Practically, we implemented this with the FLO_FUNC attribute of VEDA-TIMES [134].

[6] While we explore in the RTTV scenario the impacts of consumers giving less weight to travel time for their mobility choices due to increased productivity while traveling, e.g. due to improved vehicle automation, we still assume that driving time is fully accounted for traveling regarding the TTB, even though the consumer can potentially perform multiple tasks simultaneously.

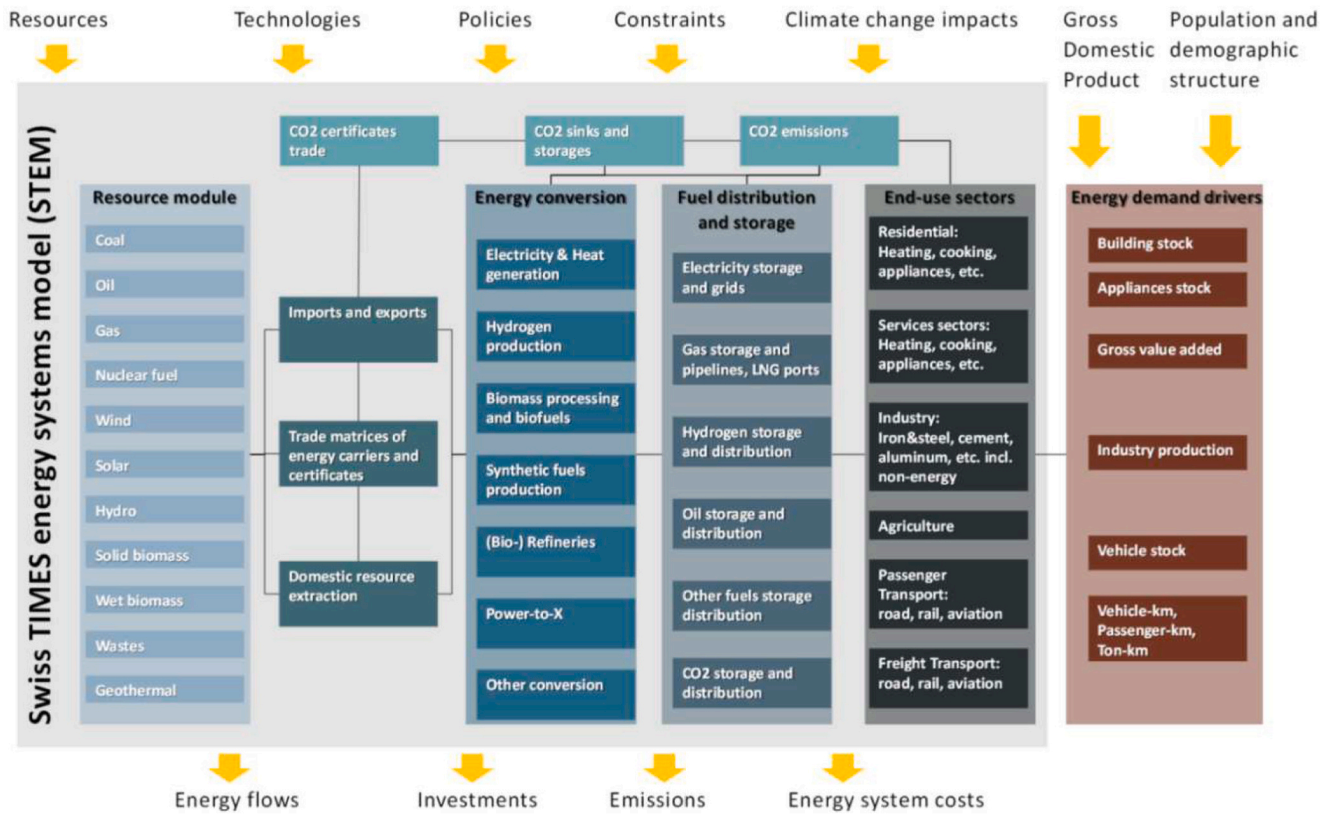

Fig. 1. Schematic overview of STEM's model structure *(adopted from* [77]*)*.

Box 1
Key features of STEM.

The STEM model framework belongs to the TIMES family of models [134]. In its conventional variant (prior this publication), STEM simulates potential cost-optimal future pathways in terms of technology investments and usage, energy consumption, and CO_2 emissions [77–79]. While having a long-term time horizon until 2050, it reflects intraday timeslices at an hourly resolution [77–79]. Being a technology-rich bottom-up ESOM, STEM contains a detailed techno-economic technology characterization of the entire Swiss energy system (see Fig. 1) [77–79]. For more detailed specifications of STEM we refer to previous publications [75,77–81,137].

home, train stations, or the workplace), as other non-transport activities can be performed in parallel while charging [76]. Thus, assuming a constant charging rate, the charging time of electric cars is defined as the amount of electricity charged E [kWh] divided by the rated power P [kW] of the charger type (ch).

$$TIME_{i=car,ch}^{Charging}(t) = \frac{E_{i=car,j,ch}(t)}{P_{ch}} \quad (4)$$

The time durations are calibrated for each consumer segment and towards Swiss national data [3,95]. Appendix C.4 presents the TTB by consumer segment [3].

To reflect consumers' travel time valuation for their mobility choices, STEM's objective function is transformed from the traditionally single-objective optimization function into a MOO. The MOO is applied with partial objectives for travel time and costs [96]. We consider different weights ω for each objective f, allowing to find Pareto-optimal solutions [97–99]. According to the Swiss national mobility survey [3], travelers are about four times more likely to make their modal choice decision based on travel time than costs. To reflect this, we select the weights $\omega_{Time} = 0.8$ and $\omega_{Costs} = 0.2$ for the reference MOO case. Meanwhile, an ϵ-constraint limits the maximum cost-deviation from the cost-optimal solution by 10% [97,98]. The mathematical details are presented in Appendix C.5.

4. Results and discussions: model application in the context of Switzerland

Switzerland was chosen for the application of this study because Switzerland has a high share of low-carbon energy sources [100], reliable and punctual PT [101,102], high PT shares [51], and a policy goal to attain net-zero greenhouse gas emissions [103]. Appendix A elaborates on the selection of Switzerland. Section 4.1 presents the assessed scenarios, Section 4.2 provides the insights of the scenario analysis, and Section 4.3 puts the results into perspective by drawing qualitative policy implications.

4.1. Scenario definition

We apply the STEM model with elastic and multi-objective variants

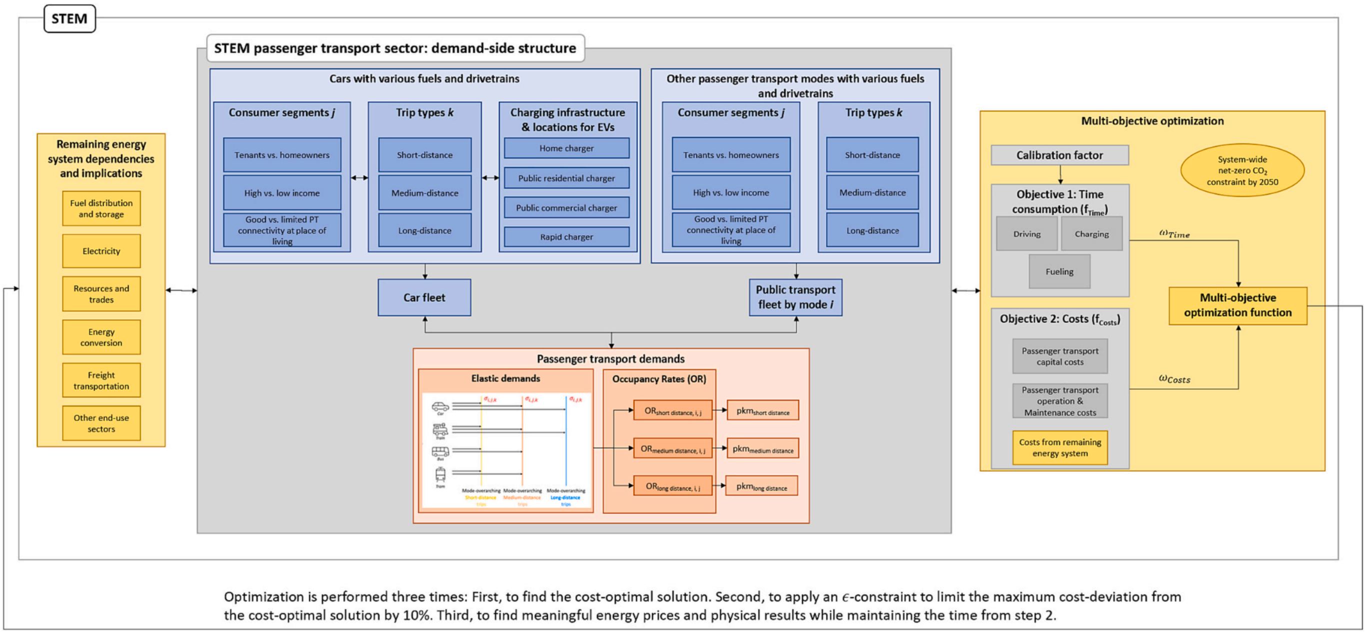

Fig. 2. Schematic visualization of the updated passenger transportation demand-side structure and the multi-objective optimization of STEM. For simplification, the figure visualizes coach buses and urban buses as 'bus' and the two types of long-distance trips as one demand.

Table 2
Mapping transport modes to trip types.

Transport Mode	Short-distance trips (S)	Medium-distance trips (M)	Urban long-distance trips (between agglomerations; L-Agglo)	Rural long-distance trips (start or finish outside an agglomeration; L-noAgglo))
Car	Yes	Yes	Yes	Yes
Urban bus	Yes	Yes	–	–
Coach bus	–	Yes	Yes	Yes
Tram	Yes	Yes	–	–
Train	Yes	Yes	Yes	Yes

to reflect the real-world option for modal shift. The scenarios applied in this work intend to inform policymakers by assessing the potential impacts of variations in travel time[7] duration[8] and travel time valuation[9] on modal shifts, vehicle deployments, and the energy system. Especially the scenarios aim to assess the systemic energy perspective for the frequently discussed policy measures of road speed limitations in Swiss cities [16–18] and on highways [19,20].

All scenarios reflect underlying decarbonization measures[10] to achieve system-wide domestic net-zero CO_2 emissions by 2050 of the 'LC100' scenario, as detailed by Kannan et al. [75]. While doing so, we distinguish two explorative elastic MOO scenarios to assess the implications of variations in future vehicle speeds and consumers' valuation of travel time for making mobility choices:

1. **Faster PT and Slowed down Cars (*FPT-SC*):** assumes that PT modes become faster to reduce travel time, whereas cars are being slowed down via speed limits or due to increased congestion. Improved PT speeds have high policy priority among Swiss people [104] and reflect, for instance, measures of enhanced digitization, higher frequencies, improved rolling stock, and PT prioritization on streets [105,106]. We conservatively assumed a 5% average PT speed improvement, considering the already efficient Swiss PT and potentially high costs for marginal speed improvements. The slowed down car speeds by 10% reflect potential policy measures for road speed limitations in cities and highways or increased congestion. Speed-specific fuel efficiency changes due to reduced car speeds are reflected according to [107].
2. **Reduced Travel Time Valuation (*RTTV*):** assumes that consumers tend to weigh travel time less for making mobility choices, e.g., due to higher productivity while traveling, which could be caused by improved information and communication technologies or enhanced car automation. Thus, the decision preference shifts from travel time towards costs, which is reflected by a switch of the MOO's partial objective weights: $\omega_{Time} = 0.2$ and $\omega_{Costs} = 0.8$.

The results of *FPT-SC* and *RTTV* are compared against an Elastic MOO baseline scenario (*EMOO-baseline*), which reflects today's mobility structures and modal choice preferences regarding the valuation of costs and time ($\omega_{Costs} = 0.2$ and $\omega_{Time} = 0.8$).

4.2. Insights from the scenario analysis

This section presents the results of the scenarios outlined in Section 4, along with additional insights from sensitivity analyses. The results demonstrate the impact of the applied measures on travel speed and travel time valuation by comparing the *FPT-SC* and *RTTV* scenarios to the *EMOO-baseline* scenario. As a reference, currently, PT accounts for

[7] While this work focusses on the consideration of travel time duration and travel time valuation in an energy systemic context, we also explored travel comfort as an objective and details are elaborated in the Appendix C.7.

[8] In this work, an increased travel time duration means that it takes a longer time to cover the same distance, i.e., a reduction in travel speed, and vice versa. However, an increased travel time does not infer that necessarily the same distances must be covered with that transport mode and the consumers spend more time in that mode. On the contrary, an increased travel time, i.e., lower travel speed, can induce shifts to another transport mode.

[9] It should be noted that we do not intend to pre-determine future user behavior but rather assess varying potential future pathways.

[10] These measures include trajectories for energy service demands and fossil fuel prices, CO_2 emission standards for buildings and vehicles, transport fuel taxes, and the Swiss phaseout of nuclear power [75].

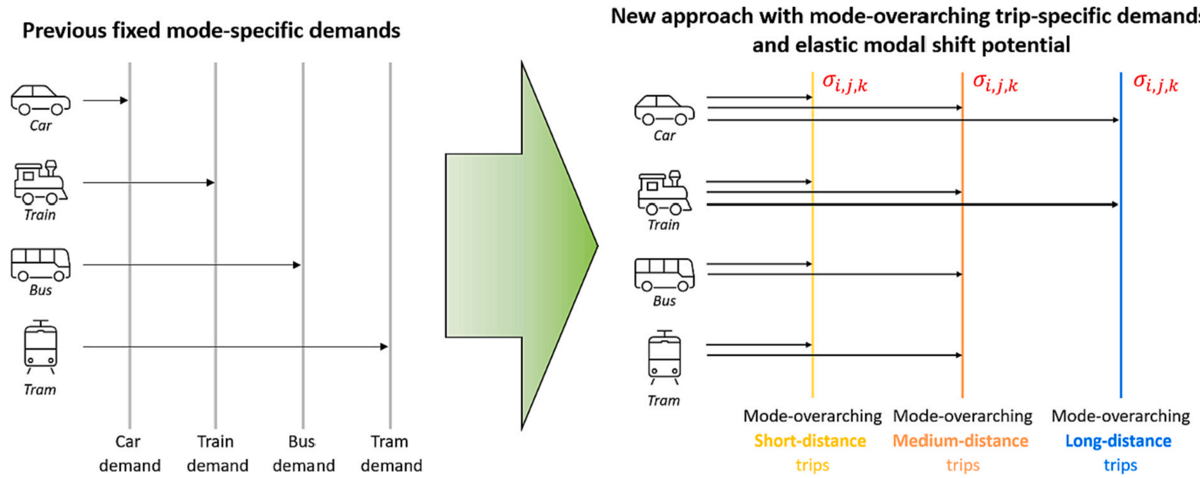

Fig. 3. Systemic changes in STEM's passenger transport demand structure from fixed mode-specific demands (left) to mode-overarching trip-specific demands with elastic modal shift potentials (right). The price elasticities of mode $\boldsymbol{i}$, consumer segment $\boldsymbol{j}$, and trip type $\boldsymbol{k}$ are denoted by $\sigma_{i,j,k}$. The visualization is schematic for one consumer segment $\boldsymbol{j}$. For simplification, the figure visualizes coach buses and urban buses as 'bus' and the two types of long-distance trips as one demand.

Table 3
Mode-, trip-, and consumer-specific short-term OPEs. Data are calculated based on references [3, 28, 90].

Consumer segment (see Appendix C.1)	Trip distance range (see Table 2)	Car	Urban Bus	Coach Bus	Tram	Train
GHIT	S	0.056	0.186	–	0.203	0.203
	M	0.100	0.428	0.583	0.467	0.467
	L-Agglo	0.184	–	1.180	–	0.944
	L-noAgglo	0.187	–	1.202	–	0.961
GHIO	S	0.056	0.184	–	0.201	0.201
	M	0.098	0.418	0.570	0.456	0.456
	L-Agglo	0.175	–	1.120	–	0.896
	L-noAgglo	0.180	–	1.157	–	0.926
GLIT	S	0.053	0.177	–	0.193	0.193
	M	0.121	0.514	0.701	0.561	0.561
	L-Agglo	0.211	–	1.345	–	1.076
	L-noAgglo	0.222	–	1.424	–	1.139
GLIO	S	0.050	0.169	–	0.184	0.184
	M	0.113	0.485	0.661	0.529	0.529
	L-Agglo	0.221	–	1.419	–	1.136
	L-noAgglo	0.214	–	1.374	–	1.099
LHIT	S	0.053	0.179	–	0.195	0.195
	M	0.100	0.425	0.579	0.463	0.463
	L-Agglo	0.187	–	1.201	–	0.961
	L-noAgglo	0.184	–	1.181	–	0.944
LHIO	S	0.052	0.176	–	0.192	0.192
	M	0.097	0.412	0.562	0.450	0.450
	L-Agglo	0.183	–	1.173	–	0.938
	L-noAgglo	0.180	–	1.152	–	0.921
LLIT	S	0.064	0.215	–	0.235	0.235
	M	0.112	0.477	0.650	0.520	0.520
	L-Agglo	0.216	–	1.380	–	1.104
	L-noAgglo	0.215	–	1.376	–	1.100
LLIO	S	0.064	0.213	–	0.233	0.233
	M	0.115	0.486	0.662	0.530	0.530
	L-Agglo	0.218	–	1.398	–	1.118
	L-noAgglo	0.224	–	1.437	–	1.149

Note. OPE values reflect the percentual demand change per percentual cost change for the same transport mode. An absolute value less than one means that "prices cause less than proportional consumption changes" [29] (p. 13)., whereas values larger than 1 mean that "price changes cause more than proportional consumption changes" [29] (p. 13).

26%[11] of land-based motorized passenger transport in Switzerland [51]. Electric Vehicles (EVs) (Battery EVs (BEVs) and Plugin-Hybrid EVs (PHEVs)) make up 4% of the car fleet [108], whereas their sale share increased to 25% in 2022 [109]. In comparison, *EMOO-baseline* contains a PT share of 27% in 2030, 30% in 2040, and 32% in 2050. Its EV share in the car fleet accounts for 36% in 2030, 74% in 2040, and 88% in 2050. Detailed results of *EMOO-baseline* and its comparison to STEM's non-elastic cost-optimal variant are presented in Appendix C.5. The supplementary results of the core scenarios are in Appendix D.2.

4.2.1. Implication on modal shift

In the *FPT-SC* scenario, which is characterized by faster PT and slowed down car travel speeds (see Section 4), consumers shift from cars to PT due to their preference for time over costs in the MOO. Fig. 4 shows on the left-hand axis the modal shift to PT that ranges between 2030 and 2050 in total from 2.8 to 4.8 billion passenger kilometer (bpkm) (7–14% increase in PT demand). The right-hand-axis of Fig. 4 shows that this relates to a 3–4% increase of PT in the modal demand split.[12] The PT uptake in *FPT-SC* reflects the modal shift sensitivity towards travel speed.

Fig. 4 shows the break-up of such total modal shifts by short-, medium-, and long-distance trips. For the *FPT-SC* scenario, its speed variations induce limited modal shifts on short-distance trips, mainly because cars remain the faster option despite the assumed faster PT and slower cars. Only in 2030, when conventional cars still dominate the car fleet, a slight shift occurs from cars to urban buses, but this vanishes in following years when more EVs penetrate the car fleet, as they can be charged without time losses. On the other hand, a shift from cars to trains occurs in medium-distance trips (~2 bpkm) and long-distance trips (1–2 bpkm between 2030 and 2050). Additionally, in 2030 a slight shift from cars to coach buses occurs on long-distance trips, reflecting that BEVs have in 2030 still a higher need for rapid charging on long-distance trips than in later years due to improved battery ranges.

Not only do we find distinctive impacts from the overarching speed measures in *FPT-SC* for the various trip types, but also do speed measures on different trip types and for the different modes have varying

[11] The modal split value is for 2019 (before the COVID-19 pandemic), since the pandemic strongly impacted the modal split, but the latest trends are indicating that transport levels are this year returning to pre-COVID-19 levels.
[12] The terms 'modal split'and 'modal share'are used analogous and both refer to the percentual pkm demand covered by a certain mode in comparison to the pkm demand of all modes [135].

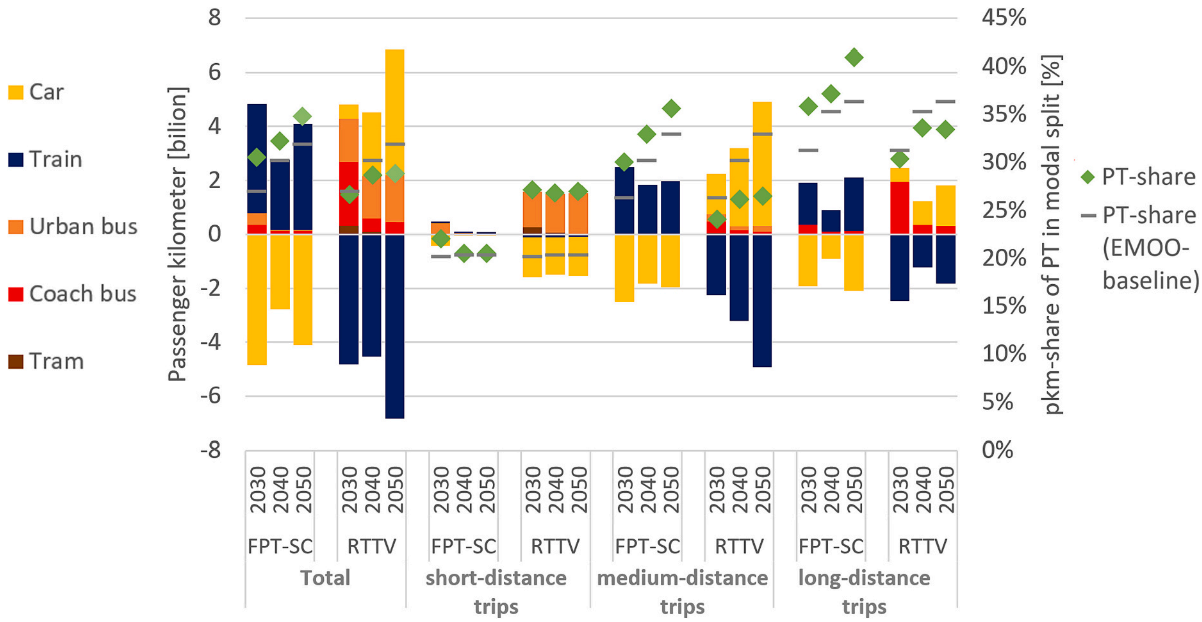

Fig. 4. Mode-specific modal shift delta and PT demand share, in total and as break-up by trip distance category. The left axis presents the modal shift delta in bpkm for *FPT-SC* and *RTTV* relative to *EMOO-baseline*. The right axis presents the PT demand share for *FPT-SC* and *RTTV* (green diamond) compared to *EMOO-baseline* (grey line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

impacts on the occurring modal shifts[13] (see Appendix Fig. D.2–1). Relatively moderate modal shifts occur from reducing car speeds only on short-distance trips, e.g., due to congestion or speed limits in cities. Nonetheless, the impacts of such are more pronounced in the short-term (2030: +0.7 $bpkm_{PT}$) than in the long-term (2050: +0.1 $bpkm_{PT}$), because the 2050 car fleet primarily consists of BEVs, which can be charged more time-saving than refueling conventional cars compared to PT. In contrast, car speed reductions on medium- and long-distance trips, reflecting road speed limitations on highways, lead to a more impactful shift to PT, as its demand increases by 1.8–3.6 bpkm (+5–10%) between 2030 and 2050. These higher modal shifts compared to car speed reductions on short-distance trips are caused, on the one hand, by the increasingly competitive travel speed of PT on longer trips, and on the other hand, by the higher demand uptake potential of trains across all consumer segments for longer trips than for short-distance trips, for which they tend to be only a viable option in urban areas (where trains also compete with other PT modes). For similar reasons, faster PT speeds contribute in *FPT-SC* stronger to the modal shift on medium- and long-distance trips than on short-distance trips (Appendix Fig. D.2–2). Again, the modal shifts induced by faster PT speeds occur stronger in the short-term (2030: +2.2 $bpkm_{PT}$ (+6%); Appendix Fig. D.2–1) than in the long-term (2050: +1.6 $bpkm_{PT}$ (+4%)), because of the uptake of EVs, which are mostly charged without time losses for the consumer. These insights underpin that the time savings of PT modes against cars are more pronounced for modal shift on medium- and long-distance trips and that the time savings charging electric cars while performing other activities contrary to the need for fueling conventional cars show an effect in the long-term due to their larger market penetration.

In the *RTTV* scenario, in which consumers weigh costs more than the travel time, Fig. 4 shows that in total, trains have a reduced demand (2030: −4.8 bpkm; 2050: −5.8 bpkm, compared to *EMOO-baseline*) because the clear travel speed advantages of trains compared to other PT modes and cars play a lower role, whereas other road-based modes are more competitive in terms of (marginal) costs than (marginal) travel time. The total *RTTV* results in Fig. 4 show further that in 2030 the reduced train demand shifts primarily to other PT modes, such as coach buses (+2.4 bpkm; +138%), urban buses (+1.6 bpkm, +73%), and trams (+0.3 bpkm; +56%). This requires strong PT capacity extensions while the car demand remains almost stable in 2030. By 2050, cars become more dominant by substituting 3.3 bpkm of the train demand, while urban buses contribute the most among other PT modes. The underlying causes for the changes between 2030 and 2050 lie in the car fleet, which consists increasingly of EVs: firstly, EVs can be charged at locations where consumers do not have to compromise on time (contrary to conventional cars); secondly, the levelized EV costs become increasingly competitive over time; thirdly, EVs can cover increasingly longer distances and thus have a reduced need for rapid charging (which causes time losses) to cover long-distance trips.

The *RTTV* modal shifts further differentiate on a trip-level, also shown in Fig. 4. On short-distance trips, the train demand remains stable, but a shift from cars to urban buses occurs (2050: +1.4 bpkm), showing their higher competitiveness when consumers value costs over travel time. On medium- and long-distance trips, train demand is substituted by coach buses and cars. The shift towards coach buses becomes particularly present on rural long-distance trips (2050: +15% pkm). Fig. 4 shows further that the shift towards coach buses reduces over time while the shift towards cars increases. The increasing shift towards cars is caused by the increased use of BEVs, which are more time-saving for consumers than other cars (on trips that do not require rapid charging). This and their potential to help achieve net-zero CO_2 emissions in 2050 contribute to the observed trend.

While we mainly assess two contrasting scenarios with different travel speeds and weightage between travel time and costs, we also investigated a combined approach of the measures applied in *FPT-SC* and RTTV. The combined approach shows (Appendix Fig. D.2–4) that the 2050 modal split of PT (29%) would only be slightly higher than in RTTV (+1.2 bpkm; PT-split: 29%) but much lower than in *FPT-SC* (−7.6 bpkm; PT-split: 35%). This underpins the importance of travel time

[13] The total modal shift that results from the combined implementation of different speed variation measures (such as lowering car speeds on short-, medium-, and long-distance trips and enhanced PT speeds) is less than the modal shift seen when each measure is implemented separately and the results are added up. This is because some marginal modal shift effects are double-counted, as they are already taken into account when only one measure is used and are also taking place when only another measure is applied.

valuation for the modal shift towards PT.

In-line with other studies assessing modal shifts in systemic contexts [110,111],we find both in our cost-optimal scenario (Appendix D.1) and in the EMOO-variants (this section) an increased modal split of PT in the long-term future compared to today. While we find a two percentage point (pp) increase in the modal split from car to PT (currently 26%) by 2050 in the cost-optimal variant, it increases by six pp. in *EMOO-baseline*, three percentage points in *RTTV* and nine pp. in *FPT-SC*. In contrast, the Swiss national transport perspectives find an increase by four pp. compared to today in their baseline scenario, which is a stronger increase than in their remaining scenarios [110]. Another study that assesses modal shifts by applying an ESOM for northern European countries [111] finds a modal shift increase by four pp. in the cost-optimal scenario and seven pp. in the elastic scenario, being in a similar range to the results presented in this work.

Modal shift responses vary across consumer segments, e.g., in *FPT-SC*, the total PT demand increases by 9% (2050), whereas it increases among high-income segments by 13% and low-income segments by 6%. This higher potential of high-income segments can be attributed to the fact that they currently drive on average more with cars (Appendix Fig. C.4–2) and spend more time traveling (Appendix Table C.4–1). Thus high-income segments have higher absolute modal shift- and time-saving-potentials, which outweighs in *FPT-SC* their lower cost sensitivity (lower CPSE), as costs account for only 20% of the MOO (see Table 3 and Eq. (1)). The CPSE variation by income plays a more relevant role in *RTTV*, which assumes a stronger tendency towards cost reduction: while Fig. 4 indicates for *RTTV* a shift towards cars, compared to *EMOO-baseline*, this occurs predominantly in the cost-sensitive low-income segments, compared to the high-income segments.

Furthermore, consumers living in areas with good PT connectivity (mainly urban places) show a higher PT uptake potential, particularly in the shift from cars to urban buses and trams on short-distance trips depicted in Fig. 4.

4.2.2. *Impacts on the transport sector and the energy system*

Given the systemic interdependencies between the energy and transport sectors, the modal shifts induce impacts on fuel supply chains and deployed technologies to provide an optimized energy system that meets the adjusted demands. The following presents and discusses the implications in *FPT-SC* and *RTTV* compared to *EMOO-baseline*, focusing on car driving and fuel shifts in the transport sector.

For *FPT-SC,* there occurs a demand shift within cars from PHEVs, Hybrids, and Fuel Cell EVs (FCEVs) towards BEVs and Internal Combustion Engine Vehicles (ICEVs) (Appendix Fig. D.2–3), despite the overall reduced car demand due to modal shifts to PT by 3.8 bpkm in 2050 (−4% pkm_{cars}; Fig. 4). The increased BEV demand accounts in 2040 for 6.6 bpkm (+15% pkm_{BEV}) and in 2050 for 2.4 bpkm (+4% pkm_{BEV}), whereas the increased ICEV demand accounts in 2040 for 3.5 bpkm (+23% pkm_{ICEV}) and in 2050 for 1.9 bpkm (+34% pkm_{ICEV}).

Considering the differences between homeowners and tenants, Fig. 5 shows that homeowners generally deploy more BEVs than tenants due to their ability to install private home chargers[14] (see [76]). However, due to the already relatively high BEV demand by homeowners in *EMOO-baseline* (88% pkm_{cars} in 2050; Fig. 5), their additional uptake potential is limited, whereas tenants' lower BEV deployment in *EMOO-baseline* (49% pkm_{cars}; Fig. 5) leaves a higher potential for additional uptake. As depicted in Fig. 6, this uptake potential is utilized in *FPT-SC,* where tenants substitute hybrid cars and PHEVs with BEVs, leading to a demand increase in BEVs by 19% $pkm_{BEV,tenants}$ (2050: +3.9 bpkm by BEVs of tenants) covered by 250,000 additional BEVs among tenants. This is driven by the lower time losses for charging BEVs compared to refueling non-electric cars, which becomes, in *FPT-SC,* a more important factor for the overall travel time as the car travel speed is reduced.

While cars in the *RTTV* scenario are generally more used due to the modal shift from PT to cars, compared to EMOO-baseline (Fig. 4), Appendix Fig. D.2–3 shows an overall strong car shift from BEVs and Hybrid cars towards PHEVs (2050: shift by 13.7 bpkm towards PHEVs; 14% of the total *RTTV* car-pkm). Despite the reduced BEV demand, we find that the overall EV driving (BEV and PHEV) increases in 2040 by 9.2 $bpkm_{EV}$ (+13%) and in 2050 by 5.0 $bpkm_{EV}$ (+6%). Depending on the car size, our results show that PHEVs cover between 65% and 78% of the distance traveled powered by electricity (2050: 8.5 PJ). Besides that, the PHEVs use 100% synthetic−/biodiesel, and gasoline-powered PHEVs contain a 28% ethanol blend. Thus, 10% of the distances covered in PHEVs are powered by conventional fuels (gasoline).

On a consumer level, Fig. 6 shows for *RTTV* that homeowners move from BEVs to PHEVs, which relates to the cost advantages of PHEVs. This links to the facts that, firstly, the time benefits of BEVs are minor compared to PHEVs because both are primarily charged without time losses for the consumer, and PHEVs need to refuel only occasionally at a conventional fuel station. Secondly, the higher weight of costs in the *RTTV* scenario's optimization reduces the relevance of potential time benefits of BEVs compared to other cars. Tenants substitute their hybrid cars with PHEVs and FCEVs (Fig. 6). This advanced shift towards electric-powered cars emphasizes the need for stronger car decarbonization, arising from the modal shift from PT to cars (compared to EMOO-baseline), requiring more fuel than PT. This additional fuel demand mitigates the decarbonization efforts if the additional car demand is not powered with low-carbon electricity.

Fig. 7 compares in 2030 and 2050 for short- and long-distance trips the car-pkm share covered with each drivetrain type. It shows that BEVs are used in 2050 about one-third less on long-distance trips than on short-distance trips in *EMOO-baseline* and *FPT-SC*, which both weigh travel time over costs, whereas BEVs require on long-distance trips rapid charging, imposing time losses for consumers. Due to such time losses of BEVs on long-distance trips, the model finds in *EMOO-baseline* a more efficient solution by using more ICEVs and PHEVs in relative terms three times and 2.5 times, respectively, more on such trips (compared to short-distance trips), despite the need for achieving net-zero by 2050. The effect of higher ICEV usage on long-distance trips becomes intensified in *FPT-SC*, as CO_2 emissions are mitigated by the modal shift from cars to PT (compare with Fig. 4), easing the need for other CO_2 emission reductions, which is reflected in the usage of ICEVs[15] for 21% of the long-distance trips compared to 12% in *EMOO-baseline.* In RTTV, where the role of cost reduction is more relevant than the travel time, Fig. 7 shows that BEVs are still used more on short-distance trips than long-distance trips, but this difference is less pronounced. This reflects that the need for rapid charging penalizes the usage of BEVs more from a time perspective than a cost perspective. Compared to *EMOO-baseline*, by 2050, PHEVs primarily substitute BEVs on short-distance trips and ICEVs and Hybrids on long-distance trips. The former reflects that the time advantages of BEVs on short- and medium-distance trips (where consumers can charge without experiencing time losses) are less relevant in *RTTV,* and their uptake is dampened when costs play a more relevant role. In contrast, the latter reflects the additional need for decarbonization among cars due to the lower PT usage. The results show that the latter can, in RTTV, be more effectively achieved by using PHEVs than deploying BEVs and rapid charging infrastructure.

A general trend observed with varied travel speeds is that the modal shift towards PT occurs most strongly in 2030, weakens in 2040 (but still takes place), and rebounds in 2050 to a stronger level than in 2040 but

[14] Due to current Swiss policies [136], we assume that only homeowners have access to private home chargers. Tenants, however, can still access public chargers in residential and commercial areas and rapid chargers along highways (which can all also be accessed by homeowners). More details on the EV charging in STEM can be found in another study [76].

[15] In *FPT-SC*, the remaining ICEVs in 2050 are powered with a blend of gasoline (69%) and ethanol (31%).

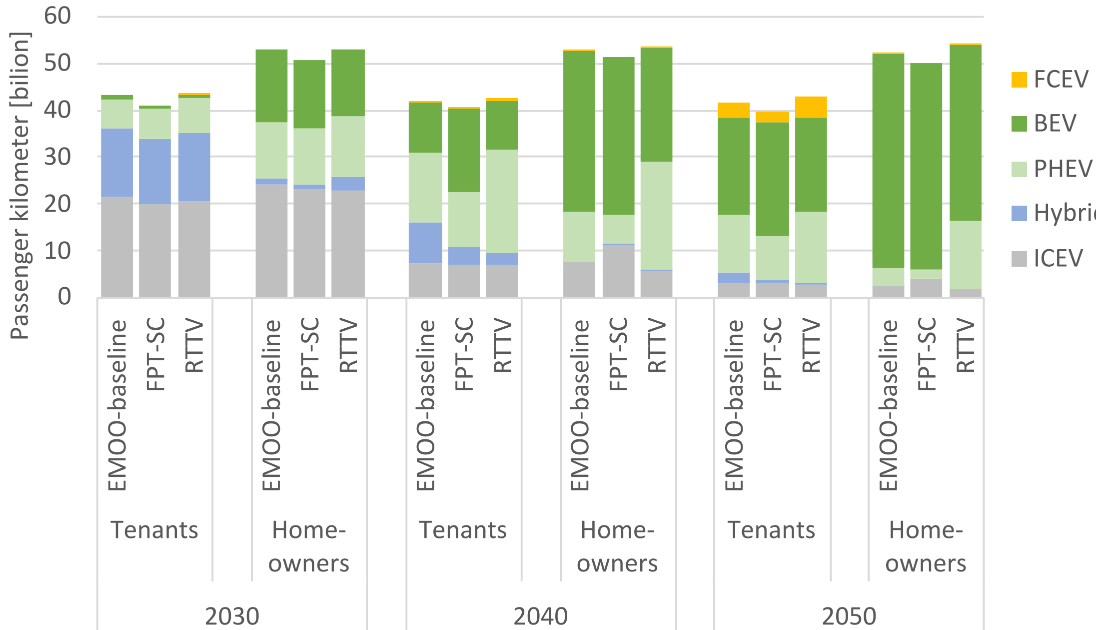

Fig. 5. Car-pkm of tenants vs. homeowners by drivetrain in *EMOO-baseline*, *FPT-SC*, and *RTTV*.

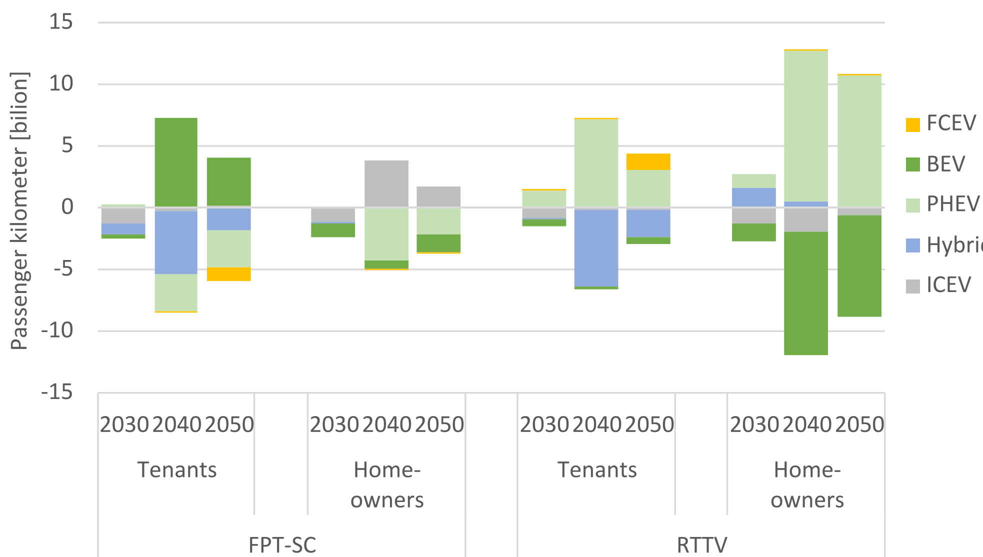

Fig. 6. Delta of car-pkm of tenants vs. homeowners by drivetrain for *FPT-SC* and *RTTV* relative to *EMOO-baseline*.

weaker than in 2030 (Fig. 4). This reflects the interaction of several dynamics in the wider energy system. For example, in the *FPT-SC* scenario in 2030, the low-carbon electricity generation from new renewable sources (e.g., wind, solar, and biomass) is 16% (11.3 TWh), still relatively limited and primarily substitutes the phase-out of nuclear electricity. Thus, the electricity supply for additional BEVs is limited, and the model rather deploys a higher level of PT. The additional PT uptake in 2030 is primarily diesel-powered but still provides efficiency and time-saving advantages compared to cars. In 2040, more low-carbon electricity from new renewables is available, and BEVs become less electricity-intense due to fuel efficiency improvements. As BEVs are not yet dominating the car fleet, the model determines a stronger potential to deploy more BEVs at the expense of a reduced modal shift to PT. Given the tightening decarbonization need, most of the additional PT demand in 2040 is electricity-powered. In 2050, most cars are BEVs in the EMOO-baseline scenario; thus, their additional uptake potential is more limited than in 2040. Therefore, the strengthened shift by 2050 towards PT (fully electrified besides coach buses which consist partially still of hybrid diesel vehicles) reflects the effective contribution of the transport sector towards net-zero decarbonization in 2050 beyond the vehicle shift to BEVs. These insights align with studies suggesting that modal shift becomes less effective for climate change mitigation in the future, compared to today, due to fuel efficiency improvements in cars [112].

We find that energy-systemic changes primarily occur in the transportation sector. Most energy carriers freed up by modal shifts are used elsewhere in the transport system, such as by light- and heavy-duty freight vehicles or other passenger transport modes (Fig. 8). Fig. 8 shows that this effect becomes particularly prevalent for electricity consumption: In *FPT-SC,* modal shift towards PT causes more PT electricity consumption, which substitutes electricity consumption in cars and freight transport, and vice versa in *RTTV* (Fig. 8). Appendix Fig. D.2–5 shows the hence low changes in the entire transport sector fuel mix, besides a substitution effect between gasoline-powered cars with diesel-powered PT in *FPT-SC* (Fig. 8). On the one hand, this reflects

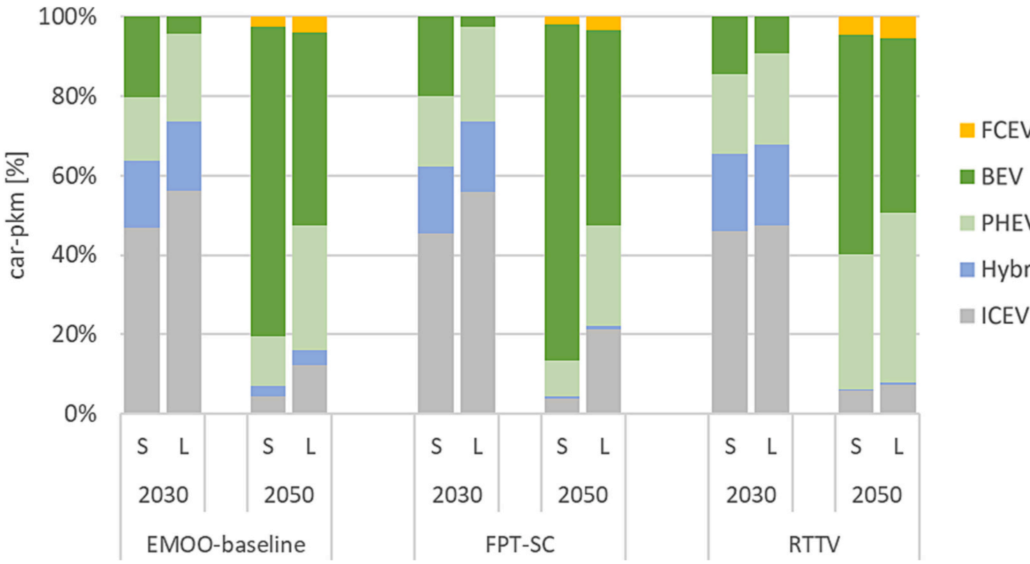

Fig. 7. Share of car-pkm by drivetrain on short- (S) and long-distance (L) trips in 2030 and 2050 in *EMOO-baseline*, *FPT-SC*, and *RTTV*.

that all applied scenarios must achieve net-zero CO_2 emissions in 2050. Thus when modal shift towards PT occurs as an additional decarbonization measure, the need for decarbonization elsewhere in the energy system is alleviated.[16] We find that such alleviations primarily take place in the transport sector itself. This reflects, on the other hand, the flexibility in achieving a low-carbon transport sector, as various competitive technology options and decarbonization measures for emission reductions are available (e.g., fuel efficiency improvements, vehicle shift to BEVs or FCEVs, modal shift towards PT or shift towards cars powered with low-carbon electricity, use of low-carbon synthetic fuels, biofuels). Implications in the wider energy system consist mainly of minor variations in producing hydrogen, biofuels, biogases, and hydrogen-based synthetic fuels to provide an optimal fuel supply for the changed transportation demands.

4.3. Policy implications

Based on the results, several implications exist for policymakers:

1. **Faster PT speeds on medium- and long-distance trips:** we found that improving PT speed is especially impactful on medium- and long-distance trips, which led in our scenario to 5–10% higher PT demand, primarily covered by trains and coach buses. Our results align with the policy wish of the Swiss population for prioritizing PT improvements in the transport sector [104]. Therefore, policies focusing on improving PT could encourage consumers to shift from cars to PT. While Switzerland's PT travel speed is already high, potential measures involve enhanced digitization, investments to achieve higher PT frequencies, and faster modes due to improved rolling stocks. As the shift to PT leads as a side-effect to substituting PHEVs with BEVs, which implies more commonly the deployment of private home chargers, the need for public chargers in commercial locations reduces by 20% in 2050 (11,000 fewer chargers with 22 kW each).
2. **Limiting road speeds on highways:** the analysis finds that the modal shift effect to PT can be further enhanced when the travel speed of cars is reduced, particularly on medium- and long-distance trips. Policymakers could consider limiting highway road speeds, taking examples from countries such as the Netherlands [113,114] and Austria [19,20]. The modal shift achieved via the combined approach of faster PT speeds and highway speed limits reduces the need for electrifying hard-to-electrify land-transport-modes, such as heavy-duty trucks, by 11% and decreasing the hydrogen demand in land-based transportation by 34% by 2050. This enables redirecting such resources to other sectors that can use them more effectively to decarbonize. Notably, given that trips in cities are primarily short-distance, we find that the currently discussed and implemented speed limits in Swiss cities (for noise reduction) [16–18,115] have limited impact on modal shifts.[17]
3. **Promoting EV market penetration:** EVs are an important decarbonization technology and are more time-saving for consumers than conventional cars. The study found that such time-advantages become more noticeable with increasing EV market penetration over time. Therefore, policymakers should make passive EV charging[18] options, such as private home chargers, easily available to everyone to induce faster EV market penetration by utilizing related time savings of EVs. However, policymakers should remain aware of potential rebounds regarding higher car demands and less shift to PT.
4. **Balancing travelers' decision factors:** the study found that trains are less competitive in terms of costs than travel time. However, as train traveling provides leverage over cars for decarbonization,[19] policies should balance both aspects to encourage train usage. Thus, policies on reducing train travel costs, particularly for low-income consumers with higher price sensitivity, could subsidize PT through employers or social insurance. Furthermore, to mitigate travelers' shift from trains to cars, policymakers could promote coach buses on long-distance trips, as they are more cost-effective than trains and could dampen capacity expansion limits of the rail

[16] This reflects that the decarbonization measures taking place in each individual scenario are interrelated: the potential decarbonization impact of one measure may be lessened when another measure makes a greater contribution to decarbonization because the overall level of systemic decarbonization does not change. For instance, when more decarbonization occurs due to modal shifts towards PT, less decarbonization might occur by a car shift to low-carbon EVs.

[17] This is consistent with arguments that city speed limits reduce congestion and thus do not effectively affect the average car speed [20,47].

[18] Passive EV charging refers to charging that can occur without time compromising on travel time for the consumer. For instance, at home, at work, and at commercial locations like train stations or supermarkets.

[19] Furthermore, trains are advantageous to cars in terms of air pollution, noise reduction, urban planning, human health, and similar.

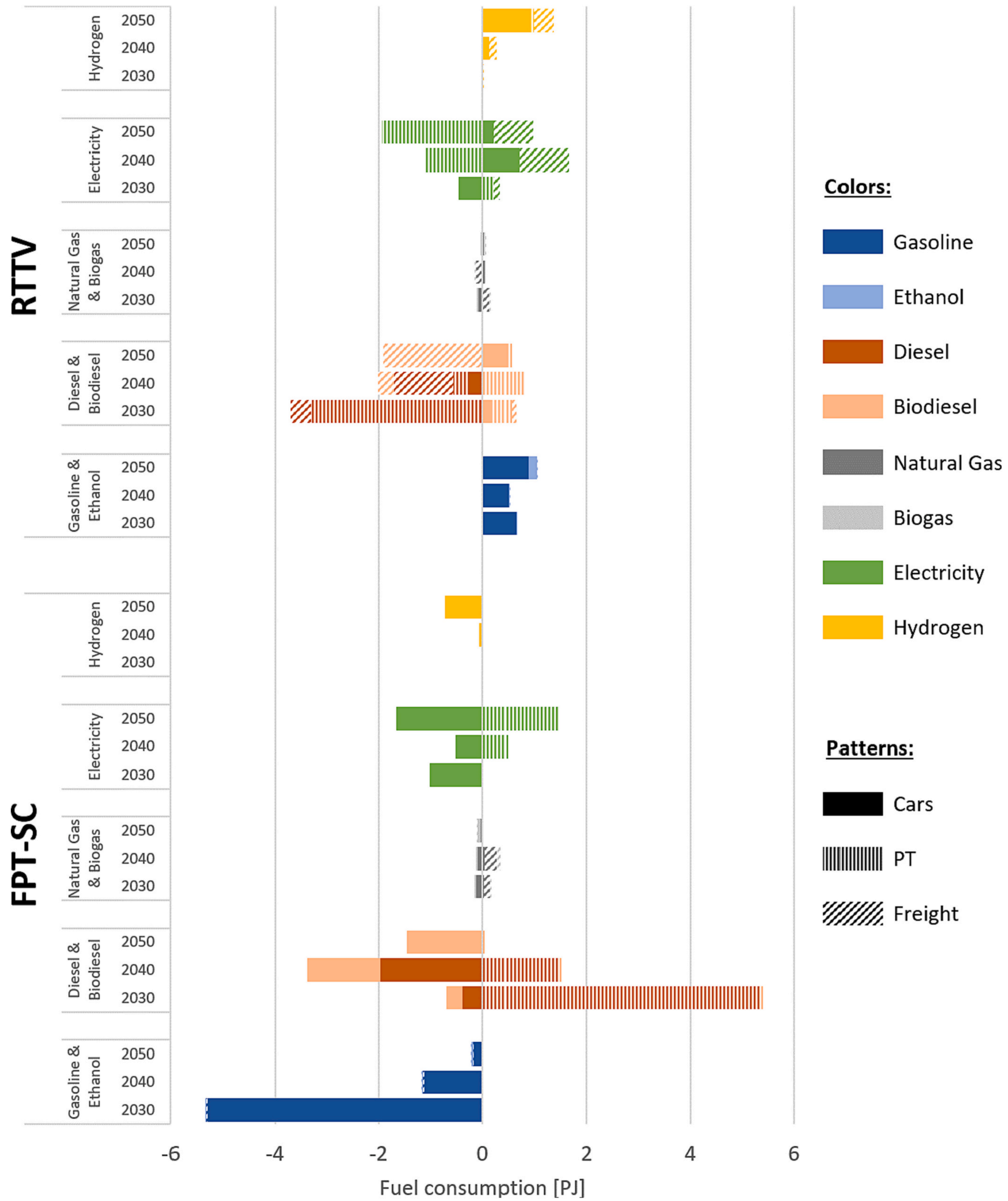

Fig. 8. Fuel-specific fuel consumption delta of land-based transportation of *FPT-SC* and *RTTV* relative to *EMOO-baseline*. The colors distinguish fuels, and the patterns distinguish cars, PT, and freight transport.

network. Moreover, when lower costs are prioritized, an indirect effect is that the higher PHEV deployment, which come less commonly with private home chargers than BEVs, implies an additional public charging capacity at daytime-charging locations of 1 GW by 2050 (+42%; equivalent to 45,000 chargers with 22 kW each or 6600 rapid chargers with 150 kW each).

A combination of policies can be effective that targets different aspects of transportation, such as improving the travel time savings of PT against cars and promoting EVs while considering consumer heterogeneity and targeted policies for different trip distances. This could result in a stronger focus on policies that encourage PT usage, which could lead to reduced transport emissions.

5. Limitations and future work

While this work made advancements in reflecting travel time in a bottom-up ESOM and assessing the systemic implications of such for the mobility and energy system, we acknowledge a set of limitations that could be advanced in future work. This work does not claim to forecast the real-world future, but rather provides potential future pathways that can achieve net-zero CO_2 emissions by 2050 under cost- and time-optimal energy system trajectories, providing valuable insights for policymakers.

By distinguishing Swiss-specific price-elasticities across household income and trip distance, we could reflect such values with a relatively high degree of socioeconomics detail [3,28]. This contrasts other studies where the lack of detailed elasticity data imposed challenges [32,59,61,62]. Nonetheless, we acknowledge that weighted mode-specific OPEs were used to proxy CPSEs, as the availability of CPSE data is limited. Future work could use the outcomes of a current study on Swiss mode-specific CPSE data [116]. Moreover, future work could distinguish that travel demands are more elastic at off-peak times than at peak times [32]. Furthermore, varying elasticities and related modal shift potentials by trip purpose could be considered [24,28].

While this study assessed modal speed variations, which imply potential policy measures and infrastructure expansions/limitations, it did not consider the infrastructure costs required to accomplish the assumed speed variations. Historical data shows that specific infrastructure costs are highest for rail-based PT (0.20–0.23 CHF/pkm), followed by road-based PT (0.11–0.12 CHF/pkm), and is lowest for private car transport (0.06–0.07 CHF/pkm) [117], which aligns with such trends in other studies [57,58]. For the findings of this study, this means that the consideration of infrastructure costs will likely amplify the modal shifts even more, as we found shifts towards cars when costs played the dominant role in the optimization and shifts to PT when time played the dominant role. Nevertheless, this work shed valuable insights into the possible efficacy of modal shift as a decarbonization measure. While others [56–58,60] considered road/rail infrastructure investments to enhance travel speed, they reported high uncertainty levels. For instance, Pye and Daly [57] report for rail-based modes infrastructure costs of ~0.22 CHF/pkm in 2035, exceeding the remaining costs approximately by a factor of ten, whereas Tattini et al. [58] report ~0.13 CHF/pkm (2030) for train infrastructure, approximately being equal to the remaining costs.[20] Complementary work is necessary to assess the need for new PT infrastructure, such as new railway tracks or separate PT road lanes, while considering how much of the existing capacity can meet additional demands from modal shifts.

This work makes an important first step for going beyond conventional cost-optimization by reflecting the well-quantifiable aspects of costs and travel time in a MOO. Future work could assess which additional aspects [3] can be well quantified in ESOMs in contrast to which may vary strongly between individuals and thus might be better suited for other model frameworks, such as agent-based models. Regarding travel time, it is noteworthy that the travel speed aspects investigated in this work are usually investigated from a transport and traffic perspective in dedicated model frameworks [22,23,47,84,90,118–120]. However, as investigated in this work, the energy-systemic perspective of such measures' impacts has previously remained under-investigated. Further research could explore how else consumers will utilize saved time and to which extent this could lead to rebound effects [38]. Also, future work should consider how changes in travel behavior and enhanced digital solutions for work and leisure could impact the absolute travel demand [41].

Although the spatial details remain relatively aggregated, which is a common caveat in ESOMs [121–123], this work reflects various trip types, consumer segments, and location-based EV charging options. Thus, instead of focusing on single trips or precise locations, the applied model assesses the broader impact of long-term travel time implications for the mobility transformation and wider energy system. Nevertheless, for future work, it could be valuable to link the demands for certain transport modes to reflect intermodal journeys to reflect the complementary nature of various modes [124]. Further, future work could reflect non-motorized modes, such as walking and cycling, which are often used to cover the last mile from and to PT but are not covered in this work. Utilizing data of traffic models [125,126] could provide an interesting avenue for harnessing travel time data of various modes with a higher level of detail.

The underlying assumptions for both scenarios reflect trends going beyond the geographical scope of Switzerland, as many countries discuss road speed limits on highways [19,20] and in cities [42–47], and the potential shift towards a lower weight for travel time could also occur internationally due to the global trend towards advanced information and communication technologies and the potential uptake of autonomous vehicles in the future. Thus, the insights provided by this work are also relevant in an international context and could be similar in other countries, even though focusing on Switzerland. However, it should be considered that also other aspects, such as PT reliability and punctuality, are important for consumers' potential shift towards PT. While such aspects reflect low barriers for shifts to PT in Switzerland, they might impose higher barriers in other countries. Nonetheless, the methods developed in this work can be adopted for analyses with different geographical dimensions and could be extended to better account for such barriers.

6. Conclusion

Modal shift towards PT is a key strategy for decarbonizing passenger transport [127]. However, ESOMs, often used to inform these discussions, typically overlook the importance of non-monetary factors for modal shifts. This study addresses this limitation by integrating consumers' travel time duration and valuation into STEM, an advanced national ESOM, to consider some non-monetary mobility decision factors of various consumer segments and trip types. The work provides a transferable methodology in the TIMES modeling framework based on the specific Swiss case.

This study applies the advanced STEM to address three research questions regarding the implications for modal shift and the transport sector transformation from 1) measures leading to faster PT and slowed down car speeds, 2) potential changes in travel time valuation for consumers' mobility choices, and 3) the distinction of such aspects by consumer segments and trip types. This study quantifies such aspects in an explorative scenario analysis with pathways towards net-zero emissions by 2050 to suggest measures for encouraging modal shift to PT and amplifying the transport sector's decarbonization potential.

PT speed increase by 5% and average car speed reduction by 10% on

[20] For cars, Pye and Daly [57] report infrastructure costs of ~0.04 CHF/pkm in 2035, accounting for less than half of their remaining costs, whereas Tattini et al. [58] report ~0.07 CHF/pkm (2030) for road-based mode, accounting almost for the same as the remaining costs.

medium- and long-distance trips can increase the use of PT by 5–10% (+1.8–3.6 $bpkm_{PT}$) between 2030 and 2050, when consumers continue weighing travel time over costs. Further, the analysis shows in such configuration that the additional modal shift towards PT, compared to the baseline scenario, is stronger in 2030 (+4.8 $bpkm_{PT}$) than in 2050: (+4.0 $bpkm_{PT}$), as the future car fleet is expected to consist of increasingly more EVs, which are more time-saving for consumers than conventional cars because EVs can be charged without compromising travel time. Thus, rapid EV deployment can reduce pressure on potentially expensive rail network extensions to meet increasing PT demands. However, although EV uptake is an effective decarbonization measure, several reasons speak for promoting shifts towards PT, such as reduced energy consumption, benefits for human health and the environment, improved quality-of-living in cities, and increased congestion caused by more car use which could in turn lead to slower cars and induces shifts to PT – however, this study did not consider such rebound effects. The potential shift to PT becomes mitigated if consumers start weighing travel time less than costs in their mobility choices, for instance, due to enhanced productivity while traveling. In such case, we find that electric cars play a more dominant role in decarbonization (2040: +9.2 $bpkm_{EV}$ (+13%); 2050: +5.0 $bpkm_{EV}$ (+6%)). Given the insights of this analysis, if policymakers want to encourage modal shifts towards PT, they could consider policies such as highway road speed limits and invest in efficient PT through measures such as enhanced digitization, improved rolling stocks, and higher PT frequencies. To achieve such modal shift effects via economic measures, a carbon tax or higher fossil fuel prices could be considered.[21] Furthermore, these effects vary across consumers' socioeconomic conditions and agglomeration of living, which are important factors for their sensitivity towards travel time and cost changes. For example, low-income consumers tend to be more sensitive to costs, whereas high-income consumers are more sensitive to travel time savings. Overall, the findings of this work provide nuanced insights for policymakers regarding the implications for modal shift of currently discussed speed limitations in Swiss cities [16–18] and the international trends towards lower speed limitations on highways [19,20].

The inclusion of non-monetary decision variables in ESOMs and their application in a multi-objective optimization framework offer new insights into alternative technological pathways and policy options for decarbonizing the energy and transport system. However, weighing different non-monetary variables is highly subjective and requires not only high-quality data but also clear values for those non-monetary variables. The methods developed in this work can be easily adapted to other geographic locations for any model with the TIMES modeling framework or in similar ESOMs. The data availability, however, has been excellent for this Swiss case study and should be assessed for the geographic locations of other studies before implementing the developed methods in order to achieve their good transferability.

Future work could differentiate trip purposes and reflect intermodal journeys, strengthening the analysis of modal shift potentials. Including non-motorized modes such as walking and cycling could provide additional modal shift opportunities, especially on short-distance trips.

Overall, while enhanced modal shift to PT can potentially alleviate the need for other decarbonization measures, our results present optimal pathways, and practical obstacles may prevent reaching net-zero targets. From a modeling perspective, future work could ensure that the stronger application of one mitigation measure does not alleviate the application of another measure. Thus, we suggest exploring how all decarbonization measures, including modal shift, could be integrated most effectively to potentially even achieve an energy system with net-negative CO_2 emissions.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used the tools Grammarly (by Grammarly Inc.) and ChatGPT (by OpenAI) in order to improve readability and language of texts written by the authors. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Sandro Luh: Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ramachandran Kannan:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Russell McKenna:** Writing – review & editing. **Thomas J. Schmidt:** Writing – review & editing, Supervision. **Tom Kober:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Sandro Luh reports financial support was provided by Swiss Federal Office of Energy. Ramachandran Kannan reports financial support was provided by Swiss Federal Office of Energy.

Data availability

Data will be made available on request.

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Appendix A. Supplementary background: the case for Switzerland

Switzerland was chosen for this work due to its well-functioning PT system, with one of the highest PT shares in Europe [51]. Its high reliability and punctuality [101,102] let Swiss PT users experience higher satisfaction and, therewith, fewer perceived barriers to shifting towards PT [24] compared to other countries [128]. As such barriers are more challenging to quantify in an ESOM but play a lesser role in Switzerland, our country choice gives the unique advantage to focus on the tradeoff between travel time and costs (which both can be well quantified). Further, Switzerland has a competitive advantage against many countries, as its domestic energy mix already consists of a relatively high share of low-carbon energy sources [100], making electrified (public) transport modes even more advantageous from a climate perspective. Moreover, while Switzerland pledged to the Paris Agreement with a long-term climate strategy to attain net-zero greenhouse gas emissions by 2050 [103], public debates are ongoing on how this

[21] It's noteworthy that such economic measures were not directly considered in the analysis of this work.

can be achieved.

Appendix B. Supplementary literature overview: bottom-up ESOMs considering travel time and endogenous modal shift options in the transport sector

Pye et al. [32] applied a whole energy systems model with cost-optimal endogenous modal shifts and OPEs. Daly et al. [54–56] developed a test model that considers travel time linked and a Travel Time Budget (TTB). Further, their model links potential travel infrastructure investments to travel speed variations, so-called travel time investment [55]. Considering various consumer segments, Pye & Daly [57] implemented this approach in a whole ESOM. While their model can still invest in travel infrastructure, this does not accelerate the mode's travel speed. Their approach distinguishes urban and rural trips; transport modes can only compete when covering the same trip type. Tattini et al. [58] implemented a similar concept in TIMES-DKMS. In another approach, Tattini et al. [60] developed a transport-only model focusing on modal choice. Their aspect of time also considered other Level-of-Services (LoS) than driving through calculating the intangible costs for each LoS, i.e., the value of time. Also, they linked the travel time to various consumer segments to reflect population heterogeneity. However, their modal shift is not triggered through elasticities. Instead, each mode's exogenous demand is relaxed, and the commodities (fuel, travel time, infrastructure, and consumer-perceived costs) needed to fulfill each modal demand are limited or linked to exogenously calculated (intangible) costs. Thus, their model still optimizes costs while considering such non-monetary constraints. Salvucci et al. [59] present a model limited to the transport sector that reflects modal shift through CPSE of various transport modes that can compete on various trip distance range classes. While utilizing the functionalities of the elastic TIMES extension [129], they inspired this work's endogenous modal shift implementation. All models listed so far do not reflect an intra-annual time resolution. Salvucci et al. [61] reflected a similar endogenous modal shift approach like in [59]. However, contrary to previous work, they [61] reflect the passenger and freight transport sector, consider 32 intra-annual timeslices, and apply a whole energy system model. Pedinotti-Castelle et al. [62] adopt that approach for another whole energy systems model.

Appendix C. Supplementary methodology

C.1. Consumer segmentation

Appendix Table C.1–1
Summary of consumer segment parameters. (adopted from [76]).

#	Abbreviation	PT connectivity at the place of living (G/L) [2]	Household income (HI/LI) [3]	Household ownership type (T/O)
1	GHIT	Good	High Income (>10,000 CHF)	Tenant
2	GHIO	Good	High Income (>10,000 CHF)	Owner
3	GLIT	Good	Low Income (≤ 10,000 CHF)	Tenant
4	GLIO	Good	Low Income (≤ 10,000 CHF)	Owner
5	LHIT	Limited	High Income (>10,000 CHF)	Tenant
6	LHIO	Limited	High Income (>10,000 CHF)	Owner
7	LLIT	Limited	Low Income (≤ 10,000 CHF)	Tenant
8	LLIO	Limited	Low Income (≤ 10,000 CHF)	Owner

Note. [1] The data for defining and calibrating the consumer segments were acquired via the Swiss Mobility and Transport Microcensus 2015 [3].
[2] The PT connectivity at the place of living is determined based on the PT quality classes calculated by the Swiss Federal Office for Spatial Development (ARE) [130]: 'good' reflects the ARE ratings A, B, and C; 'limited' reflects the ARE ratings D, and 'none'.
[3] The cut between 'high' and 'low' household income at 10,000 CHF reflects the rounded average gross household income in Switzerland in 2015–2017, which is 9951 CHF [131].

C.2. Aggregated passenger transport demands

To let all passenger transport modes (cars, trains, trams, urban buses, and coach buses) compete, an aggregated passenger transport demand in passenger kilometers (pkm) substitutes the previous mode-specific vehicle kilometer (vkm) demands. The pkm demand considers mode-specific Occupancy Rates (OR) [3]. While ORs distinguish for cars by consumer segments and trip types (Appendix Table C.2–1), such differentiation is impossible for PT modes because they are simultaneously used by different consumers and for different trip types (Appendix Table C.2–2).

Appendix Table C.2–1
Share of vkm and average OR in 2015 of cars by trip distance range and consumer segment. Data source: [3].

Consumer segment	Trip distance range (see Table 2)	Share of car-vkm traveled on the corresponding trip (2015) [3]	Average OR [3]
GHIT	S	14%	1.53
	M	51%	1.52
	L-Agglo	17%	1.88
	L-noAgglo	18%	1.72
GHIO	S	18%	1.48
	M	54%	1.59
	L-Agglo	9%	1.66
	L-noAgglo	19%	2.05
GLIT	S	19%	1.43
	M	52%	1.49
	L-Agglo	13%	1.66
	L-noAgglo	17%	1.75
GLIO	S	23%	1.41
	M	50%	1.58
	L-Agglo	10%	2.24
	L-noAgglo	18%	1.90

(continued on next page)

Appendix Table C.2–1 (*continued*)

Consumer segment	Trip distance range (see Table 2)	Share of car-vkm traveled on the corresponding trip (2015) [3]	Average OR [3]
LHIT	S	13%	1.46
	M	64%	1.45
	L-Agglo	7%	1.77
	L-noAgglo	16%	2.07
LHIO	S	16%	1.45
	M	57%	1.51
	L-Agglo	9%	1.69
	L-noAgglo	17%	2.16
LLIT	S	19%	1.40
	M	61%	1.47
	L-Agglo	5%	1.99
	L-noAgglo	16%	1.69
LLIO	S	21%	1.43
	M	57%	1.57
	L-Agglo	4%	1.75
	L-noAgglo	17%	1.94

Appendix Table C.2–2
Share of vkm and average OR in 2015 of PT modes by transport mod and trip distance range (adopted from [76]).

Mode	Trip distance range (see Table 2)	Share of modal km traveled (2015) [3]	Average OR[1] [3,132,133]
Train	S	5%	108
	M	55%	108
	L-Agglo	46%	108
	L-noAgglo	14%	108
Urban Bus	S	71%	10
	M	23%	10
	L-Agglo	2%	–
	L-noAgglo	4%	–
Coach Bus	S	2%	–
	M	19%	21
	L-Agglo	26%	21
	L-noAgglo	53%	21
Tram	S	90%	35
	M	10%	35
	L-Agglo	0%	–
	L-noAgglo	0%	–

Note. [1] PT modes are shared mobility means. Thus, their occupancy rates are assumed to be aggregated across consumer segments and trip types.
[2] – reflects that the mode does not cover this trip type in STEM (see Table 2). A threshold of 5% in the trip-share of modal km traveled is applied to reflect a certain mode for that trip type in STEM.

C.3. Technical concept for enabling modal shift in STEM

To enable modal shift, we orientate on the TIMES Micro documentation that linearized substitution elasticities to make them feasible for the TIMES linear programming framework [129]. First, a non-elastic baseline scenario (superscript *0*) with fixed demands DM for each mode *i* (component), consumer segment *j*, and trip type category *k* is simulated to provide the baseline marginal costs for each modal demand. In the next step, an elastic simulation receives such baseline marginal costs as input. In addition, this elastic simulation contains a tax or policy to trigger changes in the marginal costs compared to the baseline scenario. Such marginal cost changes can lead to modal shifts in the elastic scenario if such shifts provide a more cost-effective solution. Thus, the mode-specific demand in the elastic scenario

$$\boldsymbol{DM}_{i,j,k}(\boldsymbol{t}) = \boldsymbol{DM}^{\mathbf{0}}_{i,j,k}(\boldsymbol{t}) - \sum_{l=1}^{m} \boldsymbol{sm}_{i,j,k,l}(\boldsymbol{t}) + \sum_{l=1}^{n} \boldsymbol{sn}_{i,j,k,l}(\boldsymbol{t}) \tag{5}$$

depends in year *t* on the mode-specific baseline demand $DM^0_{i,j,k}$. Moreover, two step variables, *sm* and *sn*, reflect the modal shift towards the upper and lower direction, respectively [129]. The variables *m* and *n* are the number of linearization steps considered in optimizing the elastic approach. We selected ten linearization steps as a feasible tradeoff between sufficient steps to solve the elastic model with good detail and a feasible computational time. The marginal mode-specific cost variation between the baseline and elastic scenario and the various linked conditions outlined in Section 3 determine how much modal shift occurs. We refer to the literature for more mathematical and technical details on the generic elastic approach [59,129].

Further, the model's volume-preserving condition has been enabled. This means the total pkm demand across all transport modes *i* in the elastic variant must equal the non-elastic baseline variant (index *0*). Again, this constraint is valid for each consumer segment ***j*** and trip type ***k***:

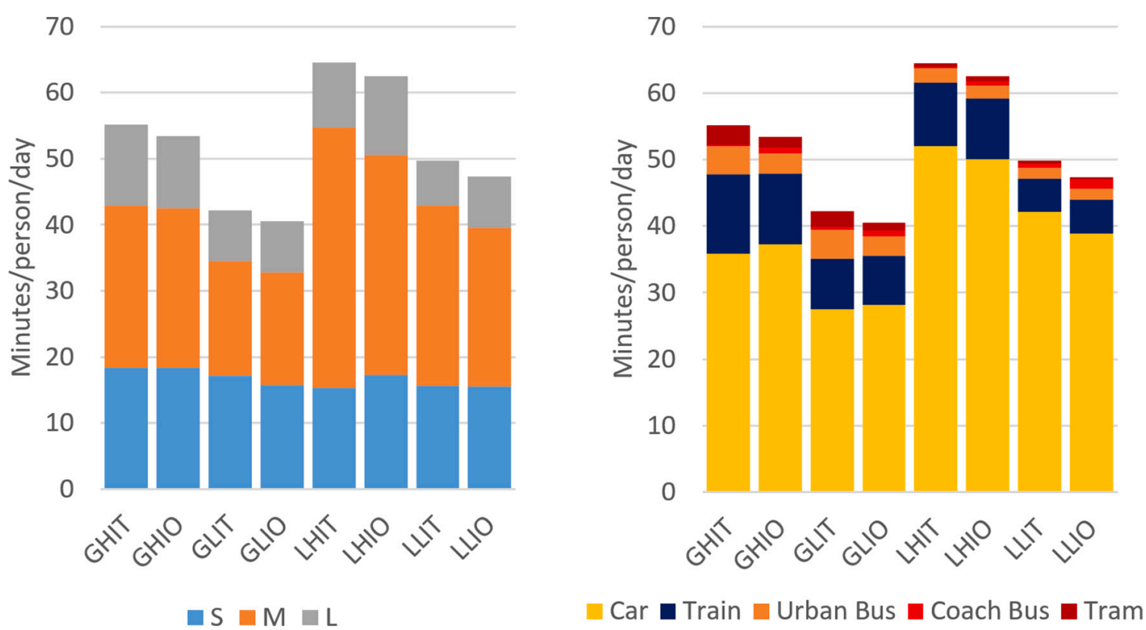
$$\sum_i \boldsymbol{DM^0}_{i,j,k}(\boldsymbol{t}) = \sum_i \boldsymbol{DM}_{i,j,k}(\boldsymbol{t}) \forall \boldsymbol{j}, \boldsymbol{k} \tag{6}$$

C.4. Travel Time Budgets, driving time, driving distance, and driving speed

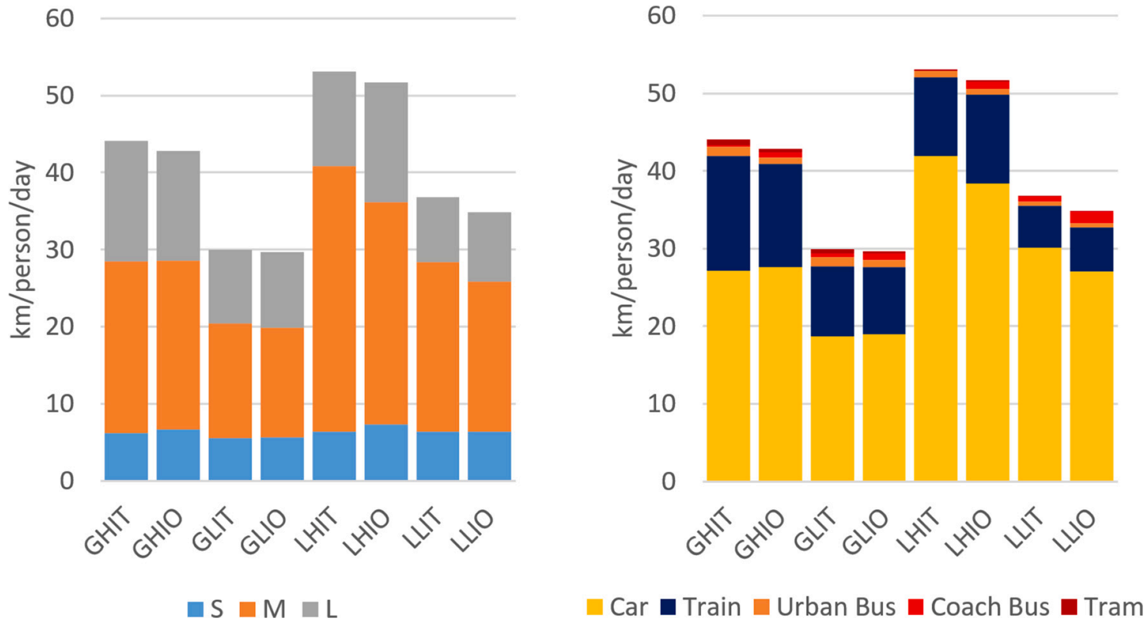
Our Swiss-specific data reflect the literature findings on varying TTBs across socio-demographic groups, particularly between high- vs. low-income segments [25].

Appendix Table C.4–1
Travel Time Budget by consumer segment. Data source: [3].

Consumer segment	$TTB^{daily}_{j,per\ person}$ [minutes/person/day]	TTB^{annual}_{j} [million hours/year]		
		2030	2040	2050
GHIT	61.66	320	337	346
GHIO	58.17	356	375	385
GLIT	52.15	700	737	757
GLIO	52.52	360	379	389
LHIT	62.15	123	130	133
LHIO	59.93	488	514	528
LLIT	51.26	292	308	316
LLIO	50.21	532	560	575
Total CH	54.67	3173	3340	3428



Appendix Fig. C.4–1. Average driving time [*minutes/person/day*] by consumer segment in 2015. The data are disaggregated by trip-distance category (left) and transport mode (right). Data source: [3].



Appendix Fig. C.4–2. Distance traveled per person per day by consumer segment in 2015. The data are disaggregated by trip-distance category (left) and transport mode (right). Data source: [3].

Appendix Table C.4–2
Average driving speed [*vkm/h*] in 2015 of passengers by transport mode, consumer segment, and trip distance category. Data source: [3].

Mode	Trip distance range (see Table 2)	GHIT	GHIO	GLIT	GLIO	LHIT	LHIO	LLIT	LLIO
Car	S	21.5	22.5	20.3	22.0	25.5	25.4	25.0	25.1
	M	49.4	50.9	47.5	46.8	51.1	49.8	47.1	47.0
	L	68.6	72.9	67.9	74.5	73.8	70.6	71.7	65.0
Train	S	38.3	41.1	39.5	38.3	41.6	44.2	35.9	39.5
	M	69.2	67.2	65.8	63.7	60.5	64.9	59.4	60.5
	L	93.4	93.7	89.6	86.0	83.8	98.3	88.8	88.7
Urban Bus	S	16.0	16.8	15.4	16.6	20.3	20.5	18.6	19.3
	M	24.6	30.6	33.7	35.7	32.2	34.3	29.4	33.5
	L	–	–	–	–	–	–	–	–
Coach Bus	S	–	–	–	–	–	–	–	–
	M	78.4	40.0	40.3	41.5	N/A	52.1	44.9	40.8
	L	51.9	41.8	52.3	53.7	N/A	83.0	63.3	66.8
Tram	S	14.1	15.4	14.8	15.5	13.5	15.5	16.2	14.6
	M	34.0	19.5	29.4	30.1	43.5	23.1	35.9	31.2
	L	–	–	–	–	–	–	–	–

Note. [1] – indicates that the mode does not cover this trip type in STEM (see Table 2).
[2] Consumer segment-specific observations for some modes were insufficient to provide conclusive data, resulting in a non-applicable (N/A) value. The average Swiss value has been applied in the model in such a case.

C.5. Multi-objective optimization: mathematical details

The model's simulation for the MOO is executed in three consecutive steps,[22] so-called "*States-Of-the-World[s]*" [96] (SOWs):

1. **Step 1 (SOW = 1):** STEM simulates the case with cost-optimal cumulative annual costs of all years *t* (with discount rate *d*), serving as baseline result:

$$\boldsymbol{Objective}^{SOW=1} = min\left(\sum_t (\mathbf{1}+\boldsymbol{d})^{\boldsymbol{reference\ year}-\boldsymbol{t}} * \boldsymbol{annual\ costs}(\boldsymbol{t})\right) \quad (7)$$

2. **Step 2 (SOW = 2):** STEM finds a solution that optimizes for the combination of minimum travel time TTB_j^{annual} (weight: w_{Time}) and minimum systemic *Costs* (weight: w_{Costs}):

[22] In our model setup with the activated ulterior concept of modal shift (Section 3.1), such shifts can take place in each SOW while meeting the respective objective function

$$\textbf{\textit{Objective}}^{SOW=2} = \omega_{Time} * f_{Time} + \omega_{Costs} * f_{Costs} = \omega_{Time} * \min_{Time}\left(\sum_t TTB_j^{annual}(t)\right) + \omega_{Costs}\min_{Costs}\left(\sum_t (1+d)^{reference\ year - t} * \textbf{\textit{annual costs}}(t)\right) \quad (8)$$

The maximum cost-deviation[23] in SOW = 2 must be within ϵ percentage from the cost-optimal solution of SOW = 1:

$$(1-\epsilon)*Objective_{Costs}^{SOW=1} \leq Objective_{Costs}^{SOW=2} \leq (1+\epsilon)*Objective_{Costs}^{SOW=1} \quad (9)$$

3. **Step 3 (SOW = 3):** To find meaningful energy prices and physical results, STEM simulates once again a cost-optimal solution

$$\textbf{\textit{Objective}}^{SOW=3} = \min\left(\sum_t (1+d)^{reference\ year - t} * \textbf{\textit{annual costs}}(t)\right) \quad (10)$$

while maintaining the travel time from SOW = 2:

$$\textbf{\textit{Objective}}_{TIME}^{SOW=3} = \textbf{\textit{Objective}}_{TIME}^{SOW=2} \quad (11)$$

To ensure fair competition between the various partial objectives in SOW = 2, the cumulative travel time and transport costs (without the weights) were calibrated to the same absolute value in a baseline scenario.

C.6. Comparing our methodology against shortcomings of previous studies

Appendix Table C.6–1 summarizes how this work addresses several methodological shortcomings emphasized in previous studies [59,111]. This work will go one step further and apply the advanced model in explorative scenarios (see Section 4) that provide valuable insights for policymakers regarding the RQs outlined in Section 1. Overall, this study provides a holistic approach, combining multiple aspects of travel time and modal shift while reflecting various consumer segments and trip types. Our approach outperforms previous studies by utilizing an advanced MOO to evaluate changes in travel time valuation with a national ESOM with cross-sectoral flexibility options. To our knowledge, this study is the first to integrate such a variety of factors into a single integrated model.

Appendix Table C.6–1
Summary of methodological shortcomings in previous studies and how they are addressed in this work.

Aspect	Methodological shortcomings in other studies (partially determined by [59,111])	How this work addresses the shortcomings
Factors influencing modal choice	Multiple factors influence modal choice, but ESOMs usually focus only on costs.	Our work reflects the interplay between costs and travel time[1].
Consumer heterogeneity	Consumers across socioeconomic groups evaluate factors impacting modal choice differently, but ESOMs mostly lack in reflecting such heterogeneity.	This work links the endogenous modal shift advancements to eight consumer segments, which vary in their modal shift responses[2].
Travel Time Budget (TTB)	Some models consider modal shifts but do not reflect the time consumers dedicate to travel (TTB) [25]. This could lead to unrealistic modal shifts.	Our model entails an overarching and consumer segment-specific TTB. This even allows for reflecting varying TTBs across socio-demographic groups.
Spatial dimension	While adopting various transport modes depends on their spatial accessibility, this is usually entirely aggregated in ESOMs.	Consumer segments disaggregate the current trip-type-specific modal demands, distinguishing households, e.g., with good and limited PT connectivity and low and high income. The maximum modal uptake potentials relate to the current demands, reflecting their spatial accessibility[3].
Temporal resolution	Most approaches lack an intra-annual temporal resolution but reflect mobility demands and energy supply annually. However, these temporal simplifications of demand and supply patterns could be a bottleneck for reflecting the timing of charging or the capacity of PT at peak hours.	Our model contains 288 intra-annual timeslices, reflecting seasonal, daily, and hourly variations.
Full energy system perspective	Some advanced approaches for considering travel time and modal shift are limited to the transport sector, i.e., lacking systemic links to the energy system.	Our model contains 288 intra-annual timeslices, reflecting seasonal, daily, and hourly variations.

Note. [1] Beyond that, our model is set up also to consider travel comfort, but this is outside the scope of this work for simplification purposes.
[2] This is because each consumer segment is, among others, characterized by its split of trip type demands, modal choice calibration, and income- and trip-specific CPSE.
[3] When for a certain consumer segment, e.g., households in areas with limited PT connectivity, the current mode-specific demand is low, then its uptake potential is limited, as the maximum uptake is relative to the current demand.

C.7. Consideration of other non-monetary factors in the multi-objective optimization

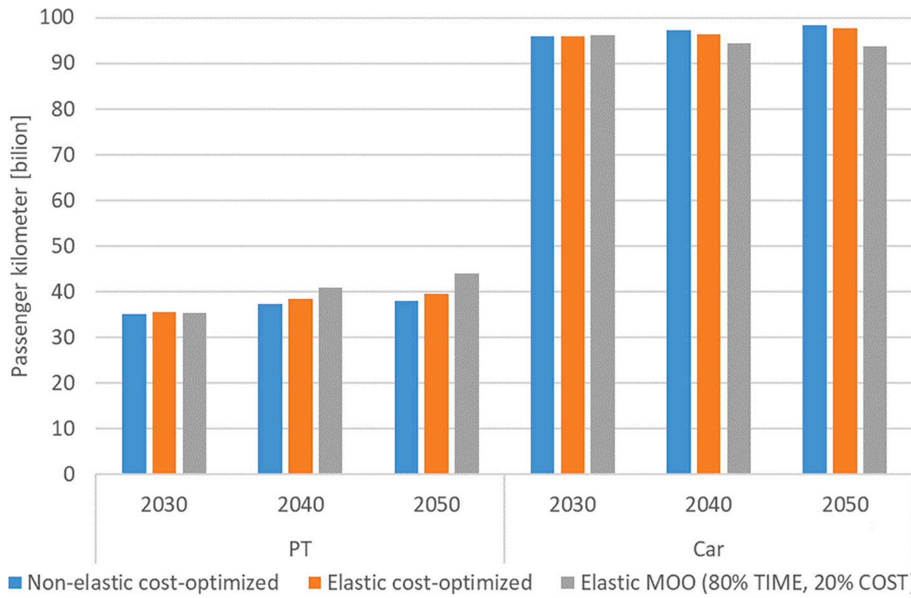
This work focusses on implementing the non-monetary factors of travel time duration and travel time valuation into the otherwise cost-optimal model framework since those are some of the most important modal choice decision factors in addition to costs. Nonetheless, we experimented also with implementing other non-monetary factors into the model, such as the travel comfort. However, we excluded such aspects in this paper to limit its complexity in terms of interpreting the results. A dedicated comparison of the results presented in this work against considering other non-monetary aspects may be presented in a separate study.

[23] The cost deviation can go in the upper or lower direction.

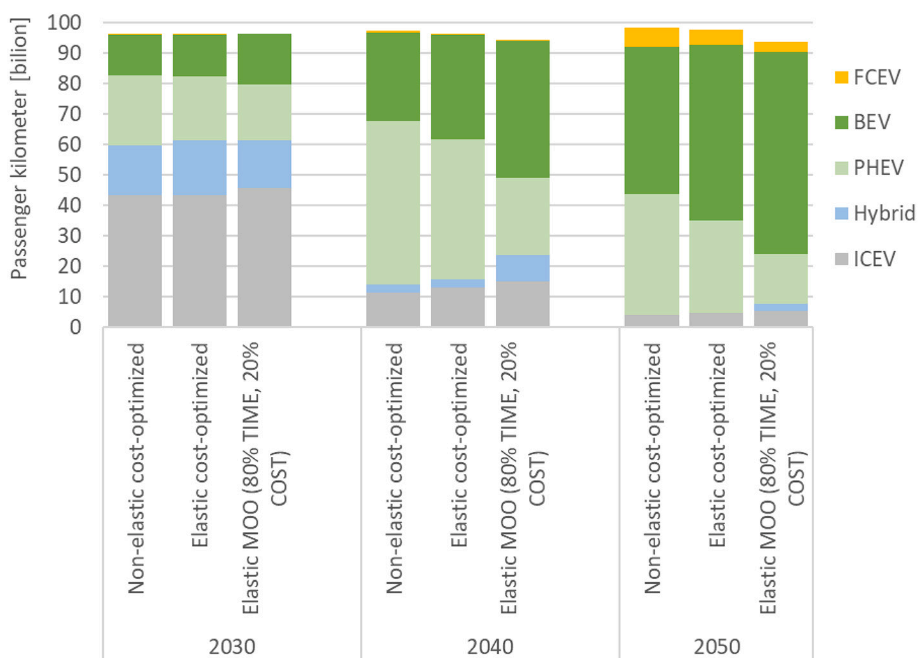
Appendix D. Supplementary results

D.1. Elastic MOO baseline scenario vs. elastic cost-optimized scenario vs. non-elastic cost-optimized scenario

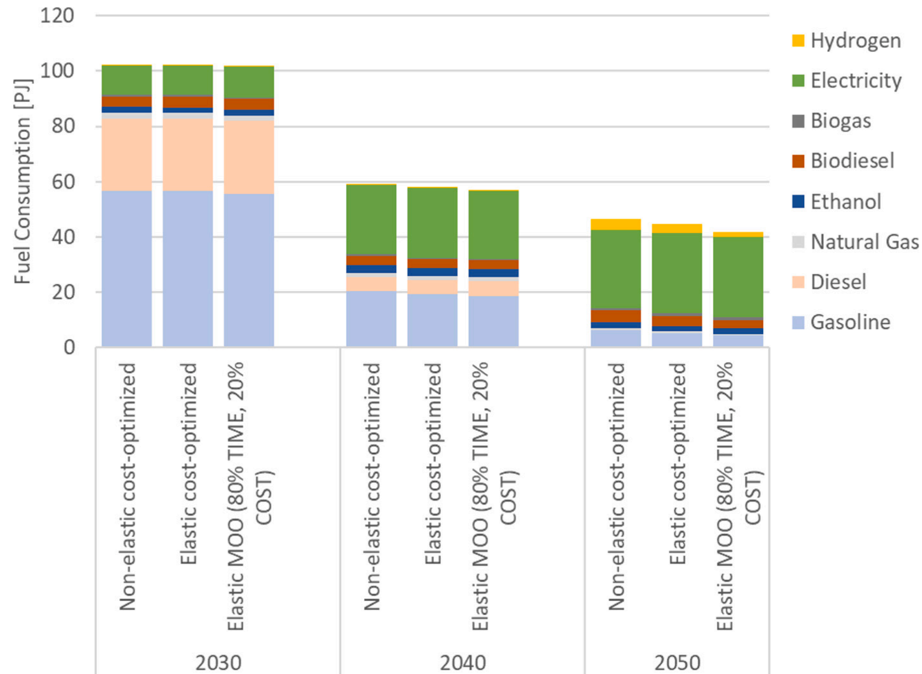
The delta results presented in this article's main body are compared against the elastic MOO baseline scenario (*EMOO-baseline*). This section presents the results of the *EMOO-baseline* compared to the non-elastic cost-optimizing variant and the elastic cost-optimizing variant of STEM. All scenarios achieve system-wide net-zero emissions by 2050.



Appendix Fig. D.1–1. Passenger kilometer demands of PT and cars in the non-elastic cost-optimized vs. elastic cost-optimized vs. elastic MOO (*EMOO-baseline*) STEM scenarios.

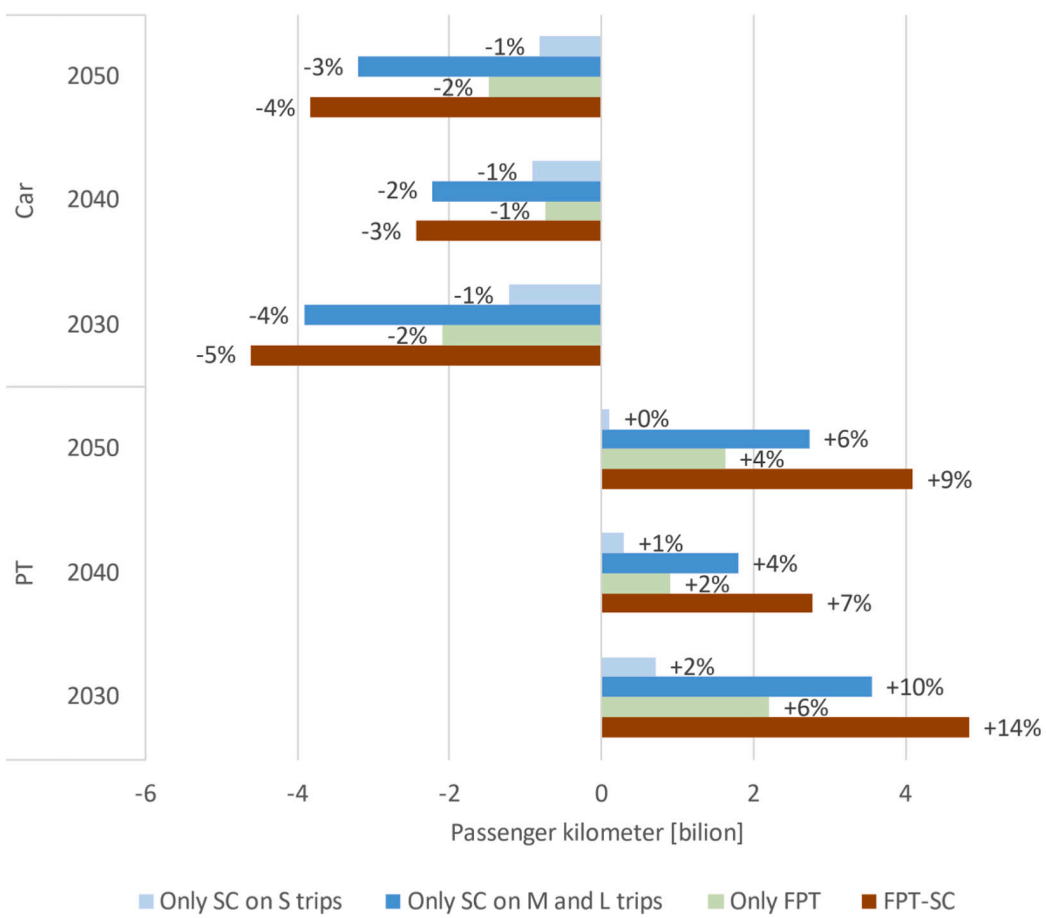


Appendix Fig. D.1–2. Car pkm by drivetrain type in the non-elastic cost-optimized vs. elastic cost-optimized vs. elastic MOO (*EMOO-baseline*) STEM scenarios.

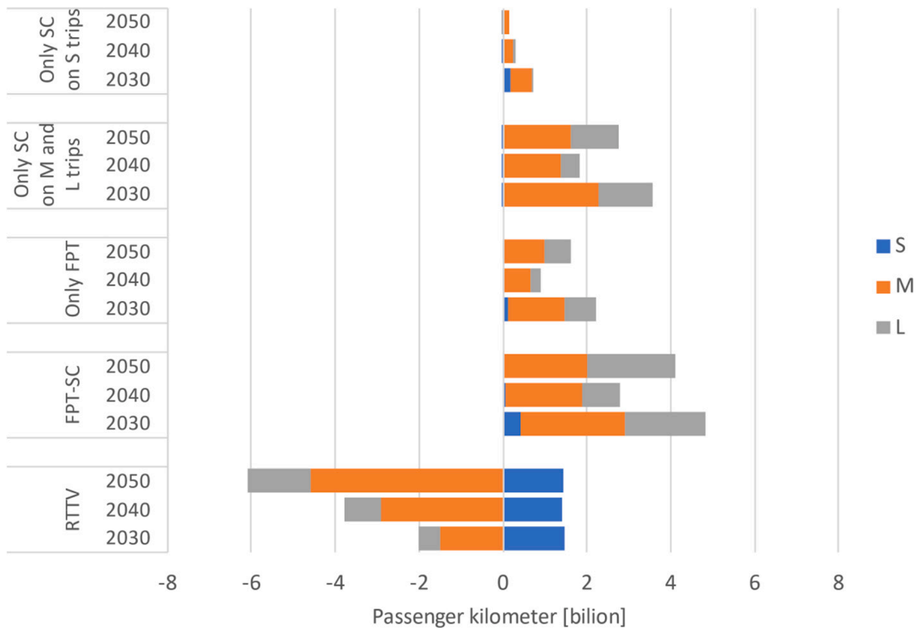


Appendix Fig. D.1–3. Car fuel consumption in the non-elastic cost-optimized vs. elastic cost-optimized vs. elastic MOO (*EMOO-baseline*) STEM scenarios.

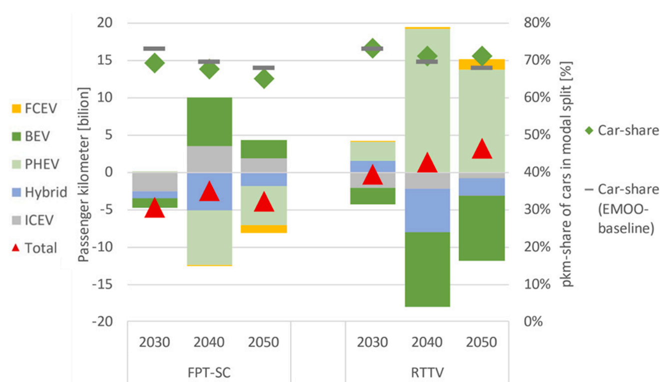
D.2. Supplementary results for core scenarios



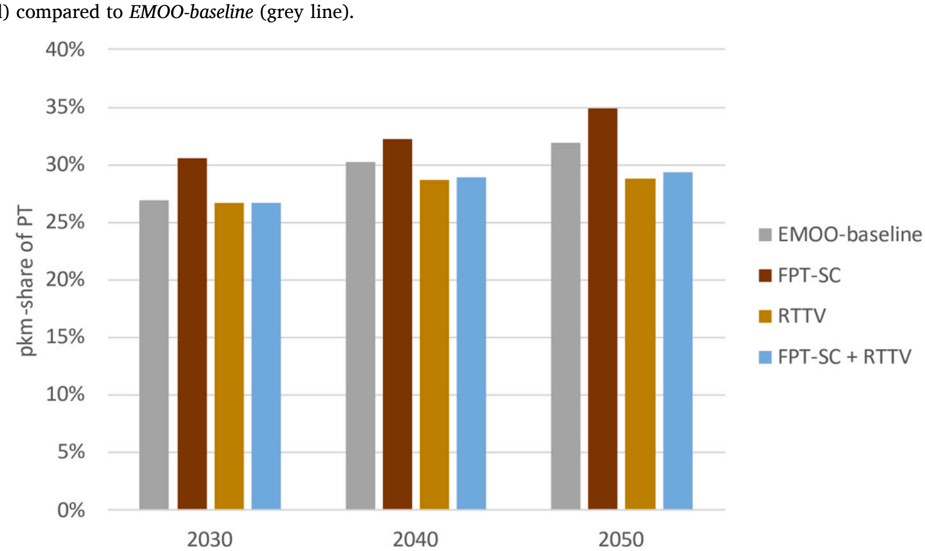
Appendix Fig. D.2–1. Delta in pkm driven with PT and cars compared to the *EMOO-baseline* scenario of the individual measures for travel speed variations. While the bars reflect the absolute delta, the percentage values reflect the relative delta for cars and PT.



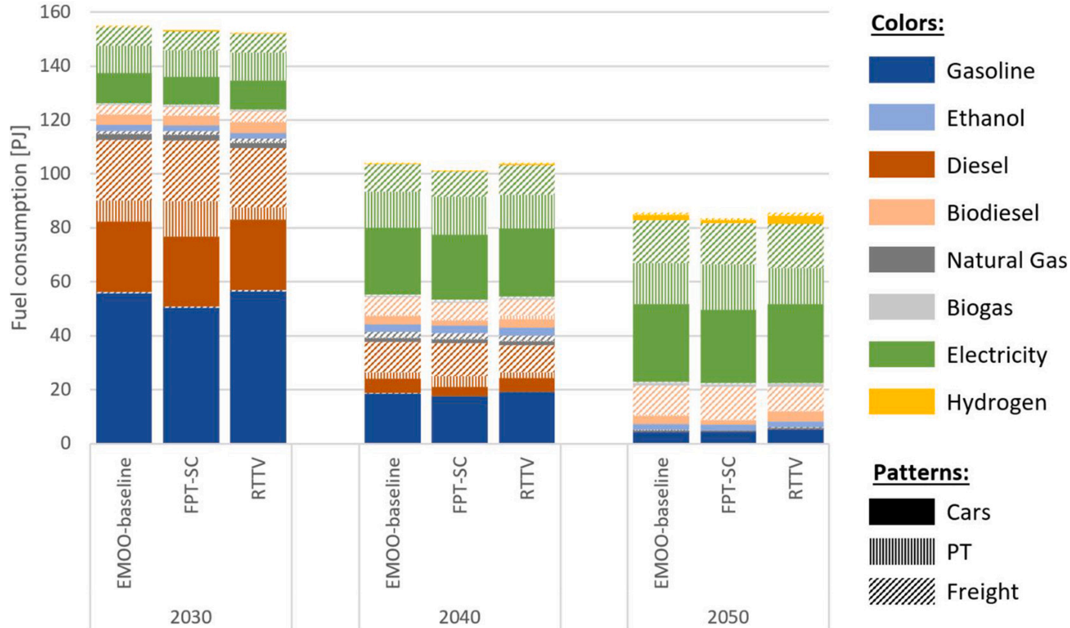
Appendix Fig. D.2–2. Delta in PT pkm distinguished by short-, medium-, and long-distance trips (S/M/L) compared to EMOO-baseline of the individual measures for travel speed variations and travel time valuation.



Appendix Fig. D.2–3. Delta of car-pkm by drivetrain for *FPT-SC* and *RTTV* relative to *EMOO-baseline*. The left axis presents the total vehicle shift delta of cars in bpkm for *FPT-SC* and *RTTV* relative to *EMOO-baseline* (red triangle) and the drivetrain-specific shifts (bars). The right axis presents the pkm-share of cars for *FPT-SC* and *RTTV* (green diamond) compared to *EMOO-baseline* (grey line).



Appendix Fig. D.2–4. Pkm-share of PT between 2030 and 2050 of the scenarios *EMOO-baseline*, *FPT-SC*, *RTTV*, and *FPT-SC* + *RTTV*.



Appendix Fig. D.2–5. Fuel-specific fuel consumption of land-based transportation in *EMOO-baseline*, *FPT-SC*, and *RTTV*. The patterns distinguish cars, PT, and freight transport.

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