

Article

Sustainable Passenger Transport in Spain: A System Dynamics Assessment of Endogenous Responses and Non-Additive Policy Interactions to 2050

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Abstract

Sustainable mobility requires reducing energy use and emissions while considering accessibility and pressure on low-carbon resources. This study assesses passenger transport in Spain to 2050 with a system-dynamics model linking demand, modal and powertrain choice, fleet turnover, charging and fuel origins. Choice equations are estimated on pre-COVID data, with specification selection using 2001–2014 and evaluation with 2015–2019, followed by estimation with 2001–2019. Post-2019 observations provide diagnostic comparisons. Stylized Avoid–Shift–Improve packages share a common policy-reference approximation. In 2050, REF reaches 797.1 Gpkm, 754.9 PJ and 22.46 Mt of attributed operational CO₂. Avoid, Shift, medium Improve and high Improve reduce this emissions indicator by 9.87%, 0.39%, 2.07% and 3.94%, respectively. Both integrated packages are subadditive at the endpoint, while medium ASI is superadditive cumulatively. Parameter, policy-intensity, regulatory, resource-cap and fleet-allocation sensitivities qualify these comparisons. Uncapped high ASI with Fossil-Free fuels approaches zero attributed operational CO₂, but high resource caps raise its 2050 value to 29.49 Mt. Physical combustion remains positive. These conditional experiments identify energy, climate and resource trade-offs; they do not establish life-cycle neutrality, equitable accessibility or probabilistic forecasts.

Keywords: sustainable mobility; sustainable development; passenger transport; system dynamics; Avoid–Shift–Improve; policy interactions; resource-stress diagnostics; attributed operational emissions



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1. Introduction

Decarbonizing passenger transport is a system-transition problem rather than a single-technology substitution. Transport activity, accessibility, modal structure, vehicle ownership, powertrain adoption, infrastructure, fuel supply, and the carbon intensity of electricity evolve together and on different timescales. The IPCC therefore frames transport mitigation as a combination of demand reduction, modal shift, energy efficiency, electrification, and low-carbon fuels, while emphasizing that rapid reductions require coordinated action across these levers [1]. This coordination remains difficult in practice: in the European Union, growing mobility demand has partly offset improvements in efficiency and alternative-energy uptake, and transport emissions in 2023 remained above their 1990 level [2].

This challenge is particularly relevant for Spain. Transport accounted for 32.5% of the country's greenhouse-gas emissions in 2023, making it the largest emitting sector [3]. Spain's updated National Energy and Climate Plan (PNIEC 2023–2030) combines electrification, renewable deployment, efficiency, modal change, and measures for rail, aviation, and navigation, within an economy-wide target of reducing greenhouse-gas emissions by 32% from 1990 levels by 2030 [4]. At the European level, the Sustainable and Smart Mobility Strategy similarly calls for a 90% reduction in transport emissions by 2050 and relies on both zero-emission vehicles and a more sustainable multimodal system [5]. These objectives create a need for national models that can evaluate not only whether a prescribed end-state is technically feasible, but also how demand, user choice, policy, and slowly changing capital stocks may produce—or obstruct—the transition path.

Sustainable mobility links climate mitigation to access and resource use, rather than treating traffic growth as a welfare objective [6]. Regulatory, financial, organizational and social barriers also shape implementation alongside technology [7]. Accordingly, this study evaluates emissions, energy and low-carbon resource requirements together. Accessibility and distributional outcomes remain outside the quantified boundary; reduced activity is not assumed to deliver an equitable transition by itself.

The Avoid–Shift–Improve (ASI) framework provides a useful organizing principle for this problem: avoid unnecessary motorized travel, shift remaining activity toward lower-impact modes, and improve vehicles and energy carriers [1,6,8–10]. However, the three dimensions cannot be assessed as independent wedges. Lower energy use per kilometre may reduce generalized travel costs and stimulate additional activity; changes in income and fuel prices alter both demand and modal preferences; and improvements in one mode can draw activity from another. The road-transport literature reports a measurable direct rebound from fuel-economy gains, with its magnitude varying substantially by time horizon, income, prices, and empirical method [11,12]. Consequently, scenario results can be biased when travel demand, modal shares, or technology penetration are imposed independently of the costs and policies generated within the scenario itself.

Whole-energy-system optimization models represent endogenous modal substitution through travel-time budgets, infrastructure constraints or substitution elasticities [13,14]. Luh et al. incorporate travel-time duration and valuation into Swiss TIMES to assess speed-induced modal shifts [15]. These approaches explore optimized system configurations. Evolutionary models such as FTT:Transport emphasize heterogeneous vehicle choice and interacting policy instruments, mainly for private road transport [16]. Fleet models distinguish sales from in-use shares through retirement, survival and replacement dynamics [17–19]. These approaches offer complementary explanations, but demand generation, modal competition, powertrain diffusion and fleet turnover are often represented at different levels of aggregation.

System dynamics connects stocks, flows, feedbacks and delays, allowing policy responses to depend on previous decisions [20]. Applications examine modal shift and electrification [21] and the adoption of electric, compressed-gas and biofuel vehicles [22]; Gómez Vilchez and Jochem review vehicle-fleet composition models [23]. Coverage nevertheless varies. A freight-sector review finds limited combinations of strategies and external conditions within individual studies [24]. For passenger transport, the integration challenge is to connect demand, modal competition, technology adoption and energy carriers while retaining their distinct adjustment times.

Recent work sharpens these distinctions: fleet-turnover analysis highlights the lag between sales and in-use technologies [19], transport-data reconstruction improves historical comparability [25], and multi-model demand-side studies reveal variation across intervention and modelling assumptions [26]. Göhlich et al. combine urban transport simulation

with vehicle design, operational costs and life-cycle assessment [27]. Such complementary boundaries motivate explicit reporting of what each model evaluates, alongside historical agreement and conditional prospective robustness.

This study builds directly on the passenger-transport module developed for the Within Limits Integrated Assessment Model (WILIAM). Its first published application demonstrated a detailed multimodal and multi-powertrain system-dynamics structure for Spain and used the ASI framework to compare behavioural and technological measures, reporting final energy, direct carbon dioxide emissions, and additional material requirements [28]. The present work is designed as a substantive extension rather than a repetition of that application. It shifts the analytical focus from comparing prescribed ASI configurations to tracing policy outcomes when total passenger demand, modal allocation, powertrain choice, and vehicle stocks respond jointly to income, prices, policy signals, behavioural drivers, technical feasibility, and stock-turnover inertia. Distance, occupancy and efficiency input trajectories are common across the scenarios; no scenario-specific changes to these inputs are claimed.

Two energy-carrier issues make this extension necessary. First, the operational benefit of electrification depends on the electricity consumed and on how rapidly electricity production is decarbonized; cross-regional evidence shows that electricity carbon intensity is a key boundary condition for the emissions performance of electric vehicles [29]. Second, liquid and gaseous low-carbon fuels can use parts of the existing vehicle and refuelling infrastructure and may be especially relevant where direct electrification is difficult. Their role is nevertheless constrained by production cost, conversion losses, sustainable biomass, renewable electricity, hydrogen, and carbon-source availability [30–33]. Treating a low-carbon fuel share as an unconstrained exogenous substitute can therefore transfer the mitigation burden outside the transport model without revealing the scale of the implied resource claim.

This modelling need is reinforced by the European policy architecture. The revised Renewable Energy Directive allows Member States to meet a transport target through either a 14.5% reduction in greenhouse-gas intensity or a 29% renewable-energy share by 2030 and establishes sub-targets for advanced biofuels and renewable fuels of a non-biological origin [34]. ReFuelEU Aviation mandates increasing shares of sustainable aviation fuels, including a synthetic-fuel sub mandate [35], while FuelEU Maritime progressively reduces the greenhouse-gas intensity of energy used on board ships [36]. These instruments make fuel provenance, timing, price, and availability analytically important, even when the selected emissions boundary is narrower than a full well-to-wheel or life-cycle assessment.

The contribution is the integration, for Spain, of mutually dependent mechanisms that are often analysed separately: endogenous prospective demand, competition among passenger modes, powertrain substitution, fleet accumulation and retirement, charging, and fuel origins with distinct prices and emissions attribution. This is a national application and an extension of the WILIAM passenger module, not a claim that these individual mechanisms are new. Their integration makes it possible to test whether a policy benefit is offset by demand response, turnover delay or fuel-resource requirements.

The objective is to compare conditional passenger-transport pathways for Spain under a common calibrated reference. Eleven modes and ten powertrain categories are represented, with infeasible combinations excluded. Historical activity and technology information draws primarily on JRC-IDEES-2023 [25]. Historical share comparisons assess agreement with available data, while prospective sensitivity tests evaluate how parameter and policy assumptions affect the scenario conclusions.

The study makes three contributions. First, it connects prospective demand, modal and powertrain choice, charging and fleet turnover in a common stock–flow structure.

Second, it distinguishes fossil, biogenic and synthetic fuel origins, including price feedbacks and explicit operational emissions attribution. Third, it compares ASI packages using endpoint, cumulative-emissions, interaction and resource-limit tests. Sustainable-development relevance is assessed through energy demand, attributed emissions and resource pressure; accessibility, affordability, equity and health are not directly quantified and cannot be inferred from passenger-kilometres alone.

The analysis is organized around three research questions: (1) How do endogenous demand, modal, technology, and fleet responses alter the effectiveness and timing of passenger-transport decarbonization policies? (2) How do electrification and low-carbon fuels interact across heterogeneous transport modes when electricity carbon intensity and fuel availability are represented explicitly? (3) Which combinations of Avoid, Shift, and Improve measures remain effective when income, prices, behavioural responses, fleet inertia, and resource pressures are considered jointly? The emissions boundary covers combustion emissions from ICEs, HEVs, and the fuelled share of PHEV operation, together with electricity-production emissions for BEVs, the electric share of PHEVs, and electric rail, and attributed hydrogen-production emissions. Upstream fuel production, vehicle and infrastructure manufacturing, and a complete well-to-wheel or life-cycle assessment are outside the scope; the paper therefore does not claim full life-cycle carbon neutrality for biogenic or synthetic fuels.

The remainder of the paper is structured as follows. Section 2 defines the system boundary, model architecture, historical reconstruction, choice and fleet equations, low-carbon-fuel module, emissions accounting, and scenario design. Section 3 presents calibration and validation and then compares the simulated pathways. Section 4 discusses policy interactions, rebound, the allocation of electrification and low-carbon fuels across modes, and the principal limitations. Section 5 summarizes the conclusions.

2. Materials and Methods

During the preparation of this manuscript/study, the authors used OpenAI ChatGPT (GPT-5.5), accessed through the Codex interface for language revision, code development and checking, data comparison, figure preparation and interpretation. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

2.1. System Boundary, Temporal Scope, and Model Architecture

The model extends the WILLIAM passenger-transport structure [28]. Total historical demand is supplied through 2023; most policy ramps begin in 2025 and the carbon-price branch in 2028. Historical choice calibration, prospective policy settings and the additional resource-cap and stock-target experiments are distinguished in Sections 2.6, 2.8 and 2.9. Distance, occupancy and vehicle-efficiency input trajectories are common across scenarios. The COICOP projected-price and oil-index routes are inactive.

The causal chain connects socioeconomic drivers and policy instruments to generated passenger demand, modal allocation, powertrain choice, fleet stocks, vehicle activity, charging availability, final energy, fuel origin, and carbon dioxide emissions (Figure 1). Generated demand is the mobility produced by the demand module; allocated demand is distributed through endogenous mode and technology shares; satisfied demand is limited by the service supplied by the corresponding fleet, annual vehicle distance, and load factor. Satisfied activity drives energy use and emissions.

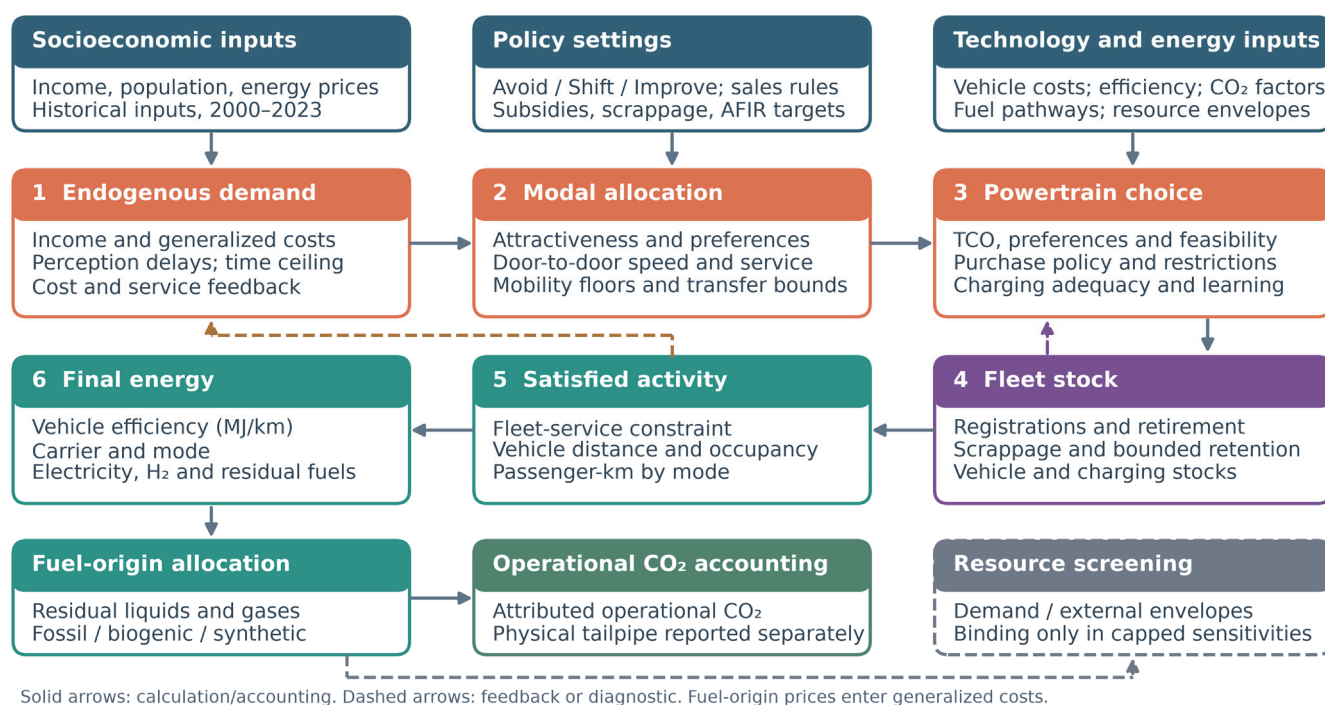


Figure 1. Model architecture and information flow. Socioeconomic, policy and technology inputs feed six stages: demand generation, modal allocation, powertrain choice, fleet turnover, satisfied activity and final energy. Fuel-origin allocation precedes operational CO₂ accounting. Fuel-origin prices enter generalized costs. Resource envelopes are non-binding in central scenarios; separate capped sensitivities impose fossil backfilling and cost feedback.

The model is operational rather than a full life-cycle assessment. It includes combustion emissions and attributed emissions from electricity and hydrogen production, but excludes vehicle and battery manufacturing, infrastructure construction, upstream fuel processing outside the adopted factors, non-CO₂ greenhouse gases, and non-exhaust emissions. Physical tailpipe, fossil-origin, and attributed operational CO₂ are retained as separate indicators.

2.2. Modal and Technological Resolution

The modal dimension contains light-duty vehicles (LDVs), two- and three-wheelers (2W/3Ws), bus, urban rail, conventional rail, high-speed rail, domestic aviation, intra-European aviation, international aviation, marine transport, and non-motorized transport (NMT). The technological dimension comprises gasoline ICEs, diesel ICEs, LPG ICEs, gas ICEs, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery-electric vehicles (BEVs), fuel-cell electric vehicles (FCEVs), electric traction (EV), and human-powered vehicles (HPVs).

Technical feasibility and availability exclude impossible combinations and prevent premature entry. HPV denotes bicycles in 2W/3W and walking in NMT. Bicycle activity is estimated rather than independently observed. Bicycle HPV is inactive in competitive transfers but retains a fixed 29.46% allocation within the full 2W/3W group; Figure 2d includes this component explicitly. The two-wheeler calibration errors concern the motorized split after normalization. Walking is also a fixed allocation assumption. Neither active-mobility component is presented as a calibrated competitive-choice outcome. Gas denotes compressed natural gas, distinct from LPG.

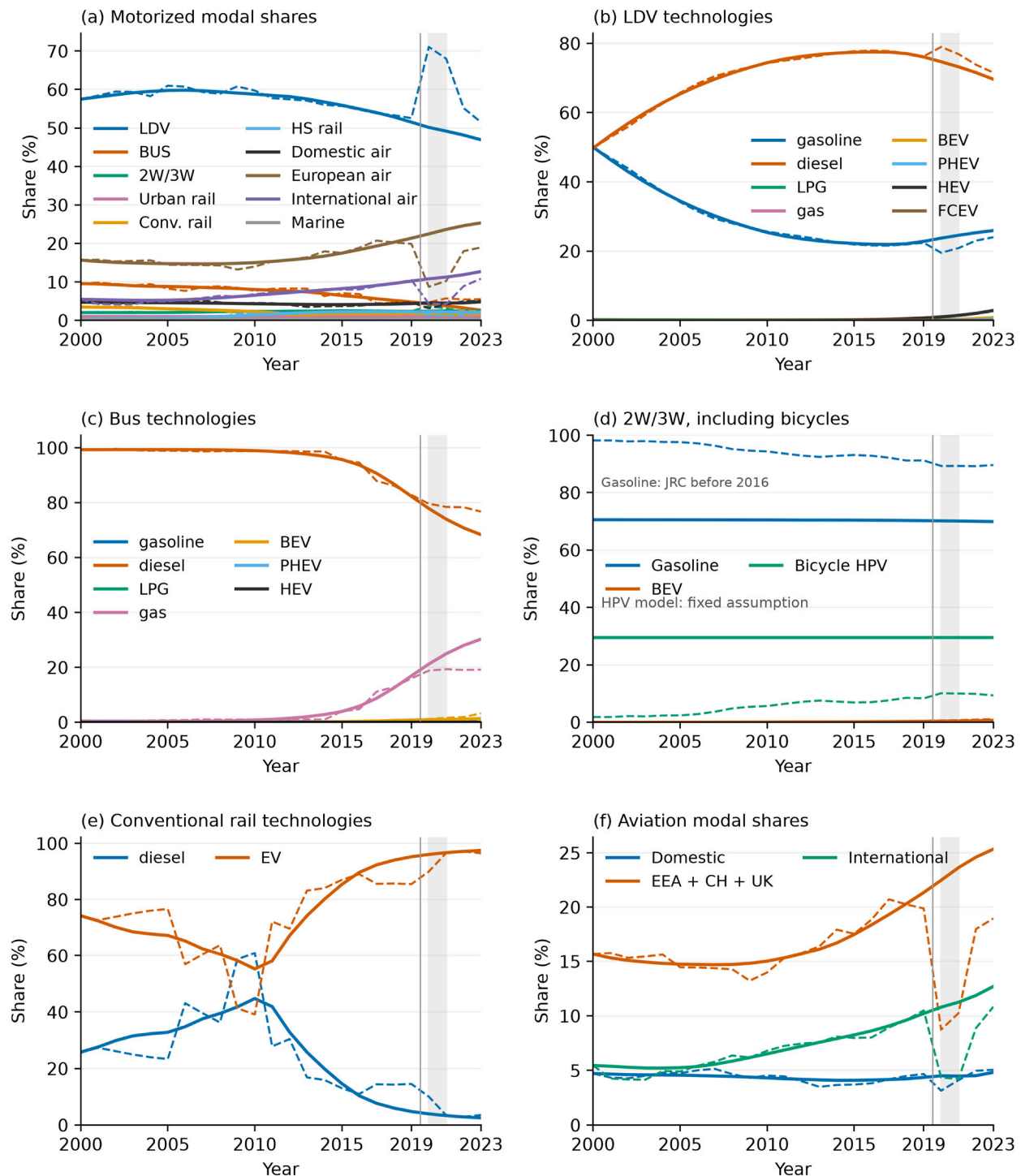


Figure 2. Historical share benchmarks and the final calibrated simulation. Solid: final calibrated simulation; dashed: source-based benchmarks. All panels span 2000–2023; grey shading marks 2020–2021. Panels (a,f) use motorized modal activity; technology panels use within-mode shares. Panel (d) spans 0–100% and includes bicycles: model HPV is fixed at 29.46%, whereas its benchmark is an activity estimate. Gasoline follows the JRC classification in 2000–2015 and stock-based allocation thereafter; BEV benchmarks start in 2016. International air is the extra-European category defined in Section 2.6. LDVs: light-duty vehicles; BUS: bus; 2W/3Ws: two/three-wheelers; Conv./HS: conventional/high-speed rail; EEA + CH + UK: European Economic Area, Switzerland and United Kingdom; BEV/PHEV/HEV: battery/plug-in hybrid/hybrid electric; FCEV: fuel-cell electric; EV: electric rail; LPG: liquefied petroleum gas; gas: natural gas; HPVs: human-powered vehicles. Figure S1 enlarges LDV fits. Calibration errors retain motorized denominators.

2.3. Endogenous Passenger Transport Demand

Aggregate demand is supplied through 2023. Thereafter, desired demand per capita responds to perceived real disposable income and generalized private-mobility cost, including money and time. The central assumption holds aggregate real disposable income at its 2023 level through 2050; population remains time-varying, so real income per capita need not be constant. This is a transparent boundary assumption, not a macroeconomic forecast. Historically estimated choice preferences are held at their terminal calibrated levels and subsequent policies act on those bases. No aggregate 2050 demand, energy or emissions result is a calibration target. Table A1 identifies the effective demand and common behavioural parameters. The demand formulation is:

$$D^*(t) = D_0^p \left[\frac{Y_p(t)}{Y_0} \right]^{\varepsilon_Y} \left[\frac{C_p(t)}{C_0} \right]^{-\varepsilon_C} \quad (1)$$

In Equation (1), $D^*(t)$ denotes desired annual passenger demand per capita, D_0^p the continuity-adjusted hand-off level, $Y_p(t)$ and $C_p(t)$ perceived real income per capita and generalized private-mobility cost, and Y_0 and C_0 their reference levels. The effective income elasticity ε_Y is 0.5994135 and the active generalized-cost elasticity ε_C is 1. These inherited demand settings are distinguished from the newly estimated choice parameters. Income and cost perception delays are 1.8 and 2.5 years. The stored monetary-price elasticity belongs to an inactive branch.

The continuity adjustment connects supplied historical demand to prospective endogenous demand. Historical demand, including the COVID contraction, is an input and cannot independently validate demand generation. The forcing series and the share benchmark also differ in coverage of maritime and estimated active mobility; their provenance and denominators are documented in Supplementary Data S1. Historical evaluation therefore concerns allocation shares conditional on activity, rather than a claim that the demand equation predicts the historical aggregate.

$$D_{max}(t) = 365 N(t) T_B \left[\sum_m \frac{s_m(t)}{v_m(t)} \right]^{-1} \quad (2)$$

In Equation (2), $D_{max}(t)$ is the aggregate annual travel-time ceiling, $N(t)$ population, T_B the daily time budget, and $s_m(t)$ and $v_m(t)$ the modal share and effective door-to-door speed. The bracketed sum is inverse harmonic system speed. The ceiling limits the feasible demand response; it is not a prescribed traffic target.

The effective door-to-door speeds include access, waiting, transfer, and congestion effects. They are held at historical values until the policy splice, so the dynamic ceiling does not retroactively modify the 2000–2023 reconstruction. A smooth saturation function avoids discontinuities as generated demand approaches the ceiling.

2.4. Endogenous Modal and Powertrain Choice

Modal and powertrain shares evolve by pairwise transfers (Equations (3) and (4)). Attractiveness combines conjunctural cost TC and absolute cost TA as $CP_1 \cdot TC + (1 - CP_1) \cdot TA$, together with the applicable calibrated residual, availability, infrastructure and policy terms. $CP_1 = 1$ removes only TA ; price response through TC remains active. Modal cost uses technology shares as weights. Destination inertia, seeding, maximum shares and technical feasibility control transfers. Residual preferences represent fitted unobserved influences, not independently identified causal effects; they remain active after the historical period.

The modal outflow from an origin depends on its share above the minimum, while entry into a destination depends on its current share plus a seeding term and on remaining

capacity. Technology flows use the origin share, destination seeding and destination headroom. Quarter-year transfers are bounded by available origin mass and destination capacity, preserving non-negative shares and closure. Prospective mobility floors protect bus, conventional rail, high-speed rail and maritime activity. Their 2030 reference levels are approximately 4.316%, 1.660%, 2.153% and 0.334%, respectively, introduced over 2025–2030. These are structural scenario assumptions, not observed demand targets or estimates of a socially optimal minimum. Table A2 reports the mode-specific choice coefficients.

$$\frac{dS_i}{dt} = \sum_{j \neq i} F_{ji} - \sum_{j \neq i} F_{ij} \quad (3)$$

where S_i is the dimensionless share of modal or powertrain option i , t is measured in years, and F_{ij} is the annual share-transfer flow from option i to option j .

$$F_{ij} = \max(0, S_i - S_{i,min})(S_j + \omega) \\ \times \max(0, S_{j,max} - S_j) \max(0, A_{ij}) \\ \times (1 - \iota_j) M_{ij} \quad (4)$$

F_{ij} is the annual transfer from i to j ; A_{ij} is pairwise attractiveness; ι_j is destination inertia; M_{ij} is binary transfer feasibility; and ω is seeding. For technology competition, the origin term is S_i without subtraction of a minimum share. A transfer-rate normalization of 1 year^{−1} is used. Flows are subsequently limited to feasible quarter-year mass and capacity.

2.5. Fleet Stock, Turnover, and Charging Infrastructure

Required vehicle stocks are obtained from satisfied passenger activity, mode-specific load factors, and annual distance per vehicle. New registrations close the gap between required and available service while replacing normal retirements. Technology-specific additions enter the corresponding stocks and retirements leave them. A stock–activity closure caps realizable LDV service at available fleet capacity and reallocates any shortfall across technologies with spare capacity; residual unmet demand is reported explicitly. This prevents a desired technology share from being interpreted as usable service before the necessary vehicles exist.

The Improve packages combine anticipatory attractiveness penalties with turnover responses. Policy-induced ICE LDV scrappage is linked to net BEV additions and limited by eligible stock remaining after natural wear in each integration step. Retirements leave the stock and are excluded from delayed replacement demand. Separately, owners can retain existing ICEs, HEVs and PHEVs when replacement gaps persist. This response adjusts over two years, extends natural lifetime by at most 20%, and does not relax new-sales restrictions. Retention is disabled in the PNIEC stock-target experiment, whose additional replacements are paired one-for-one with eligible retirements.

Public charging is reconstructed from European Alternative Fuels Observatory (EAFO) AC and DC charging points through 2025 [37]. Historical points are converted to equivalent public power using representative power levels and the 2024-Q1 EAFO anchor of 28,655 points and 973.6 MW. After the 2025-Q4 splice, charging power is an endogenous stock with a two-year construction delay and 15-year technical lifetime. The fleet-dependent AFIR target is 1.3 kW per BEV plus 0.8 kW per PHEV [38]; AFIR+ multiplies this target by 1.5. Independent Spain-specific work likewise identifies installed charging power and corridor coverage—not charger counts alone—as material constraints [39].

Effective charging adequacy is the minimum of the power-adequacy ratio and territorial coverage. Coverage is normalized to 25,600 public points, the level at which the Spanish REVE platform reported a point within 50 km of any peninsular location [40]. The BEV

range-anxiety term follows a bounded Hill function of effective adequacy, so additional charging has diminishing returns once both power and coverage are sufficient.

$$Anxiety_{BEV}(t) = -\frac{A_{max}}{1 + \frac{Adequacy(t)^n}{A_{50}}} \quad (5)$$

where *Adequacy* is the dimensionless minimum of the charging-power and territorial-coverage adequacy ratios, A_{max} is the maximum magnitude of the BEV charging-anxiety penalty, A_{50} is the adequacy ratio at which half of this penalty remains, and n is the dimensionless Hill exponent controlling the curvature of the response.

2.6. Historical Data, Calibration and Evaluation

Historical activity benchmarks use JRC-IDEES-2023 for motorized passenger transport over 2000–2023 [25], supplemented by the supplied maritime series and Spanish fleet and rail statistics. Passenger cars, powered two-wheelers, buses, rail and aviation are extracted separately; bus activity is counted once. European aviation follows the EEA plus Switzerland and the United Kingdom, while international air denotes the complementary extra-European category, excluding the separately reported domestic and European categories. LDV technology activity is estimated from harmonized DGT stocks weighted by JRC occupancy and annual mileage; HEVs and FCEVs use documented operating proxies. The high-speed rail endpoint for 2023 uses the CNMC correction. These processed allocations are not direct technology-specific passenger-kilometre observations.

Walking and bicycle activity are assumption-based, not independent annual observations. Modal calibration uses ten motorized modes after removing HPV activity. Two-wheeler technology calibration uses combined motorcycle/moped zero-emission stock proxies for 2016–2019. Earlier independent gasoline/BEV splits remain excluded. Figure 2d displays the earlier JRC gasoline classification without treating it as an observed zero BEV share. The 2024–2025 extension is not scored. Supplementary Data S1 documents provenance and observation masks. Additional methodological explanations, Supplementary Tables and Figures S1–S5 are provided in Supplementary Information.

The year 2000 initializes shares. Specification selection fits 2001–2014 and evaluates 2015–2019; the selected structure is then re-estimated with 2001–2019 for prospective use. Because the 2015–2019 window has informed successive specification choices, it is described as specification validation, not a blind external test. The final model is compared separately with 2020–2021 and 2022–2023 as shock and recovery diagnostics. The motorized 2W/3W score uses only available proxy years and cannot provide a comparable pre-2015 estimation/holdout exercise. Table 1 summarizes modal-share errors across the estimation and evaluation windows; Table 2 reports technology-share errors within each mode.

Table 1. Modal-share error by estimation and evaluation window.

Parameter Set/Window	Role	Modal RMSE (pp)	N
Selection fit 2001–2014	Selection	0.403	140
Specification test 2015–2019	Selection	1.166	50
Final fit 2001–2019	Final	0.458	190
Shock 2020–2021	Final	7.939	20
Recovery 2022–2023	Final	3.021	20

RMSE is in percentage points over the ten motorized modal shares. The selection and final parameter sets are distinct. Specification validation informed model selection and is not blind external validation. N is the number of mode-year entries. Shock and recovery rows use the final parameters without re-estimation.

Table 2. Technology-share error within each mode (percentage points).

Mode	Selection 2001–2014	Specification 2015–2019	Final Fit 2001–2019	COVID 2020–2021	Recovery 2022–2023
LDV	0.199	0.728	0.242	1.988	1.074
BUS	0.074	5.000	0.469	2.089	4.887
2W/3W *	Not scored	0.283	0.071	0.174	0.234
Conv. rail	6.755	7.201	8.449	4.306	0.710

Entries include historically feasible technology cells under the documented observation mask; structural zeros can lower pooled errors. LDV and motorized 2W/3W activity splits include fleet-weighted proxies. The 2W/3W selection-period fit is not scored because no eligible pre-2015 technology observations exist; its 2016–2019 comparison is diagnostic. Conventional-rail error is not diluted by the non-competing electric urban and high-speed modes. * The 2W/3W selection-period fit is not scored because no eligible pre-2015 technology observations exist; its 2016–2019 comparison is diagnostic.

Bounded nonlinear least squares with multiple initial points estimates active modal and technology-choice parameters and parsimonious residual paths. Modal residuals are scaled by the square root of historical mean share, with additional weights on LDV, aviation and maritime activity. Technology residuals are similarly scaled to retain information from small shares. A focused four-coefficient preference correction improves LDV gas and PHEV fit while constraining deterioration in gasoline, diesel, BEVs and HEVs. Remaining boundary parameters and compensating terms preclude a claim of complete parameter identification. Model calibration and scenario simulations were performed using Python 3.12.14, with the integrated model executed using PySD 3.14.3. The fast calibration equations reproduce the historical shares of the integrated model to numerical precision.

The final pooled motorized modal RMSE is 0.458 percentage points in 2001–2019, compared with 1.166 pp in the 2015–2019 specification-validation window using the selection parameters. Final within-mode technology RMSE is 0.242 pp for LDVs, 0.469 pp for BUS and 8.449 pp for conventional rail. The motorized 2W/3W proxy fit is 0.071 pp over 2016–2019. These unequal levels of agreement are retained rather than described as uniform validation.

2.7. Final Energy and Attributed Operational CO₂

For each feasible mode–powertrain combination, vehicle-kilometres equal satisfied passenger-kilometres divided by the mode-specific load factor. Final energy is vehicle-kilometres multiplied by effective energy consumption in MJ per vehicle-kilometre. PHEV energy is split between electricity and liquid fuel using the modelled electric-driving fraction; electric rail uses the EV category, and HPVs consume no modelled final fuel energy.

The principal emissions indicator assigns combustion CO₂ to the fossil-origin fraction of liquid and gaseous fuels and adds the specified electricity- and hydrogen-production emissions (Equation (6)). The selected electricity intensity reaches zero in 2050. Physical tailpipe CO₂ is reported separately and counts combustion regardless of carbon origin. Near-zero attributed operational CO₂ therefore does not imply disappearance of combustion, full well-to-wheel decarbonization or life-cycle neutrality.

$$\text{CO}_{2,\text{op}}(t) = \sum_f E_{L/G,f}(t) f_{\text{foss},f}(t) EF_{\text{comb},f} + E_{el}(t) CI_{el}(t) + E_{H2}(t) CI_{H2}(t) \quad (6)$$

where $E_{L/G,f}$, E_{el} , and E_{H2} are annual final-energy consumption of liquid or gaseous fuels, electricity, and hydrogen, respectively; $f_{\text{foss},f}$ is the fossil-origin fraction and $EF_{\text{comb},f}$ the combustion emission factor of each liquid/gaseous combination f ; and CI_{el} and CI_{H2} are the production carbon intensities of electricity and hydrogen. Energy quantities are expressed in MJ/year and emission factors and carbon intensities in kg CO₂/MJ. The summation index f runs over all applicable mode–powertrain–carrier combinations.

2.8. Low-Carbon Fuel Representation and Resource Diagnostics

Residual liquid and gaseous demand is split into fossil, biogenic and synthetic origins, with shares summing to one. Ten pathways are represented: conventional ethanol, conventional FAME, advanced HVO/BTL, bio-SAF, biomethane, e-gasoline, e-diesel, e-kerosene, e-methane and e-LPG. The central cases share the same historical fuel-origin configuration through 2025; CP and FF alternatives diverge prospectively. Fuel origin affects user prices and subsequently demand and technology choice, so changing origin is not only an emissions-accounting operation.

The reference approximates the policy architecture specified in the cited EU instruments [34–36,38,41]. Regulation (EU) 2023/851 sets fleet-average CO₂ reduction requirements rather than aggregate ZEV-sales quotas [41]. The model uses intermediate LDV ZEV-sales floors of 15% and 55%, followed by 100% from 2035, as a transparent approximation. The implemented schedule interpolates the stage transitions during 2029–2030 and 2034–2035. PHEVs do not count as ZEVs; the BEV/FCEV allocation remains endogenous. Manufacturers, pooling, credits, compliance flexibilities and separate car/van markets are not represented. The weaker-mapping sensitivity halves the intermediate floors to 7.5% and 27.5%, preserving the 2035 endpoint and other policies. National BUS results do not impose Clean Vehicles Directive procurement quotas because the eligible procurement subset is not resolved [42].

Central fuel pathways are screened against non-binding resource envelopes. Four additional cases impose the high envelopes on REF, LCF-FF, ASI-H-CP and ASI-H-FF after 2025. Biogenic and synthetic shares are proportionally reduced where requirements exceed an envelope; unmet low-carbon requirements are backfilled by fossil fuel. Electricity for direct hydrogen is reserved before the remaining PtX electricity is allocated to synthetic fuels. The resulting fuel origins and prices enter the normal demand and choice equations. All six resource balances are checked quarterly; direct hydrogen remains below its envelope and is not independently curtailed. This is a physical-availability sensitivity with explicit back-filling, not a model of cross-sector allocation or scarcity prices (Supplementary Data S1).

2.9. Scenario Design and Policy Experiments

Eleven central cases include a no-EU LDV control, the common reference and its policy additions, and a PNIEC stock-target benchmark (Table 3). Avoid, Shift, Improve and Fossil-Free are stylized policy-intensity experiments, not forecasts of implementation, estimated Spanish policy potentials, equal-cost interventions or optimized packages. All retain the same historical choice calibration. The no-EU case disables the LDV regulatory proxy only; it is not a no-policy counterfactual for the entire transport system.

Avoid combines the carbon-price pathway with a 2025–2035 reduction in effective door-to-door speed from 30 to 20 km/h for LDVs and 32 to 30 km/h for 2W/3Ws. Shift changes effective speeds from 16 to 32 km/h for BUS, 22 to 50 for urban rail, 45 to 90 for conventional rail and 90 to 180 for high-speed rail, and relaxes their capacity ceilings toward 0.20, 0.10, 0.10 and 0.20. These are accessibility and service-quality shocks, not literal nationwide cruising-speed forecasts or imposed shares. Alternative cases halve the speed increments: LDV 25, 2W/3W 31, BUS 24, urban rail 36, conventional rail 67.5 and high-speed rail 135 km/h. Carbon pricing and capacity assumptions remain unchanged in those speed-intensity tests.

Medium Improve adds a 15% LDV-BEV purchase subsidy, the anticipatory regulatory-disutility signal, AFIR charging, and bounded endogenous owner retention to the common EU-policy reference approximation. High Improve raises the subsidy to 30%, links it to ICE scrappage, and activates AFIR+. The common EU sales floor already reaches 100% ZEVs from 2035; the Improve restriction additionally excludes new HEV and PHEV sales at that date. Retention can extend natural service life by at most 20% when a stock gap persists and never permits prohibited new sales.

Table 3. Central scenario design and analytical role.

ID	Scenario	Fuel	Additional Intervention	Role
S00	REF-no-EU	CP	LDV EU sales proxy off	Reference diagnostic
S01	REF-CP	CP	Common policy reference	Reference
S02	Avoid-CP	CP	Carbon price; private-mode speed	Isolated Avoid
S03	Shift-CP	CP	Public speeds and capacity	Isolated Shift
S04	Improve-M-CP	CP	15% BEV subsidy; sales restriction	Medium Improve
S05	Improve-H-CP	CP	30% subsidy; scrappage; AFIR+	High Improve
S06	LCF-FF	FF	Prospective fuel-origin pathway	Fuel sensitivity
S07	ASI-M-CP	CP	Avoid + Shift + medium Improve	Integrated medium
S08	ASI-H-FF	FF	Avoid + Shift + high Improve	Integrated high FF
S09	ASI-H-CP	CP	Avoid + Shift + high Improve	High CP comparator
S10	PNIEC target	CP	High ASI + paired replacement controller	4.76-million stock target

CP and FF denote Current-Policy and Fossil-Free fuel-origin assumptions. S09 isolates high ASI with CP fuels; S10 is an imposed stock-target benchmark, not an additional historical calibration target. The reference uses one approximation of the cited EU policy architecture. Add-on effects are measured against that reference.

The PNIEC benchmark translates the national 5.5-million electric-vehicle ambition [4] into a model-covered target of 4.76 million BEVs, PHEVs and FCEVs in 2030. The central allocation follows 2025 modelled motorized fleet composition: approximately 3.9245 million LDVs, 0.8288 million motorized 2W/3Ws and 6736 buses. A controller adds only the replacements needed beyond ordinary turnover to follow a linear electrified-stock path from 2025 to 2030. Every additional electrified vehicle replaces one eligible non-electrified vehicle, with allocation among BEVs/PHEVs/FCEVs determined by the model's contemporaneous choice weights. Inherited minimum electrified-sales interventions are neutralized during the controlled period to avoid imposing a conflicting allocation. Retention is disabled. Two alternatives vary the 2W/3W target by $\pm 25\%$, hold BUS fixed and adjust LDVs so the total remains 4.76 million. This benchmark imposes a quantity without estimating the expenditure or administrative effort required.

2.10. Output Indicators and Numerical Verification

Outputs include annual trajectories, 2030/2050 endpoints and the sum of annual 2024–2050 attributed operational CO₂. The uncertainty exercise varies seven axes at two levels across REF and five CP packages (84 OAT runs): income elasticity, generalized-cost elasticity, technology cost sensitivity, BEV charging anxiety, road-vehicle lifetime, BEV learning and BUS/2W technology-adjustment rates. Each package is compared with the reference under the same perturbation. All changes start after 2025 to preserve the calibrated historical state. Six weaker-EU-mapping runs, two speed-intensity variants, four binding-resource cases and two alternative PNIEC allocations supplement the central cases. Three fixed-demand runs quantify rebound for the two Improve packages. These deterministic ranges are not confidence intervals or a joint probabilistic analysis.

For either endpoint or cumulative attributed operational CO₂, avoided emissions in scenario s are $\Delta E_s = E_{REF} - E_s$. Net interaction is $J_{ASI} = \Delta E_{ASI} - (\Delta E_A + \Delta E_S + \Delta E_I)$. Positive J denotes superadditivity; negative J denotes subadditivity. A proportional-overlap benchmark, $E_{REF}[1 - \prod_i(1 - \Delta E_i/E_{REF})]$, provides a separate mechanical-overlap comparison over isolated policy components i . Neither residual identifies the individual contribution of rebound, modal substitution or timing. Rebound uses paired demand treatments: gross savings compare REF and Improve with both demands fixed to the central REF trajectory; net savings compare the corresponding endogenous-demand cases. Rebound equals one minus the ratio of net to gross savings for positive gross savings. Supplementary Data S1 reports the calculations and numerical checks.

3. Results

3.1. Historical Calibration and Evaluation

With final parameters, motorized modal RMSE rises from 0.458 pp in 2001–2019 to 7.939 pp in 2020–2021 and 3.021 pp in 2022–2023 (Table 1). The historical LDV share falls again during the recovery as aviation and collective transport recover; the smooth simulated choice dynamics do not reproduce the abrupt COVID reallocation. No epidemic-choice mechanism is fitted. Historical aggregate demand is supplied separately and must not be counted as validation of endogenous demand.

Recovery-period technology RMSE is 1.074 pp for LDVs, 4.887 pp for BUS, 0.710 pp for conventional rail and 0.234 pp against the motorized 2W/3W proxy (Table 2). In the 2015–2019 specification comparison, BUS and conventional rail have errors of 5.000 and 7.201 pp. Good final-period fit or recovery fit does not remove this evidence of limited temporal transferability. Prospective sensitivity therefore explicitly perturbs weak-mode adjustment, rather than assuming all coefficients remain stable to 2050.

The four-coefficient LDV refinement improves gas and PHEV RMSE in the selection-validation window by approximately 70% and 20%, respectively. Final 2001–2019 errors are 0.0070 pp for natural gas and 0.00059 pp for PHEVs. These gains concern small technology shares and do not establish full model identification. The final parameter set retains the boundary and collinearity limitations.

3.2. Reference Pathway and Cross-Scenario Comparison

REF reaches 74.28 Mt of attributed operational CO₂ in 2030. In 2050 it reaches 797.1 Gpkm, 754.9 PJ and 22.46 Mt, with 90.52% BEVs in the LDV stock. Cumulative 2024–2050 attributed emissions are 1.399 Gt. These prospective totals are outputs under the historical calibration and scenario assumptions, not fitted 2050 anchors (Table 4).

Isolated Avoid, Shift, medium Improve and high Improve reduce attributed operational CO₂ in 2050 by 9.87%, 0.39%, 2.07% and 3.94%, respectively. Their cumulative reductions are 4.21%, 3.17%, 0.85% and 4.28%. Thus, Avoid provides the largest isolated endpoint reduction, whereas high Improve performs slightly better cumulatively. These are conditional comparisons at the specified intensities.

All policy cases use the same calibrated reference settings. Table 4 reports central scenario outcomes; resource and parameter sensitivities are analysed separately. The scenarios are conditional experiments rather than forecasts or optimized national plans.

Table 4. Central scenario outcomes relative to the common reference.

Scenario	Demand Gpkm	LDV BEV Stock %	Energy PJ	Fossil Energy %	Attr. CO ₂ 2030 Mt	Attr. CO ₂ 2050 Mt	Cum. Attr. CO ₂ Gt
REF-CP	797.1	90.52	754.9	47.19	74.28	22.4646	1.399
Avoid-CP	690.8	91.15	690.6	45.13	71.94	20.2466	1.340
Shift-CP	804.7	86.39	729.8	46.08	72.52	22.3781	1.354
Improve-M-CP	800.8	90.82	746.0	46.92	74.19	21.9992	1.387
Improve-H-CP	800.0	95.34	738.8	46.80	73.89	21.5794	1.339
LCF-FF	739.9	90.00	671.4	0.00	71.97	0.0015	1.146
ASI-M-CP	715.0	89.32	654.7	45.07	69.62	19.7271	1.278
ASI-H-FF	684.9	90.16	600.1	0.00	67.45	0.0007	1.059
ASI-H-CP	713.5	90.18	650.9	45.14	69.54	19.6205	1.265
PNIEC target	713.2	86.15	636.0	44.40	64.78	19.0044	1.206

All endpoints refer to 2050 except the labelled 2030 column. CO₂ denotes attributed operational CO₂; cumulative values sum annual 2024–2050 emissions. LDV BEV is an in-use stock share. Near-zero FF results are not zero life-cycle emissions. PNIEC is a controlled stock-target experiment.

3.3. Endogenous Demand and Modal Responses

Avoid reduces 2050 demand from 797.1 to 690.8 Gpkm. Shift reaches 804.7 Gpkm, while medium and high Improve reach 800.8 and 800.0 Gpkm. Service improvements and lower monetary operating costs can increase generated activity even when final energy falls; demand and emissions rankings consequently differ (Figure 3).

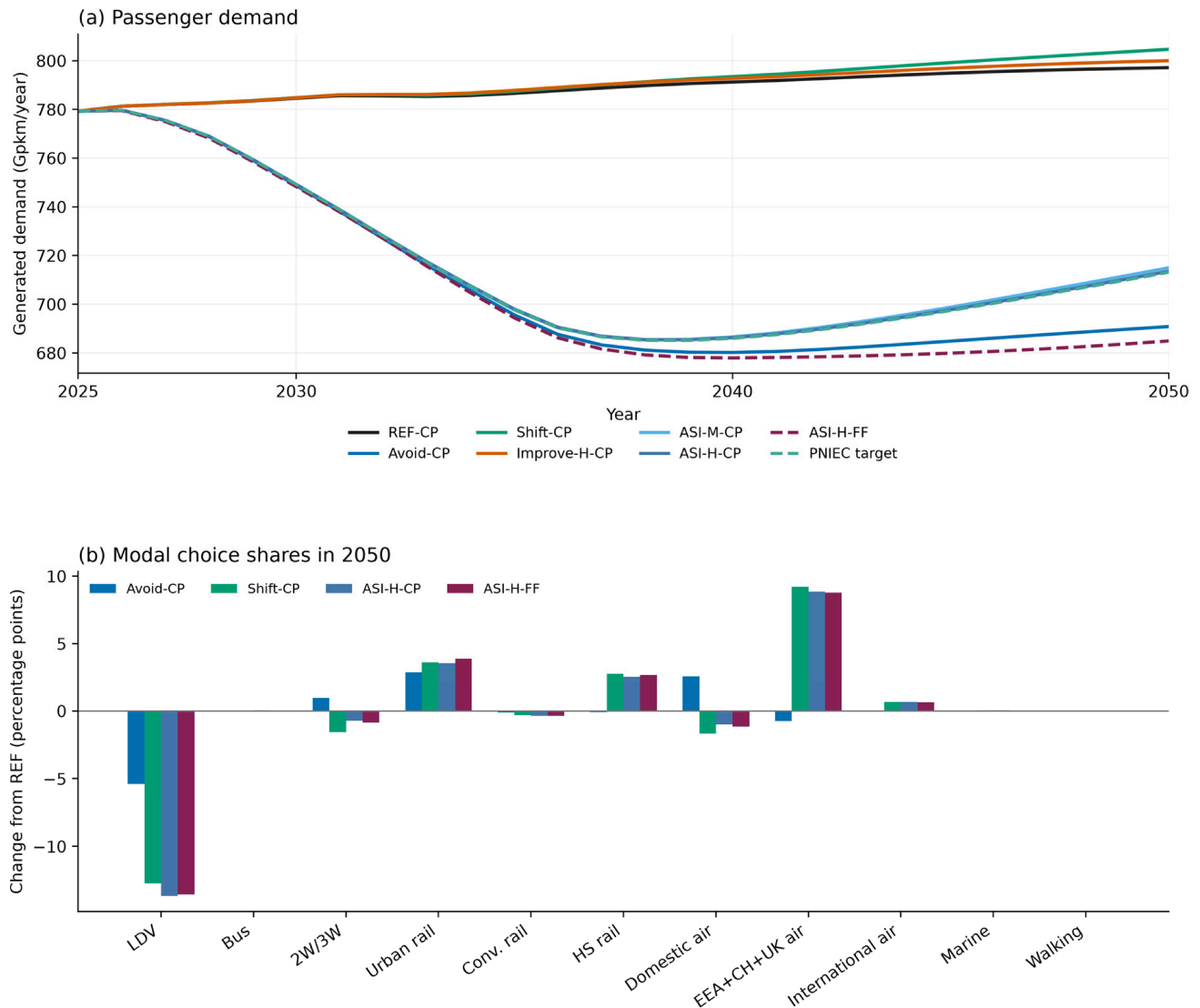


Figure 3. Endogenous demand and modal responses. Panel (a) reports generated passenger demand. Panel (b) shows 2050 modal choice-share differences from REF, using the complete modal allocation including the fixed walking assumption. These are choice allocations, distinct from shares of fleet-served activity. EEA + CH + UK denotes European Economic Area, Switzerland and United Kingdom; international air is its complement. Scenario labels follow Table 3.

High ASI reaches 713.5 Gpkm with CP fuels and 684.9 Gpkm with FF fuels. Fuel-origin prices feed back into costs, so FF is not an emissions-factor-only comparison. Mobility floors and capacity limits also shape the allocation; the model does not imply that essential public-transport services can disappear without constraint.

The travel-time ceiling is a feasibility limit rather than a prescribed activity target. The scenario contrasts also depend on income, perceived generalized costs, modal accessibility proxies and adjustment delays. They do not measure household welfare or the accessibility delivered by each passenger-kilometre.

3.4. Technology Adoption, Fleet Turnover, and Charging

In-use LDV BEV shares in 2050 are 90.52% in REF, 90.82% in medium Improve, 95.34% in high Improve and 86.15% in the PNIEC benchmark. Sales interventions do not immediately determine fleet or activity allocations because additions, retirement, service requirements and utilization mediate the response.

In every scenario subject to the additional Improve restriction, new ICE, HEV, and PHEV sales are exactly zero from 2035; in REF-CP, the adopted EU floor instead requires all new LDV sales to be zero-emission from 2035. The owner-retention factor rises smoothly where a stock gap persists and never exceeds 1.20. Charging adequacy and technology-specific costs continue to determine the allocation among eligible alternatives.

Charging infrastructure follows fleet composition and the AFIR-based power and territorial-coverage requirements. Fleet additions, natural retirement and policy-induced scrappage enter a consistent stock balance. Charging adequacy affects technology attractiveness, but the experiments do not identify it as the sole empirical explanation for low electrification in any national mode. Figure 4 shows technology-choice allocations.

Figure 4 compares the complete technology allocations in 2030 and 2050 across all ten main scenarios for LDVs, 2W/3W, bus and conventional rail. In-use BEV stock shares are reported separately in Figure S5. LDV subsidies and the LDV ZEV-sales proxy do not impose equivalent national BUS or two-wheeler mandates. Their outcomes depend on calibrated choices, availability and turnover. The competitive two-wheeler calibration concerns the motorized split; bicycle HPV retains a fixed 29.46% allocation, whose mismatch with the historical estimate is visible in Figure 2d. This fixed allocation is not evidence of a physical electrification ceiling or of successful bicycle calibration. Charging adequacy alone is not established as the cause of a low BEV share.

3.5. Final Energy, Low-Carbon Fuels, and Resource Diagnostics

Final energy in 2050 is 754.9 PJ in REF, 654.7 PJ in medium ASI, 650.9 PJ in high ASI with CP fuels and 600.1 PJ in high ASI with FF fuels. Medium and high Improve reach 746.0 and 738.8 PJ; the PNIEC target case reaches 636.0 PJ. Carrier and origin composition explain why the energy ranking need not equal the attributed-emissions ranking.

The resource diagnostic compares low-carbon fuel and production-electricity requirements with screening envelopes. Synthetic-liquid energy and the electricity required to produce it are not additive final-energy resources: they refer to different stages of the same conversion chain. Figure 5 reports resource requirements relative to the high envelope, rather than treating an exceedance as available supply.

With binding high envelopes, attributed operational CO₂ in 2050 is 35.67 Mt in REF and 29.49 Mt in ASI-H-FF. Comparing capped CP and FF cases retains 7.39% of the nominal incremental FF endpoint reduction on REF, and 8.36% on high ASI. These percentages concern the incremental fuel-origin benefit, not the entire ASI package. Supplementary Data S1 also reports cumulative retention and the quarter-year resource balances.

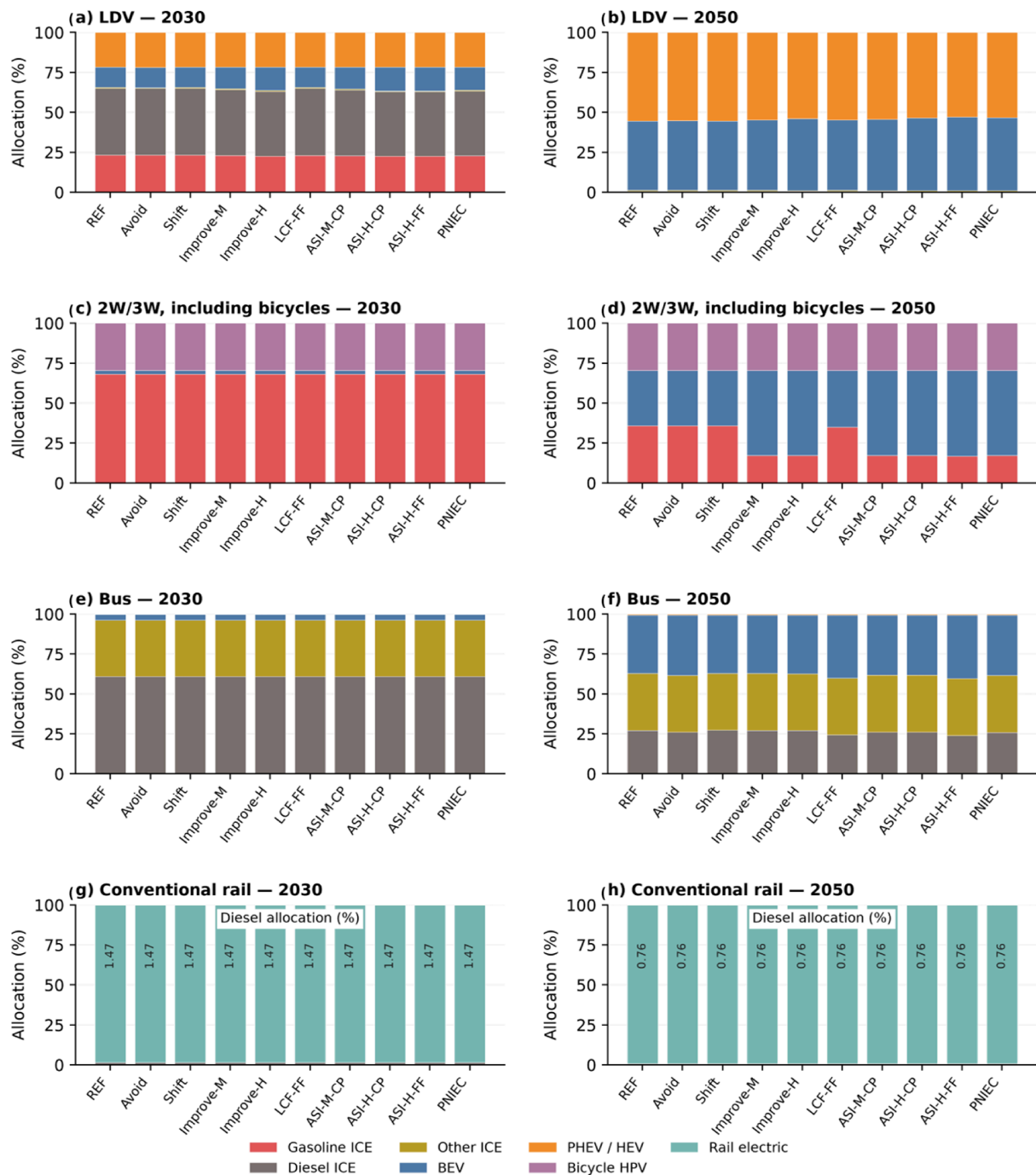


Figure 4. Technology allocations in 2030 and 2050 across the ten main scenarios. Columns show 2030 and 2050; rows show LDV, 2W/3W, bus and conventional rail. Stacks are technology-choice allocations, not sales, vehicle stocks or fleet-served activity. Urban and high-speed rail are excluded because they are always 100% electric in the model. Diesel percentages are labelled within the conventional-rail panels. Diesel traction can consume fossil, biogenic or synthetic liquid fuels; low-carbon origins are not separate powertrains (Figure 5). Bicycle HPV is included in 2W/3W. Other ICEs combine LPG and natural gas; PHEVs and HEVs are combined. Figure S5 reports BEV fleet shares. REF denotes REF-CP; isolated Avoid/Shift/Improve and ASI-CP use CP fuel origins; FF denotes Fossil-Free assumptions. PNIEC is the covered-fleet stock-target benchmark.

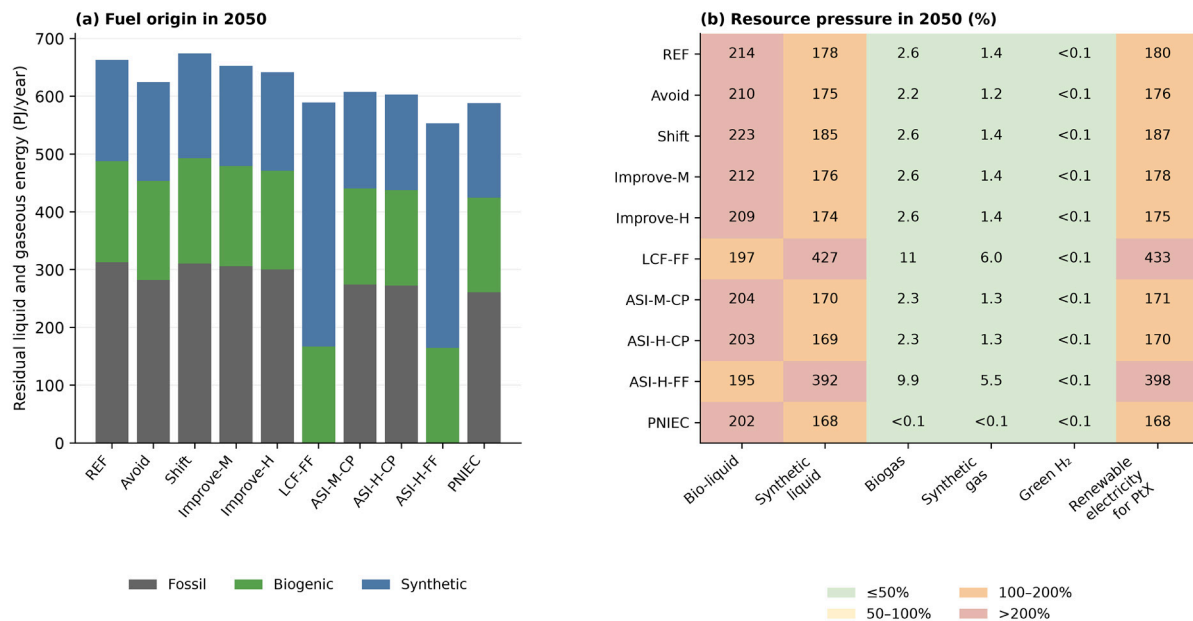


Figure 5. Residual-fuel origins and resource pressure in 2050. Panel (a) shows residual liquid and gaseous final energy by fossil, biogenic and synthetic origin for all ten main scenarios; direct electricity and hydrogen are separate carriers and are excluded from these stacks. Panel (b) reports demand divided by the corresponding high resource envelope, multiplied by 100, for bio-liquids, synthetic liquids, biogas, synthetic gas, green hydrogen and renewable electricity for power-to-X (PtX). Green: $\leq 50\%$; yellow: 50–100%; orange: 100–200%; red: $>200\%$. Exceedance is a screening result, not assured supply. PtX electricity is a production input and must not be added to synthetic-fuel energy as an independent final-energy contribution. Figure S4 shows total final-energy trajectories.

3.6. Carbon Dioxide Attribution and Policy Interactions

The emissions indicators diverge when biogenic and synthetic fuels are combusted. The attributed operational indicator counts fossil-origin combustion and the prescribed electricity/hydrogen production contributions, whereas the physical diagnostic retains combustion CO₂ regardless of origin. The selected electricity-intensity pathway reaches zero in 2050, but a small, attributed residual can remain from other included terms. Near-zero FF values therefore do not imply the disappearance of combustion or life-cycle impacts.

Endpoint avoided emissions are 2.218 Mt/year for Avoid, 0.087 for Shift, 0.465 for medium Improve and 0.885 for high Improve. The interaction calculation uses the same CP fuel pathway on all sides, preventing fuel substitution from being mistaken for an ASI interaction. Figure 6 presents the attributed-emissions trajectories and endpoint and cumulative avoided emissions.

Medium ASI has $J = -0.032$ Mt/year in 2050 and +0.0053 Gt cumulatively. High ASI has $J = -0.346$ Mt/year and -0.0300 Gt. Both are subadditive at the endpoint, but medium ASI is superadditive over the cumulative window. The sign therefore depends on the package and time basis. The proportional-overlap comparison in Supplementary Data S1 is a mathematical benchmark and does not separately identify behavioural mechanisms.

The no-EU LDV control reaches 26.54 Mt and 808.8 PJ in 2050, versus 22.46 Mt and 754.9 PJ in REF. This is a 15.35% emissions difference relative to the control. It measures dependence on the modelled regulatory proxy rather than a causal estimate of the legislation. The weaker intermediate mapping is evaluated against matching policy cases in Supplementary Data S1.

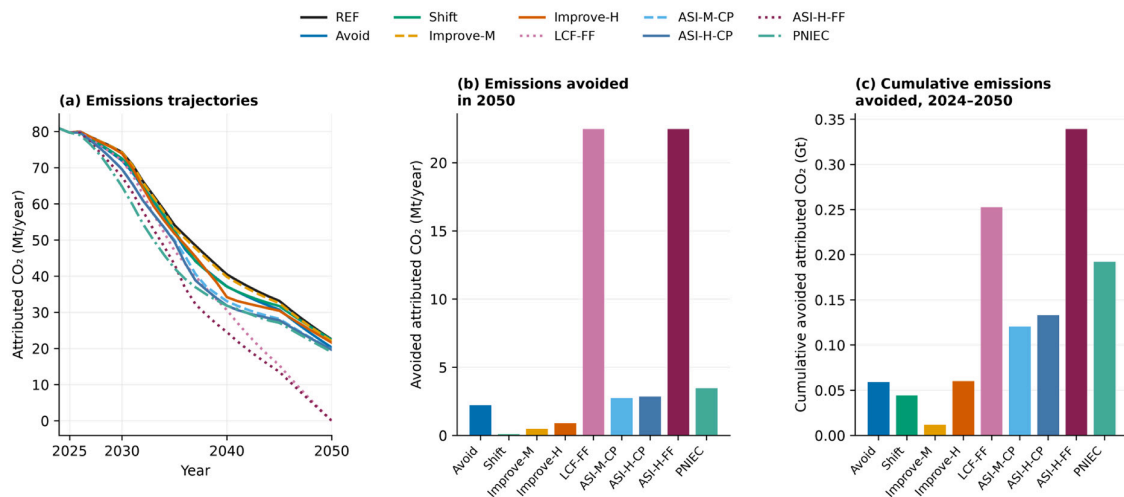


Figure 6. Attributed operational emissions and avoided emissions. Panel (a) shows annual trajectories for all ten main scenarios. Panel (b) shows emissions avoided in 2050 relative to REF; panel (c) shows the sum of annual avoided emissions over 2024–2050. REF is omitted from (b,c) because its avoided emissions are zero. Colours identify scenarios; labels follow Figure 4 and Table 3. Positive bars denote reductions from the common REF. Figure S2 separately reports the four matched resource-cap experiments and the attributed/physical-tailpipe comparison for all ten scenarios. Near-zero attributed CO₂ does not imply disappearance of combustion or life-cycle impacts.

Uncapped LCF-FF and ASI-H-FF reach 0.0015 and 0.0007 Mt of attributed operational CO₂ in 2050, while physical tailpipe CO₂ remains 42.19 and 39.67 Mt. Figure S2 separates those accounting indicators from the binding-resource sensitivities. Neither is a complete life-cycle inventory.

The central endpoint ordering is Avoid-CP > Improve-H-CP > Improve-M-CP > Shift-CP. It is preserved in 14 of 15 matched OAT/regulatory comparisons. Cumulative comparisons are reported separately because the ordering differs at the central parameter set. Table 5 and Figure S3 show the effects and ranges. Conditional stability across the tested variations is not evidence of robustness to every plausible parameter combination or model structure. Table 6 reports the endpoint and cumulative net interactions.

Table 5. Central reductions for the four isolated Current-Policy packages relative to REF-CP.

Scenario	2050 Reduction (%)	2024–2050 Reduction (%)
Avoid-CP	9.87	4.21
Shift-CP	0.39	3.17
Improve-M-CP	2.07	0.85
Improve-H-CP	3.94	4.28

Note: Endpoint reductions refer to attributed operational CO₂ in 2050; cumulative reductions cover 2024–2050. Structural and accounting sensitivities are reported separately and are not probability intervals.

Table 6. Net ASI interaction relative to the sum of isolated CP effects.

Package	2050 (Mt/Year)	2024–2050 (Gt)
ASI-M-CP	−0.0324	+0.00530
ASI-H-CP	−0.3456	−0.03001

3.7. Sensitivity, Rebound and Fleet-Target Allocation

OAT endpoint reductions range from 6.64–12.92% for Avoid, −0.48–1.20% for Shift, 1.62–2.45% for medium Improve and 3.35–4.55% for high Improve. Figure S3 shows these

ranges against matching perturbed references. Halving the speed-policy increments gives endpoint reductions of 5.59% for Avoid and -0.32% for Shift. Under the weaker EU mapping, Shift reduces emissions by 1.96% and medium Improve by 1.78%, reversing their central ordering; Avoid remains the largest isolated endpoint reduction. These tests qualify the ranking and do not interpret parameter ranges as probabilities.

The stock-target controller reaches 4.7600 million covered electrified vehicles in 2030 with no net vehicle creation by the additional replacement flows. Varying the 2W/3W allocation by $\pm 25\%$ while offsetting LDVs and holding BUS fixed produces a 2050 attributed operational CO₂ between 18.997 and 19.012 Mt. This is sensitivity to allocation conditional on achieving the same imposed target. It does not measure policy cost, prove that the target is administratively attainable or constitute independent model validation.

For medium Improve, paired simulations give gross/net 2050 energy savings of 12.26/8.96 PJ; for high Improve, 18.75/16.11 PJ. Corresponding rebound ratios are 26.92% and 14.06%; cumulative ratios are 14.23% and 3.60%. These are aggregate model counterfactuals conditional on the common REF activity trajectory, not empirical rebound estimates. Figure 7 shows the carbon-price signal, generalized costs and paired energy-savings comparisons used to quantify rebound.

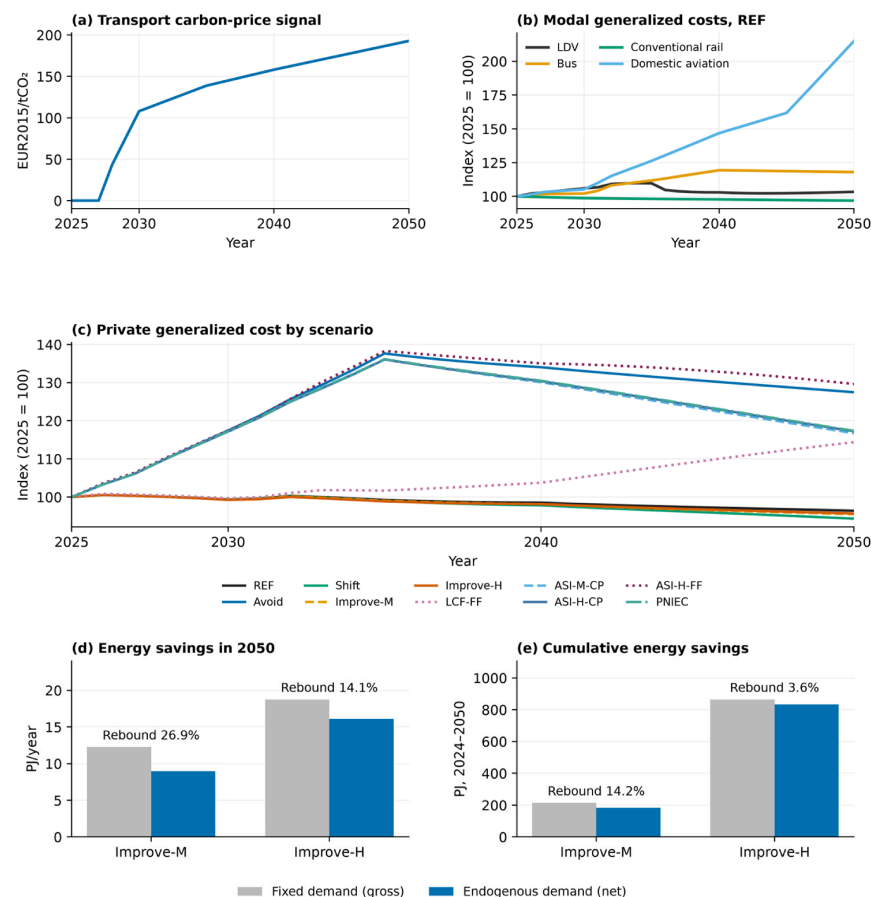


Figure 7. Carbon price, generalized costs and energy rebound. Panel (a) shows the transport carbon-price signal used in Avoid-containing scenarios. Panel (b) indexes four REF modal generalized costs to 2025 = 100; panel (c) indexes each scenario's private generalized cost entering aggregate demand to its 2025 value. Panels (d,e) compare gross fixed-demand and net endogenous-demand energy savings for isolated medium and high Improve, in 2050 and cumulatively over 2024–2050. Rebound = $100 \times (1 - \text{net/gross})$, with percentages labelled above each pair of bars. These are conditional model counterfactuals, not empirical rebound estimates. Figure S3 reports deterministic sensitivity ranges separately.

4. Discussion

4.1. Implications for Passenger-Transport Decarbonization

The endpoint and cumulative comparisons support different emphases. Avoid gives the largest isolated 2050 reduction at the tested intensities, while high Improve performs slightly better cumulatively. Both integrated CP packages reduce more emissions than any isolated component, but their reductions cannot generally be obtained by adding isolated effects. The policy intensities are not normalized by expenditure, welfare cost or implementation difficulty, so the ordering is not a cost-effectiveness ranking.

This temporal result is consistent with fleet-transition studies emphasizing the distinction between new-sales shares and the in-use stock [17–19], with cumulative-budget work showing the importance of early car-use reductions [43], and with system-dynamics applications in which policy sequence and feedbacks determine the transition path [20–22,24]. The contribution here is to resolve demand, modal competition, powertrain diffusion, charging, and residual fuel origin in the same integrated scenario system, while keeping its historical limitations explicit.

Recent demand-side and fleet-turnover studies emphasize coordinated interventions and timing [8–10,18,19,26,43]. Brand et al. examine UK pathways combining reduced travel, modal shift and vehicle changes, with life-cycle and health outcomes [44]. Here medium and high ASI reduce attributed operational CO₂ in 2050 by 12.19% and 12.66%. These magnitudes are not directly comparable across policy references, geographies, intensities and accounting boundaries. The medium package's negative endpoint interaction and positive cumulative interaction show why a distant endpoint alone does not describe the transition.

4.2. Electrification Versus Low-Carbon Fuels Across Modes

Direct electrification reduces energy requirements, but its incremental effect depends on the regulatory reference and turnover. The PNIEC test demonstrates the replacement effort implied by an imposed near-term electrified-stock quantity under alternative allocations; target attainment is a control condition, not an estimated behavioural outcome. The broader sustainability assessment would also require the costs, materials and distributional consequences of accelerated replacement, which are outside this operational boundary. Mediterranean public-transport analysis also shows that the financial attractiveness of electric buses varies with local conditions and discount rates [45]; emissions reductions alone do not establish procurement affordability.

LCFs are most defensible as a residual option for aviation, remaining combustion vehicles, and other difficult-to-electrify services. The FF trajectory nearly eliminates attributed fossil-origin emissions, but renewable-carbon fuels still produce physical tailpipe CO₂ when combusted. In addition, synthetic-liquid, bio-liquid, and PtX-electricity requirements exceed their high screening envelopes in the Fossil-Free cases. These findings reinforce the conversion-loss and resource constraints identified in the electrofuel, aviation-fuel, and hydrogen literature [10,30–33].

4.3. Demand, Modal Shift, and Behavioural Feedbacks

Demand responds to both money and time costs, so efficiency and service improvements can partly increase activity. Swiss modelling shows that modal outcomes depend on travel-time duration and valuation [15]. Ribeiro et al. instead calculate the modal shifts required to meet an urban emissions target in Braga [46]. Those target-based shares are not observations or transferable national forecasts. Here the small emissions effect of the tested Shift package is conditional on the model and policy intensities; it does not

measure public-transport accessibility benefits or the full potential of active mobility, whose allocation is fixed.

Negative endpoint interaction terms indicate that summing isolated benefits overstates the combined endpoint reduction. Each policy changes the activity, technology and emissions base on which the others operate. Positive cumulative interaction for medium ASI shows that this statement is time-dependent. The net residual and proportional-overlap benchmark are consistent with several feedback and timing mechanisms; they do not identify a unique behavioural cause.

4.4. Policy Implications for Spain

For Spain, the comparisons suggest assessing demand management, service quality and electrification together under an explicit policy reference. Earlier turnover can improve cumulative outcomes, while Avoid reduces energy-service pressure at the endpoint. Subsidies, charging and replacement measures should be evaluated with their costs and distributional consequences, not only their attributed CO₂ effect. Mobility floors preserve selected essential services in the scenarios, but their social adequacy would require regional accessibility evidence. Spain-specific modelling finds that separating urban and non-urban demand changes decarbonization pathways and estimated costs [47], reinforcing the need to test these national results at a finer spatial resolution.

Low-carbon fuel deployment should be considered alongside direct electrification and demand measures, with explicit attention to conversion losses and competing resource uses. The capped tests show that most of the incremental FF endpoint benefit can disappear even when the total ASI package retains substantial mitigation. They provide a physical-availability sensitivity, not a complete allocation of scarce renewable resources across the economy.

Finally, faster bus and rail services require matching capacity, frequency, and accessibility. The modal ceilings used here are feasibility constraints, not targets, and the modest Shift result shows that capacity expansion alone does not guarantee a large national modal transition. The results are conditional pathways for Spain, not forecasts or welfare estimates.

4.5. Limitations and Future Research

The principal limitation is the operational emissions boundary. Vehicle and battery production, infrastructure construction, upstream fuel-processing emissions outside the attributed factors, indirect land-use change, non-CO₂ aviation effects, other greenhouse gases, local air pollutants, and non-exhaust particles are excluded. The near-zero FF result must therefore not be described as full well-to-wheel or life-cycle neutrality. Integrated life-cycle approaches such as Göhlich et al. [27] illustrate the broader assessment needed before comparing technologies on total environmental performance.

Historical and prospective uncertainty remain substantial. The specification-validation window has informed model selection, COVID choice changes are not reproduced, and the two-wheeler technology history relies on limited allocation proxies. Several inherited choice parameters remain at bounds or compensate one another; good trajectory fit does not establish causal identification. Constant aggregate real income and fixed terminal preferences condition the projections. OAT holds the historical state fixed and tests individual future perturbations; it does not propagate calibration uncertainty, joint parameter distributions or alternative structures. The resource-cap experiment imposes backfilling without a scarcity-price or competing-sector model, and the EU sales proxy omits manufacturer-level compliance. The fixed bicycle allocation does not reproduce the supplied historical bicycle estimates and is not independently validated.

The model is national and does not represent household heterogeneity, settlement density, accessibility, distributional incidence, regional charging disparities, or the full age distribution and used-vehicle trade of individual vehicles. The endogenous retention mechanism is deliberately parsimonious: it changes the mean natural lifetime by at most 20% and does not model inspection failure, maintenance expenditure, second-hand prices, or cross-border exports. Future work should estimate this response empirically and integrate explicit vehicle-age cohorts. Sustainable mobility also encompasses access, affordability, safety and distributional equity, which are not measured here. The modelling architecture may transfer to other countries, but its coefficients and numerical pathways require country-specific inputs, calibration and validation.

5. Conclusions

This study links passenger demand, modal and technology choice, fleet turnover, charging and fuel origins to examine sustainable-mobility trade-offs in Spain. Historical estimation supports conditional policy comparisons but does not validate a unique trajectory to 2050. The model distinguishes fitted choice preferences, inherited demand assumptions, policy settings and imposed quantity benchmarks. Sustainable development also requires accessibility and equity outcomes that are not quantified here.

At the central settings, Avoid, Shift, medium Improve and high Improve reduce attributed operational CO₂ in 2050 by 9.87%, 0.39%, 2.07% and 3.94%. Both combined CP packages are subadditive at the endpoint; medium ASI is superadditive cumulatively. These results support coordinated assessment rather than adding isolated mitigation wedges. Parameter and policy sensitivities qualify the numerical outcomes and do not supply probabilistic confidence.

Uncapped high ASI with FF fuels approaches zero attributed operational CO₂, but high resource caps raise the 2050 result to 29.49 Mt and physical combustion remains positive. Direct mitigation through demand, service provision and electrification must therefore be assessed alongside the resource requirements of residual fuels. The scenarios quantify operational energy and attributed CO₂ trade-offs, not full life-cycle neutrality or a complete sustainable-transport strategy.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18199914/s1>, Supplementary Data S1: Supplementary_Data.xlsx, contains historical series and provenance, estimation/evaluation metrics, scenario definitions, annual outputs, OAT and policy sensitivities, interaction, resource-cap, rebound and PNIEC-allocation calculations. Supplementary_Information.pdf provides supplementary methods and tables, detailed LDV fits (Figure S1), resource-cap and accounting comparisons (Figure S2), deterministic sensitivities (Figure S3), energy trajectories (Figure S4), BEV stock shares (Figure S5) and explanatory captions. These two files constitute the Supplementary Materials intended for publication.

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Abbreviations

The following abbreviations are used in this manuscript:

AFIR	Alternative Fuels Infrastructure Regulation
ASI	Avoid-Shift-Improve
BEV	Battery-electric vehicle
BTL	Biomass-to-liquid
CO ₂	Carbon dioxide
CP	Current-Policy low-carbon-fuel trajectory
EAFO	European Alternative Fuels Observatory
EV	Electric traction
FAME	Fatty acid methyl ester
FCEV	Fuel-cell electric vehicle
FF	Fossil-Free low-carbon-fuel trajectory
GHG	Greenhouse gas
HEV	Hybrid electric vehicle
HPV	Human-powered vehicle
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
JRC-IDEES	Joint Research Centre Integrated Database of the European Energy System
LCF	Low-carbon fuel
LDV	Light-duty vehicle
NMT	Non-motorized transport
PHEV	Plug-in hybrid electric vehicle
pkm	Passenger-kilometre
PNIEC	Plan Nacional Integrado de Energia y Clima
PtX	Power-to-X
R ²	Coefficient of determination
RMSE	Root-mean-square error
SAF	Sustainable aviation fuel
SD	System dynamics
TCO	Total cost of ownership
WTW	Well-to-wheel

Appendix A. Model Parameters and Sensitivity Settings

Table A1 reports effective demand, choice and sensitivity settings. Table A2 reports mode-specific CP_1 and inertia parameters. CP_1 weights TC and $CP_2 = 1 - CP_1$ weights TA . Maximum shares are capacity parameters and minimum shares include the prospective essential-mobility assumptions.

Table A1. Selected aggregate-demand, LDV technology-choice, learning, and charging parameters.

Parameter	Effective Central Setting	Prospective OAT/Note
Income elasticity	0.5994135	0.30; 1.20
Generalized-cost elasticity	1	×0.75; ×1.25
Real aggregate income, 2050/2023	1	Constant central path
Modal TA sensitivity	6.73544	Historically estimated
Technology TA sensitivity, LDVs	0.43149	All mode sensitivities ×0.75/1.25
BEV charging-anxiety amplitude	0.0958696	×0.5; ×1.5
BEV learning per doubling	0.08	0.04; 0.12
Effective road-vehicle lifetime	Mode/technology-dependent	×0.8; ×1.2 after 2025
BUS/2W technology adjustment	1 – destination inertia	×0.75; ×1.25; inertia clipped [0, 0.995]
Modal/technology seeding	0.1/0.000124	Fitted, common within level
Price-memory time	1.688 years	Fitted
Natural-lifetime retention cap	1.20	Disabled in PNIEC target
Historical preference extrapolation	Constant terminal calibrated level	Policy changes added to base

Table A2. Selected modal and nested technology-allocation parameters.

Mode	Modal CP ₁	Modal Inertia	Tech. CP ₁	Tech. Inertia Range
LDV	0.1713	0.2500	0.0000	0.3915–0.4018
BUS	0.0000	0.2992	0.0345	0.0443–0.4040
2W/3W	0.1157	0.2988	0.2327	0.3995–0.4000
RAIL_URBAN	0.0000	0.2997	0.2090	0.7771–0.7771
RAIL_CONV	0.0317	0.3137	1.0000	0.3210–0.3474
RAIL_HS	0.0124	0.2953	0.2090	0.7771–0.7771
AIR_DOMESTIC	0.0000	0.2679	0.2090	0.0429–0.0429
AIR_INTRA_EU	0.0346	0.2178	0.2090	0.0429–0.0429
AIR_INTERNATIONAL	0.0000	0.2900	0.2090	0.0429–0.0429
MARINE	0.0024	0.3004	0.2090	0.0429–0.0429
NMT	0.9519	0.3000	0.2090	0.7771–0.7771

Note: Technology inertia varies by destination powertrain; the displayed range covers historically active technologies. A zero TA weight leaves TC price response active. Entries for modes without historical powertrain competition are inherited structural settings, not independently estimated technology-choice parameters. NMT is fixed. Prospective mobility floors apply as described in Section 2.4.

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