Beyond Techno-Centered Decarbonization Roadmaps: Designing Demand-Side Pathways for Sustainable Mobility

Short title: Demand-Side Pathways for Sustainable Mobility

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Abstract

Decarbonization roadmaps for the automobile sector predominantly rely on supply-side improvements and electrification, yet their ability to deliver the required environmental reductions remains uncertain. This study introduces the Demand-Side Decomposition Analysis framework, which consistently integrates demand-side mitigation into a parametrized life cycle assessment of the automobile value chain and links environmental impacts with decent living standards to identify pathways compatible with both environmental limits and basic social needs. Applied to Swiss terrestrial mobility, this novel framework shows that current technology-centered roadmaps fail to simultaneously meet climate targets and copper supply constraints. Achieving these objectives requires coordinated activation of all demand-side levers, including reducing travel demand, shifting transport modes, and improving vehicle intensities. Substantial reductions in motorized travel distance and vehicle size, alongside high electrification rates, are necessary. These findings call for repositioning demand-side mitigation at the core of ecological transition pathways, with supply-side improvements acting as enabling supports.

Authors summary

Political plans to make cars more sustainable focus on cleaner vehicle production and the transition to electric vehicles. Using life cycle assessment to evaluate these technology-centered strategies, we show that these roadmaps are insufficient to meet climate targets and increase the risk of shortages of critical materials such as copper. These findings highlight the need for demand-side solutions (i.e, changing mobility consumption patterns). However, such measures alter the level or nature of mobility services provided, raising acceptability challenges. To address this issue, we developed a method for designing demand-side pathways that achieve environmental goals while ensuring that basic mobility needs are met. Rather than prescribing a single pathway, the method preserves flexibility in how demand reductions are combined across different mitigation levers. Our results reveal that all sustainable mobility pathways share several hard constraints: high rates of vehicle electrification, substantial reductions in motorized travel demand, and a shift toward smaller vehicles. Beyond these requirements, multiple combinations of demand-side measures can achieve the desired outcomes, including greater use of public transport and active mobility, eco-driving practices, vehicle sharing, and higher occupancy rates. Overall, our work highlights opportunities to adapt the pathways to different preferences and contexts while remaining within environmental boundaries.

1. Introduction

Car mobility accounts for about 10% of global energy-related greenhouse gas (GHG) emissions in 2023[1]. Across the full vehicle life cycle, from vehicle production through use and end-of-life, it generates substantial impacts on climate, air quality, land use, and resource consumption.

Achieving substantial reductions in these environmental impacts requires the deployment of comprehensive mitigation strategies. Mitigations are commonly grouped into two broad categories: supply-side and demand-side measures [2,3]. Supply-side mitigation encompasses changes in technologies, production processes, and energy and material supply chains that reduce the environmental intensity of providing goods and services. In contrast, demand-side mitigation targets change in the level, composition, and nature of demand for goods and services. This includes modifications in activity levels, lifestyles and consumption choices.

Automobile industry strategies and public roadmaps have to date overwhelmingly prioritized technology-centered pathways [4–14] with a broad portfolio of supply-side mitigation measures, including innovations in vehicle and powertrain component technologies [15–17], eco-design [18–20], material lightweighting [21–24], improvement of manufacturing processes [25–27], circular economy and recycling strategies [23,28,29] or digitalization of the industry [30,31]. On the demand side, strategies largely emphasize market transitions towards electrified powertrains. Early commitments to full electrification for 2035 have recently been softened towards greater technological flexibility, with increasing emphasis on hybrids, hydrogen or alternative fuels [32,33].

These measures support a sectoral strategy aiming to preserve existing automobile-centered business models and production volumes as structural changes to the role of the car, vehicle size and performance, and fleet growth. The overall automobile demand remains largely absent from transition strategies [34]. Although some roadmaps acknowledge additional demand-side measures (e.g., speed reduction or shift to public transportation), these are typically treated as complementary levers, potentially substitutable by sufficiently rapid technological progress, rather than as a core requirement for systemic transformation [1,8,12,35,36].

Despite the prominence of these transition roadmaps, the literature increasingly indicates that what is being implemented today remains insufficient, with observed outcomes still closer to a business-as-usual trajectory than to the Paris Agreement 1.5°C pathway [13,36–40]. Several structural factors cast doubt on the sufficiency of current long-term strategies.

First, literature shows that existing roadmaps remain inconsistent with Paris Agreement pathways. A central limitation lies in their scope: most focus primarily on tailpipe emissions, while giving limited attention to other life cycle stages of automobiles (such as car manufacturing or infrastructure construction), thereby increasing the risk of burden shifting and exceeding carbon thresholds when assessed on a full life cycle basis [38,41–44]. In addition, these roadmaps often insufficiently address other environmental pressures, particularly those related to mineral resource demand (e.g., copper and lithium) [45–49]. Roadmaps also increasingly rely on immature technological development, including hydrogen-based fuels, fuel cell vehicles, biofuels or carbon capture and storage [38,50,51]. The IEA 2050 net-zero scenario typically relies on 50% of non-mature technologies [1]. This makes the roadmaps dangerously uncertain [52].

Second, literature shows that the automobile industry is running behind these (insufficient) roadmaps, as some anticipated mitigations did not materialize at the expected scale or speed. Even if electric vehicle (EV) adoption is progressing, it remains slower than expected, with a 5-10% gap between the roadmap's ambition (30% of new vehicles electrified in 2025) and reported results (20-25% of new EVs) on the global vehicle market [41,43]. Supply-side improvements are also facing delays, due to significant gaps between automobile manufacturers objectives and suppliers commitment [43,53], but also due to delays in innovation pathways [38,43,54,55]. This tendency is likely to persist, as the automobile industry continues to prioritize incremental improvements to existing technologies, whereas alignment with climate roadmaps requires more fundamental structural changes in the sector [14,38,43,56].

Third, reported supply-side improvements have been systematically offset by countervailing market trends, notably the shift towards larger, heavier, and more powerful vehicles [14,44,57–60], together with increases in vehicle sales and total vehicle-kilometers travelled [7,36,38,61]. These increases are partly driven by rebound effects, whereby efficiency and cost reductions associated with technological improvements stimulate additional mobility demand, representing a structural limitation of supply-side mitigation strategies [62–65]. As a result, incremental efficiency improvements are observed, but absolute reductions in fleet-level emissions remain elusive [14].

These dynamics feed directly into an active debate in the academic literature regarding whether technological innovation can be sufficient on its own and about the appropriate level of priority that should be assigned to demand-side mitigation. A growing body of synthesis work argues that demand-side mitigation must be treated as a central lever of decarbonization strategies, rather than as a purely complementary option [40,45,50,66–74].

Placing demand-side mitigation at the center of ecological transition roadmaps introduces new methodological challenges that existing approaches remain insufficient to address comprehensively.

First, the identification of demand-side mitigation options remains incomplete. The Avoid–Shift–Improve (ASI) framework[75] has been widely applied in the transport sector to categorize demand-side strategies (e.g., reducing travel demand, shifting transport modes, and improving vehicle efficiency) [3,76–78]. While it provides a useful conceptual classification, its application remains largely qualitative, with limited methodological guidance for systematically operationalizing these measures within environmental assessment frameworks.

Second, dominant environmental assessment frameworks are primarily supply-oriented. Life cycle assessment (LCA), although widely used to capture impacts across all stages of vehicle life cycles, is designed and used to represent technological systems and traditionally excludes demand dynamics [67,79–81]. Conventional functional units, such as 1 vehicle-kilometer, scale impacts to a fixed service level and therefore exclude key demand-side dimensions (e.g., total travel demand). In addition, demand-side effects are often embedded within technology-centered performance indicators. For example, vehicle mass (technological parameter) actually reflects both demand-side choices (e.g., vehicle size) and supply-side characteristics (e.g., material efficiency) [58]. This aggregation obscures the specific role of demand-side changes and limits the ability to assess their mitigation potential independently from supply-side improvements [82]. Consequently, existing studies either assess exogenous scenarios of demand [77,78,83–85] or focus on a limited number of demand-side parameters, with limited insight into interactions and synergies between demand-side and supply-side strategies [45,46,70,86,87].

Third, unlike supply-side strategies, demand-side measures may involve changes or reductions in functionality or service levels [88]. As a result, they must navigate a delicate balance between safeguarding essential needs, ensuring social acceptability, while enabling substantial reductions in environmental impacts [89]. However, the co-evaluation of environmental performance and social fairness remains largely underexplored [71,90]. Conceptual frameworks such as consumption corridors have been proposed to frame sustainable consumption within a space bounded by environmental limits and human basic needs [91]. The development of decent living standards (DLS) [92] provides a basis for quantifying the lower bound of this space by defining socially acceptable minimum levels of consumption. Together, these approaches offer a valuable starting point for identifying safe and socially acceptable demand-side pathways. Further work is still needed to develop a framework capable of identifying potential trade-offs between acceptable environmental impacts and decent living standards.

In response to these gaps, this paper pursues five main objectives. First, a parametrized LCA framework capable of exhaustively assessing supply-side and demand-side mitigation strategies for terrestrial mobility is developed. Second, the framework is applied to quantify the environmental impacts of Swiss terrestrial mobility and to determine the magnitude of reductions required to meet international environmental targets. Third, realistic prospective supply-side improvement scenarios are built, and their mitigation potential is assessed with the LCA framework; by contrast, the extent to which demand-side mitigation is required to meet environmental targets is determined. Fourth, the concept of the consumer corridor is operationalized by the Demand-Side Decomposition Analysis (DSDA) framework, which links LCA to decent living standards and identifies demand-side pathways compatible with environmental limits, basic social needs, and technological constraints. Fifth, the framework is connected to a well-being indicator to identify socially preferable demand-side pathways and inform federal objectives and policy design.

2. Results

We derived from the parametrized LCA framework (see SI-1, Section 2.1) an open-source model that computes climate change impacts and copper demand (proposed as a proxy indicator for resource use) to evaluate terrestrial mobility in Switzerland as a function of exogenous supply-side scenarios and endogenous demand-side parameters. We calculated that current Swiss terrestrial mobility generates 17.4 $MtCO_2e$/yr (15% of consumption-based national emissions[93]) and consumes 3.3 ktCu/yr. To meet the 2°C Paris Agreement and comply with a fair share of global copper extraction capacities, the Swiss terrestrial mobility shall target 1.0 $MtCO_2e$/yr and 3.2 ktCu/yr by 2050. These values are obtained by downscaling global thresholds to Swiss terrestrial mobility (egalitarian paradigm (global to national) and grandfathering paradigm (national to mobility sector) were applied, see SI (section SI-2.2.4)). This paper seeks demand- and supply-side pathways to reach these thresholds.

To do so, we constructed three prospective supply-side scenarios (pessimistic, medium, optimistic), combining vehicle-level improvements from literature with supply-chain evolution based on SSP/IAM pathways (see Methods – Table 1). Demand-side mitigation was represented through up to eleven adjustable parameters describing mobility demand, vehicle sizes and driver behavior. These parameters are bounded between a business-as-usual (BaU) scenario, which considers that demand-side parameters remain unchanged from 2025 to 2050, and a lower bound defined by decent living standards and technical limits (DLS&TL). This lower bound corresponds to the highest reduction which still ensures minimum mobility needs for the projected 10.3 million inhabitants in 2050 (e.g., 4950 km travelled per person per year), while respecting technological feasibility (e.g., minimum vehicle size) and social acceptability (e.g., realistic speed reduction) (see Methods – Table 2).

Results are generated for different levels of aggregation of the demand-side parameters: (1) scenario-based comparisons to assess the necessity of demand-side measures; (2) aggregation into Avoid, Shift and Improve categories to evaluate their combined effects; and (3) full parameter disaggregation to characterize the range of feasible demand-side pathways compatible with environmental targets.

2.1 Current Roadmaps are insufficient to meet carbon mitigation targets and need to include demand-side mitigations

Fig 1 represents the reduction of 2025 GHG emissions and copper demand for the three supply-side scenarios and for three demand-side mitigation configurations (business-as-usual, full electrification, DLS&TL).

Results show that supply-side improvements alone are insufficient to align the automobile sector with long-term environmental targets. With stable demand-side parameters until 2050 (BaU scenario), even the most optimistic supply-side scenario leads to a climate change impact score seven times above the corresponding target (Fig 1 – left column).

Moreover, complementing supply-side improvements with full electrification of the fleet (while all other demand-side parameters remain unchanged at BaU value) reduces the climate change overshoot but does not eliminate it, with remaining 2.5-8 times above the threshold

(Fig 1 – middle column). This pathway, however, leads to an increased copper consumption which exceeds the fair share of copper supply for the Swiss mobility by a factor 3-5, illustrating the risk of burden shift to increased resource demand associated with large-scale electrification.

While industrial roadmaps that marginalize or postpone demand-side measures are unlikely to deliver effective pathways, supply-side improvements remain necessary for expanding the corridor for a socially fair transition within environmental limits. Indeed, GHG emissions remain above targets for the pessimistic supply-side scenario (+20%) for the DLS&TL demand-side scenario (Fig 1, right column), while medium and optimist supply-side scenarios meet and exceed the target by a margin of -30% and -50%, respectively.

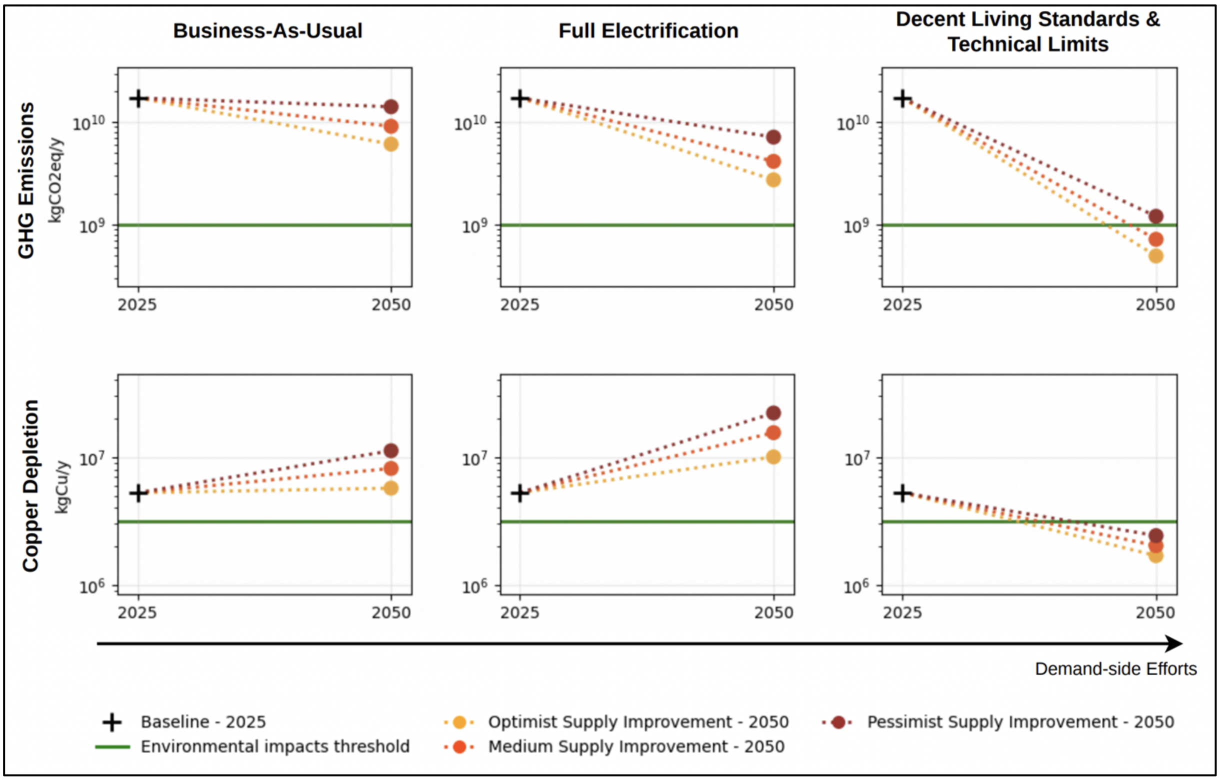

Fig 1. Prospective life-cycle environmental impacts of Swiss terrestrial mobility depending on supply-side and demand-side improvement scenarios. Each column corresponds to a demand-side configuration: left, business-as-usual (demand-side parameters remain unchanged from 2025 to 2050); middle, full electrification of the fleet (all other demand-side parameters held constant); right, decent living standards and technical limits scenario (DLS&TL), which represents the minimal requirements of demand-side parameters which satisfy mobility needs for the population, while remaining technologically feasible and socially acceptable. Climate change impacts (top row, kgCO2eq/yr) and copper use (bottom row, kgCu/yr) are simulated for 2025 (black cross) and 2050. Colored points represent projected 2050 impacts resulting from the combination of demand-side scenario with three supply-side improvement scenarios: pessimistic (yellow), medium (orange), and optimistic (brown). The green horizontal line indicates the environmental target for 2050.

2.2 Coupling Avoid-Shift-Improve Mitigations is necessary

Having established the necessity of demand-side mitigation, this section analyses how demand-side levers must be combined to meet a sustainable Swiss mobility. It aggregates demand-side parameters based on the three ASI mitigation categories as follows: Avoid (annual distance travelled per person); Shift (modal reallocation from private automobiles to alternative modes); Improve (vehicle GHG and copper intensity per person-kilometer). Impact scores are computed across the full range of Avoid, Shift and Improve mitigation levels to identify combinations compatible with environmental targets. Fig 2 maps this space of feasible mitigation pathways by calculating for each combination of Avoid and Shift the maximum vehicle intensities allowed to remain in the GHG emission thresholds (left map) and copper threshold (right map).

The results demonstrate that achieving environmental targets requires coordinated reductions across demand levels (avoid), modal distribution (shift) and vehicle intensity (improve). Because 'Improve' mitigation is bounded by technical and social limits, the lowest vehicle intensities achievable under maximum 'Improve' efforts across medium supply-side improvement are 17 gCO2e/p.km and 52 mgCu/p.km (blue lines in Fig 2). The results indicate that these improvements in vehicle intensity alone are insufficient to offset high travel demand. Per-capita travel demand must decrease to at least 7230 km/p/y (-34% relative to the BaU situation) to comply with environmental targets (Point 1 in Fig 2). Travel demand should be further reduced to 6300 km/p/y if modal shift remains at its BaU level (Point 2). In this configuration, the GHG emissions are more constraining than copper depletion. Conversely, strong reductions in travel demand and modal shifts towards alternative transportation cannot fully compensate for insufficient improvements in vehicle performance. Even when Avoid and Shift parameters are reduced to their decent living standards value, vehicle GHG and copper intensities must not exceed 33 gCO2/p.km and 98 mgCu/p.km, respectively, to meet national climate and copper targets for the mobility sector (Points 3a and 3b in Fig. 2). This corresponds to reductions of 90% and 70% relative to BaU vehicle intensities (see SI, Fig. SI-1.4).

Supply-side innovations increase the size of the space of solutions. Achievable vehicle intensities decrease under the optimistic supply-side scenario (orange dashed contour in Fig. 2 when considering maximum 'Improve' effort, including 100% electrification). As copper use becomes the most constraining threshold, an alternative scenario with limited electrification (91%) is considered to reduce material pressure, yielding minimum vehicle intensities of 12.5 gCO2e/p.km and 32.5 mgCu/p.km (orange line). As a result, the space of feasible solutions expands in comparison with medium SSI: the maximum allowable travel demand increases to 10150km/p/y (Points 4a and 4b in Fig. 2).

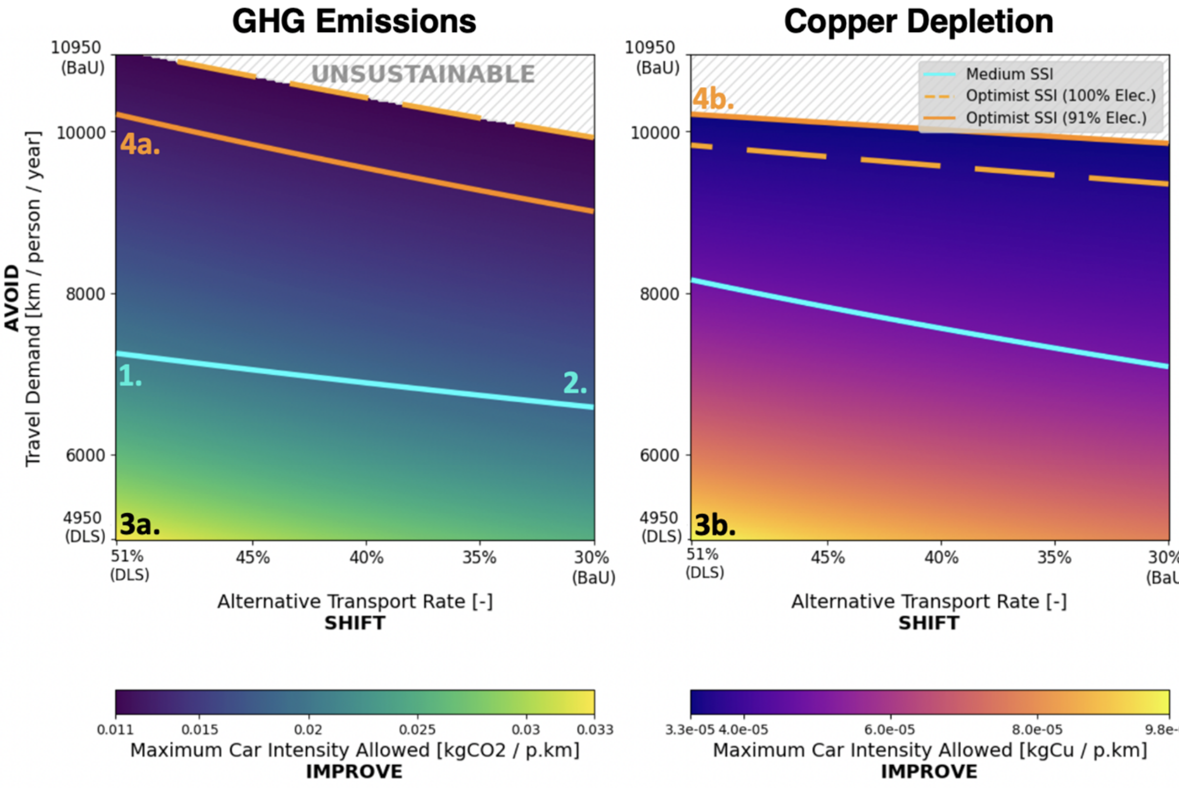

Fig 2. Representations of Avoid-Shift-Improve pathways to meet environmental targets. The maps display the 'Avoid' (distance travelled per person) and 'Shift' (share of public transportation and active mobility) space, varying between business-as-usual values and the decent living standards for Switzerland. 'Improve' mitigations are aggregated as vehicle

intensities (climate change and copper impacts per passenger-kilometer). For each Avoid–Shift combination, the color indicates the maximum climate change (left map) and copper (right map) intensities compatible with environmental targets. Because 'Improve' mitigation is bounded by technical and social limits, the curves indicate the lowest vehicle intensities achievable under maximum 'Improve' efforts across supply-side improvement (SSI) and electrification scenarios: medium SSI (blue), optimistic SSI with full electrification (orange dashed), and optimistic SSI with constrained electrification (91%) (orange solid). Grey hatched areas correspond to unsustainable Avoid–Shift combinations that would require vehicle intensities beyond these technological limits.

2.3 Demand-side Decomposition Analysis

In this section, eleven demand-side parameters are considered as independent levers: distance travelled (Avoid); share of public transport and share of active mobility (previously aggregated into the Shift category); electrification rate, vehicle occupancy, number of cars, vehicle size, engine size, battery autonomy, speeding, and driver behavior (previously aggregated into the Improve category).

We operationalized the consumption corridor concept[91] (space of solutions meeting both the environmental targets and decent living standards) through the development of the Demand-Side Decomposition Analysis (DSDA) method. This DSDA method maps all combinations of demand-side configurations compatible with the Swiss environmental targets for the terrestrial mobility, while leaving flexibility in how reductions are distributed across parameters.

Fig 3 illustrates the results of the DSDA considering the medium supply-side scenario improvements. The average reduction scenario (gold line) represents a first demand-side pathway that uniformly activates all demand-side parameters (normalized by the distance between the BaU and DLS&TL values). The average reduction reaches approximately 87% under this scenario, which corresponds to a pathway combining high electrification (91%), compact vehicle sizes (8.4m^3), and substantial reductions in per-capita travel demand (5700 km/p/y). Such a level of transformation highlights the magnitude of demand-side change required by 2050, particularly given that these measures remain largely absent from current industrial and policy roadmaps.

The uniform reduction scenario represents only one pathway among many. The color gradients defined for each parameter indicate the extent to which changes in one parameter require compensatory adjustments in others. It reveals differences in their systemic importance.

The results identify hard constraints in the system. Three parameters exhibit strict minimum requirements: per-capita travel distance (7230 km), fleet electrification rate (44 %), and vehicle size (13.3 m^3). They represent necessary conditions for achieving environmental targets (though insufficient in isolation). Any fleet configuration or individual mobility pattern exceeding these minimum requirements is automatically incompatible with environmental limits, leading to configurations unsustainable by themselves. Beyond these hard constraints, highly sensitive parameters, such as vehicle occupancy, engine size, and the share of active mobility, require careful control as insufficient reductions must be compensated by substantially greater efforts in other parameters. In contrast, less sensitive parameters, such as speeding and driver behavior, contribute comparatively less to overall system performance and offer more flexibility without significantly increasing the burden on other levers.

While the average reduction pathway provides a useful baseline for defining sustainable pathways, it does not account for well-being considerations, which may limit its social feasibility. An alternative well-being-oriented pathway (blue line in Fig 3) is constructed by weighting demand-side parameters according to their contribution to higher societal well-being, based on the quantitative approach of Creutzig et al. (2022) [76]. Despite associated uncertainties, this scenario provides a structured basis for identifying socially desirable pathways and informing policy and investment decisions.

Alternative pathways can be explored in the DSDA interactive tool (dsda-mobility.streamlit.app) by dynamically adjusting the consumption corridor under alternative assumptions. It allows real-time variation of the results for alternative environmental targets (due to changes in downscaling paradigms) and supply-side improvement scenarios (see SI1 - Section 1.4). It also enables users to personalize the demand-side bounds and to build their own pathway.

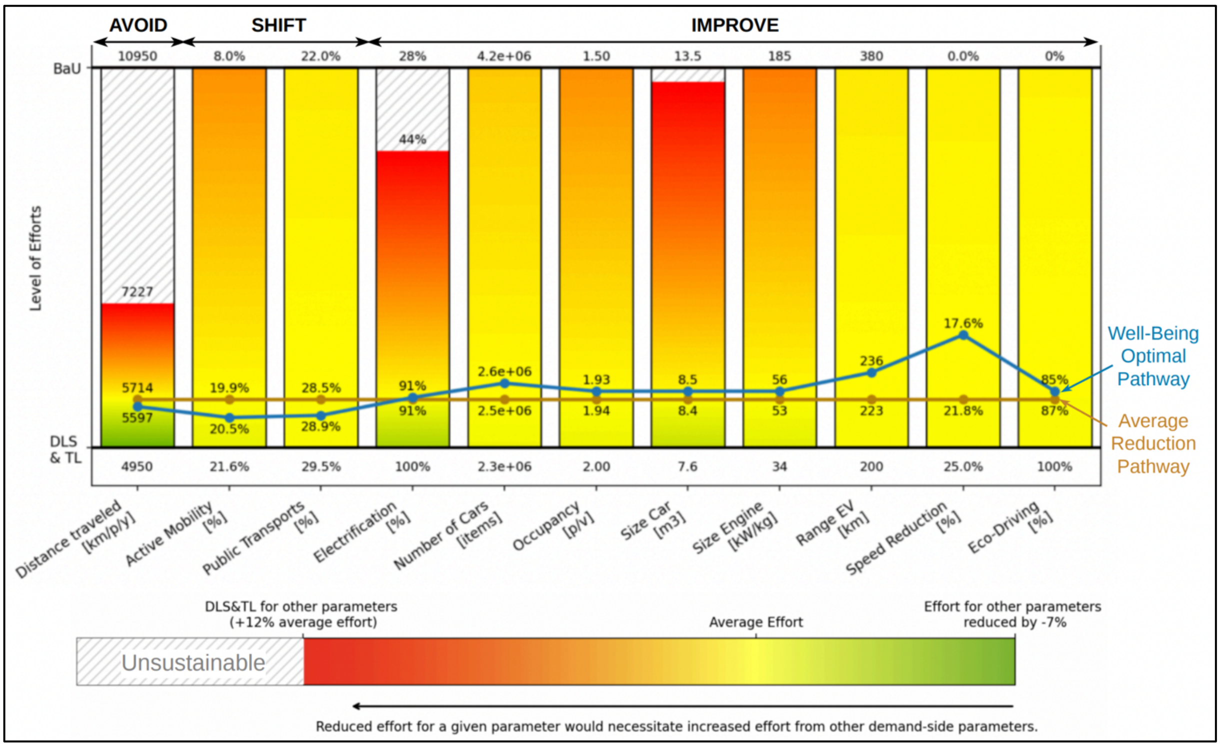

Fig 3. Demand-side Decomposition Analysis.

The figure disaggregates eleven demand-side parameters classified according to the Avoid–Shift–Improve framework. The top of each column corresponds to the BaU value. The lower bound corresponds to the maximum reduction compatible with either decent living standards or technical limits, defining the DLS&TL boundary.

The gold line indicates the average level of activation of all parameters required to reach environmental targets when reductions are distributed uniformly across the corridor. A color gradient from green to red represents the sensitivity of the system to variations in each parameter, defined as the extent to which changes in that parameter require compensatory activation of other demand-side parameters (expressed in % additional efforts from other parameters). Green indicates that lower activation of other parameters is sufficient, whereas red indicates that stronger compensatory reductions are required. Grey hatched areas represent parameter ranges for which no feasible combination with other parameters can meet environmental targets (even when all other parameters are set to their DLS&TL values). The boundary of this region defines the minimum reduction level required for the parameter. The blue line represents the well-being pathway, corresponding to a demand-side configuration prioritizing parameters associated with higher well-being co-benefits while remaining within environmental limits.

3. Discussion

3.1 Repositioning the roles of supply-side and demand-side mitigations

The results challenge the prevailing assumption that supply-side improvements alone can achieve sustainable mobility targets, supporting growing evidence in the literature [40,45,50,66–70] that technological innovation can no longer be considered a sufficient solution. These findings call for repositioning demand-side mitigation as a central component of decarbonization strategies, rather than as a secondary or complementary lever. While multiple demand-side pathways can meet environmental targets, all require the combined activation of several levers, including high electrification rates, vehicle downsizing, and substantial reductions in motorized mobility demand. We confirm that neglecting distance reduction measures (i.e., ‘Avoid’ mitigation) is insufficient to meet target [94,95].

Innovation remains a facilitator that expands the available space within the consumer corridor. By reducing impacts per unit of mobility, innovation increases the margin between the minimum socially acceptable consumption level and the maximum environmentally permissible one, thereby allowing greater flexibility for individual choice without violating collective constraints, and increasing the social fairness of demand-side mitigation pathways.

3.2 DSDA enables the generation of Interactive Demand-Side Pathways

The results presented in this study should be understood as living and evolving outputs rather than fixed prescriptions. The online tool is proposed to support scientists, policymakers, and citizens in exploring the implications of prioritizing alternative demand-side parameters and testing mitigation strategies under heterogeneous needs, preferences, and contextual constraints. This approach is a call for integrating societal and political participation in dealing with trade-offs among levers influencing both environmental performance and consumption patterns.

Moreover, given the social and political sensibility of modifying the mobility demand, the DSDA framework plays a central role in preserving individual and collective flexibility to adapt their mobility practices within a sustainable corridor. Additional comfort, performance, or functionality can be accommodated, provided that total consumption remains within the corridor. This framing shifts the focus from prescribing uniform reductions to enabling context-sensitive adaptations that reconcile environmental constraints with social well-being.

The framework is readily transferable to other national contexts. While the model structure and equations remain unchanged, adaptation requires adjusting (i) demand-side parameter bounds to reflect local mobility patterns and needs, (ii) background processes, and (iii) environmental thresholds. However, the main trends are not expected to differ substantially, as these elements show limited variability across contexts: (i) DLS exhibit relatively low variation between countries [96]; (ii) the globalization of automobile manufacturing, combined with the convergence of electricity systems towards low-carbon sources [1], is expected to result in limited differences in background impacts across regions; and (iii) environmental thresholds were defined using an egalitarian allocation approach and a life cycle perspective, ensuring comparable per-capita mobility-related impacts worldwide and accounting for GHG emissions and resource consumptions outside the Swiss territorial jurisdiction.

3.3 Implications for industrials, drivers and public policies

The framework developed in this study provides a structured baseline for the automobile sector to operationalize demand-side mitigation. By translating environmental limits and decent living standards into quantified mobility parameters, it establishes reference trajectories against which different actors can assess their contribution to sustainability transitions. The framework enables each stakeholder to evaluate its role based on the parameters it directly influences, while situating these contributions within the broader system-level constraints.

For industrial actors, the approach allows them to determine whether the fleet of vehicles they produce expands or constrains the ability of consumers and policymakers to remain within environmental and social boundaries, even though manufacturers control only a subset of demand-related parameters. This involves fixing the average values associated with vehicle design and fleet electrification and then assessing the remaining space left for other parameters that depend on user behavior, such as travel demand, occupancy, and modal choices.

For consumers, it becomes possible to assess whether mobility practices remain within the consumer corridor, and to what extent personal choices either preserve or reduce the room available for others to meet their own mobility needs within environmental limits. This perspective shifts the focus from isolated behavioral change to shared responsibility in managing a finite space of sustainable mobility consumption.

For public authorities, results provide guidance for defining federal objectives and policy instruments that jointly address supply-side and demand-side dimensions. The quantified pathways can inform infrastructure planning, regulatory standards, fiscal incentives, and mobility policies by clarifying the relative contributions required from technology, markets, and behavioral change. More broadly, the framework enables policymakers to assess whether proposed measures expand or restrict the system’s capacity to meet environmental limits while ensuring decent living standards, thereby supporting coherent and coordinated transition strategies across the automobile sector.

3.4 Limitations and future work

This study involves several simplifications across all stages of the assessment.

First, the modelling framework relies on several simplifying assumptions. The analysis focuses on a limited set of powertrain technologies, namely gasoline and battery electric vehicles, and therefore does not capture the full diversity of existing or emerging options such as diesel or hybrid powertrains. In addition, vehicle and energy consumption modelling are based on simplified relationships that do not fully represent all physical phenomena, including temperature effects, material ageing, and dynamic battery behavior. Some relationships are also linearized, including those linking vehicle volume and surface, or vehicle lifetime and cumulative travelled distance. Future work should therefore broaden both the range of technologies and the physical mechanisms represented. In this respect, the parametrized structure of the framework provides strong flexibility for future developments, as refined formulations or additional technologies can be incorporated by modifying or further decomposing specific parameters while preserving the overall model architecture.

Second, the results are subject to uncertainties related to data availability and background modelling. Prospective modelling of technological innovation is constrained by limited data availability and industrial confidentiality [97]. Moreover, the use of SSP/IAM-based scenarios introduces structural uncertainties, as highlighted in previous studies [81]. Finally, some aspects of the analysis, such as the quantification of well-being associated with demand-side mitigation, or the definition of the paradigms for calculating the downscaling factors [95], remain inherently uncertain due to their qualitative nature. Future work should further develop uncertainty quantification methods, improve data transparency, and strengthen the integration of social science approaches to better capture behavioral and well-being dimensions.

Finally, copper depletion is quantified using a bottom-up approach based on bill-of-materials derived from life cycle inventories, in the absence of a fully operationalized impact assessment method for resource depletion. This approach may introduce discrepancies, particularly due to incomplete accounting of background copper flows [98]. The inventories and results should therefore be updated once a harmonized and operational impact assessment method for material depletion is developed and adopted by the community.

4. Methods

4.1 LCA framework for environmental impact calculation

4.1.1 Extending the scope to the vehicle fleet

The LCA conducted in this study adopts an extended functional unit defined as *one year of Swiss terrestrial mobility,* excluding aviation and water-based transport. This system-level functional unit is intentionally chosen in place of conventional functional units such as vehicle-kilometers (v.km) or passenger-kilometers (p.km), which are well-suited for technology comparisons but insufficient to capture demand-side dynamics. In particular, traditional functional units do not allow to explicitly represent the contribution of key demand-side parameters such as total distance travelled, modal distribution, or the rate of electrification, as these choices are already embedded in the functional unit. Since all of them influence the environmental impacts of the mobility system, enlarging the functional unit to allow the analysis of their relative contribution to the system provides more valuable insight for system-scale decisions. Consistent with this system-level functional unit, the system boundaries include the complete life cycle of vehicles and energy carriers, including vehicle manufacturing, assembly and maintenance, the use phase with associated energy consumption, end-of-life treatment, and the required infrastructure construction and maintenance.

4.1.2 Parametrized inventories

This section presents the main assumptions and the key parameters (i.e, parameters characterizing a process or a technology) that support the parametrized modeling of the LCI of the system. The p-LCI framework is designed to explicitly distinguish between supply-side parameters, which characterize technologies and production processes that can be improved through industrial and technological progress, and demand-side parameters, which describe market structure, usage patterns, and consumer behavior that can be influenced through social, economic, and policy levers. The detailed structure and equations used to calculate the flows are provided in **Supplementary Information (section SI-2.1)**.

Mobility Service is described by the total distance travelled per person per year, the average vehicle occupancy rate, and the modal distribution between private cars, active mobility (walking and cycling), and public transportation (bus and rail). These parameters determine the total demand for vehicle-kilometers required to satisfy personal mobility needs.

Automobile Fleet Composition is represented through demand-side parameters describing the size of the vehicle fleet (number of vehicles in use) and the electrification rate of the fleet.

Automobile design is modelled through a modular representation that distinguishes three main subsystems: the vehicle body, the engine or powertrain, and the battery for electric vehicles. Each subsystem is characterized by a set of global parameters commonly used to describe vehicle performance and dynamics, including mass, rolling resistance coefficients, aerodynamic drag coefficients, or powertrain elements indicated efficiencies and frictionrelated parameters [82]. These intermediate parameters are further expressed as functions of two types of input parameters: (i) size-related parameters—respectively the vehicle volume, the rated power of the powertrain, and the battery capacity in kWh, and (ii) supply-side technological parameters reflecting material choices, design efficiency, and technological maturity. For example, the mass M of the vehicle body is modelled as $M = \rho \cdot V$, where ρ represents the effective material density of the vehicle structure and V its volume. The automobile design is used as an input to automobile manufacturing, assembly, and maintenance processes.

Manufacturing of the car body, engine and battery is proportional to their respective mass. The impacts per vehicle-kilometer are obtained by dividing by the lifetime of the vehicle.

Automobile Use Phase is modelled by estimating vehicle energy consumption based on the PETRAUL framework [82]. In addition to vehicle design characteristics, this approach considers parameters describing driving aggressiveness (speed or braking intensities). These parameters allow behavioral aspects of vehicle use to be assessed explicitly. The details of the PETRAUL model are available in SI (section SI-2.1).

Infrastructure includes road construction and maintenance, which is deemed proportional to the mass of the vehicle as recommended by Simons et al. (2016) [99], and the charging infrastructure for electric vehicles, which is deemed equivalent, regardless of the size of the vehicle, as modeled by Sacchi et al. (2022) [100].

Cradle-to-Gate. Cradle-to-gate elementary processes correspond to the processes supplying the main materials, infrastructure and energy sources required by the automobile. It also corresponds to the complete modeling of alternative means of transportation (train, bus, plane). They are based on models from the literature [99,100] and *ecoinvent* database v3.11 [101]. All these assumptions and models are available in SD-1.

4.1.3 Impact Categories Selected

To ensure clarity of representation and maintain a focus on demand-side mitigation, the analysis is limited to GHG emissions and copper depletion. GHG emissions are included as a core indicator because it is central to Swiss climate policy objectives for 2050 and represent a dominant environmental concern associated with the transport sector [102,103]. Copper depletion is selected as a complementary indicator to capture resource-related constraints, as copper is a critical material for automobile technologies—particularly for electric powertrains, batteries, and electrical infrastructure—and is expected to become a limiting factor under large-scale electrification pathways [47].

Climate change (short term) from Impact World + v2.1 life cycle impact assessment method [104] is considered for computing the impacts across the complete life cycle of vehicles and mobility services. Copper flows are quantified for all cradle-to-gate processes by directly analyzing copper inputs in the underlying *ecoinvent* inventories. Manufacturing losses are added where relevant to reflect actual material extraction requirements. Further details and assumptions are provided in SI-1, section 2.2.1 and SD-1.

4.2 Assessment of Supply and Demand-side Mitigation Scenarios

4.2.1 Supply-Side Improvements Scenarios

Supply-side mitigation is represented through prospective improvements in both foreground and cradle-to-gate systems. In addition to the current performance scenario, three prospective supply-side improvement scenarios are defined to reflect different levels of technological progress: pessimistic, medium, and optimistic. Table 1 summarizes the main assumptions of each supply-side scenario.

Foreground improvements correspond to innovations in the vehicle itself, targeting reductions in energy consumption and in environmental impacts associated with vehicle production. A review of prospective automobile innovations is performed [17,35,86,105–116]. It provides estimates for the evolution of the main technological parameters of the model. For each parameter, a range of values is established, and these values are consistently combined to construct the three innovation scenarios (see SI, section SI-2.2.1).

Cradle-to-gate improvements encompass changes in the upstream systems that supply energy, materials, and transport services, including electricity generation, material production, and the performance of alternative transport modes. Cradle-to-gate system evolution is modelled using the PREMISE database, which translates integrated assessment model (IAM) scenarios into life cycle inventory data. The optimistic scenario is based on SSP2–PkBudg1150–REMIND, reflecting a sustainability-oriented and techno-optimistic pathway characterized by rapid decarbonization, high energy efficiency improvements, and strong deployment of low-carbon technologies (1.7-2.0 °C carbon budget). The medium scenario relies on SSP2–NPi–Remind, representing a middle-of-the-road development trajectory with moderate climate ambition and incremental technological progress (2.5-2.7°C carbon budget). The pessimistic scenario adopts SSP5–NPi–Remind, which corresponds to a fragmented world with limited international cooperation, slow technological diffusion, and high-carbon energy systems (<3.5°C carbon budget).

Table 1: Representative parameter values and assumptions for the four supply-side improvement scenarios.

	Current Perf.	Pessimist SSI	Medium SSI	Optimist SSI
Foreground				
Vehicle Density [kg/m3]	102	100	81	66
Vehicle Lifetime [y]	17	17	18.5	21
GV Engine Density [kg/kW] (*)	2.3	2.3	2.4	2.9
GV Engine indicated efficiency [-]	44.2%	45.3%	46.4%	47.4%
EV Engine Density [kg/kW] [-]	1.5	1.5	1.4	1.2
EV Engine indicated efficiency [-]	97.7%	97.7%	99.1%	99.6%
EV Battery Density [kg/kWh]	4.0	3.6	2.8	1.6

Background				
SSP/RCP Scenario	None	SSP5-NPi	SSP2–NPi	SSP2–PkBudg1150
Electricity Intensity [gCO2e/kWh]	92	119 (**)	51	21

(*) The weight of the engine increases due to the development and integration of turbocharging engine in the fleet (more efficient).

(**) The phase-out of nuclear power leads, in the pessimistic scenario, to an increase in the carbon intensity of electricity.

4.2.2 Demand-side Parameters and Scenarios

The two bound scenarios for demand-side parameters are the current business-as-usual situation and decent living standards. Table 2 encompasses the main parameters for the four scenarios.

Current fleet. Personal mobility and fleet are evaluated using Swiss federal statistics and open-access databases (see SI). The number of cars, vehicle sizing and electrification rate are calibrated to represent the existing vehicle fleet, including legacy vehicles from previous years.

Business-as-Usual. The BaU scenario assumes that recent vehicle sales trends (2024–2025) persist over time, resulting in a projected 2050 fleet with similar composition, vehicle size, and electrification rate. Mobility demand and modal share are held constant at 2025 levels.

Full Electrification. This scenario consists of a business-as-usual situation but with full electrification of the fleet. It aims to model the current roadmaps.

Decent Living Standards & Technical Feasibility (DLS&TL). The decent living standards (DLS) for personal mobility represent the minimum level of service required to satisfy basic needs of the projected 10.3 million inhabitants of Switzerland in 2050 [117]. It guarantees a minimum level of mobility to all citizens in order to ensure access to essential activities such as work, education, healthcare, and social participation. Specific annual travel distances and distributions of transport modes are adapted from the Swiss-specific analysis by Millward-Hopkins et al. (2025) [118]. Vehicle ownership is assumed at one car per household in intermediate and rural areas, plus one for households with children [119], and one shared car per seven inhabitants in urban areas [120].

Other demand-side parameters are not explicitly addressed in the DLS literature but remain constrained by technical and social feasibility limits. We bounded the average vehicle occupancy rate to two persons per vehicle, reflecting empirical evidence that higher average occupancy levels are unlikely to be sustained in daily mobility contexts [46,84]. The smallest five-seat vehicle currently available on the Swiss market has a volume of 8.5 m^3, while a widespread shift towards two-seat vehicles (minimum volume of 6.7 m^3) is limited by resulting increases in required occupancy rates. Minimum engine power is determined to be 34W per kilogram of the car body. An average autonomy range of 200 km to ensure usability and acceptability of electric vehicles is considered as a feasibility threshold for EV battery size [121,122]. In addition, feasible eco-driving practices and speed reductions are derived from the literature [87,123]. The corresponding assumptions and parameter values are detailed in SI (section SI-2.2.2).

Table 2: Key parameter values for the four demand-side mitigation scenarios.

ASI Category	Demand-side Parameters	Current Fleet	Business-as-usual	Full Electrification	DLS&TL
-	Population Size [inh.]	9.1M	10.3M	10.3M	10.3M
Avoid	Per-capita mobility demand [km/p/y]	10950	10950	10950	4950
Shift	Active Mobility [-]	8.0%	8.0%	8.0%	21.6%
	Public Transports [-]	22%	22%	22%	29.5%
Improve	Electrification Rate [-]	5%	28%	100%	100%
	Number of Cars [units]	4.8M	4.23M	4.23M	2.3M
	Occupancy Rate [p/v]	1.5	1.5	1.5	2
	Size Car Body [m3]	12.8	13.5	13.5	7.6
	Engine Power [W/kg of car body]	96.8	185	185	34
	EV Autonomy [km]	380	380	380	200
	Speed Reduction Rate [-]	0%	0%	0%	25%
	Ecodriver Rate [-]	0%	0%	0%	100%

4.2.3 Environmental Targets

Thresholds are established for the two indicators considered in this study: climate change and copper depletion. Global targets are derived from the literature: greenhouse gas emissions compatible with a 2 °C pathway are limited to 6.8×10^{12} $kgCO_2eq.y^{-1}$ globally[124], and the global copper extraction threshold for 2050 is set at 2.1×10^{10} $kgCu.y^{-1}$ [48]. These global thresholds are downscaled to the Swiss level using an egalitarian allocation approach based on Switzerland's share of the global population. The resulting national budgets are then allocated to terrestrial mobility using a grandfathering approach, whereby the share assigned to the sector is proportional to its territorial CO_2 emissions relative to Switzerland's total life-cycle CO_2 emissions. Under these assumptions, the greenhouse gas emission and copper consumption thresholds for the Swiss terrestrial mobility system are estimated at 1.0×10^9 $kgCO_2eq.y^{-1}$ and 3.2×10^6 $kgCu.y^{-1}$ respectively. Detailed calculations and assumptions underlying the derivation of global targets and the downscaling approach are provided in SI (section SI-2.2.4). Alternative targets, exploring different global thresholds and allocation assumptions, are also included for uncertainty analysis.

4.3 Demand-side Decomposition Analysis

The DSDA method provides a representation of all demand-side configurations compatible with Swiss terrestrial mobility environmental targets. Demand-side parameters are allowed to vary between their BaU and DLS&TL values.

4.3.1 Average Reduction per Parameter

The average reduction is computed by uniformly activating all demand-side parameters, normalized by their distance between BaU and DLS&TL values. Beginning from the DLS&TL configuration (maximum effort), parameter values are progressively and uniformly relaxed while ensuring compliance with environmental thresholds. The average reduction corresponds to the point at which environmental impacts exactly meet the most constraining threshold.

4.3.2 Sensitivity along the corridor

The color map of each parameter “corridor” represents its sensitivity relative to the average reduction. The reference level (yellow) corresponds to the average reduction across all parameters.

First, the parameter is fixed at its BaU value. If this deviation can be compensated by adjusting the other parameters while still meeting DLS&TL constraints, the additional uniform effort required from the remaining parameters is computed. This defines the upper sensitivity bound (red). If such compensation is not feasible (i.e., it would require exceeding DLS&TL levels), the parameter exhibits a strict minimum requirement. This minimum is determined by fixing all other parameters at their DLS&TL values and identifying the lowest admissible effort for the parameter. The darkest red indicates this minimum level, while values beyond it are shown as unsustainable (grey hatched area). In both cases, a linear gradient is assumed between the average reduction (yellow) and this upper bound (red).

Second, the parameter is fixed at its DLS&TL value, and the corresponding uniform reduction in effort allowed for the other parameters is computed. This defines the lower sensitivity bound (green), with a linear gradient between the average reduction (yellow) and this value.

4.3.3 Well Being Optimal Pathways

An alternative pathway is defined to maximize well-being outcomes. For each demand-side parameter, a well-being score is assigned based on the methodology of Creutzig et al. (2022), which quantifies synergies and trade-offs between demand-side mitigation options and the Sustainable Development Goals (SDGs) on a scale from −3 to +3. These scores are aggregated across all SDGs to obtain a total well-being score for each mitigation option. The well-being pathway is computed as for the average reduction, but parameters are relaxed from the DLS&TL configuration in inverse proportion to their well-being scores, thereby prioritizing measures with higher well-being benefits.

Author contributions

Gabriel Magnaval: Conceptualization, Methodology, Software, Investigation, Data Curation, Validation, Visualization, Writing – original draft. **Soline Corre:** Methodology, Investigation, Visualization, Writing – review & editing. **Maël Mouhoub:** Software, Data Curation, Writing – review & editing. **Manuele Margni:** Supervision, Conceptualization, Methodology, Writing – review & editing, Funding Acquisition. **Anne-Marie Boulay:** Supervision, Conceptualization, Methodology, Writing – review & editing, Funding Acquisition.

Conflicts of interest

The authors declare no competing interests.

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Data availability

Further information on this study is presented in Supplementary Information and in Supplementary Data 1, 2 and 3 (see Supplementary Information section). All additional data required to generate the work and the code used in this paper are available via Zenodo: https://zenodo.org/records/19497008 [125]. In addition, the interactive web-based tool developed using Streamlit, which allows users to explore the DSDA framework, is available at: https://dsda-mobility.streamlit.app/.

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

During the preparation of this work, the authors used ChatGPT (based on GPT-4) to improve readability and language in the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Supplementary Material

Supplementary Information.

Supplementary Results 1.1-1.4 and Methods 2.1-2.3.

Supplementary Data 1.

Comprehensive datasets used to operationalize the model, including supply-side improvement scenarios, demand-side parameter bounds, environmental threshold calculations, background processes modeling and assumptions, and any other useful parameters.

Supplementary Data 2.

Analysis of the FEDRO database of the current Swiss vehicle fleet, detailing the processing of raw data to derive average parameter values used in the model.

Supplementary Data 3.

Calculation of well-being scores used to construct the well-being-optimized demand-side pathway within the DSDA framework.