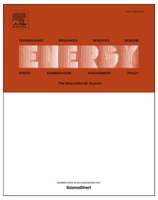
Energy 305 (2024) 132313

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Exploring the potential of a novel passenger transport model to study the decarbonization of the transport sector

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ARTICLE INFO

Handling editor: Neven Duic

Keywords:
Passenger transport
Direct GHG emissions
System dynamics
Transport energy
Materials demand
Behavioural change
Private transport
Public transport

ABSTRACT

To explore sustainability strategies in the transport sector in a holistic way, a model dedicated to passenger transportation has been created as a part of the multiregional WILIAM model (Within Limits Integrated Assessment Model). Based on system dynamics, our model increases the diversity of existing passenger transport models within Integrated Assessments Models by offering a detailed representation of the dynamics of the transition for different technologies and transport modes combining technological and behavioural changes. It calculates the energy demand, direct emissions and additional material requirements of the transport sector and can be linked to other submodules of WILIAM to study different feedback loops. Here we report the validation of the offline model and illustrate its usefulness and practical applicability. First, a Baseline transport scenario for Spain was developed and parametrized. This scenario describes the plausible evolution of the Spanish passenger transport system in the absence of ambitious environmental policies but nevertheless achieves a reduction of total direct CO_2 emissions from passenger transport from 66 Mt CO_2/year in 2022 to 60 Mt CO_2/year in 2035, after which emissions remain constant until 2050. Subsequently, following the Avoid-Shift-Improve approach, various behavioural change measures and technological improvements were introduced. The comparison of the different modelled measures reveals that the most effective tested strategy to reduce direct emissions is the transition to battery electric power trains for cars, buses, and motorcycles, however at the cost of the highest material requirements. Further work will be dedicated to the study of the implications of the link of this sub-module with the rest of WILIAM.

1. Introduction and background

In the context of accelerating climate change, EU member states have made commitments to become climate neutral by reducing greenhouse gas direct emissions in all economic sectors by at least 55 % below 1990 levels by 2030 [1], including the transport sector as a key source of greenhouse gas (GHG) direct emissions and the sector where direct emissions have increased the fastest [2]. However, to mitigate direct emissions related to the transport system through environmental policies and/or behavioural change measures, it is necessary to determine what percentage of these direct emissions correspond to each type of transport, as this would make it possible to develop strategies that address each type of transport specifically. Technological advances and the development of a new transport infrastructure have proven to be insufficient to meet emission reduction targets, and thus, might need to be complemented by a promotion of significant changes of mobility behaviour [3]. Given that the use of personal vehicles, along with food production and residential housing use, is one of the main sources of direct emissions per capita worldwide [4], the case for inducing changes in behavioural patterns to decarbonise our societies gains further relevance.

A wide range of different policies and behavioural change measures related to the (passenger) transport sector have been developed and explored in the literature. These can be grouped according to the ASI (Avoid – Shift – Improve) approach to sustainability which was developed in the 1990ies in Germany precisely to structure policy measures aiming at reducing the environmental impact of transport [5].

Under *Avoid* all measures are included that focus on improving the efficiency of the system by reducing the need for the use of transport, such as carpooling, carsharing or vehicle sharing in general, seek greater efficiency in the use of private transport. Quantitative studies have explored the GHG emissions reduction potential of direct policies of cars use reduction [6], ride sharing [7], the increase of car occupancy [8], and car population control [9], as well as measures that affect total

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https://doi.org/10.1016/j.energy.2024.132313
Received 19 December 2023; Received in revised form 20 June 2024; Accepted 2 July 2024

transport demand by focusing on reducing the number of annual kilometres of vehicle use [10,11]. Last, a series of studies focuses on the relationship between teleworking and transport behaviour which is mediated by external factors (e.g. the Corona crisis [12]) by climate policies [3,11,13] or by individual motivations to change behaviour [14]. Equally, studies have attempted to quantify the transport-related emission reductions of behavioural changes regarding the purchase of goods and services such as online shopping [15,16], and regarding leisure, such as a reduction of leisure trips [15] and transatlantic flights [17] or even more restrictive measures that eliminate all air transport services [6]. Last, studies have investigated the impacts of carpooling and tip-chaining on GHG direct emissions [18], energy savings [19] and distance traveled [20], as well as the impacts of carpooling/carsharing on GHG direct emissions [13] and energy consumption [21],

Measures that fall within the *Shift* category focus on the shift from a less efficient mode of transport to a more efficient one in terms of environmental impact. Policies that have been quantified include a shift of 15 % of overall passenger transport demand to urban transport [11], shifting short-haul air travel to train [15], increasing active modes of transport (walking or cycling) [8,11], or shifting the entire car consumption to other modes of transport [17]. In some cases, these measures are supported by policies that incentivise the shift to cleaner modes through carbon taxes [4], joint measures to support the acquisition of alternative fuel vehicles together with fuel taxes [22], and others measures that facilitate a transport modal shift,[1] such as investment in public transport infrastructures and public space use plans, which are expected to have the potential to achieve reductions of up to 50 % in GHG direct emissions between 2011 and 2040 in Europe [23].

Last, measures of the category *Improve* focus on reducing the impacts caused by vehicles by improving vehicle efficiency within the given mode of transport. The literature that has researched the impacts of measures of the *Improve* category has mainly focused on cars such as replacing current cars with newer, more efficient ones [17,19], or buying smaller cars [3]. Further measures whose impacts on energy use and GHG emission reductions have been quantified include the change to new technologies and alternative fuels, such as changing from gasoline to electric motorcycles with [24], from gasoline to hybrid cars [17], and the shift to fuel efficient vehicles [18]. Changes in the driving mode, while keeping the same vehicle, also allow improvements in energy efficiency, e.g. a fuel-efficient driving style [3,19], which also referred to as eco-driving [13,14]. It has been shown that even fostering proper vehicle maintenance generates sustained energy reductions [19].

Apart from the wide variety of policies addressing the passenger transport sector, different Integrated Assessment Models (IAMs) have been developed in recent years that include the transport sector and enable a coupling of this sector with other sectors and the biophysical system. Most transport IAM models are equilibrium top-down models, and some of them integrate behavioural changes by varying factors in the equilibrium equations. Among the equilibrium models, there are partial equilibrium models like IMAGE [25], TIAM-UCL,[2] and general-equilibrium models like IMACLIM [26], MESSAGE-Transport [27,28], WITCH [29], and GEM-E3T-ICCS [30]. Regarding the transport module, the models MESSAGE, TIAM-UCL and WITCH use least-cost minimization algorithms, while the remaining models use discrete choice equations for calculating the vehicle choice in each scenario. Other transport models in use include the TRIMODE model, a multimodal transport model that covers all modes of passenger and freight transport in Europe and its neighbouring countries. It is based on a general equilibrium approach that represents the behaviour of economic agents (consumers, producers, government) and the functioning of markets (goods, factors, money) in an open economy. The TRIMODE model also incorporates environmental and climatic aspects, and makes it possible to assess the impact of different transport policies on social welfare [31]. Likewise, the UKTCM (United Kingdom Transport Carbon Model), a partial equilibrium model that represents the behaviour of the passengers and transport operators, allows estimating the carbon direct emissions of the transport sector in the UK under different demand, supply and policy scenarios. UKTCM covers a high range of vehicle technologies and makes it possible to explore a broad range of policy interventions [32]. Finally the GCAM model is a dynamic recursive economic model that takes into account prices to explore the implications of the different policies applied [33].

Despite the wide range of different policies and behavioural change measures that have been explored in the literature, and despite the significant amounts of IAMs accounting for the transport sector, systematic and thorough comparisons of the quantitative effect of different transport policies addressing technological and behavior/lifestyle changes with regard to GHG mitigation are underdeveloped in the literature [34], Appendix I. One consequence of this it the scarcity of plausible 'Baseline scenarios' for the transport sector that describe the likely development of the transport sector in the absence of environmental policies, as well as the comparison of this Baseline scenario with alternative scenarios including different policy and/or behavioural change measures. However, systematic scenario analysis is of special importance for transport models integrated in greater IAMs, as well as for transport modules that offer a high degree of detail about different modes of transport and their power trains, since they can reveal interesting results and point to effective policy instruments.

This work takes a first step towards a systematic quantification of possible and desirable future developments of the transport sector by presenting a novel passenger transport system dynamics model that can offer a detailed representation of the transport sector and introduces a wide range of different policies and/or individually motivated behavioural changes relying on key variables such as modal split,[3] load factor of private transport modes, or vehicle efficiency.

Our research contributes to the burgeoning field of transport models and sustainable mobility policies in the following ways: First, in contrast to the models reviewed, the model presented in this work is a bottom-up system dynamics model (cf. section 2.3) that integrates direct measures of behaviour change on physical elements of the passenger transport system without relying on partial or general equilibrium of neoclassical economics. At the same time, it is able to simulate policies addressing both technological and behavioural change, and thus, increases model diversity in the literature focusing on technological as well as lifestyle-oriented scenarios in the transport sector [35,36]. Second, our model accounts for the complexity of technologies used in modern passenger transport systems: It offers the possibility to represent different types of motorisations and to cross-reference them with different modes of transport, including both the energy consumed, and the direct GHG emissions generated, i.e. CO_2, methane, and nitrous oxide, which, in comparison to existing studies regarding car mobility and electricity generation [37], or different behavioural and mobility typologies in urban transport [38], allows a more detailed analysis of the environmental impacts of technological and behavioural changes in the transport sector.

Third, being a sub-module of the newly developed IAM 'WILIAM' [39–41] our transport model can be linked with other submodules to explore different complex feedback loops. One relatively simple example is the linking between the transport and the material sub-module to explore the effect of material demands generated within the transport sub-module on mineral scarcity calculated in the material

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[1] Transport modal shift refers to a change from one form of transport to another, for example a switch from cars to bus, or airplane to train.

[2] TIAM-UCL: model details available at https://www.ucl.ac.uk/energy-models/models/tiam-ucl.

[3] Modal split: the term "transport modal split" refers to the distribution or allocation of passengers among different transportation nodes within a particular geographical area or network.

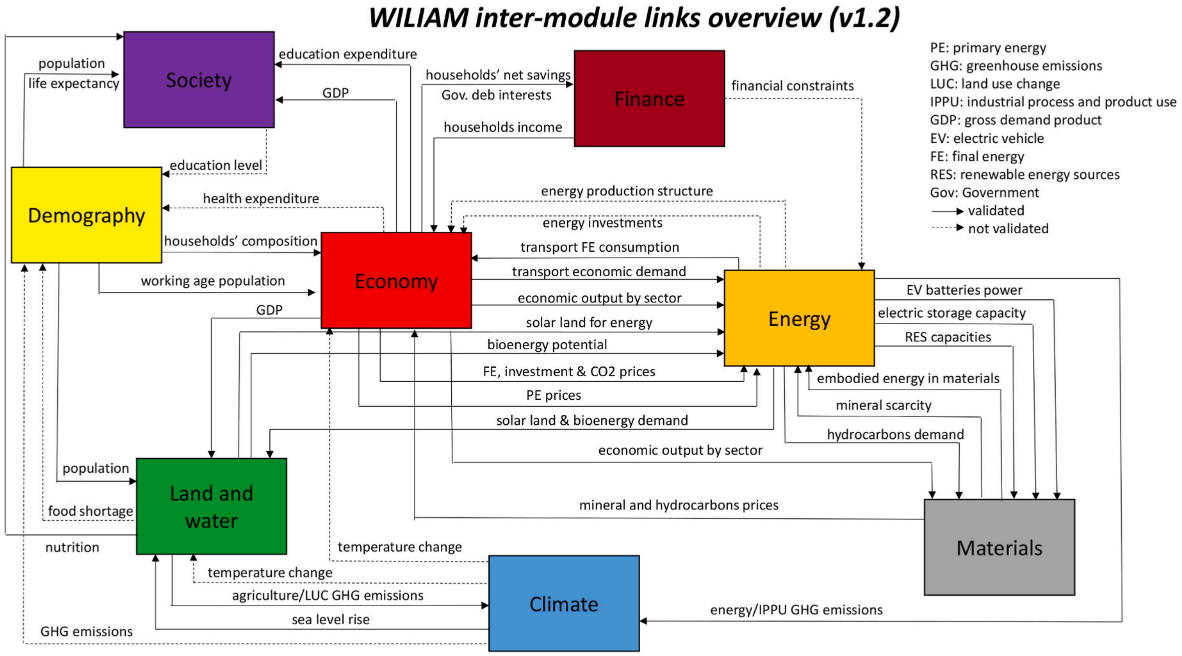

Fig. 1. Overview WILIAM

sub-module (cf. section 2.2). Although the literature on transport electrification and material implications is rapidly evolving [42,43], studies that calculate the material demand for a range of different transport scenarios are still rare [44].

To illustrate the usefulness and practical applicability of the model, a transport scenario for Spain is developed and parametrized to describe the plausible evolution of the Spanish passenger transport sector in the absence of ambitious environmental policies. A first attempt is then made at exploring the effect of different transport measures on the scenario outcome and on corresponding biophysical parameters such as energy, materials, and greenhouse gas emissions.

2. Materials and methods

A system dynamics (SD) approach was used to develop the transport model which is at the same time a sub-module of the IAM WILIAM. SD allows simulating different scenarios resulting from the dynamic interactions between multiple variables in time which leads to insights about the system's behaviour remain hidden to a static or reductionist analysis [45]. The approach can handle the inherent complexity and non-linear relations characteristic of passenger transport systems since it allows to represent various feedback loops between variables. Additionally, it allows to consider external factors affecting transportation systems, such as economic conditions, government policies, and lifestyle changes.

2.1. Combination of system dynamics and Avoid-Shift-Improve methodology

This paper employs a combined approach, utilizing both the SD approach to modelling with the ASI (Avoid-Shift-Improve) methodology to represent behavioural changes of households and their consequences for energy consumption, direct emissions and mineral demand, in our transport model. ASI is considered a viable alternative to the classical Predict-Provide-Manage approach by offering a broader perspective for the design of a less environmentally harmful transport system. *Avoid* focus on the efficiency of the whole transport system by reducing or avoiding the need to travel, *Shift* seeks to improve efficiency through transport modal changes,[4] and *Improve* refers to change vehicles efficiency maintaining the same transport mode (internal combustion engines to battery electric systems) (cf. section 1). The approach enables us to structure the main variables that define the total transport demand and to split this demand into its constituent parts in such a way that it is possible to modify each of its factors and thus to apply different behavioural change measures [46].

2.2. Overview of the 'Within Limits Integrated Assessment Model'

The Within Limits Integrated Assessment Model (WILIAM) has been developed under the LOCOMOTION H2020 project [47]. WILIAM v1.2.0.8 [41] is a SD policy-simulation model which was designed to address a series of common and relevant limitations in the field of IAMs, and can be seen as a follow-up and extension of the IAM MEDEAS [48]. WILIAM comprises 8 integrated modules of earth and human systems: (1) demography, (2) society, (3) economy, (4) finance, (5) energy, (6) materials, (7) land and water, and (8) climate. Fig. 1 shows an overview of its structure, including the main linkages between modules. A detailed description of the model is available in Refs. [40,49].

2.3. Transport sub-module

Within the WILIAM energy module, a passenger transport submodule has been developed to model the behaviour of household transport demand and calculate both the energy consumed and the

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[4] Transport modal changes refers to shifts or transitions in the utilization of different transportation modes within a given region or transportation system over a certain period. These changes can involve alterations in the proportion of passengers or freight choosing one mode of transport over another, such as a decrease in car usage accompanied by an increase in public transport use or cycling.

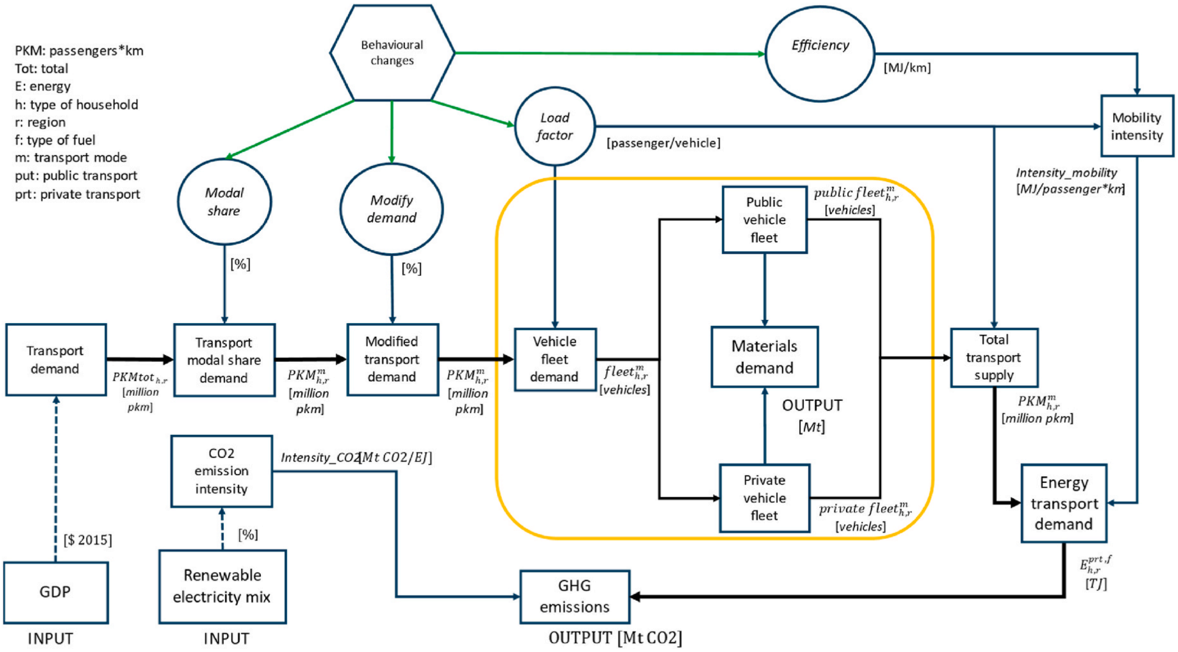

Fig. 2. Transport submodule internal diagram. The four main behaviour-related parameters are depicted in circles. Key variables influencing different parts of the model are written in Italics. Units are written in brackets.

emissions generated by this demand.

2.3.1. *Structure of passenger transport sub-module*

Within the energy module of WILIAM, a multi-regional passenger transport sub-module has been developed which facilitates the in-depth study of the specific cases of the countries belonging to the EU, which means considering a total of 35 global regions and countries.

The integration of the transport sub-module in WILIAM required the adaptation of the sub-module to a series of conditioning factors such as the fact that the total transport demand variable was determined by the sub-module of households (a part of the economic module) or that the energy demand has two possible outputs, public and private transport, as shown in Fig. 2. For the first exploration of the potential of the transport sub-module through the development of a Baseline scenario (cf. section 4.1), the variables *transport economic demand* (of the economic module) was disconnected from the transport sub-module to ease reporting the internal dynamics of the sub-module. Thus, it was necessary to make slight changes to the transport sub-module and its linkages to WILIAM, so that the variable that calculates the total demand for transport does not come from the 'households' submodule but is exogenously modelled based on the historic evolution of GDP. Likewise, since WILIAM calculates the emission intensity on a regional rather than on a national level, and the CO_2 emissions intensity of electricity production depends on the share of renewables in the *national* electricity mix (Fig. 2), the percentage of renewable electricity needs to be introduced exogenously. In the case of Spain, the percentage of renewable technologies for electricity production has increased from 20 % in 2006 to 50 % in 2023. Estimates from historical adjusted projections point to a renewable electricity production of almost 90 % in 2050 (see Supplementary Material S3.1). All other linkages with the different submodules were maintained. Thus, apart from the exogenous input variables *GDP* and *CO_2* electricity emission intensity all the variables necessary to implement behavioural change policies in the model, such as the modal share of the vehicle fleet, the load factor of the transport mode, the efficiency of the different technologies and the transport demand shift variable (see Fig. 2). Energy demand, the demand for materials due to electric technologies and their energy storage systems is also calculated, as well as the CO2, methane, and nitrous oxide direct emissions of the entire transport fleet.

Feeding on these variables, the transport model can generate the desired demand for passenger transport by type of technology and mode of transport, and through the variable *load factor*, the vehicle fleet necessary to satisfy the demand for transport. The vehicle fleet, vehicle load factor and mobility intensity variables generate the energy demand of the transport sector. Finally, CO_2 emissions are calculated with the energy demand and the emission intensity.

The load factor variable is modelled in two different ways. For private transport vehicles the load factor follows the Baseline trends unless the exogenous *load factor* variable is modified. For public vehicles, the load factor evolves internally, towards maximum values, if a modal shift measure increases the demand for a specific transport fleet. The variables *distance* per *vehicle* and *vehicle fleet* evolve endogenously according to the modified variables *transport demand* and *load factor*.

2.3.2. *Data*

The following data sources were used to obtain the relevant historical data for the Baseline scenario and the scenario variations, i.e. vehicle load factor, annual distance traveled per vehicle, transport demand by vehicle type and engine, and energy used by transport mode and power train: for EU28 countries: The European JRC "Integrated Database of the European Energy System" (JRC-IDEES) [50], for non EU28 countries: the Supplementary Material of [51] or, and data from the JRC-IDEES database for EU [50] for specific energy demand. Spain train sector [52–54], for non-motorized transport [55], walking an cycling [56–58], Spain Air transport [59].

2.3.3. *Validation*

Validation was performed for the historical period setting the scenario parameters of the model with empirical data, and letting the model calculate endogenously the rest of variables. The main endogenous variable used for validation is CO_2 emissions per type of transport mode [60] for the period 2005–2021 (cf. section 4.1.2 Results).

2.3.4. *Measures reducing environmental impact*

The transport module allows to implement different behaviour change measures through modifications in 4 main parameters: (1)

Table 1
Categorised behavioural change measures.

Type of behavioural change	Measures
Avoid (trip distance, number of trips, both)	Teleworking [13,14,61]
	Shorter urban car trips [11]
	Closer holidays [13]
	Compact cities [23]
	Car sharing [13,61]
	Carpool [13,19]
	Increase urban car occupancy [10, 11]
	No Flying [62]
Shift (to less environmentally harmful transport mode)	Modal shift to public transport [4, 11,15]
	Modal shift to cycling [11,15]
	Modal shift to walking (ibid.)
	Modal shift airplane to train [23, 63]
	Bike sharing [61]
Improve (energy efficiency)	Switch to more fuel efficiency vehicle [18]
	Driving behaviour (ibid.)
	Buy and use smaller cars [19]
	Switch to an alternative fuel car [24]
	Fuel-efficient driving [13,14]
Combinations	Avoid short flights [13]
	Extend vehicle lifetime [3]

Transport demand; (2) Fuel consumption efficiency; (3) Transport demand share and (4) Load factor. These parameters are stored in an excel file that allows the user to modify, for each of them, the target value of the measure applied, the initial year of application of the measure and the final year in which the target value of the measure is reached (see Supplementary_material_measure_data.xlsx). Each of the four parameters depends on various multidimensional factors. For example, the 'Transport demand' parameter depends on the type of power train and the type of transport mode, with the user being able to choose between 10 different types of power trains (Internal combustion engine (ICE) gasoline, ICE diesel, ICE LPG, ICE gas, Battery Electric Vehicle (EV), Plugin Hybrid EV, Hybrid EV, Fuel Cell EV, EV, Human Powered Vehicle), and 9 different types of transport modes (Light Duty Vehicle (LDV), 2 Wheels & 3 Wheels (2W3W), Non-Motorized Transport (NMT), Bus transport, Rail transport, Domestic Air transport, Intra-EU Air transport, International Air transport, Marine transport). The fuel consumption efficiency parameter is equally determined by these 10 types of power trains and 9 types of transport modes. The transport demand share parameter depends on the type of region (35 regions to choose from which correspond to the WILIAM regions), the type of power train and transport mode. Last, the Load factor parameter depends on 3 types of the *private* transport modes (LDV, 2W3W, NMT) (for more details see Supplementary Material S1 & S2). This can be represented in a compact format as follows (brackets indicate factors, subscripts indicate dimensions):

$$Transport\ demand\left[power\ train_p, transport\ mode_t\right] \ (1)$$

$$Fuel\ consumption\ efficiency\left[power\ train_p, transport\ mode_t\right] \ (2)$$

$$Transport\ demand\ share\left[region_r, power\ train_p, transport\ mode_t\right] \ (3)$$

$$Load\ factor\left[private\ transport\ mode_{tpriv}\right] \ (4)$$

p : 10 *types of power trains*

t : 9 *types of transport modes*

$tpriv$: 3 *types of private transport modes*

r : 35 *regions*

A summary of the different behaviour changes measures that can be modelled directly or indirectly with the presented transport module is listed in Table 1.

3. Scenario analysis

A Baseline scenario of the passenger transport system in Spain was developed and quantified, and 5 variations (V1 – V5) of the Baseline scenario due to the introduction of different behaviour change measures regarding passenger transport. To show the potential of the model to evaluate different measures connected to behavioural changes at least one measure has been chosen for each of the ASI dimensions for each variation.

The storyline of the Baseline scenario consists of a plausible description of future developments in the Spanish transport system without stringent environmental policies and without significant behavioural changes in the population.

V1 accounts for behavioural change to avoid unnecessary use of cars (A), V2 explores shifts in individual mobility between transport modes (S), V3 and V4 explore the implications of the change to more efficient motorisations (I), and V5 combines different measures in the transport mode and power train of vehicles.

Concretely, V1 models behavioural changes regarding car-pooling, namely increasing the occupancy of private cars. V2 focuses on shifting air travel to train and display synergies with the increase in renewable electricity generation. The measure explored in V3 refers to behavioural changes linked to driving style (fuel-efficient driving, well

Table 2
Summary of Baseline scenario and variations.

Scenario	Definition	ASI dimension	Load factor	Modal share	Power train	Energy efficiency
BS	Baseline scenario	–	Current trends	Current trends	Current trends	Current trends
V1	Increasing the load factor of passengers' cars	Avoid	1.2 to 2	Current trends	Current trends	Current trends
V2	Shift domestic (peninsular) air to train transport.	Shift	Current trends	Air domestic → Train	Current trends	Current trends
V3	Improve efficiency	Improve[a]	Current trends	Current trends	Current trends	Increase
V4	Update road transport modes to BEV power train	Improve[b]	Current trends	Current trends	LDV, 2W 3W and BUS → BEV	Current trends
V5	Shift to public and active transport + technological change	Shift + Improve	Current trends	LDV → BUS + cycling	BUS ICE→BUS BEV	Current trends

[a] In this baseline scenario variation, energy efficiency is increased by changing the "efficiency" variable exogenously.

[b] In this case, there is an improvement in energy efficiency due to the upgrade of the fleet of land vehicles (LDV, 2W_3W and BUS) to battery electric engines, which are more efficient than internal combustion technologies.

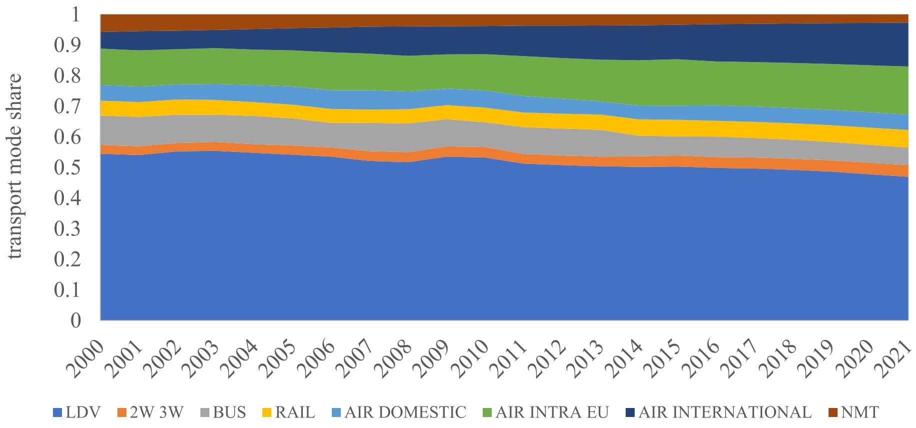

Fig. 3. Historic transport modal share demand (share of pass*km) of Spain (2000–2021).

maintained vehicles) that increases vehicle energy efficiency. Thus, the number of new vehicles can be reduced. V4 implies a change towards a specific type of engine in all road vehicles, which implies a strong investment in new types of vehicles. Finally, V5 combines measures to switch to public transport with a shift to more efficient motorisations. The 5 variations have been selected among all the possibilities of the module considering their social and scientific relevance as assessed by the literature review, and their diversity to show the versatility and potentialities of the developed submodule. Table 2 provides a summary of the Baseline scenario and the variations.

For all variations (V1–V5), the same total transport demand has been used as for the Baseline. The measures all start in 2025 and are applied

Table 3
Regression models for transport modes by power train.

Transport mode			Power train	
Type	Regression model [equation]	Transport model share in 2050, Baseline	Regression model [equation]	Power train share in 2050, Baseline
Passenger Light duty vehicles (LDV)	*LDV* = exp *(18.561 - 0.00954958*Year)*	36.2 %.	*ICE gasoline* = exp *(52.1566 - 0.0269119*Year)*	5.1 %
			ICE diesel = exp *(40.9109 - 0.0207621*Year)*	19.84 %
			ICE_LPG = 0,00135681/(1+EXP(-0,702585(Year-2017,15)))*	0.14 %
			ICE gas = 0,000680487/(1+EXP(-0,771215(Year-2019,35)))*	0.07 %
			BEV = 0,016724/(1+EXP(-0,479273(Year-2025,62))*	1.67 %
			PHEV = 0,0249084/(1+EXP(-0,799756(Year-2023,77))*	2.49 %
			HEV = 0,0694559/(1+EXP(-0,256717(Year-2030,26))*	6.9 %
2- and 3-wheel vehicles (2W 3W)	*2W_3W* = exp *(-34.3046 + 0.0153746*Year)/(1 +* exp *(-34.3046 + 0.0153746*Year))*	5.8 %	*ICE gasoline = -0.462463 + 1,20506E-7*Year^2*	4.4 %
			BEV = 0,00565139/(1+EXP(-0,379494(Year-2025,11))*	0.57 %
			HPV	0.84 %
Buses transport demand (BUS)	*157,086-0,153732*Year + 0,0000376216*Year^2*	4.03 %	*ICE gasoline* = exp *(96.7106 - 0.05223*Year)*	0 %
			ICE diesel = exp *(95.4224 - 0.0487522*Year)*	1.1 %
			*ICE gas = -0.370839 + 9,28346E-8*Year^2*	1.93 %
			BEV = 0,00350108/(1+EXP(-0,317492(Year-2022,67))*	0.35 %
			PHEV = 0,000401141/(1+EXP(-0,399996(Year-2021,9)))*	0.04 %
			HEV = 0,00596501/(1+EXP(-0,397267(Year-2022,23))*	0.6 %
Rail passengers transport vehicles (RAIL)	exp *(-23.4822 + 0.0102114*Year)/(1 +* exp *(-23.4822 + 0.0102114*Year))*	7.25 %	*ICE diesel* = exp *(170,181 - 0.086953*Year)/(1 +* exp *(170,181 - 0,086953*Year))170,181 -0.086953*Year*	0.03 %
			EV	7.22 %
Air transport inside Spain[a] (AIR DOMESTIC)	–	5.03 %	–	5.03 %
International air transport (AIR INTERNATIONAL)[b]	*0,218418/(1+EXP(-0,0808319*(Year-2013,14))*	20.8 %	–	20.8 %
Air transport inside EU (AIR INTRA EU)[c]	*0,200329/(1+EXP(-0,0461105*(Year-1996,38))*	18.47 %	–	18.47 %
Non-motorized modes[d]	–	2.42 %	–	2.42 %

[a] Excluded from the statistical analysis because of the low R-squared value, instead of this the AIR DOMESTIC share is the same that the last historic year in all the simulation.

[b] No power train analysis because airplanes only use 1 type of power train.

[c] Same as previous note.

[d] The transport modal share for NMT transport is calculated as the % needed to reach the 100 % of total transport mode.

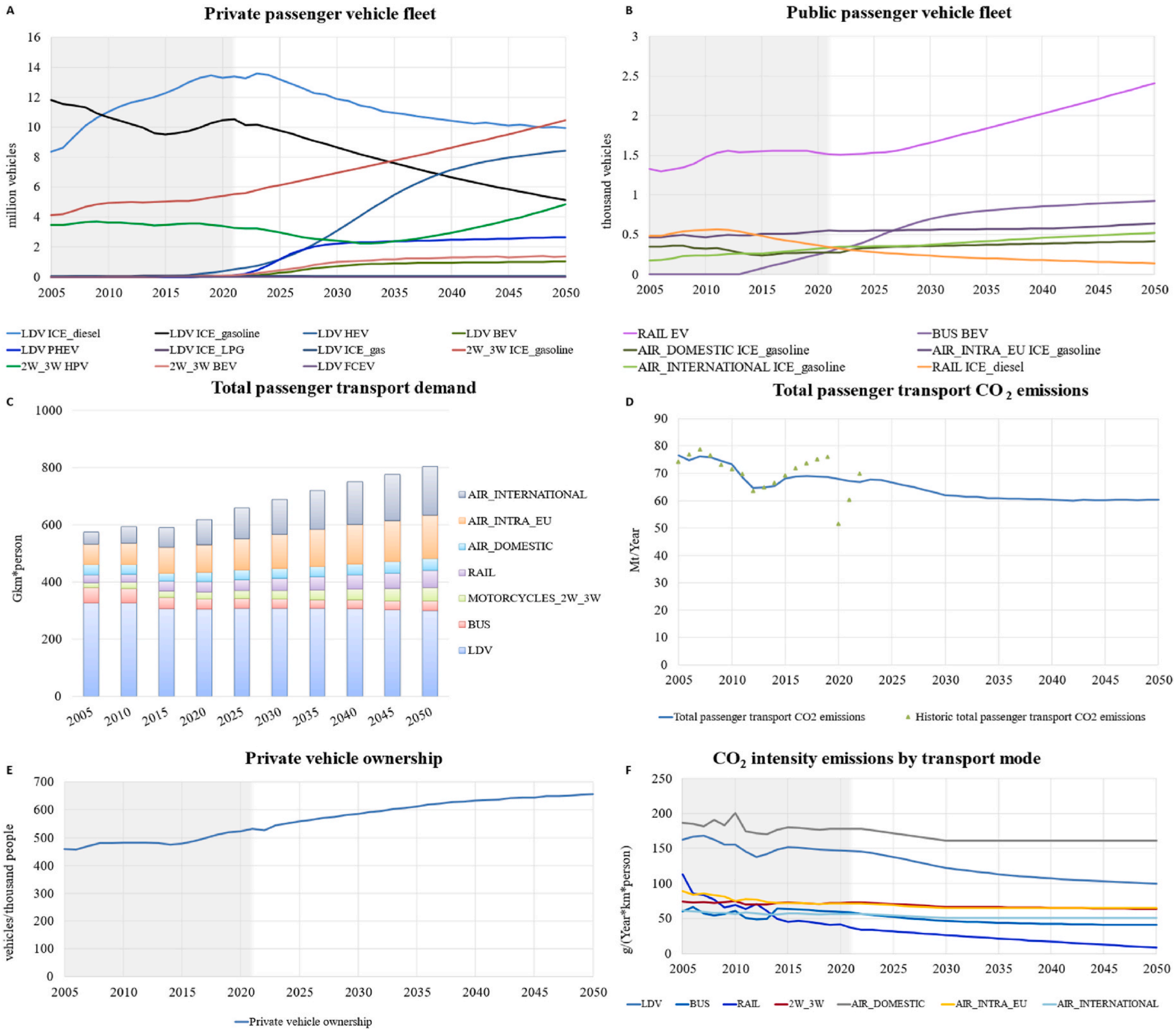

Fig. 4. Baseline scenario results (Grey area represents the historical period where empirical data was used to calibrate model parameters).

progressively until 2050.

Below is a summary of the baseline storyline that was subsequently quantified. For the full narrative see Supplementary Material S4.1.

This scenario assumes a continuation of historical trends in passenger transport occurring in the absence of major structural changes in the political and economic organisation in Spain. The tendency of Spanish citizens to use part of their higher incomes to increase their mobility remains unchanged. In line with the overall global context, most Spanish citizens prefer to travel by car, either for commuting or for private enjoyment, rather than by public transport. At the same time, an increasing number of citizens are starting to adopt mobility patterns previously reserved for other regions, including air travel within Spain, to EU countries and to other continents, mainly for recreational purposes (tourism). However, public policies prevent the trend towards car and air travel from growing exponentially at the expense of public transport. Spanish regional and national authorities remain committed to maintaining basic levels of public transport within and between cities, including minimum levels of bus transport and to follow the historical trend of promoting electricity produced by renewables.

4. Results

In the following, the results of simulating the Baseline scenario as well as its variations V1–V5 will be presented.

4.1. Baseline scenario

Before displaying the Baseline scenario's results, this subsection shortly explains main aspects of its parametrization.

4.1.1. Baseline Parametrization

The model can represent four types of main variables: Transport mode (LDV, BUS, …), power train (ICE gasoline, diesel, BEV …), final energy (electricity, liquids, gas, hydrogen) and GHG direct emissions (cf. Table S3, Supplementary Material). Consequently, the parametrization of the Baseline scenario had to address all four dimensions. First, total future transport demand which influences all four dimensions, was modelled as a function of future GDP growth which was projected from historical data. Second, the historical evolution and projected future development of each transport mode and each power train has been derived, using historical data and statistical analysis to extrapolate this data. Third, using the same methods, the historical and projected CO_2 intensity of electricity, which depends on the region's electricity mix and on the share of renewables, and which affects GHG direct emissions, were calculated. This led to a remarkably high share of renewables in the electricity mix at the end of the simulation in the Baseline scenario (almost 90 % in 2050). Supplementary material S4 provides further details on the parametrization process, including the main variables, equations, and statistical analyses. A strong increase in the end-of-life (EOL) recycling rates of materials present in EV batteries is assumed (for details consult the Supplementary Material).

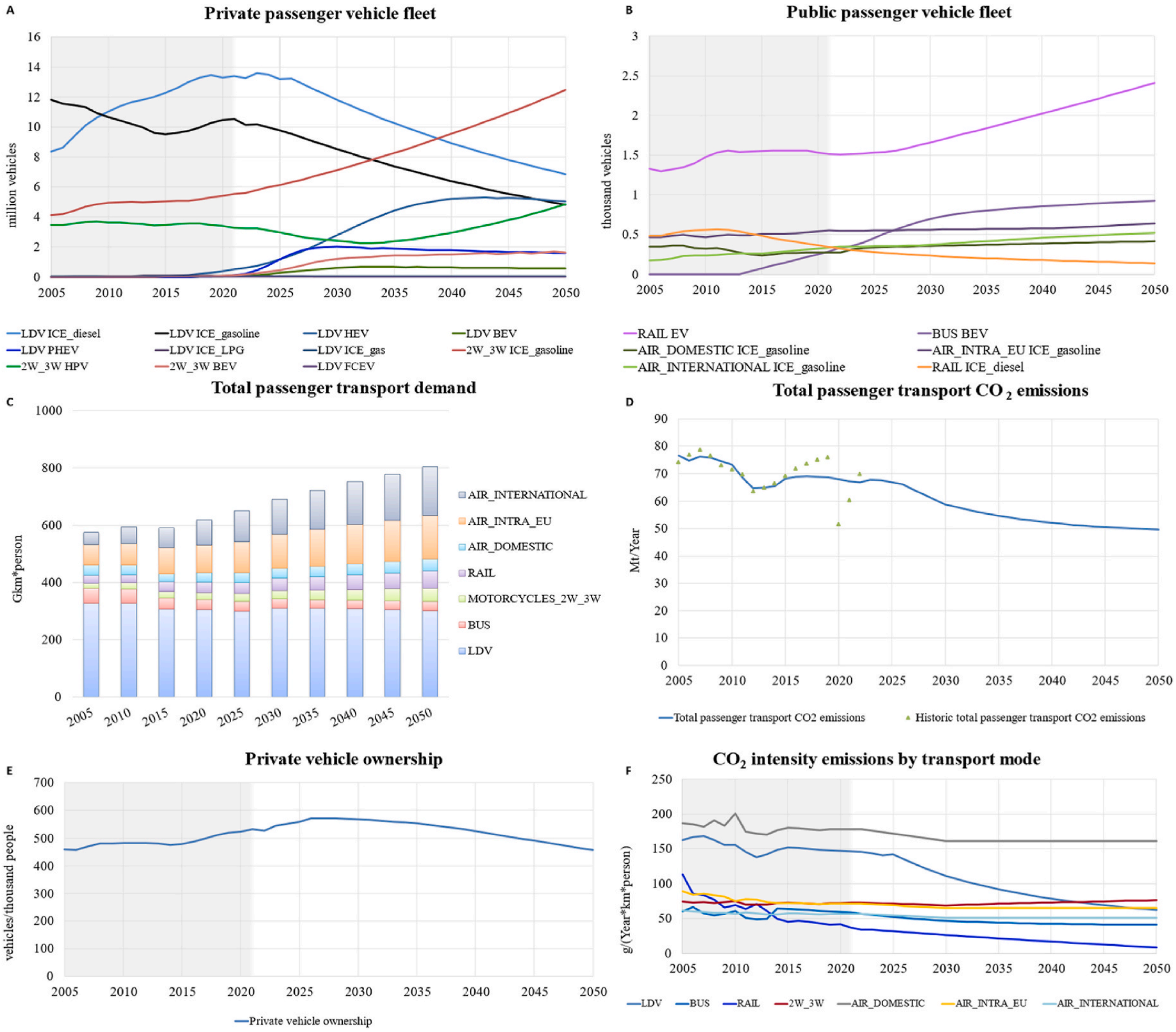

Fig. 5. Baseline Variation 1 (Grey area represents the historical period where empirical data are used for the scenario parameters of the model).

Fig. 3, shows the historic evolution of transport demand (pass*km) shares by transport mode while Table 3 gives an overview of the equations describing the projected future evolution of the different transport modes and power trains.

4.1.2. Baseline Results

The historical data and the estimated values for the Baseline scenario for the main variables is shown in Fig. 4. An increase in the motorisation rate (passengers cars/1000 inhabitant) from 531 cars/1000 inhabitant to close to 700 cars/1000 inhabitant can be observed in the year 2050 (Fig. 4E.) The stabilization in the CO_2 direct emissions (Fig. 4D) is due to the assumed increase in the fleet of alternative fuel cars (Fig. 4A). These alternative technologies are mainly hybrid electric (LDV HEV), plug-in hybrid and battery electric cars (LDV BEV)) together with the increase in the share of renewables in electricity production (Supplementary Material S3.1).

In the year 2050, the fleet of pure electric cars (LDV BEV) represents almost 30 % of total LDVs, while gasoline (LDV ICE gasoline) and diesel (LDV ICE diesel) still represent about 60 % (97 % in 2021).

Fig. 4D shows that the obtained CO2 emissions match well with the empirical data for the period 2005–2022. Note that 2020 (COVID) represents an outlier (our method for estimating pkm is not designed to capture “black swan” events) but after the end of lock-in, the model again estimates with high precision the CO_2 emissions of the year 2022.

4.2. Baseline variation 1 (Avoid): Increasing the load factor of passengers’ cars

For this measure, the load factor of light passenger vehicles has been modified to model an increase in car occupancy from 1.2 passengers/vehicle to two passengers/vehicle. This increase lies in the range of what has been modelled in the literature [8,10,11].

As car occupancy is increased, the number of vehicles needed to satisfy transport demand is estimated to be much lower, reaching new break-even points above those at 4.32 million for gasoline LDVs and about 8.14 million for diesel LDVs, down from 10.52 million and 13.37 million with respect to 2021 data (Fig. 5A). Breaking with historical trends, in this scenario variation private car ownership decreases to historic levels (480 cars per 1000 inhabitants) in 2050.

All this will affect energy and direct emissions as shown in Fig. 5-F. The variable CO_2 direct emissions intensity by transport mode describes CO_2 direct emissions per passenger-km. This intensity is reduced by half since LDVs will emit half the CO_2 per passenger-km, as can be seen in Fig. 5-D: the total direct emissions of the passenger transport vehicle fleet for Spain drops from 66.87 Mt/year in 2025 to 49.56 Mt/year in 2050, a reduction of 25 %.

4.3. Baseline variation 2 (Shift): Shift domestic (peninsular) air to train transport

The transport demand matrix allows air transport to be differentiated

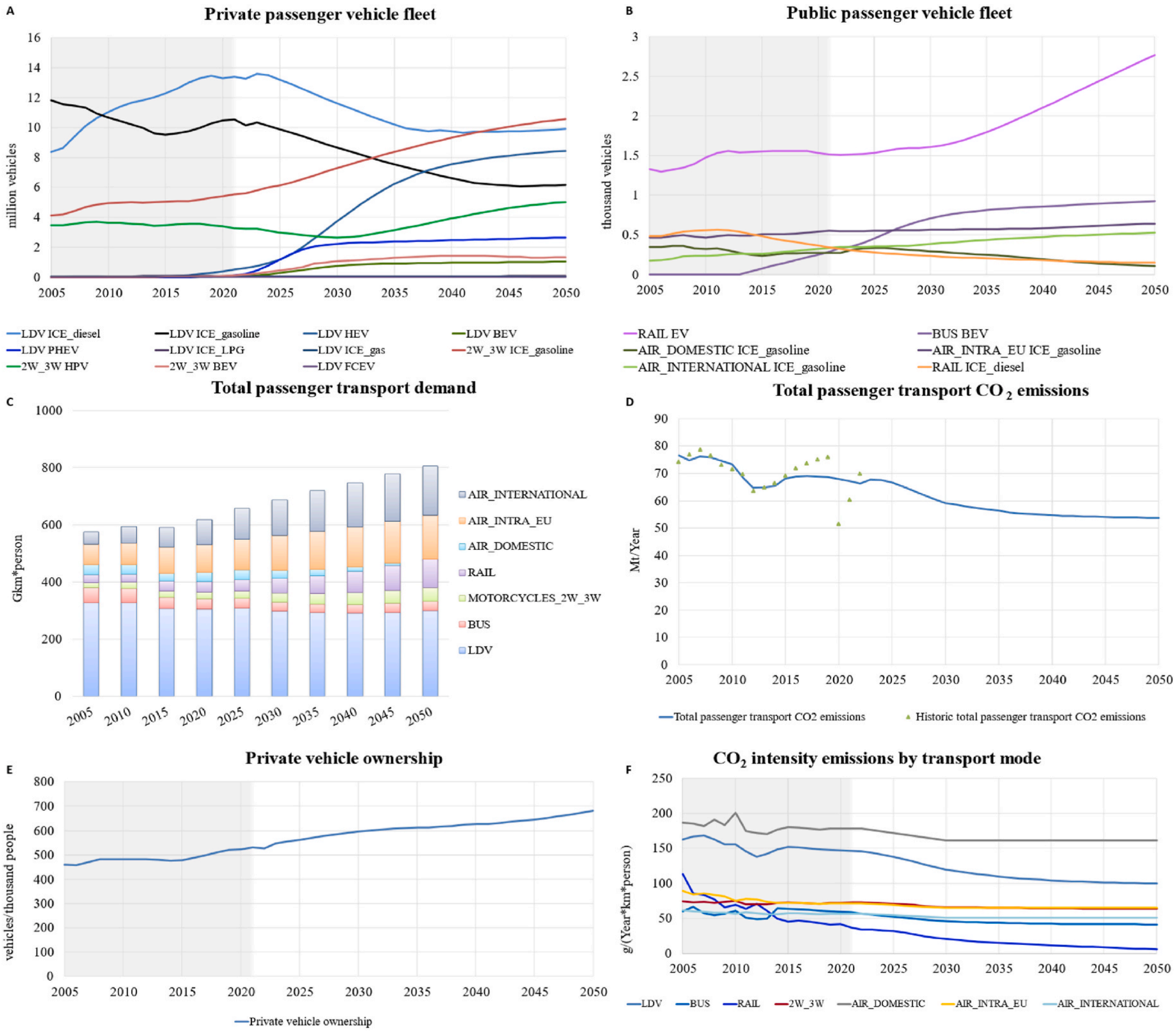

Fig. 6. Baseline Variation 2 (Grey area represents the historical period where empirical data are used for the scenario parameters of the model).

into three types, domestic air transport, intra-European air transport and international air transport. A scenario variation case was simulated in version 2 focusing on domestic air transport, simulating scenario variation case in which this type of transport is progressively reduced in favor of rail transport. However, it has been taken into consideration that part of the demand for domestic air transport is related to Spanish Islands. Thus, for those cases it is not possible to make a modal shift to rail transport for this type of journey. Therefore, data from the last historical year are used for the calculations, so that only 60 % of the total domestic air transport demand is shifted to rail (Supplementary Material S4.6). The rest of the domestic air transport demand has been added to intra-EU flights. For this purpose, the elements of the transport demand matrix for domestic air transport and rail transport have been modified (ibid.). Therefore, the demand for *modified* domestic air transport in the target year has been reduced from the initial value of 5.03 %–0 % in the target year, while the demand for rail transport by electric trains has increased to reach 12.25 %. As a result, in this scenario variation, the modified total air domestic transport demand is reduced to 0 in 2050. (Fig. 6C).

The policy of shifting towards greater use of electric trains to the detriment of short air travel, leads to a significant increase in the electric train fleet, from 1513 in the initial year to more than 2700 at the end of the implementation of the measure. (Fig. 6B).

The kilometers traveled per type of transport per year are much higher for passenger airplanes than trains. while the load factor is much higher for trains, with 250 passengers/vehicle compared to ninety passengers/airplane on average. However, since the total annual distances traveled by aircraft are ten times greater, the total number of trains needed to absorb the demand for domestic air transport is greater than the number of aircraft that cease to operate on these types of routes.

As can be seen in Fig. 6F, the transport CO_2 direct emissions intensity is much higher for airplanes than for trains (188 gCO_2/(person-km) vs 33.46 gCO_2/(person-km) in 2021). Consequently, direct emissions drop by 19 % until 2050 compared to 2025.

There is also a decrease in the intensity of direct emissions from rail transport since the share of electric trains in the total number of trains increase, and direct emissions from electricity generation decrease due to renewable energies (cf. 4.1.2.).

The type of behavioural change modelled in this scenario variation has the additional advantage that electric trains demand energy directly from the power electricity lines and do not require to carry batteries to store electrical energy, which eliminates the problem of consuming scarce materials for the fabrication of batteries.

At the same time, private vehicle ownership follows historical trends in this scenario variation.

4.4. *Baseline variation 3 (Improve): Improve efficiency*

Although the efficiency of vehicles can be improved by purchasing new cars with new technologies, there are also various measures that can be carried out by users without having to change their vehicles, such as fuel-efficient driving or good car maintenance.

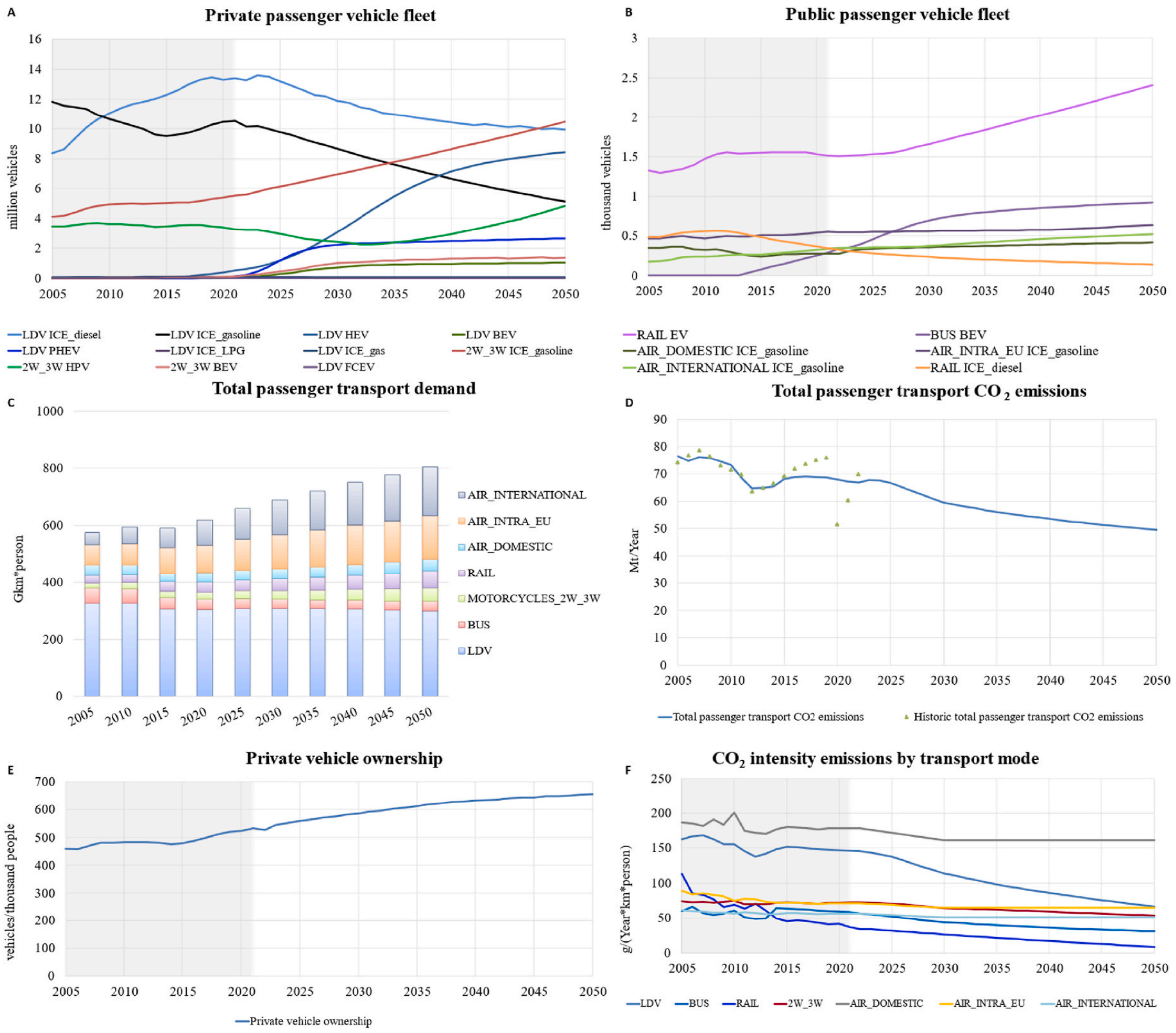

Fig. 7. Baseline Variation 3 (Grey area represents the historical period where empirical data are used for the scenario parameters of the model).

To simulate this kind of behaviour change, in this Baseline variation, different efficiency improvements have been applied to all the engines of the road transport modes (LDV diesel, gasoline, LPG, gas, BEV, PHEV and HEV; diesel, gasoline, LPG, gas, BEV, PHEV and HEV buses; as well as gasoline and BEV 2W3W vehicles) (see Supplementary Material S4.7). On average, a 23 % improvement has been applied to cars.

All the transport modes and power train maintain the same share as in the Baseline scenario, but there is an increase in the efficiency of the motorisations. Consequently, the total CO_2 direct emissions of the passenger transport sector are reduced by 25 % between 2025 and 2050 (Fig. 7F) because of the implied the improvement in the CO_2 direct emissions intensity by transport mode. The other variables, however, do not show any significant changes regarding the Baseline scenario.

4.5. *Baseline variation 4 (Improve): replace 'internal combustion engine' road transport modes with 'Battery Electric Vehicle' power train*

For this measure, the different types of road transport (LDV, 2W 3W and BUS) have been modified so that all motorisations are exclusively powered by battery electric systems (BEV) (cf. Supplementary Material S4.8).Thus, all 3 types of vehicles will run on electricity and will need batteries for storage, which will result in a significant increase in the use of materials needed for the construction of the batteries (cf. Fig. 11). This implies also that the entire fleet of public buses is converted to battery electric power train (Fig. 8-B). The massive and rapid increase in BEV technology is shown in Fig. 8A.

Direct CO_2 emissions, due to the use of more energy efficient electric motors and the region's energy mix, are reduced to 34 Mt/year in the year 2050 (49 % reduction) (Fig. 8-D). Fig. 8-E provides more details on the positive effect of introducing the new types of motorizations on the CO_2 emission intensity.

4.6. *Baseline variation 5 (Shift+Improve): shift to public transport and active transport + technological change*

This scenario combines *shift* with *improve* measures, i.e. it shifts car mobility towards other types of mobility (public transport by bus and active transport by bicycle) but at the same time the fleet of public buses is completely electrified (only BEV buses are used). The use of buses increases until the maximum EU 27 value in 2050 (20 %) while cycling increases up to 8 % (also the maximum in the EU27 region (see Supplementary Material S4.9)). Thus, a proportional reduction in the demand for LDV transport has been modelled, proportional for each type of power train to reach the mentioned transport demand share in bus and cycling. Fig. 9-C shows the modal split of total transport demand every 5 years until 2050.

This variation in the modal split generates a dynamic change in the vehicle fleet that is reflected in Fig. 9-A, where the number of bicycles increases from 3,2 million bicycles in use to more than 45 million in 2050. There is also an increase in the number of battery electric buses needed to meet the new demand for public transport. Meanwhile, the car fleet decreases, reducing car ownership to 320 cars per one thousand

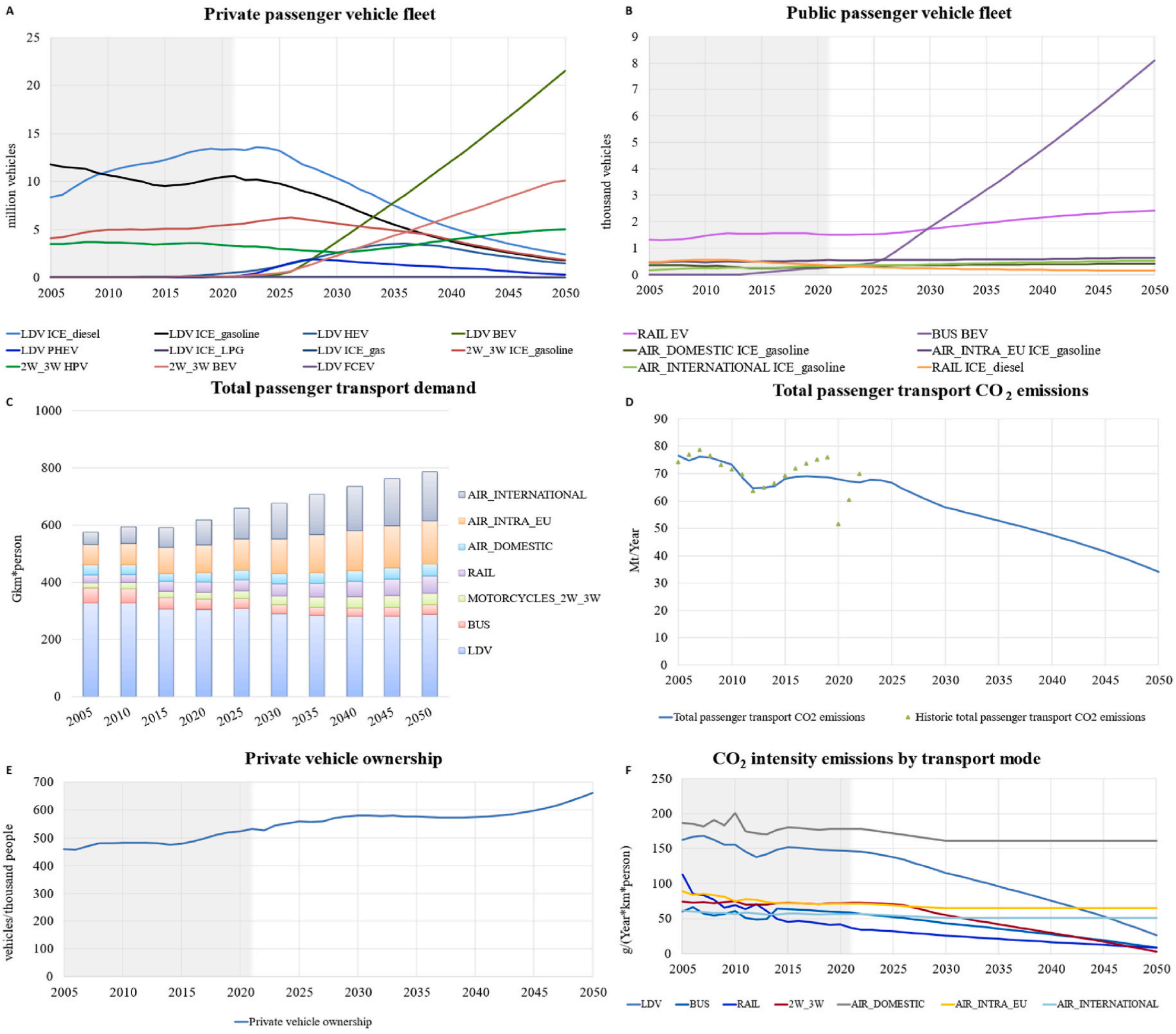

Fig. 8. Baseline Variation 4 (Grey area represents the historical period where empirical data are used for the scenario parameters of the model).

inhabitants (Fig. 9-E).

The decrease in the emission intensities of 2- and 3-wheel vehicles is due to the large increase in the bicycle fleet (2W 3W - HPV), which has zero direct CO_2 direct emissions, and the shift to battery electric buses and no to diesel buses, which has an impact on the total direct emissions from passenger transport as shown in Fig. 9-D, where a significant reduction in direct emissions can be observed.

5. Discussion

The Baseline variations differ significantly from the Baseline in the evolution of the car fleet: V1 achieves a 31 % reduction in the car fleet by 2050 compared to the Baseline scenario, while V5 achieves a reduction of 54 %. Thus, in V1, the motorisation rate decreases from 656 cars/1000 inhabitants in the Baseline to 456, while in V5 the decrease reaches 354 cars/1000 inhabitants. V4 does not reduce the number of cars, but on the contrary, it requires multiplying the number of BEVs by 20, from 1 million in the Baseline to more than 20 million by 2050 (of a total of 29 million operating cars). V5 requires the bus fleet to almost double, from 32,000 vehicles to more than 62,000 by 2050, while the number of bicycles multiplies by more than 9 from less than 5 million on the Baseline to more than 45 million by 2050. In V2 (switching from domestic air to trains), the train fleet only increases by 15 %, i.e. from 2400 vehicles to more than 2700 in 2050. The demand for transport is only affected in V2 and V5, since these variations explore shifts between different transport modes: The V5 measure allows the greatest reduction in the demand for transport in the case of cars, reducing it by 70 % and shifting this demand towards buses and bicycles. Conversely, V2 increases the demand for train transport by 60 %. Regarding CO_2 direct emissions, it is V4 that achieves the greatest reduction with −43 % CO_2 direct emissions in the 2050 with respect to the Baseline, followed by V5 with a 31 % reduction. V1 and V3 achieve the same reductions (−18 %), while the least effective variation is V2 (−11 %). The CO_2 direct emissions of the whole passenger transport sector for the Baseline scenario and the variations are displayed in Fig. 10.

Taking into account all the changes produced in V1 to V5, our findings point to the fact that, although every measure produces positive effects with regard to direct GHG emissions, and also create significant changes in key variables of the transport system such as the use of cars or electric power trains, no single variation of the Baseline is sufficient to alone drastically reduce direct emissions close to net zero emissions [20, 23]. Rather, to achieve radical deviations from the Baseline scenarios that would imply deep changes in the transport system, along with enormous cuts in direct emissions, a combination of multiple variations, including a reduction in total transport activity, would be necessary [65, 66]. The question of whether such ambitious transport policies can be expected to occur in the current socio-economic system on the national, EU and international level, will be crucial for a successful transition to a low-carbon transport sector but lie outside the scope of this article.

The most effective measure in terms of direct CO_2 emissions reduction has been found to be V4, i.e. changing the power trains of cars, buses and motorcycles to battery electric power trains, because this

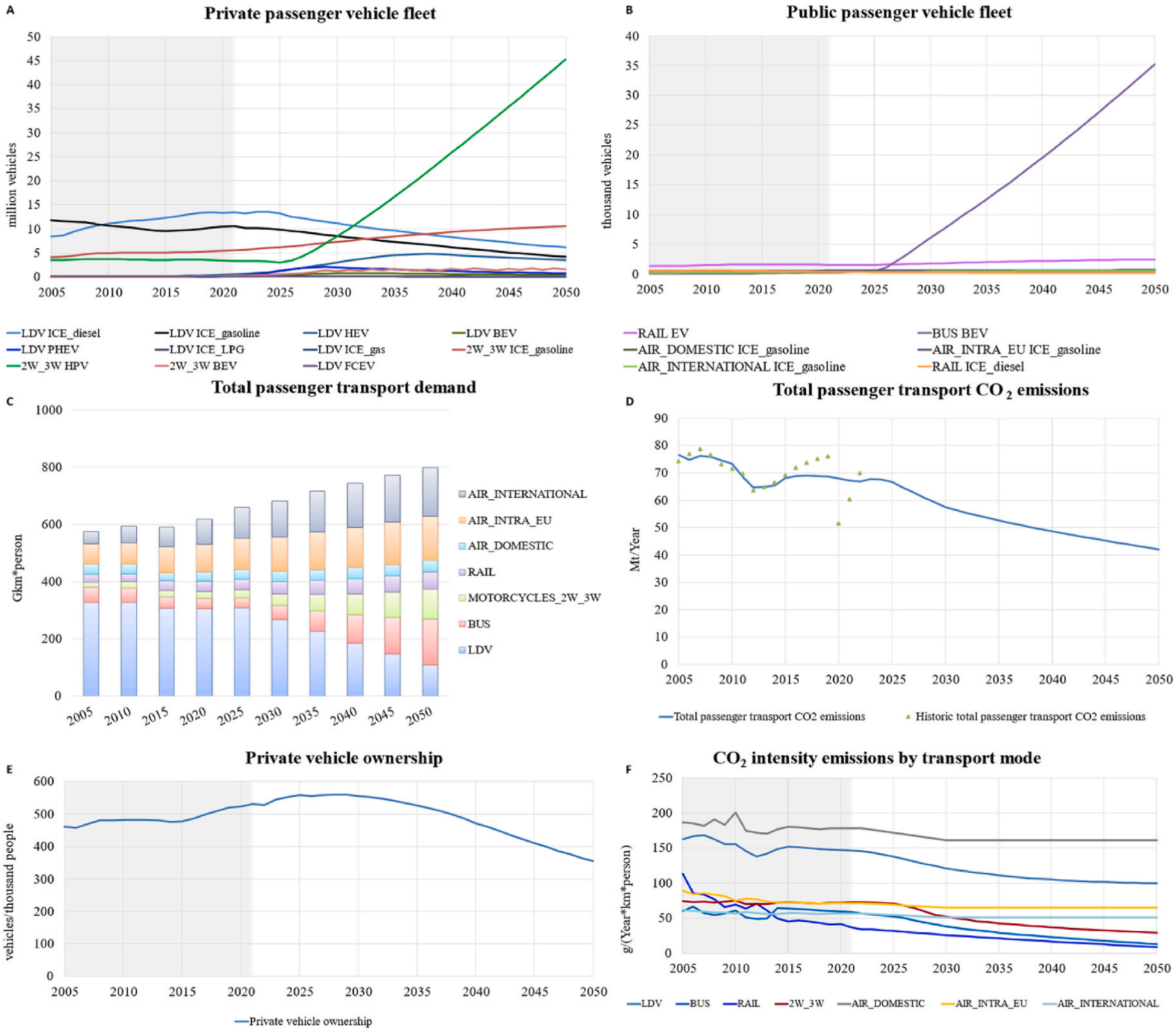

Fig. 9. Baseline Variation 5 (Grey area represents the historical period where empirical data are used for the scenario parameters of the model).

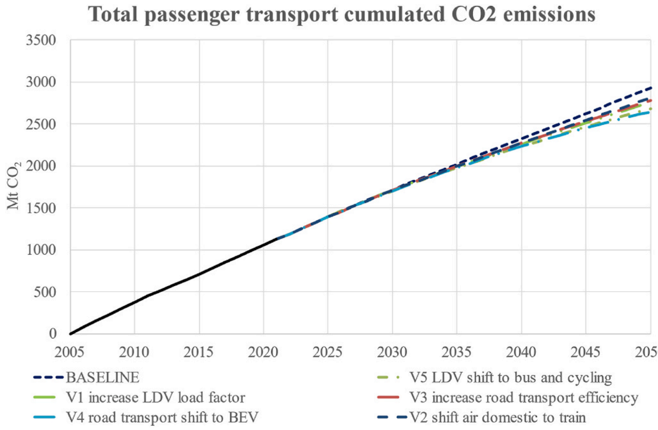

Fig. 10. Accumulated passenger transport CO_2 direct emissions starting in 2005.

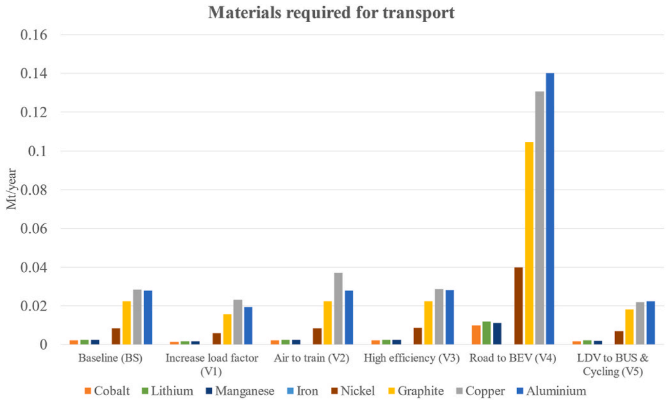

Fig. 11. Materials required for the vehicle fleets in the final year. For details cf [64].

implies a total conversion of the road transport fleet to a more efficient technology in terms of energy consumption per passenger transported and at the same it takes advantages on the high share of renewable electricity assumed in the Baseline parametrization. However, V4 also would enormously increase the demand for materials needed for a transition of this magnitude (see Fig. 11), and the effect on indirect emissions associated has not been taken here into account [64]. In V4 the demand for critical materials for the implementation of the new fleet of electric vehicles is the highest, with an average consumption that is 4 times higher than in the Baseline. On the other hand, the V1 achieves the largest reduction in material consumption compared to the Baseline scenario, with an average reduction of 30 %, since increasing car occupancy through carpooling measures reduces the need to build new vehicles.

The second most effective measure in terms of CO_2 direct emissions is implemented in V5 (shift to battery electric buses and bicycles). In this case emission reductions are smaller since more than 10 % of the cars still run on fossil fuels. However, the fact that transport demand is met by buses and bicycles, which are more efficient in terms of materials needed per passenger transported, has a clear advantage over the previous scenario when considering the demands for materials and other energy needed for the new fleets.

Our study, which was mainly driven by methodological reasons, i.e. to demonstrate the potential of the developed transport model within WILIAM, nevertheless presents some methodological limitations: First, monetary restrictions of households and governments have not been considered, which would have rendered the implementation of certain measures inviable such as changes in transport modes representing a monetary burden. Second, absolute material demand restrictions have not been imposed which would probably render impossible the implementation of V4 on a global scale. Third, strong increases in the recycling rates of EV batteries were assumed which result in lower material demand. Although it is likely that in the future the recycling rates of batteries will improve with their large-scale expansion and technological maturity, achieving these very high levels of recycling will be challenging for the industry due to complexities and thermodynamic limits in the recycling processes, supply-chain complexities, difficulties to set appropriate regulatory frameworks and incentives, etc.

Last, another dimension to consider in scenarios with a large increase in the share of public transport is the role of private actors in the development of new technologies if the share of private transport continuously shrinks. In these scenarios, public actors would become decisive since they would need to realize most investments in research and the development of new motorisation technologies.

Future work could extent the present study addressing several key factors: First, sustainability transitions in the passenger transport sector beyond Spain could be studied, given that the transport module covers 35 world regions. A multiregional analysis would make it possible to compare how direct emissions would be affected by the application of the same measures in different territories. Second, the relationships and interactions between different modules of WILIAM should be investigated, especially the interactions between the transport module and the economic module. In this way, additional measures could be introduced, such as restricting the purchase of new vehicles by household type or studying the relationship between income and transport demand by vehicle type, as well as the associated indirect emissions due to additional transport infrastructures. Third, the model could be improved by endogenizing certain model variables such as the cost of mobility ($/km), which, in addition to the energy and emission outputs, can serve as input for behavioural changes in transport modes. Another example would be endogenizing the variable describing the maximum passenger load factor per vehicle to dynamically link the public vehicle occupancy rate to the flow of new public vehicles. Fourth, integrating the possibility of climate disasters in the scenarios through thorough analysis and extrapolation of historical data is essential for fostering resilience and could be introduced in future work to produce a more accurate result. Last, the idea is to link the data produced by the energy module regarding the percentage of biofuels in gasoline and diesel fuels with the transport submodule to modify this value through policies, and to study the effects on GHG direct emissions. Thus, future work could be directed to explore how all the measures would need to be combined in a consistent way within the fully linked WILIAM to achieve ambitious climate mitigation goals for passenger transport.

6. Conclusion

The decarbonization of the passenger transport sector represents an ambitious political objective that requires long-term planning and the exploration of a wide range of policy and demand-side measures [67]. In this paper, a novel transport model was presented, designed to be integrated as sub-module in WILIAM and demonstrated its potential to simulate and compare different behaviour change related measures. Based on system dynamics, our model increases the diversity of existing passenger transport models within Integrated Assessments Models by offering a detailed representation of the dynamics of the transition for different technologies and transport modes combining technological and behavioural changes. Moreover, this model has been designed to be fully linked with the households' submodule representing the monetary dimension in WILIAM. A Baseline scenario for the evolution of the transport sector up to 2050 was developed and parametrized in the absence of stringent sustainability policies. In this baseline scenario, in 2050, even with an increase of the share of alternative fuels in transport, more than 88 % of cars and 90 % of buses still use fossil fuels. For alternative transport modes, the percentage of transport demand covered by bicycles is very low (0.8 %), and for bus transport, the figure is below the EU27 average (6.21 % Spain vs 10 % EU27). The baseline results also show that air transport is becoming the mode of transport with the highest growth share of all modes. All these data point to a continuation and even worsening of the current situation in terms of dependence on non-renewable and polluting sources, as well as modes of transport that are very difficult to convert to technologies with less impact on the environment. For this reason, the effects of five variations of this scenario have been developed and explored following the ASI (Avoid-Shift-Improve) dimensions [5], including a diversity of measures such as the change of the entire fleet of road vehicles to electric vehicles, the massive use of public transport to the detriment of private transport, the promotion of light transport modes or the replacement of plan by train travel. It was found that all measures have positive impacts on direct CO_2 emissions and significantly change the passenger transport landscape. However, some may be problematic from the point of view of material scarcities and could worsen the indirect CO_2 emissions. No variation alone was able to lead to a deep decarbonization of the transport sector given that the current work was designed rather as a methodological study to validate the module and test its functionality. Future work will be directed to expand the number of transport policies to design consistent transition scenarios for Spain and/or other regions fully linked with the rest of WILIAM. These simulations would benefit from addressing some limitations of the model discussed in section 5 and would allow to compare different behavioural change related measures in the transport sectors of multiple countries and regions.

CRediT authorship contribution statement

David Álvarez-Antelo: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Arthur Lauer:** Writing – review & editing, Visualization, Methodology. **Íñigo Capellán-Pérez:** Writing – review & editing, Validation, Supervision, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work has been partially developed under the LOCOMOTION project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement no 821105, and under

RethinkAction project, funded by the Horizon 2020-EU.3.5 programme under grant agreement No 101037104. Programme. Iñigo Capellán-Pérez also acknowledges financial support from a Juan de la Cierva-Incorporación Research Fellowship of the Ministry of Economy and Competitiveness of Spain (no. IJC2020-046215-I).

Acronyms

BEV	battery-electric vehicle
BUS	buses
FCEV	fuel-cell electric vehicle
GHG	greenhouse gas
GDP	growth domestic product
HEV	hybrid electric vehicle
ICCT	International Council on Clean Transportation
IPCC	Intergovernmental Panel on Climate Change
LDV	light duty vehicles
PHEV	plug-in hybrid electric vehicle
p-km	passenger*kilometre
2W	two-wheeler vehicle
3W	three-wheeler vehicle
NMT	non-motorized transport

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.132313.

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