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Key factors influencing the global passenger transport dynamics using the AIM/transport model

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ABSTRACT

A bottom-up passenger transport model named AIM (Asia-pacific Integrated Model)/Transport model is developed by incorporating behavioral parameters and transportation technological details. This model is based on discrete based choice modelling covering 17 global regions soft-linked with the AIM/CGE (Computable General Equilibrium) model. In this paper, the model is used to assess the impact of various factors like travel time, energy efficiency improvement, load factor, mode preference along with environmental awareness factors on transport demand, energy and emissions. The modelling assessment results show that travel speed and land-use patterns have significant impact on the travel demand. High occupancy rate and shift towards the mass-transit system result in energy and emissions reduction. Implementation of carbon tax aligned with the two-degree target results in a 22% cumulative emission reduction from 2005 to 2100 relative to the baseline case. However, the reduction potential can be increased to 42% by combining behavioral and technology related mitigation options like mass-transit system speed improvement, transit oriented development, efficiency improvement, preference towards eco-friendly technologies and high vehicle occupancy.

1. Introduction

Transport is the second largest source of energy-related emissions, accounting for 23% in the total energy-related global emissions in 2010 (Sims et al., 2014). Global transport CO_2 (carbon dioxide) emissions are projected to double along with the 170–300% increase in global transport demand by 2050 compared to the 2005 level (IEA, 2009). Technological change, travel demand reduction, energy efficiency improvement and fuel shift are some of the key mitigation strategies proposed in the literature (Azar et al., 2003; IEA, 2014; Pietzcker et al., 2014). The electrification of transport along with greater penetration of renewable or nuclear power sources in the electricity sector would play an important role in the de-carbonization of the transport sector (McCollum et al., 2013; Kyle and Kim, 2011). However, there is no robust agreement on the long-term transport-related emission pathways (Girod et al., 2013b). It has also been argued that due to slow turnover of vehicle stock and transport infrastructure, continuous reliance on fossil fuels and limited scalability of the biofuels, it would be difficult and expensive to decarbonise the transport sector in the long term (Creutzig et al.,

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2015; Schäfer, 2009). The number of light-duty vehicles is also expected to double by 2050 with growing population and affluence in developing countries (Sperling and Gordon, 2009). Without taking travel behavior relation mitigation options such as telecommuting car-pooling & use of sustainable and energy efficient modes (Girod et al., 2013a; Sims et al., 2014), it would be difficult to have deep emissions cuts from the transport sector. This implies that developing countries still have an opportunity to bring behavioral changes in travelling patterns that can assist in the low carbon transformation of transport sector.

The mode choice decision for a given trip is affected by various attributes associated with different modes such as travelling cost, egress and access travel time, in-vehicle travelling time, public transport accessibility levels, unobserved preference for the mode as well as individual characteristics like income & age (Wen and Koppelman, 2001; Zahavi, 1974; Ashiabor et al., 2007; Scheiner, 2010). Discrete choice modelling has been widely used to compute mode choices based on mode, technology and individual attributes in transport planning models (Girod et al., 2012, 2013a; Kyle and Kim, 2011; Ben-Akiva et al., 1993; Horne et al., 2005; Rivers and Jaccard, 2006). In this methodology, the utility associated with alternative modes are modelled by including the variables that describe characteristics of alternative modes and variables that influence people's preferences among different modes. But transport planning models are not well suited to analyze the changes in transport energy consumption due to changes in fuel prices in the mitigation scenarios. In contrast to transport planning models, Energy-Environment-Economy (E3) models can estimate the change in energy prices endogenously in climate-constrained scenarios. However, these E3 models does not capture the effect of driving patterns, people attitude towards new technologies, charging infrastructure that in turn influences travel demand and modal share as mentioned in the review study done by Schäfer (2012). Therefore, there is a need to incorporate the mitigation options by inducing behavioral changes in the transportation sector to understand the trade-off associated with climate policies in a holistic manner. Energy-Environment-Economy models have been categorized into four categories based on the methodology used to include the travel behavior in the transport sector model/module (see Table 1 for details). Several studies have been published that focused on the behavioral aspects using multinomial logit (MNL) - type equations in the global integrated assessment model (Girod et al., 2012, 2013b; Kyle and Kim, 2011). Lin and Greene (2011) used MA3T vehicle choice model based on the nested multinomial logit approach to capture the consumer behavior and estimated the market shares of different vehicle technologies under alternative policy scenarios. Horne et al. (2005) incorporated the behavioral realism in the hybrid energy-economy model named CIMS and used MNL approach for evaluating mode and fuel choices under different policy scenarios for Canada. Girod et al. (2012) estimated the travel demand share for different modes and technologies using nested logit model linking with the TIMER model taking into account travel time and travel budget concept. Kyle and Kim (2011) simulated the future passenger as well as freight travel demand for different modes using the MNL–type equations. Daly et al. (2014) incorporated travel behavior using travel time budget constraint in the bottom-up, technology-rich TIMES model at the national level. However, the bottom-up model still fails to assess the change in the travel demand in response to the change in fuel prices in the mitigation scenario. The supply and quality of transport infrastructure also have an effect on people's mode choices. Infrastructure supply is included as an endogenous determinant only in IMCLAIM-R to estimate transport demand (Waisman et al., 2013) (see the S.I. for transport representation in different models).

In this study, we focus on one of the E3 type[1] i.e. top-down type models, AIM/CGE (Computable General Equilibrium) model where change in the travel demand depends on the elasticity of substitution and relative price. Several researchers have been using AIM/CGE as a core of climate change mitigation study (Hasegawa et al., 2013; Fujimori et al., 2014b, 2015). However, transport sector is poorly represented in the AIM/CGE model. For the private car usage in household, energy consumption is formulated under the LES (Linear Expenditure System) function and the transport demand generated in industrial sectors (including bus, tax and others) is simply formulated as a part of industrial activity. Therefore, there are two critical disadvantages in the current form related to the transport representation in AIM/CGE model. First, the modal shift is not endogenously determined. Second, the transport sector is represented at a highly aggregated level without much technological details and factors like travel time cost and mode preference. Due to high aggregation level, it is difficult to incorporate behavior and technology related mitigation options and assess their influence on the passenger transport sector. Some integrated assessment models have more advanced representation such as IMAGE and GCAM that incorporate multi-nominal logit function. EPPA is a global CGE model which has better representation of the transport sector (Karplus et al., 2013), however it cannot deal with the modal shift (Paltsev et al., 2004).

The main objective of the study is to improve the transport sector representation in AIM/CGE, by soft-linking the bottom-up type transport model, named as AIM/Transport, which uses MNL-type equation to incorporate the mitigation options related to travel behavior. Then, the influence of different factors such as technology, preferences, environmental awareness, income and population on the passenger transportation choices and demand are quantified using the model for different regions in the world, which in turn have an influence on the energy and emission profiles of the global transport sector.

The paper is structured into four sections. Section 2 describes the methodology and details of the AIM/transport model which is soft linked with the AIM/CGE model and scenario framework. Section 3 presents the results representing the effect of different factors on travelling pattern followed by the discussion and conclusion sections.

[1] Refer Sathaye and Shukla (2013). Methods and Models for Costing Carbon Mitigation. *Annual Review of Environment and Resources*, 38, 137–168. For E3 model typology.

Table 1
Model classification.

Category	Models	Reference
Energy environment economy without incorporate transport behavior	AIM/CGE, Global MARKAL model, AIM/endues model, IEA-MoMo	Fujimori et al. (2014a) and Krzyzanowski et al. (2008)
Discrete choice modelling not linked with E3 models	MA3T, PRIMES-TREMOVE, TREMOVE	Lin and Greene (2011) and Capros and Siskos (2011)
Discrete choice modelling linked with E3 model	GCAM, TIMER	Girod et al. (2013a) and Kyle and Kim (2011)
E3 model with transport behavior representation	IMCLIM-R, TIMES	Waisman et al. (2013) and Daly et al. (2014)

2. Methodology

2.1. Overview

The transport model is developed for projecting the global transport demand for different modes incorporating the consumers' mode and technology preferences. The model is based on the MNL-type equations to assess the consumers' mode and technology choices in different scenarios. The transport model is soft-linked with the AIM/CGE model, which is a recursive dynamic general equilibrium model (Fujimori et al., 2012, 2014b). We constructed various scenarios to understand the transport model behavior by changing the key parameters related to the socioeconomic, technological and environmental awareness aspects.

2.2. Transport model

The global transport model is developed for 17 regions consistent with the AIM/CGE model (Fujimori et al., 2014a, 2014b). The overall structure of the travel model is presented in Fig. 1 (and details are presented in the supporting document). The travel demand for each region is calculated endogenously by multiplying the per capita travel demand of the region with its population in a given year. The per capita travel demand is estimated as a function of income and generalized travel cost (considering both technology, fuel as well as monetary time cost). This study uses GDP per capita as a proxy for income due to data limitations. Income elasticity α and price elasticity β are estimated based on regression on the historical data as shown in Eq. (1).

$$QT_{r,y} = \left(\frac{GDP_{r,y}}{POP_{r,y}}\right)^{\alpha} * (PT_{r,y})^{\beta} \tag{1}$$

$GDP_{r,y}$ Gross Domestic Product for a given region r for a given year y
$POP_{r,y}$ Population for a given region r for a given year y
$QT_{r,y}$ Per capita travel demand in Pkms for a given region r for a given year y
$\mathrm{PT}_{r,y}$ Generalized cost of transport for a given region r for a given year y
$r \in R$ and $y \in Y$ are sets of regions and years, respectively

As shown in Fig. 1, the total transport flow is divided between short and long-distance. At the next level, modes like car, two-wheeler and public transport like bus & light rail transit compete with each other for short distance travel whereas railways face competition from air for medium and long-distance travel (Dobruszkes, 2011). The share of each mode in the total passenger travel demand is calculated using MNL-type equation (Eq. (2)) based on the generalized cost of technology within each size category and monetary cost of time. The generalized cost of technology is the weighted sum of the technology multiplied with its market share (Eq. (3)) plus time cost. The monetary cost of time for each mode is estimated by dividing GDP wage rate to the door-to-door travelling speed of each mode (Eq. (4)), which is taken from the study by Kyle and Kim (2011). As per the above-mentioned method of estimating the monetary cost of time, travel time cost will increase with rise in income. It is consistent with the empirically observed trend that people tend to shift towards the fastest mode of travel due to an increase in the opportunity cost of time. The coefficient of the logit functions (α) represents the people's preference towards a particular mode and is calibrated based on the base year's mode share and technology share and for future years, the coefficient for developing countries will converge to values of developed countries.

$$SMODE_{m,d,r,y} = \frac{\left(\alpha^{mod}_{m,d,r,y} * PMODE_{m,d,r,y}^{\beta^{mod}_{m,d,r,y}}\right)}{\sum_{mp \in MC}\left(\alpha^{mod}_{mp,d,r,y} * PMODE_{mp,d,r,y}^{\beta^{mod}_{mp,d,r,y}}\right)} \tag{2}$$

$SMODE_{m,d,r,t}$ Share of each mode m for a given distance category d
$\alpha^{mod}_{m,d,r,y}$ Preference parameter for a given mode m

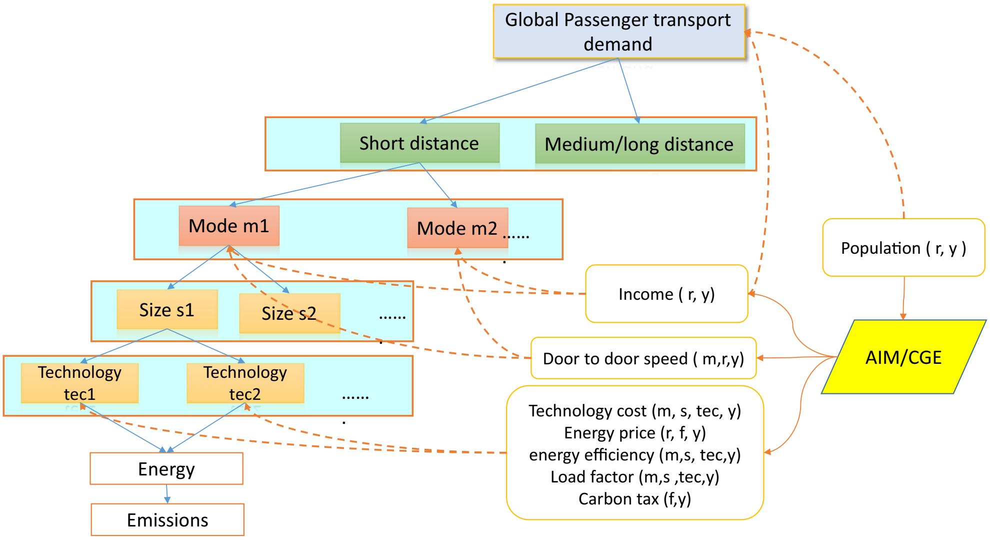

Fig. 1. Structure of the transport model (r-region; m-mode; tec-technology; s-size; f-fuel; y-year).

$PMODE_{m,d,r,t}$ Generalized price of the mode
$\beta^{mod}_{m,d,r,y}$ Price elasticity for a given mode m for a given distance category d
$m, mp \in MC$ A set of modes
$d \in D$ A set of distance (short and long)

$$PMODE_{m,d,r,y} = \sum_{tec \in m} PTEC_{tec,r,y} * STEC_{tec,r,y} + Ptime_{m,r,y} \tag{3}$$

$PMODE_{m,d,r,y}$ Generalized price of each mode
$PTEC_{tec,r,y}$ Price of each technology
$STEC_{tec,r,y}$ Share of each technology
$Ptime_{m,r,y}$ Monetary cost of time
$tec \in TEC$ A set of technologies

$$Ptime_{m,r,y} = \frac{GDP_{r,y}}{POP_{r,y} \cdot AWH_{r,y} \cdot DDTS_{r,y}} \tag{4}$$

$AWH_{r,y}$ Annual Working hours
$DDTS_{r,y}$ Door-to-door travel speed

At the next level, another MNL-type of equation is used to determine the market share of cars of different sizes, i.e., small, medium and large. The market share of each technology is selected using MNL-type equation based on the technology cost that comprises of annualized purchase cost, fuel cost, tax and subsidies. The old transportation technologies are phased out at the rate equal to the inverse of technology's lifetime. Fuel cost is a function of vehicle efficiency and fuel price. Fuel prices and emission factors for future years aligned with different scenarios are taken from the AIM/CGE model. The purchasing cost of the vehicle is annualized using 10% discount rate for all the vehicles across all the regions.

2.3. Data sources

The base year data is prepared by a systematic reconciliation of various statistical data. The list of the statistical data sources are shown in the supporting information. The basic idea of the reconciliation is that distances, transport demand volume, energy intensity, load factor and energy consumption are all simultaneously reconciled and the reconciled data should be close to the observations as much as possible. The data used for this model is shown in the supporting information. The mode and technology related parameters are calibrated using their shares in base year. Socio-economic data like GDP and population are derived from the shared socio-economic database. The technical cost and energy efficiency of transport technologies are derived from the bottom-up technological rich global AIM/Enduse model (Akashi and Hanaoka, 2012; Akashi et al., 2012). The door-to door speed used to calculate the travelling time cost is taken from the GCAM model. Table 2 lists the sources of main attributes used in the model.

Table 2
Data sources.

Data	Reference scenario	Source for base year data	Reference
Population and GDP	Region specific	SSP database	IIASA (2015)
Load factor	Region and mode specific	GCAM model	Mishra et al. (2013)
Vehicle cost	Mode, technology specific	AIM/Enduse model	Akashi and Hanaoka (2012)
Energy intensity	Mode, technology and region specific	AIM/Enduse model	Akashi and Hanaoka (2012)
Door-to door speed	Mode specific, same across region and time	GCAM model	Mishra et al. (2013)
Annual distance travelled	Mode and region specific	AIM/Enduse model	Akashi and Hanaoka (2012)

2.4. Analytical method

Further, a decomposition analysis is conducted to analyze the effect of each factor on activity, structure and intensity based on the scenario assessment results. In this study, we have performed decomposition analysis by taking differences as shown in equation 5. Although the Logarithmic Mean Divisia Index (LMDI) method (Ang et al., 1998; Sheinbaum et al., 2010) is widely used for decomposition analysis, this method is limited to the cases where all variables are positive. In this paper, there are some cases that do not satisfy the condition (in carbon tax scenario). Hence we have adopted the below mentioned method for decomposition analysis.

$$E^y - E^{y-1} \approx (P^y - P^{y-1})\frac{E^y}{P^y} + \sum(Q^y - Q^{y-1})\frac{E^y}{Q^y} + \sum(S^y_m - S^{y-1}_m)\frac{E^y}{S^y_m} + \sum(I^y_{m,f} - I^{y-1}_{m,f})\frac{E^y}{I^y_{m,f}} + \sum(C^y_{m,f} - C^{y-1}_{m,f})\frac{E^y}{C^y_{m,f}} \tag{5}$$

E^y emission in time y (y − 1 stands for previous period)
P^y Population
Q^y Activity level in passenger km travelled (pkm)
S^y_m Modal share (in % of total passenger carried by each mode m)
$I^y_{m,f}$ Energy intensity of each mode (toe/pkm using fuel f in each mode m)
$C^y_{m,f}$ Carbon content of each fuel (tCO_2/toe of each fuel)

2.5. Scenario framework

As explained earlier, the main goal of this paper is to understand how different factors affect the dynamics of the global passenger transport sector. Individual scenarios are constructed by the combination of factors such as socio-economic, behavioral, technological, environmental consciousness and climate target. In this study, we quantify the influence of six critical factors, namely, (a) travel time, (b) mode preference, (c) load factor, (d) environmental concerns, (e) energy efficiency improvement and (f) socio-economic variables on travel demand, modal share, transport energy and CO_2 emissions. In the below section, we describe individual dimensions used in this study.

(1) **Travel time:** Travel time cost is defined by Litman (2009) as "the cost of time spent of travel that includes waiting time as well as actual travel time". Travelling speed is used as one of the dimensions to compare the quality of different modes of transportation. Two individual cases are considered to quantify the influence of travel time on the travel demand and modal choices by varying the speed from the reference case where the speed is kept constant over the assessment period. The opportunity cost of time measured in the monetary terms is used as a variable to quantify the effect of any change in the travelling speed on the consumer's choices.
   (a) Speed_low scenario represents the congestion situation that arises due to high car ownership and usage with rise in income in the coming decades. In this scenario, the socio-economic assumptions like GDP and population are aligned with the Shared Socioeconomic Pathways 2 (SSP2) which is characterized as the middle-of-the-road among a range of scenarios (O'Neill et al., 2013). In this scenario, we assume that the speed of road vehicles reduces in the coming decades with the greater usage of private vehicles (Table S.7).
   (b) Speed_high scenario represents the scenario in which the government invests in bus and railways based mass transit system like bus rapid transit, mass rapid transit system and high speed railways. Building of upgraded infrastructure like elevated corridors, dedicated corridors for passenger transportation, high speed railways would result in reducing the congestion and thereby increasing the average speed of railways and bus (Table S.7). In speed_high scenario, we assume the speed of railways will increase by 1% per year reaching the average door-to-door speed of 106 km/h by 2100 (average speed between the conventional and high speed railways from (Gleave, 2004).

(2) **Preference for mode:** It can be seen from the empirical evidence that interaction between transport system and urban land-use system offers range of possibilities from the car-oriented transport development like the United States (US) to mass-transit-oriented transport development like Japan (Lipscy and Schipper, 2013). Urbanization level is expected to increase in the developing and under-developed countries in the coming decades. Three scenarios are constructed to represent the different development pathways that developing countries could follow in future.
   (a) Car_oriented scenario: In this scenario, the preference factor of US for individual mode is used as a proxy to reflect the preferences for each mode in the car oriented land-use structure (Table S.8). We assume that developing and under-developed countries will gradually converge to the US's preference factor in 2005 by 2100. The preference factor of other developed regions like European Union (EU) or Japan remain constant throughout the assessment period.
   (b) Mass_transit scenario: In this scenario, the preference factor of Japan for individual mode is used as a proxy to reflect the preferences for each mode in the transit-oriented development (Table S.8). We assume that developing and under-developed countries will gradually converge to the Japan's preference factor in 2005 by 2100. The preference factor of other developed regions like EU or US remain constant throughout the assessment period.
   The preference factor of EU is used as proxy in reference scenario to describe a "middle path" between the car-oriented and transit-oriented development (Table S.8). In the reference case, the preference factor of the under developed and developing countries will converge to the EU preference factor by 2100.

(3) **Socio-economic dimension**: Socio-economic factors like GDP and population are key drivers of future growth in transport demand. Three cases that are considered include SSP1, SSP2 and SSP3 to assess the impact of socio-economic factor on future passenger demand. SSP1 scenario has lower population but higher GDP growth rate while SSP3 has higher population but lower GDP growth rate compared with SSP2 (reference) scenario as illustrated in Figs. S3 and S4 in the appendix.

(4) **Energy efficiency improvement:** Three energy efficiency improvement cases are considered aligning with the vision set under global fuel economy initiative (Watson et al., 2009). Stringency level in terms of the target year of achieving the 50 by 50 fuel economy target set in the global fuel economy initiative differ across the scenario. It is assumed that improvement in engine and transmission, weight of an automobile material, aerodynamics, rolling resistance would result in the vehicle efficiency improvement. The annual efficiency improvement in conventional internal-combustion engine (ICE) drive-train vehicles in both cases are mentioned in Table 3. In this model, energy intensity is determined by dividing the specific energy consumed by the vehicles (MJ) by the annual distance travelled (km) and vehicle occupancy (person) that differ across regions. The base year data of energy intensity is mentioned in Table S6. The values of the annual distance travelled are kept constant across all years.
   (a) In reference scenario, 50% improvement in LDV vehicle energy efficiency from the 2005 level will be achieved by 2050.
   (b) In the high efficiency scenario (Ene_efficiency_high), 50% improvement in LDV vehicle energy efficiency from the 2005 level will be achieved by 2030.
   (c) In the low efficiency scenario (Ene_efficiency_low), 50% improvement in LDV vehicle energy efficiency from the 2005 level by 2070.

(5) **Load-factor of car:** The load factor of car decreases with increase in per capita income in the reference scenario. The regression analysis is used to assess the relationship between income and car_occupancy (see the supplementary document for details). In the occupancy high scenario, we assume that policy interventions such as carpooling initiative, transport volume control in mega-cities like odd-even rationing, road space rationing, will result in convergence of load factor for all countries. It is assumed that the car occupancy factor will converge to 2 persons per car by 2100 (details of car occupancy i.e. passenger per vehicle in the reference and occupancy_high scenarios is mentioned in Table S.5 in S.I.).

(6) **Environmental concern:** Environmental concern can have an impact both on the technology choice in two ways; (1) high environmental consciousness among people resulting in high preference for environmental-friendly car technologies like electric or hybrid car, and (2) high political consciousness putting climate change high on the policy agenda and governments make efforts to achieve the 2 °C stabilization target. The latter is addressed in the climate target section. In Advanced_Tec_high case, it is assumed that environmental concerns are high among the people compared to the reference case and they are inclined to purchase eco-friendly vehicles. The old conventional ICE, high efficiency and advanced technology vehicles like battery, hybrid, plug-in vehicles are clubbed together. Higher preference factor is given to the advanced technology vehicles in the Advanced_Tec_high scenario.

(7) **Climate target:** A carbon tax case ("withTAX") is considered corresponding to two-degree climate stabilization target along with the no carbon tax case (w/oTAX). The carbon price pathway shown in Table 4 is calculated by AIM/CGE. In the carbon tax scenario, a carbon price is imposed approximately for achieving 450 ppm CO_2 equivalent concentration (2.7 W/m^2) by 2100.

In the end four scenarios (Table 5) are developed by combining the above mentioned dimensions to quantify emission reduction potential that can be achieved by inducing changes in the travel behavior in climate constrained scenario compared to no climate policy scenario using the bottom up AIM- transport model.

Table 3
Annual energy efficiency improvement rate.

		2005–2030	2030–2050
Ene_efficiency_high	Passenger LDVs	−2.7%	−1.5%
	Buses	−1.5%	−1%
	Two wheelers	−0.8%	−0.5%
		2005–2050	2050–2100
Reference	Passenger LDVs	−1.5%	−1%
	Buses	−0.8%	−0.5%
	Two wheelers	0.4%	−0.1%
		2005–2070	2070–2100
Ene_efficiency_Low	Passenger LDVs	−1.1%	−1%
	Buses	−0.56%	−0.3%
	Two wheelers	−0.3%	−0.1%

Table 4
Carbon price aligned with 2.7 W/m^2 in 2100 climate target.

	2020	2030	2050	2070	2100
Carbon price (2005 USD/tCO_2)	16	51	194	493	690

Table 5
Assumptions of reference and low-carbon scenarios.

Scenario	With carbon tax	Without carbon tax
Reference	Reference_withTax	Reference_w/oTax
Low carbon	Low_carbon_withTax	Low_carbon_w/oTax

Reference scenario: Reference scenario assumes the continuation of ongoing dynamics in the transport sector. The car ownership and usage will increase in coming decades with rise in income in the developing countries along with reduction in the average vehicle occupancy. The assumptions related to GDP and population are aligned with the SSP 2 scenario. The assumptions related to different dimensions are mentioned in Table 6.

Low-carbon scenario: The scenario assumes the decoupling between the emission and demand growth in the transport sector. The decoupling is achieved by implementation of various mitigation strategies that include early rollout of strict fuel economy standards, investment in mass transit system and infrastructure required for supporting advanced technologies, car sharing that induces travel behavioral changes. The assumptions related to different dimensions are specified in Table 6. We implement this case together with withTax and w/oTax policies. Low_carbon withTax scenario can be interpreted as a sort of maximum CO_2 emissions reduction potential from passenger transport sector.

3. Results

3.1. Main indicators in the reference case

The overall trends of global passenger travel demand, energy and emissions in the reference case for w/oTax and withTax scenarios are shown in Fig. 2. In the reference-w/oTax scenario, the global total passenger transport demand measured in terms of the passenger km travelled (pkms) increases at an average compound annual growth rate (CAGR) of 1.24% between 2005 and 2100 and reaches 99.5 trillion pkms (tpkm) in 2100. In reference-withTax scenario, the transport demand declines to 97.5 tpkm in the year 2100 slightly lower than reference-w/oTax scenario. This result can be explained by rise in the generalized transport cost but the transport reduction is not substantial due to low share of fossil fuel based technology by 2100 (Fig. 2). The results show that energy consumption in the passenger transport sector surges from 53.8 EJ in 2005 to 106 EJ in 2100 in the reference-w/oTax scenario. However, it declines by 5.85% and 13.5% in 2050 and 2100 respectively in the reference-withTax scenario compared to reference-w/oTax scenario.

The CO_2 emissions rise at an average CAGR of 0.8% between 2005 and 2050; then at CAGR of 0.52% afterwards till 2100 in the reference-w/oTax scenario. The corresponding CO_2 emissions increase from 3923 MtCO2 in 2005 to 7409 MtCO2 in 2100, but it declines to 4338 MtCO2 in the reference-withTax scenario in 2100. The cumulative CO_2 emissions in the reference-withTax scenario are 23% lower than the reference-w/oTax scenario by the end of the century (see Table 7).

3.2. Travel demand

Figs. 3 and S2 illustrate transport demand in the reference-w/oTax scenario by five and 17 regions, respectively. It is evident from Fig. 3 that the growth rates of transport demand in developed regions like the US, Japan and the EU25 get

Table 6
Scenario framework.

Scenario	Preference parameter of advanced technologies) in 2050	Preference parameter[a] in 2100 (Mode) α^{mode}	Mode speed	Efficiency improvement	Load factor	Carbon tax	Socio-economic
Reference_w/oTax	Same as conventional technologies	EU's mode preference parameter	Constant	50% by 2050 wrt 2005	Decreases	No	SSP2
Reference_withTax	S.A.R	S.A.R	S.A.R	S.A.R	S.A.R	Yes	S.A.R
Ene_Efficiency _High	S.A.R	S.A.R	S.A.R	50%by 2030 wrt 2005	S.A.R	S.A.R	S.A.R
Ene_Efficiency _Low	S.A.R	S.A.R	S.A.R	50% by 2070 wrt 2005	S.A.R	S.A.R	S.A.R
Car_oriented	S.A.R	US's mode preference parameter	S.A.R	S.A.R	S.A.R	S.A.R	S.A.R
mass_transit	S.A.R	Japan's mode preference parameter	S.A.R	S.A.R	S.A.R	S.A.R	S.A.R
Occupancy_high	S.A.R	S.A.R	S.A.R	S.A.R	Increases	S.A.R	S.A.R
Speed_high	S.A.R	S.A.R	Increases	S.A.R	S.A.R	S.A.R	S.A.R
Speed_low	S.A.R	S.A.R	Decreases	S.A.R	S.A.R	S.A.R	S.A.R
Advanced_tec_high	High	S.A.R	S.A.R	S.A.R	S.A.R	S.A.R	S.A.R
Low carbon_withTax	High	Japan's mode preference parameter	Increases	50%by 2030 wrt 2005	Increases	S.A.R	S.A.R
Low carbon_w/oTax	High	Japan's mode preference parameter	Increases	50%by 2030 wrt 2005	Increases	Yes	S.A.R

[a] Preference factor are kept constant for developed regions, S.A.R:- Same as reference_w/oTax scenario.

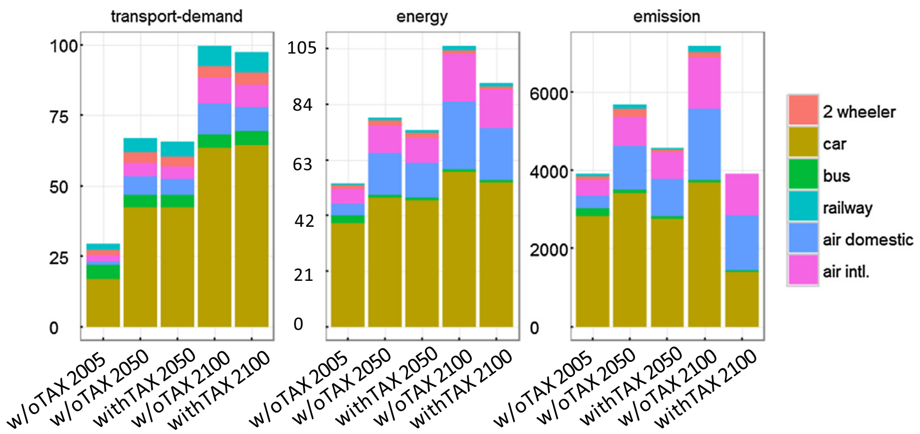

Fig. 2. Transport demand (Tpkm/year), energy (EJ/year) and emissions (Mt-CO_2/year) in the reference-w/oTax and reference-withTax scenarios.

Table 7
Emission reduction (%) in reference-withTax compared to reference-w/oTax.

	2020	2030	2050	2070	2100
Emission reduction	0.50%	4%	17%	32%	41%

stabilized (i.e. see OECD90) while developing regions like China, India and Southeast Asia (i.e. see Asia) will witness rise in transport demand over the coming decades.

The level of influence of each factor on travel demand varies across different regions (Fig. 4 for 2100). The results show that rise in the average travelling speed will reduce travelling time and travel time cost in the speed_high scenario compared to the reference scenario. The decreasing travel time cost will reduce the overall cost of transport and lead to rebound effect of increased global passenger transport demand by 1.36 tpkm/year. Similarly, in the occupancy_high scenario, the generalized cost per passenger km also reduces due to increase in the average vehicle occupancy as a result of interventions like car sharing, odd- even scheme, fixed car registration quota. Consequently, the global travel demand increases by 0.5 tpkm/year in 2100 compared to reference scenario. The travel time cost of the mass_transit system is higher compared to personal vehicles like car and two-wheeler, therefore, higher modal share of the mass_transit modes increases the overall transport cost and lead to decline of overall passenger transport demand by 0.3 trillion passenger km per year. By contrast, the transport

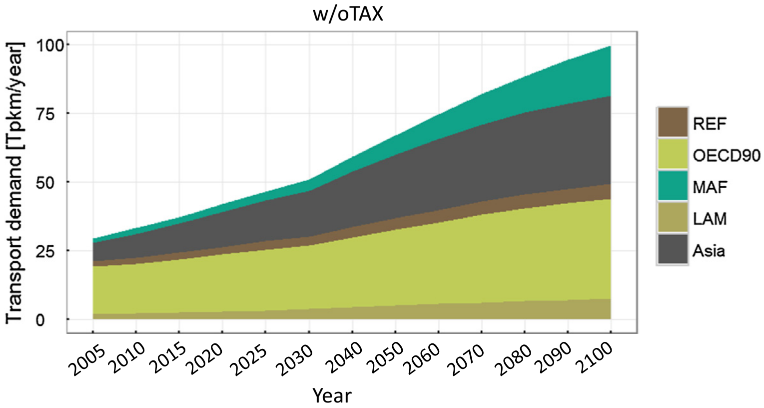

Fig. 3. Regional travel demand in the reference-w/oTax scenario; OECD90 = UNFCCC Annex I countries, REF = Eastern Europe and the former Soviet Union, ASIA = Asia excl. OECD90 countries, MAF = the Middle East and Africa, LAM = Latin America and the Caribbean (the regional mapping is shown in the supporting information).

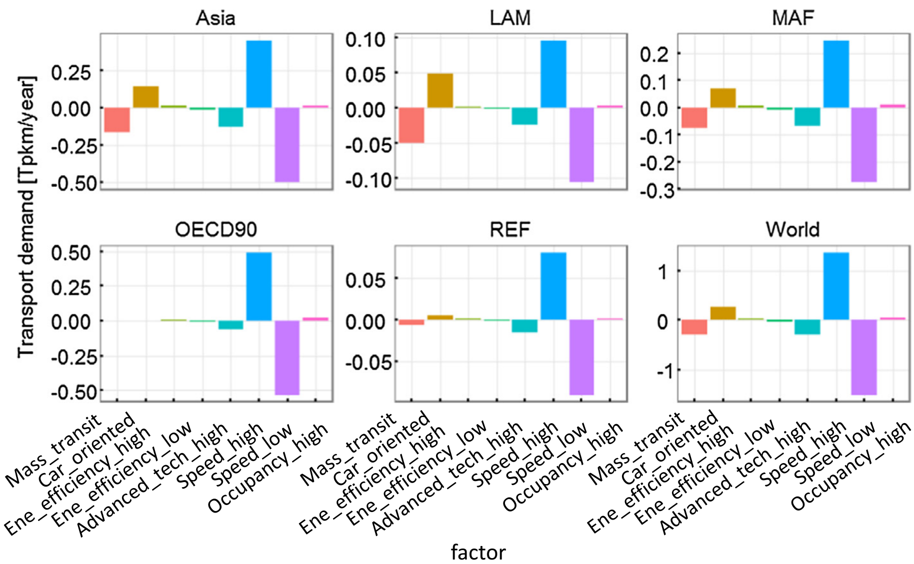

Fig. 4. Implication of each factor on regional and global travel demand in 2100 in other w/oTax scenarios compared to reference-w/oTax scenario.

demand would increase by 0.27 tpkm/year in car_oriented scenario compared to reference scenario. It can be seen from Ene_efficiency_high and Ene_efficiency_Low scenarios that technological factor like efficiency improvement does not bring any significant change in the transport demand.

In the mass_transit scenario, the travel demand decreases in the developing countries compared to developed countries. The generalized transport cost increases in case of the developing countries due to higher share of public transport whereas there is no change in passenger transport demand in case of developed countries due to stable modal structure in these two scenarios. Overall these results suggest that additional demand would be mainly induced by reducing the travelling time and increasing the vehicle occupancy rate across all regions.

3.3. Modal share

Fig. 5 shows that the global share of car increases from 57% in 2005 to 64% in 2100 in the reference-w/oTax scenario due to shift from the mass transit system towards more personalized transport mode. The travel time cost increases with rise in income facilitating the shift towards personalized mode. A closer look at the regional dynamics shows that the modal structure is relatively stable in the developed countries since the car ownership has already reached the highest level in these countries. By contrast, structural changes will take place in developing countries in the coming decades in the

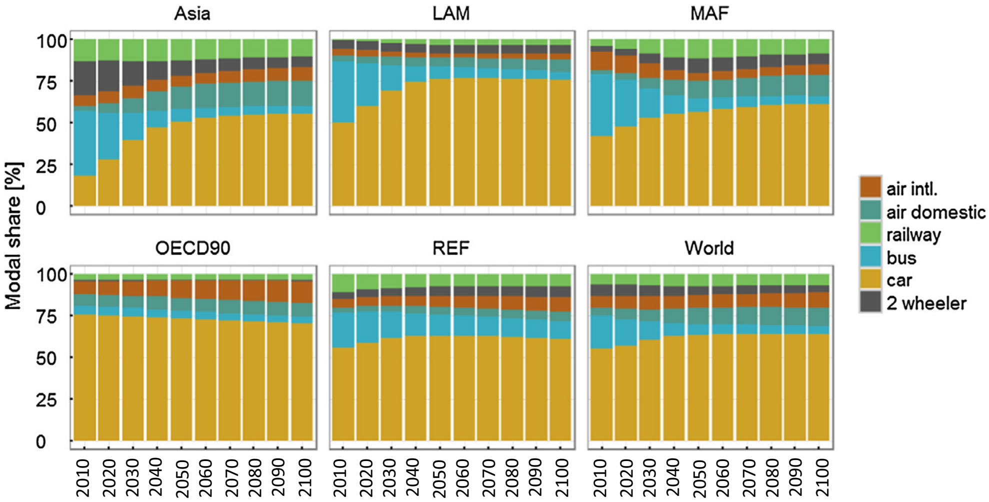

Fig. 5. Modal share in the reference-w/oTax scenario.

reference-w/oTax scenario as car ownership will increase with a rise in affluence and then stabilize with a further rise in income. For instance, the share of car increases from 15% in 2005 to 50% in 2100 in the reference scenario.

Furthermore, Fig. 6 shows the impacts of different socioeconomic factors on modal share in 2100 compared to the default settings in the reference scenario. The results show that in the speed_high scenario, we witness the 2% global transport demand shift from air to railways. Significant structural changes happen in developing countries by changing the preference parameter either in line with car_oriented or mass_transit development pattern. In the car_oriented scenario, the share of railways in the modal share decline by 5% in 2100 due to higher preference for air travel. On the contrary, the shift towards the mass transit mode like bus and railways results in 1% and 5.4% increase in their shares, respectively, higher preference coefficient for mass_transit system compared to personalized mode. In addition, the effect of other factors like efficiency improvement, preference for environmentally friendly technologies and increasing load occupancy on the modal structure is insignificant on modal share.

3.4. Energy consumption in 2100

Fig. 7 represents the implication of each factor on energy consumption in 2100 compared to the reference-w/oTax scenario. The results show that higher share of personalized mode in the car–oriented development result in 15% increase in global energy consumption whereas in mass_transit oriented development results in 16% global energy reduction due to higher share of energy-efficient public transport. Improving energy efficiency owing to the strong fuel economy improvement initiative results in 7% reduction in energy consumption in Ene_efficiency_high scenario across all regions. On the contrary, the energy consumption increases by 6.7% globally in the Ene_efficiency_Low scenario due to slackening fuel economy standards. In the occupancy_high scenario, the energy consumption reduces by 12% by increasing the personalized vehicle occupancy rate. Since the share of car in developed countries is high, increase in the occupancy level of car leads to greater reduction in the energy consumption relative to developing countries. Overall, the results indicate that the energy consumption reduces due to rise in the average speed of the mass transit system. But significant energy saving would take place by efficiency improvement, giving more preference to mass-transit system and increasing the occupancy.

Due to stable modal structure in OECD countries as mentioned in the mass_transit and car_oriented scenario description, any significant change in the energy consumption cannot be observed in these two scenarios compared to reference scenario. However, significant change in the energy consumption can be witnessed in developing regions such as Asia, LAM and MAF due to structural changes following different development pathways in the mass_transit and car_oriented scenarios.

3.5. Emissions in 2100

Fig. 8 shows that CO_2 emissions from the passenger transport sector in the w/oTax cases, compared to the reference scenario in the year 2100. The emissions from electricity generation are accounted proportional to its share in the fuel mix. The global CO_2 emissions increase by 14.6% in the car-oriented scenario whereas emissions reduce by 15% in the mass_transit scenario. Moreover, in the Ene_efficiency_high scenario, the emissions decrease by 7% whereas in the Ene_efficiency_Low scenario the emissions increase by 6.6% in the absence of strong fuel economy initiative in 2100. Furthermore, energy reduction due to higher vehicle occupancy results in 11% emission reduction in occu_high scenario. The global trend is similarly

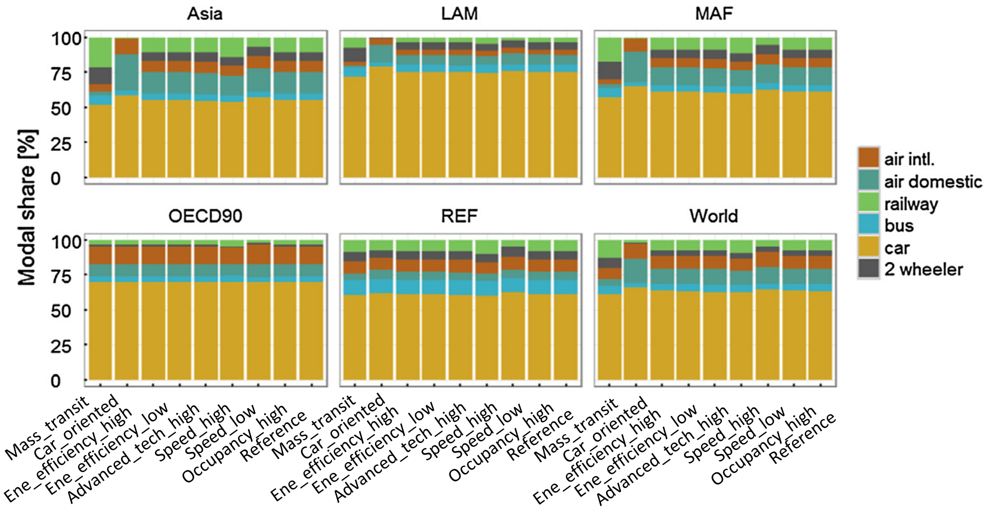

Fig. 6. Impacts of different factors on modal structure in 2100 compared with the reference-w/oTax scenario.

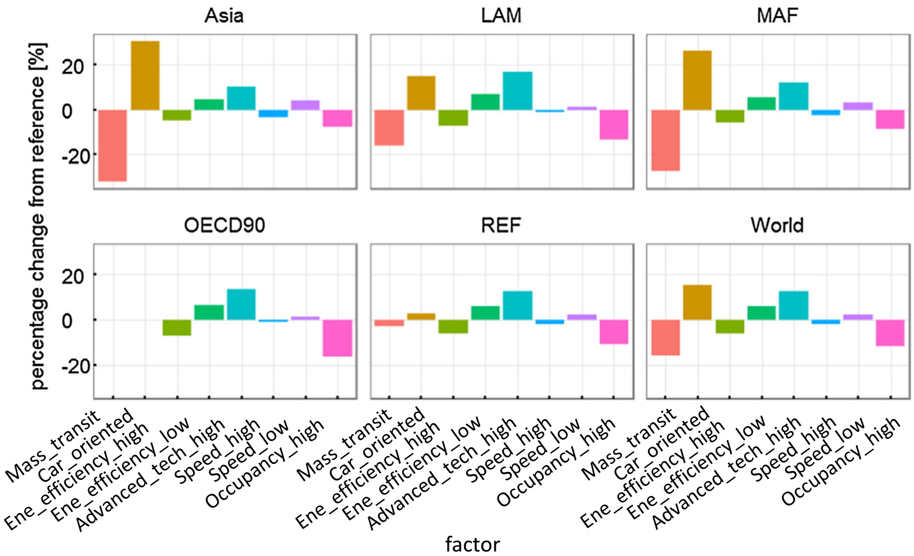

Fig. 7. Impacts of different factors on energy in 2100 compared with the reference-w/oTax scenario.

seen in other regions though the magnitude is slightly different that can be observed from Fig. 8. Therefore, shifting to the mass transit and increasing the load factor would contribute in emission reduction.

Regarding the withTax cases, although the magnitude of each factor is different from w/oTax cases, the basic order and direction of each factor is the same. For example, the preference to the mass transit and increasing the load factor are the major two factors to reduce the emissions whereas car-oriented society incurs increase in emissions. A closer look at the regional dynamics reveals that the imposition of tax results in the greater influence on the emissions magnitude in the mass_transit and car_oriented scenarios compared to w/oTax case distinctly in developing countries. The effects of other factors on emissions in the w/oTax and withTax case are not substantially different. As mentioned in Section 3.4, the modal structure will change with economic growth in the developing regions. Therefore, change in the carbon intensity due to carbon tax as discussed in Section 3.2 along with the modal shift leads to greater variations in emissions from the developing countries depending upon the direction of their development (car-oriented or mass_transit development).

3.6. Decomposition analysis

Fig. 9 presents the results of the decomposition analysis for two reference scenarios, i.e., reference-w/oTax and reference-withTax. It shows how much each factor contributes to the change in the emissions. Due to rise in income and population,

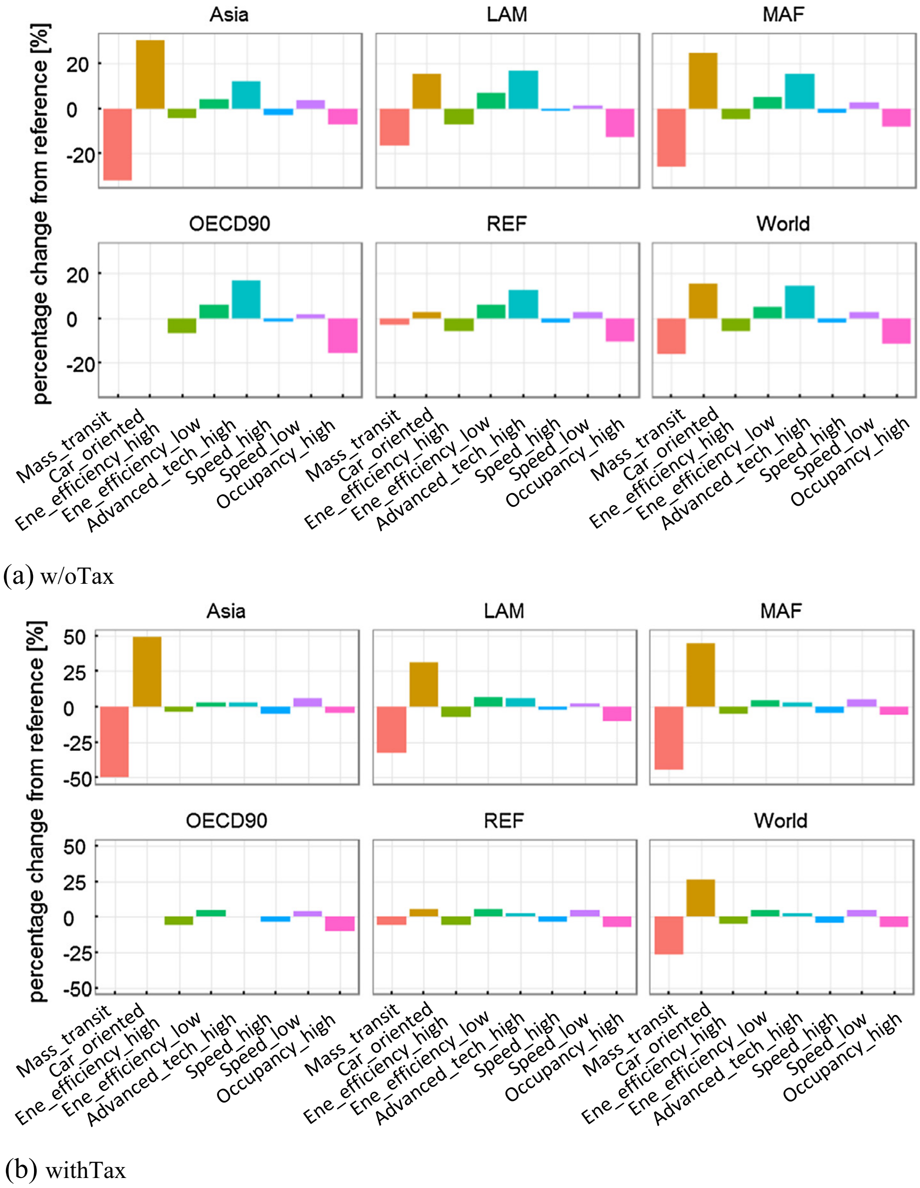

Fig. 8. Impacts of different factors on emissions in 2100 in (a) w/oTax and (b) withTax cases compared to the reference scenario.

the activity level results in the increase in the carbon emission in both scenarios. However, in the reference-withTax scenario, transport cost increase due to the imposition of the carbon tax lessens the effect of activity intensity. The structure change contributes to a higher increase in the reference-w/oTax scenario as the share of carbon-intensive mode like car is higher.

The results also reveal that in the reference-withTax scenario, energy intensity and carbon intensity effects are the two major factors in reducing the carbon emissions. The carbon intensity effect results in 37% carbon emission reduction relative to the base year. The decline in the carbon intensity is primarily due to the fuel shift from fossil fuel to electricity and biofuel in transport sector as well as decarbonization of electricity sector, which can be witnessed from energy mix in reference-withTax scenario Figs. S5 and S6. The energy intensity effect contributes to 53% reduction of the carbon emission compare to the base year due to improvement in fuel economy and penetration of advanced vehicles.

3.7. Sensitivity analysis

Driven by the rising population and income in developing countries, the travel demand is expected to surge in the coming decades (Cameron et al., 2004; Fulton and Eads, 2004; IEA, 2014). However, there are uncertainties related to the population and economic growth rates. Therefore, in this study, three scenarios are simulated with different socioeconomic assumptions

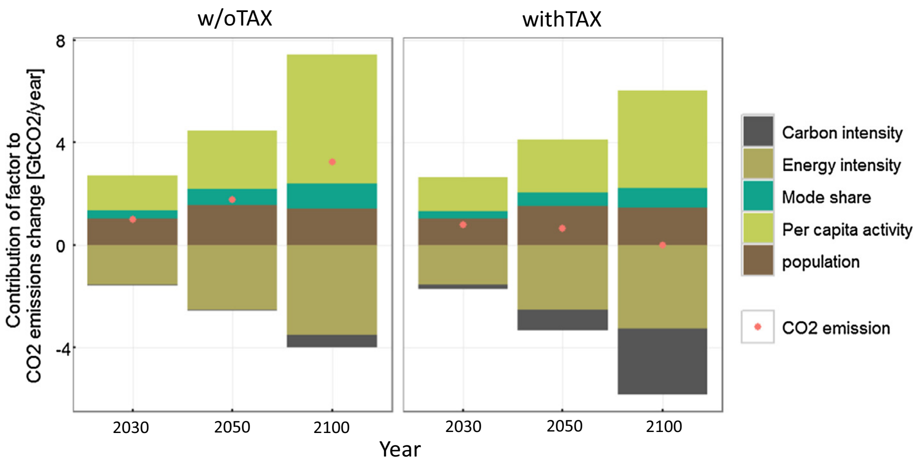

Fig. 9. Contribution of each factor to the carbon emission change in the global transport passenger sector in the reference-w/oTax and reference-withTax scenarios.

on population and GDP aligned with three shared socio-economic pathways (SSP 1–3 in Figs. S3 and S4) to estimate their impacts on future passenger transport demand.

From Fig. 10, it can be seen that the transport demand in 2100 ranges from 73.5 tpkm in the SSP3 scenario to 99.5 tpkm in SSP2 (or reference as showed in Fig. 10). In the SSP1 scenario, transport demand is higher than the reference scenario till 2080 due to higher GDP growth rate, and then stabilizes and reaches 94.5 tpkm lower than reference scenario. It can also be seen from Fig. 10 that transport demand in the SSP3 scenario is lower than the reference scenario attributed to lower GDP growth rate and less population.

Fig. 11 compares the three SSP scenarios in terms of travel intensity measured as travel demand per GDP. The travel intensity decreases from 0.65 pkm/USD in 2005 to 0.3 pkm/USD in 2100 in the reference scenario. Moreover, it declines to 0.5 pkm/USD by 2100 in the SSP 3 scenario. Conversely, due to high economic growth rate but declining population growth rate in the latter half of the century, the travel intensity is the highest in the SSP1 scenario in 2100.

4. Discussion

The discussion section is structured in two parts. The comparison is drawn between the scenario assessment results from transport model and AIM/CGE model, then the impacts of different factors on transport demand, energy and CO_2 emissions are discussed in the first part. The limitations and future research directions are discussed in the second part.

The total global energy consumption in passenger transport sector estimated using bottom-up transport model is not significantly different from the AIM/CGE model in the reference and withTax scenarios (Fig. S.7). However, the penetration of the low-carbon fuel such as electricity and biofuel is higher in AIM/CGE model compared to the bottom-up transport in the reference and withTax scenario. In AIM/CGE, fuel prices and elasticity parameters are key determinants of the final energy mix. The factors like technology cost, travel time cost and consumers' technology and mode preference that also have an influence on the final energy mix are not considered in case of AIM/CGE model. Therefore, the outcomes in this study indicate that the transport energy demand representation in AIM/CGE model could be highly optimistic with regard to the technological shift in carbon tax scenario.

However, the AIM/CGE model fails to capture the changes in modal structure, thereby making it difficult to assess the change in energy consumption due to modal shift. The results show that the transport model with mode and technological details allows inclusion of various mitigation options and assessment of its impact on transport demand and modal structure. The future transport demand trajectory is highly dependent on how population and income will evolve in future and is less dependent on the energy prices that can be witnessed from the sensitivity analysis and mitigation scenario. The decline in the transport demand is not significant in the carbon tax scenario which is in agreement with Girod et al. (2012). It is difficult to draw a comparison between the two studies as the emission trajectory aligned with RCP 2.7 used from AIM/CGE is quite lower than Girod et al. (2012). These scenario assessment results show that carbon tax would have a greater influence on the technological front, leading to the energy and emissions reduction compared to transport demand. The change in technology mix is more sensitive to carbon tax compared to the transport demand due to two factors. First, technology cost comprises of larger portion of carbon price compared to the total transport cost. Second, the price sensitivity parameter is higher in case of technology compared to transport demand.

Our results show that increase in the transport demand happen by increasing the travelling speed of mass transport system. This can be explained by the reduction in the overall cost as the travel time cost is taken into account while estimating

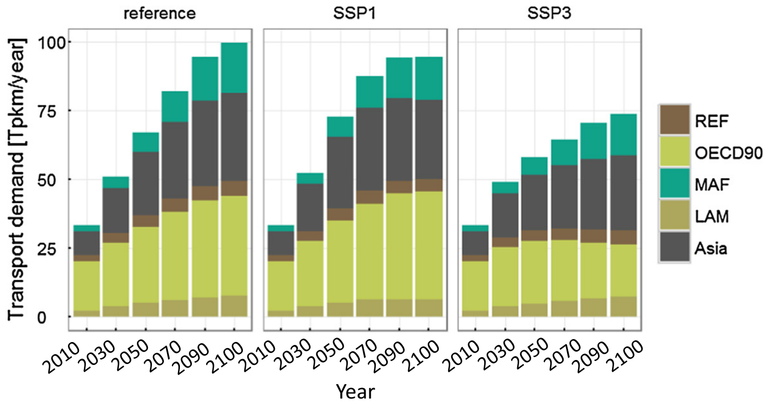

Fig. 10. Transport demand in three SSP scenarios.

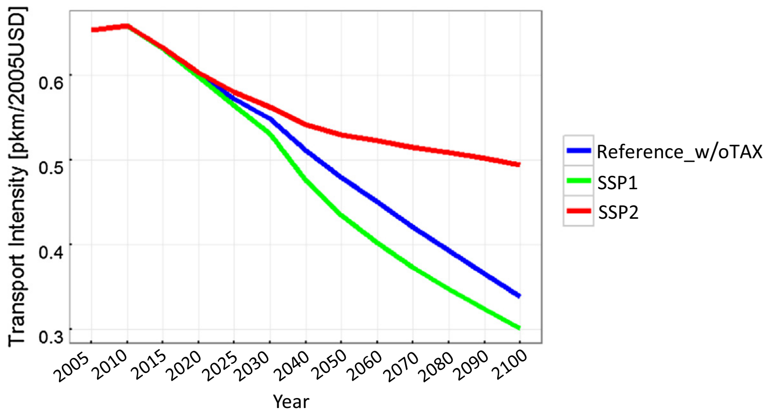

Fig. 11. Transport intensity in three SSPs scenarios.

the mode cost. This result is in agreement with the study conducted by Metz (2008) which explains that increase in travelling speed may result in accessibility improvement, and people would travel to a distant destination, which ultimately leads to a rise in the overall travel demand. The rebound effect can be witnessed due to decline in the travel time cost from the scenario analysis. The results show that the preference parameter (α in Eq. (3)) for different modes has greater influence on the modal share. In the car_oriented scenario, the parameter for air slowly increases and reaches the US level for the developing countries, in this scenario we observe that the share of air transport in China increases greater than US by 2100. This future trend is difficult to explain in absence of robust methodology to estimate trends in preference parameters related to mode and technology. From the results of this study, we can only point out that constant factor for air greater than or equal to US level may result in the higher share of air-travel in developing countries like China compared to US in 2100.

Fig. 12 shows that the cumulative emission reduction in the low_carbon-w/oTax that can be achieved by implementing various mitigation options related to travel behavior like efficiency improvement, transit-oriented development and increase in vehicle occupancy, speed improvement, preference for eco-friendly vehicle is around 18% compared to the reference scenario in the absence of the carbon tax. The reduction potential further increases to 44% by implementing the global carbon tax across all regions.

As several studies have mentioned that electrification of transport from low-carbon electricity would play an important role in the de-carbonization of the transport sector (McCollum et al., 2013; Kyle and Kim, 2011). Therefore, we have considered indirect emissions from the electricity sector to estimate the total emission from transport sector. The emission coefficient of power generation in carbon tax scenario reduces drastically and even negative in some regions due to higher carbon capture and storage at high carbon price (Fig. S.6 in supplementary document). Therefore, higher share of electric vehicles due to greater preference of eco-friendly technologies along with carbon tax scenario results in higher emission reduction.

4.1. Limitation & future research

Regarding the limitations, in the current study, we have only focused on the motorized transport modes for physical movement of passenger from one place to another and non-motorized transport options like walk and bicycles have not been

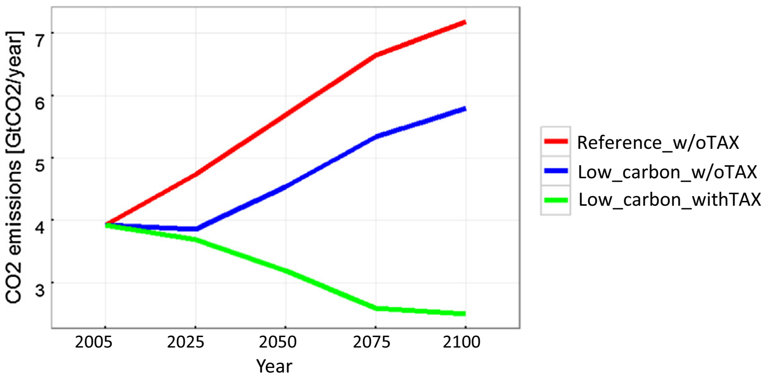

Fig. 12. Max reduction potential using different withTax strategies.

considered due to data limitation. Further research is required to estimate the potential substitution of physical travel by tele-activities due to growing penetration of the information and communication technologies. In this study, the income and price elasticity remain constant throughout the assessment period. However, in our future research we intend to determine transport demand by considering varying the future elasticities related to transport demand. In this study, we have soft-linked AIM/CGE model with the new transport model, but there is no feedback link from the transport model to the AIM/CGE model. Taking feedback from transport model to AIM/CGE model would be relevant to understand the effect of transport sector dynamics on other sectors. Also, the supply related factors such as infrastructure availability and cost are not considered in the current transport model. These factors are important to consider for understanding the passenger dynamics in the developing countries. In the global model heterogeneity among the consumers is not considered explicitly, that needs to be taken for estimating technology choices more realistically (John et al., 2000).

5. Conclusions

The key conclusions from the modelling assessment are: (1) Soft-linking bottom transport model with top-down computable general model help in capturing the effect of energy price change on travel demand and modal spilt in a climate constrained scenario; (2) The factors like population, income, travel speed and land-use development patterns would have a significant influence on the passenger transport demand. However, carbon tax would have greater influence the fuel and technology choices compared to transport demand. The carbon tax would lead to in 41% emission reduction compared to 2% demand reduction in the year 2100. (3) The emission reduction potential from passenger transport sector would increase from 23% to 44% by implementing travel behavior related mitigation options in the presence of carbon tax compared to the no climate policy scenario.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.trd.2016.10.006.

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