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LETTER

The contribution of transport policies to the mitigation potential and cost of 2 °C and 1.5 °C goals

Runsen Zhang[1,2,5], **Shinichiro Fujimori**[1,3,4] **and Tatsuya Hanaoka**[1]

[1] Center for Social and Environmental Systems Research, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba 3058506, Japan

[2] Graduate School for International Development and Cooperation, Hiroshima University, 1–5-1 Kagamiyama, Higashi-Hiroshima 7398529, Japan

[3] Department of Urban and Environmental Engineering, Kyoto University, 361 Kyoto University Katsura Campus, Nishikyo-ku, Kyoto 6158540, Japan

[4] International Institute for Applied Systems Analysis, Schlossplatz-1, 2361 Laxenburg, Austria

[5] Author to whom any correspondence should be addressed.

E-mail: zhang.runsen@nies.go.jp

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Supplementary material for this article is available online

Abstract

The transport sector contributes around a quarter of global CO_2 emissions; thus, low-carbon transport policies are required to achieve the 2 °C and 1.5 °C targets. In this paper, representative transport policy scenarios are structured with the aim of achieving a better understanding of the interaction between the transport sector and the macroeconomy. To accomplish this, the Asia–Pacific Integrated Model/Transport (AIM/Transport) model, coupled with a computable general equilibrium model (AIM/CGE), is used to simulate the potential for different transport policy interventions to reduce emissions and cost over the period 2005–2100. The results show that deep decarbonization in the transport sector can be achieved by implementing transport policies such as energy efficiency improvements, vehicle technology innovations particularly the deployment of electric vehicles, public transport developments, and increasing the car occupancy rate. Technological transformations such as vehicle technological innovations and energy efficiency improvements provide the most significant reduction potential. The key finding is that low-carbon transport policies can reduce the carbon price, gross domestic product loss rate, and welfare loss rate generated by climate mitigation policies to limit global warming to 2 °C and 1.5 °C. Interestingly, the contribution of transport policies is more effective for stringent climate change targets in the 1.5 °C scenario, which implies that the stronger the mitigation intensity, the more transport specific policy is required. The transport sector requires attention to achieve the goal of stringent climate change mitigation.

1. Introduction

All countries in the United Nations Framework Convention on Climate Change (UNFCCC) have proposed to constrain global warming to less than 2 °C relative to pre-industrial levels, as part of the Cancun Agreement [1]. However, the impacts of climate change and the capacity to cope with these impacts vary significantly between regions. The impacts projected for 2 °C warming may exceed the adaptation capacity of some vulnerable countries, such as small island nations and the least-developed countries [2]. Therefore, many countries committed to pursuing limiting warming to below 1.5 °C, as detailed in the 2015 Paris Agreement [3, 4]. Limiting warming to below 1.5 °C is ambitious and undoubtedly a very challenging task. Achieving 1.5 °C warming requires more rapid and profound decarbonization of the energy supply and, by implication, putting a relatively high price on carbon emissions [4]. The mitigation cost of achieving 2030 emissions with 1.5 °C pathways has been projected to be at least 5–6 times higher than the cost of achieving the conditional nationally determined contributions (NDCs) [5].

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The transport sector represents a quarter of global CO_2 emissions and is recognized to be one of the main causes of global warming [6–9]. The reduction of global transport-related CO_2 emissions to limit the magnitude or rate of long-term climate change will be challenging, because the continuing growth in passenger and freight activity will outweigh all mitigation measures unless transport emissions can be strongly decoupled from gross domestic product (GDP) growth [10–14]. To reduce emissions from the transport sector, policy makers are primarily pushing for more efficient vehicles, alternative sources of energy such as electricity and biofuel, electric vehicles, speed regulation, reducing vehicle miles travelled (VMT), traffic signal coordination, public transit system improvement, and other traffic management measures [15–20]. Clean energy transition, electrical energy storage, and particularly the improvement of vehicle battery technology permits an optimistic outlook for battery electric vehicles contributing to low-carbon transport [21–23]. Existing studies have explored transport policies that can contribute to the achievement of decarbonization in the transport sector [15, 18, 24–27], however, there is limited information on whether and how transport policies would be likely to affect the overall costs of mitigation and the relative importance of these policies in striving to achieve the stringent global temperature limits of below 2 °C and 1.5 °C.

Choices regarding the particular transport mode for each individual's trips generally involve consideration of attributes such as travel cost, travel time, personal preference, and individual socioeconomic characteristics; assembled across populations, the choices can determine travel behaviors and emissions for communities and nations. To better understand the collective effects, transport models such as the behavioral model, the mode choice model, and the Four Step Model (FSM) are widely applied to transport policy assessment [28–33] to provide elaborate technological descriptions and evaluations of the technological feasibility of transport policies. Although individual transport models offer powerful tools for transport planning and policy analysis at the city and regional scales in the short run, they only focus on the transport sector itself, as opposed to the interactions between the transport sector and the macroeconomic system or the response of other sectors to transport policy interventions. Given that an evaluation of the global impacts of transport behaviors and policy on the economic cost of mitigation policies in long term is challenging, the integration of transport models and integrated assessment models (IAM) offers a methodology for providing useful insights for transport planners and climate policy makers.

The transport sector has been included in integrated assessment models such as Targets IMage Energy Regional (TIMER), Global Change Assessment Model (GCAM), The Integrated MARKAL-EFOM System (TIMES), Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE), General Equilibrium Model for Economy—Energy—Environment (GEM-E3), IMACLIM-R, and The Asia–Pacific Integrated Model/Computable General Equilibrium (AIM/CGE) [34–45]. Taking AIM/CGE as an example, the transport sector is represented at a highly aggregated level, without technology details or behavior factors such as mode preference, travel cost, and travel time. The transport demand is simply included as a part of industrial activity, based on the elasticity of substitution and relative prices, and household private-car-oriented energy use is formulated under the Linear Expenditure System (LES). Because the modal split and technological selection are not endogenously determined in the transport representation, AIM/CGE fails to capture the dynamics of the technological structure and mode preference. As a result, the AIM/CGE is not useful for investigating the mitigation potential and cost of transport technological and behavioral options.

To achieve a better understanding of the role of transport policies in achieving climate change targets, especially in the context of the Paris Agreement, the main purpose of this research is to investigate the interaction between transport policies, global dynamics of transport demand volume, mitigation potential, and the cost of meeting the goal of limiting warming to below 2 °C and 1.5 °C. To capture the interplay between the transport sector and the macroeconomy, a global transport model, AIM/Transport, coupled with AIM/CGE has been used to overcome the shortcomings of individual CGE and transport models. By doing this, both the traveler's mode choice and technology details, and an interactive analysis on mitigation potential and cost of transport policies, can be incorporated into a projection of global passenger and freight transport activities, during the period 2005–2100.

The paper is organized as follows. Section 2 presents the AIM/Transport model structure, and describes the coupling with AIM/CGE, the data sources, and calibration, followed by the scenario settings including different aspects of transport policy. Section 3 provides simulation results of impacts on mitigation potential and costs of different transport polices using the coupled CGE-Transport model, and section 4 provides a discussion of the interpretation and implications of the results.

2. Method

2.1. Model structure

A transport model, AIM/Transport, is developed to project the global passenger and freight transport demand for different modes and technologies and transport-related emissions, incorporating transport mode choice and technological details. The overall model AIM/Transport model structure is shown in figure 1. AIM/Transport is a one-year interval

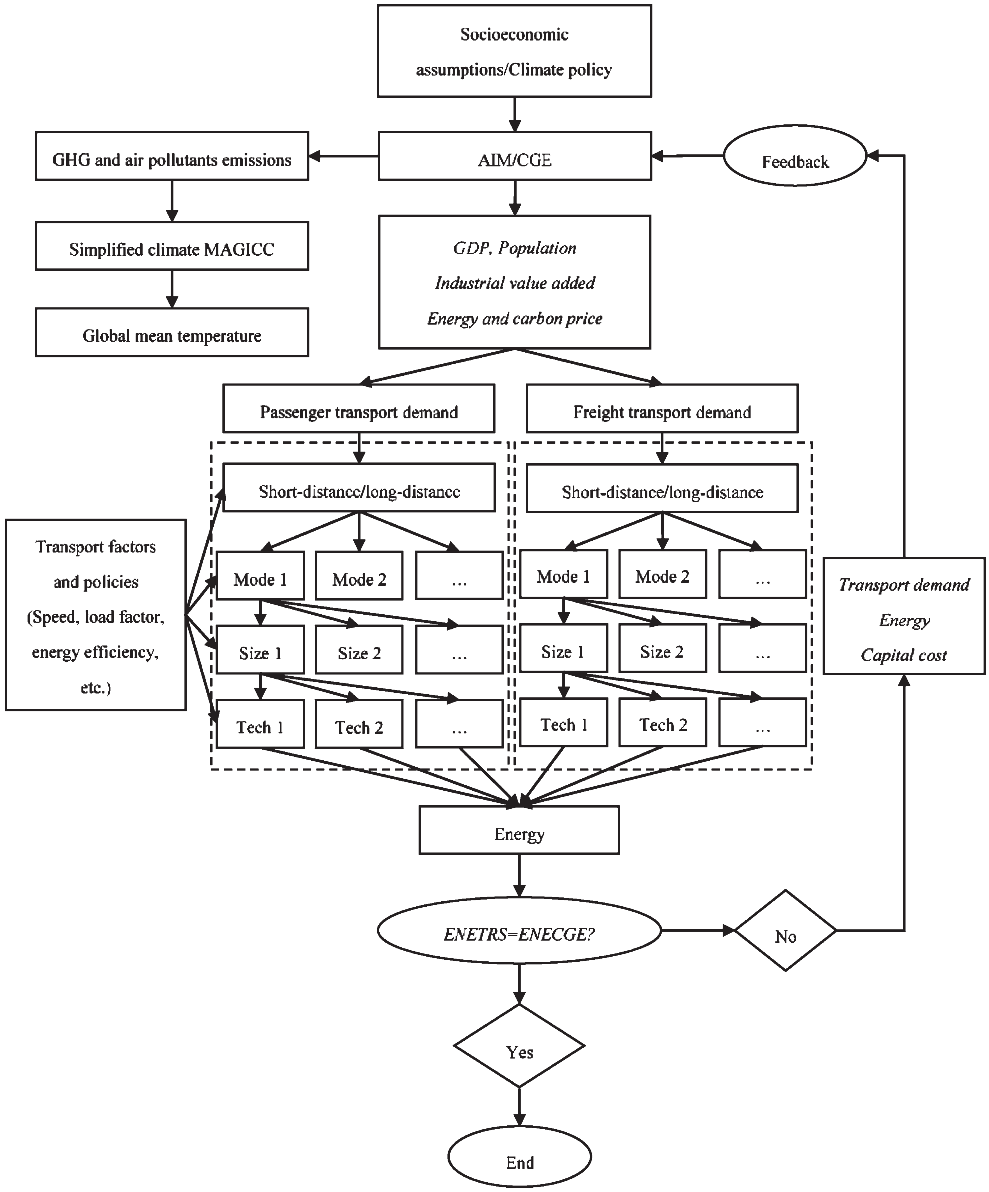

Figure 1. Model structure. ENECGE and ENETRS stand for energy consumptions computed in AIM/CGE and AIM/Transport, respectively.

recursive-type model that includes global passenger and freight transport activities for 17 regions around the world (see supporting information). The essence of AIM/Transport is a transport choice model that consists of various tiers. Passenger and freight transport flows are divided between short and long distances. At the next tier, transport modes compete for short- and long-distance travel. Here, car, bus, and two wheelers are used for short-distance passenger transport, whereas passenger transport modes for long-distance travel include passenger rail, domestic, and international passenger air. For freight transport, small truck, large truck, freight rail, domestic shipping, international shipping, domestic freight air, and pipeline are available for long-distance freight transport, while short-distance freight transport only includes small and large trucks. For the next tiers, different sizes of vehicles (i.e. small, medium, and large) and technologies are considered (see supporting information). Energy consumption and emissions in the transport sector are estimated according to technology-based transport demand.

The total transport demand is determined by the GDP, industrial value added, population, and generalized transport cost for passenger and freight, respectively. For freight transport, pipeline is handled as a dependent sector and does not compete with other freight modes, because it is not determined by industrial value added but by the quantity of oil and gas consumption. The shares of different distances, modes, sizes, and technologies are computed using multinomial logit models based on the generalized transport cost that includes device cost, fuel cost, carbon tax, and time cost. The transport technological selection is represented based on purchasing behavior, where a newly installed transport device is determined,

Table 1. Data sources for AIM/Transport.

Data	Description	Source	Reference
GDP	Region specific	AIM/CGE	[48]
Population	Region specific	AIM/CGE	[48]
Industrial value added	Region specific	AIM/CGE	[46]
Transport volume	Mode specific	AIM/Enduse	[49, 50]
Vehicle device cost	Mode and technology specific	AIM/Enduse	[49, 50]
Energy intensity	Mode and technology specific	AIM/Enduse	[49, 50]
Load factor	Region and mode specific	GCAM	[51]
Door-to-door speed	Mode specific	GCAM	[51]

and existing capital is inherited from the previous year. Particularly, technological improvements have been incorporated into the process of technological selection. Consumer preferences for advanced technologies, such as electric vehicles, are projected to increase gradually, accompanied by the deployment and promotion of technological innovation. However, the technological improvements will take considerable time for the overall global fleet to change, even if new technologies are assumed to take over a marketplace in the future, e.g. vehicle manufactures going electric. The detailed formulations are listed in supporting information.

AIM/Transport is coupled with a global computable general equilibrium model AIM/CGE to capture the interactive mechanism between the transport sector and the macroeconomy. AIM/CGE is also a one-year interval recursive-type, dynamic, general equilibrium model that covers all regions of the world and consists of 42 industrial classifications [35, 46]. AIM/CGE passes the macroeconomic variables (e.g. GDP, industrial value added, population, fuel price, and carbon price) to AIM/Transport for transport demand projection and estimation for modal split and technology shares. An iterative method was used to integrate AIM/CGE and AIM/Transport. The transport volume, transport-related energy consumption, and capital cost for transport device feedback from AIM/Transport are passed to AIM/CGE for parameter re-estimations of the transport sector in AIM/CGE. This loop continues until the energy consumptions computed in AIM/CGE (ENECGE) and AIM/Transport (ENETRS) are equal. The iterative procedure helps refine the transport representation in AIM/CGE, based on detailed AIM/Transport information [47]. Finally, global GHGs (CO_2, CH_4, N_2O, and F gases) and other air pollutant emissions (e.g. SO_2, BC, and NOx) are fed into the simplified climate model MAGICC, which generates climate outcomes such as radiative forcing and global mean temperature changes.

Parameter estimation and calibration of AIM/Transport were conducted using multiple data sources. Socioeconomic data such as GDP, industrial value added, and population were acquired from the shared socioeconomic pathways database and output of AIM/CGE [46, 48]. The transport demand volume, energy efficiency of transport technologies, and transport device cost were obtained from a global bottom-up technological model, AIM/Enduse [49, 50]. The load factor and door-to-door speed for travel time estimations were taken from GCAM [51]. The data sources used for this model are listed in table 1.

2.2. Socioeconomic and climate policy scenario settings

For the socioeconomic settings such as GDP and population, shared socioeconomic pathways 2 (SSP2) estimates were employed as default values for GDP and population in AIM/Transport, which are characterized as 'middle of the road' among a range of socioeconomic pathways [48, 52]. For AIM/CGE, a range of other parameter assumptions were applied also based on SSP2 [53]. The second scenario dimension is the climate policy dimension, denoted by 'BaU', '2D' and '1.5D'. In the 'BaU' scenario, no climate mitigation efforts are assumed, while a carbon price is imposed in the '2D' and '1.5D' scenarios.

Under the 1.5 °C scenario, by the end of this century the global mean temperature increase will be well below 1.5 °C (peaking at around 1.6 °C in 2045 and settling to 1.4 °C in 2100). The radiative forcing level associated with the 1.5 °C goal is around 2.0 W m^{-2} in 2100. Similarly, the 2 °C scenario is consistent with the 2 °C goal, with a global mean temperature peaking at 1.9 °C in 2090 and settling to 1.8 °C in 2100. The radiative forcing level of the 2 °C goal is around 2.9 W m^{-2} in 2100. The forcing target is chosen based on the SSP (Shared Socioeconomic Pathway) exercises [53, 54]. Our model allows overshoot, particularly for 1.5 °C, such that the temperature increase will peak at 1.6 °C in 2045 and then drop to 1.4 °C in 2100. The carbon price, total CO_2 emissions, radiative forcing, and global mean temperature increases for 2 °C and 1.5 °C targets are provided in the supporting information. This study here mainly attempts to touch upon very hopeful pathways of emissions, but they might be hard to realize. These scenarios are carried out mainly to explore the role of the various proposed measures in the overall effort that is undertaken.

2.3. Transport policy scenario framework

The next scenario dimension is the transport policy for simulating how different transport factors and policy interventions affect the mitigation potential and cost. We selected representative transport policies from technological and behavioral aspects [55]. Here, energy efficiency improvement (Ei_High) and

Table 2. Transport policy scenario framework.

Scenario	Description
Ei_High	50% improvement in new LDV energy efficiency from baseline level will be achieved by 2050
Tech_Innovation	Higher preference and technological selection factor is given to advanced technology vehicles (HEV, PHEV, FCV, EV) compared to the conventional ICE-driven cars
Mass_Transit	The modal preference factors of Japan are employed as a proxy to reflect the preferences in mass transit-oriented development. Developing countries will gradually converge to Japan's preference factors in 2005 by 2100
Occu_High	The occupancy factor of a car will converge to two people per car by 2100
Low_Carbon	The combination of technological innovation and behavioral change achieved by including Ei_High, Tech_Innovation, Mass_Transit, and Occu_High
Reference	30% improvement in LDV vehicle energy efficiency by 2100; advanced technology vehicles (HEV, PHEV, FCV, EV) will be introduced at a moderate rate

LDV: light-duty vehicle; HEV: hybrid electric vehicles; PHEV: plug-in hybrid electric vehicles; FCV: fuel-cell vehicles; EV: electric vehicles; ICE: internal combustion engine.

vehicle technological innovation (Tech_Innovation) were applied as transport technological factors; mass transit-oriented transport development (Mass_Transit) and vehicle occupancy (Occu_High) were used for transport behavioral factors, and the low-carbon scenario (Low_Carbon) was applied to combine technological and behavioral issues (table 2). A reference scenario was also designed to contrast the scenarios with technological and behavioral changes in terms of energy use and emissions. Moderate energy efficiency improvement and technological innovation were taken into consideration.

3. Results

3.1. Main indicators of the reference scenario

In this section, we analyze main indicators of the reference scenario without low-carbon transport policies, such as transport demand, energy consumption, and emissions. Analyses of the impacts of different transport policies and the contribution of transport policies to the reduction in mitigation cost are presented in 3.2 and 3.3, respectively. Figure 2(*a*) shows the global passenger and freight transport demand in 6 regions of the BaU case for the reference scenario without any transport policies. In the BaU reference scenario, the total passenger and freight transport demand measured in terms of the passenger km travelled (pkm) and ton km travelled (tkm) increased from 29–95 trillion pkms and 85–301 trillion tkms during 2005–2100, at an average annual growth rate of 2.4% and 2.7%, respectively. For passenger transport, the European Union, the United States, and India account for a considerable proportion of travel demand in the world, while China plays the most dominant role in freight transport. This is likely because a large increase in industrial development is simulated for China, leading to a growth in freight transport demand, while a decline in population results in a reduction in passenger transport. In addition, the transport demand in developed regions, including the European Union, the United States, and the remaining Organisation for Economic Co-operation and Development (OECD) countries, exhibited stable tendencies, although they account for large proportions. In contrast, developing regions, particularly the remaining non-OECD countries, were predicted to steadily increase over the coming decades. Mode-wise transport demands show that car and shipping demands account for large proportions of passenger and freight transport, respectively, as shown in figure 2(*b*). This implies that the private travel mode plays an increasing role in passenger transport without any decarbonized transport policy initiatives. For freight transport, navigation maintained large shares, and this trend can be seen in other studies [7, 56, 57] (also illustrated in supporting information). The reason may be that shipping is highly cost-effective and the best option for bulk goods transportation–sometimes the only option.

The final energy consumption by fuel for passenger and freight transport is displayed in figure 3. The energy consumption required by passenger and freight transport surged from 49 and 33 EJ in 2005 to 106 and 92 EJ in 2100 in the BaU scenario, but only increased to 89 and 79 EJ in the 2 °C scenario, and increased to 78 and 74 EJ in the 1.5 °C scenario. Oil played a dominant role even though it was replaced by electricity, gas, and biofuel between 2005 and 2100 in the BaU scenario, and the proportion of oil dropped dramatically in the 2 °C and 1.5 °C scenarios. These results suggest that, at least in this model, imposing a carbon price can effectively reduce the usage of oil and motivate the use of electricity and biofuels. Figure 4 shows the mode-wise CO_2 emissions for the passenger and freight transport sectors. As with energy consumption, CO_2 emissions increased at annual rates of 0.4% and 1.3% for passenger and freight transport between 2005 and 2100, whereas they changed at an annual rate of −0.4% and 0.3% in the 2 °C and −0.8% and −0.3% in the 1.5 °C scenarios due to the reduction in energy consumption, particularly the use of liquid fossil fuels that are high in emission intensity. Car and small and large trucks are the major transport modes contributing to CO_2 emissions, implying that road transportation is the primary emission source. In the 2 °C and 1.5 °C scenarios, the contribution rates of car and small and large trucks to total emissions could be reduced effectively. In particular, in the 1.5 °C scenario, instead of road transportation,

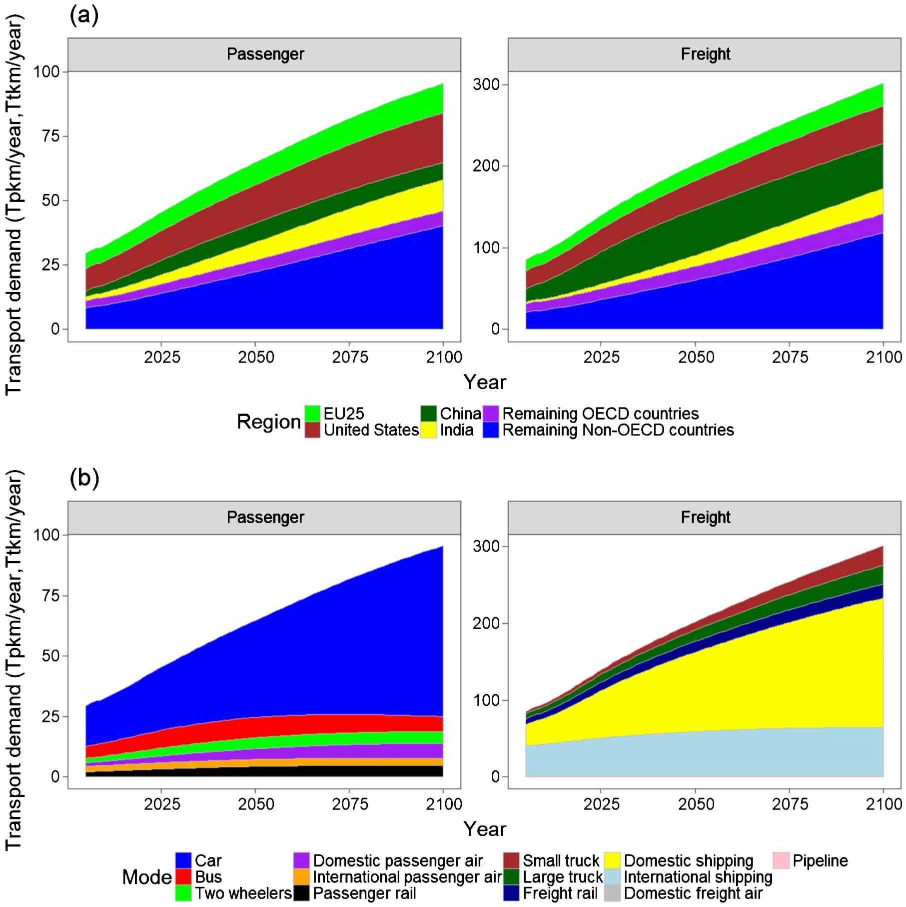

Figure 2. Region-wise (*a*) and mode-wise (*b*) transport demand from 2005–2100. Remaining Organisation for Economic Co-operation and Development (OECD) countries: Canada, Japan, Oceania, and Turkey; remaining non-OECD countries: Brazil, former Soviet Union, Middle East, North Africa, rest of Africa, rest of Asia, rest of Europe, rest of South America, Southeast Asia. OECD: Organization for Economic Co-operation and Development.

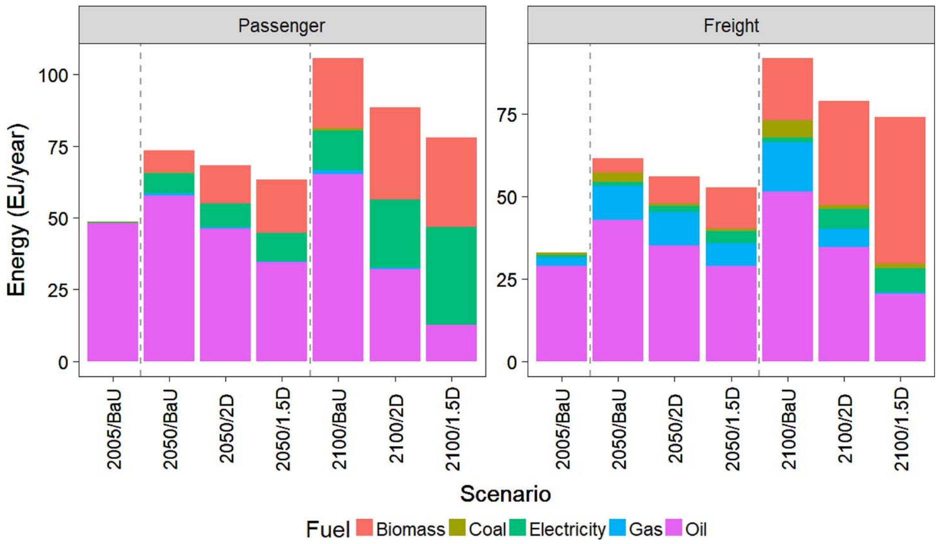

Figure 3. Energy consumption due to passenger and freight transport.

aviation and shipping become the major carbon sources for passenger and freight transport.

The Laspeyres indices were estimated for decomposition analysis to detect how much each factor such as transport activity, modal structure, energy intensity, and fuel mix contributes to the projected emission pathways [58–60]. Transport activity growth is the major contributor to emissions for both passenger and freight transport in all scenarios, as shown in figure 5. The modal shift also has a positive impact on the

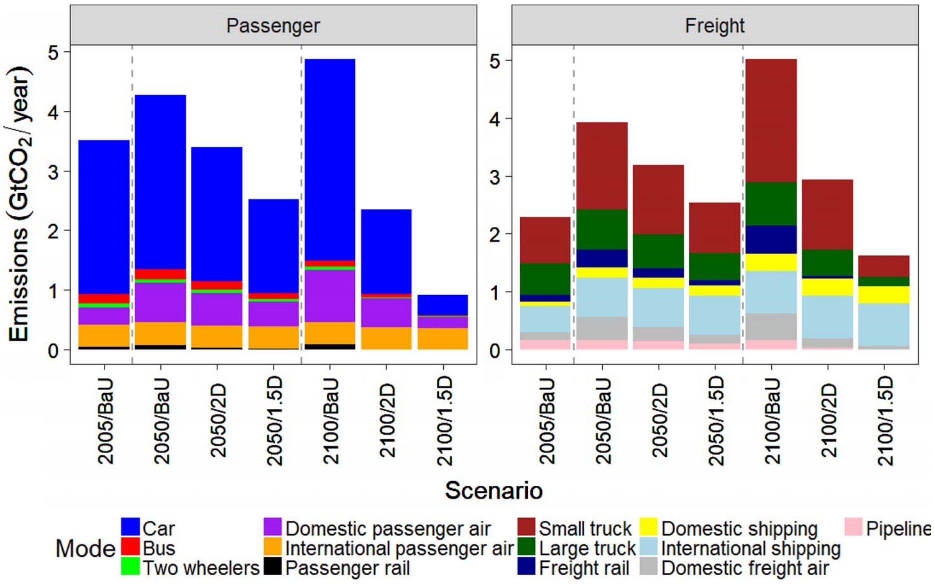

Figure 4. Mode-wise emissions from passenger and freight transport (excluding indirect emissions).

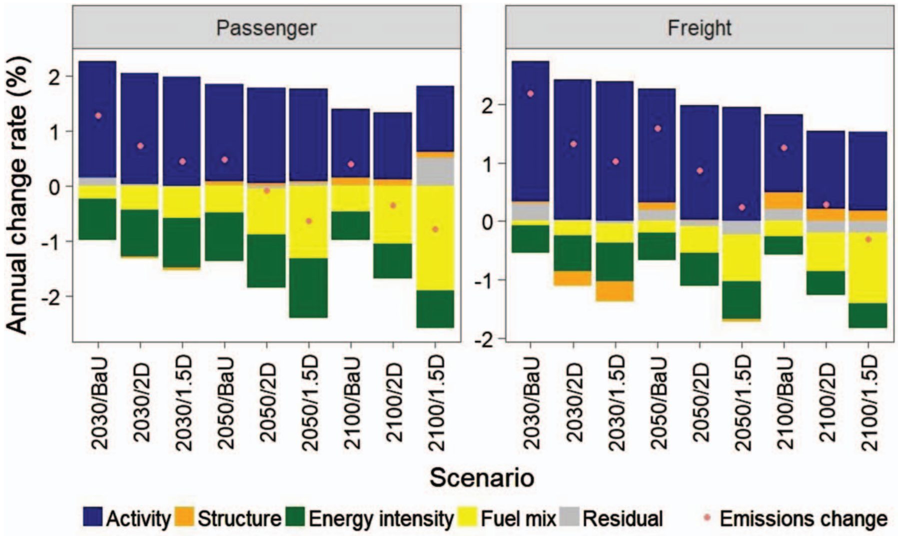

Figure 5. Laspeyres index decomposition of activity, structure, energy intensity, and fuel mix contributing to direct CO_2 emissions for passenger and freight transport. The index value indicates the annual change rate in emissions with respect to the base year.

increase of emissions, although it plays a limited role in emission changes. Energy intensity and fuel mix are the two significant factors in reducing emissions. Energy intensity made the most significant contributions, with an annual rate of −1.1% and −0.7% in 2050 in the 1.5 °C scenario for passenger and freight transport, respectively, and the highest values of fuel mix occur in 2100 in the 1.5 °C scenario. In the long-term, the influence on emission reduction of fuel mix is even more pronounced than energy intensity improvement in the 2 °C and 1.5 °C scenarios, where high emission reduction can be achieved primarily by a fuel mix shift from fossil fuel to electricity or less carbon-intensive fuels such as natural gas or biofuels.

3.2. Impacts on emissions of transport policies

As shown in figure 6(*a*), scenario simulation results proved that CO_2 emissions can be reduced by implementing transport policies such as energy efficiency improvements, vehicle technological innovations, mass transit-oriented transport developments, and increasing the occupancy rate of cars in the BaU, 2 °C, and 1.5 °C scenarios. The energy efficiency improvement in the BaU scenario has the highest reduction potential, as 22% of cumulative CO_2 emissions were reduced, whereas the lowest reduction was attributed to mass transit-oriented transport development in the 1.5 °C scenario. Although the effectiveness of each policy depends on the parameter

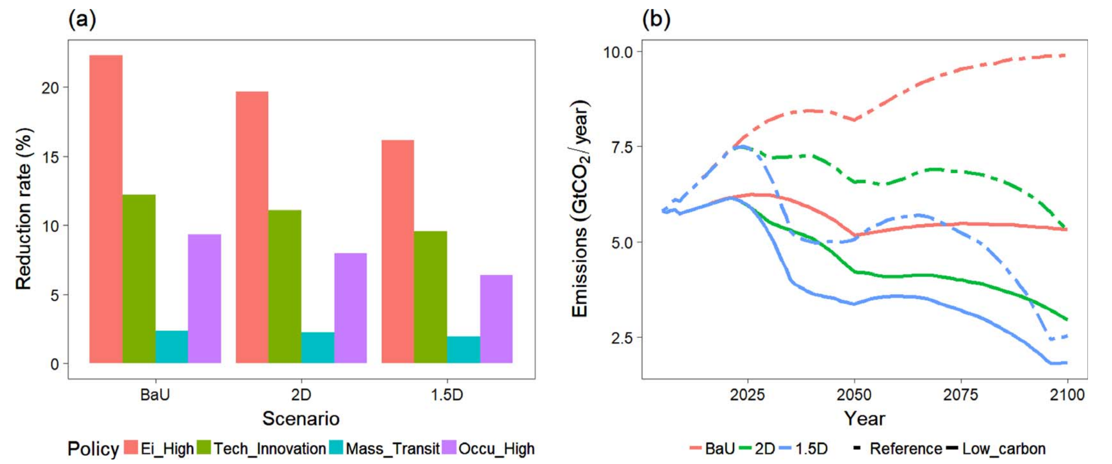

Figure 6. Impacts of transport policies on emissions: reduction potential of cumulative emissions (*a*) and emission trajectories (*b*) during 2005–2100.

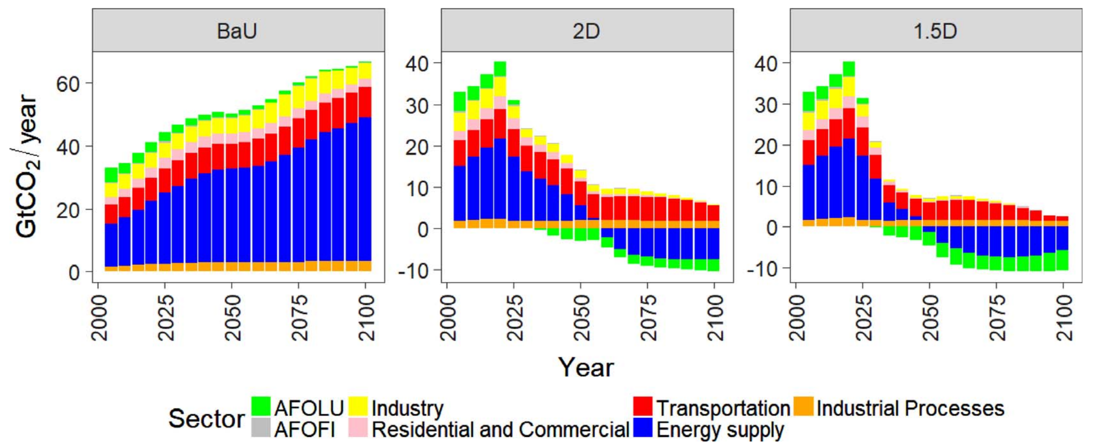

Figure 7. Global CO_2 emissions by sector.

settings from the different perspectives of technological improvement and behavioral transformation, they are equivalent in a sense that these parameter choices have been derived from actual, best practices. In summary, Ei_High, Tech_Innovation, and Occu_High have significant impacts on emission reduction, whereas Mass_Trasnsit has relatively weak effects.

Figure 6(*b*) presents the emission trajectories of the BaU, 2 °C, and 1.5 °C scenarios, with and without low-carbon transport policies. With the implementation of a low-carbon transport policy, the 2 °C scenario generated an emission trajectory similar to the 1.5 °C scenario, without any transport policy, implying that transport policies can help achieve the 1.5 °C goal only by applying the carbon tax rate of the 2 °C scenario. Maximum emission reduction can be achieved with low-carbon transport strategies combining both technological and behavioral policies. Compared with the reduction rate of 34% in the absence of a carbon price, the reduction potential of cumulative emissions due to transport policies further increased to 46% and 54% when a carbon price was implemented across all regions for the 2 °C and 1.5 °C targets. This indicates that the synergistic effect between policies in different sectors needs to be considered for maximum potential emission reduction.

Although road transportation theoretically could become completely electrified over the coming decades, it is still unclear whether there is the prospect of electrified aviation and shipping. Unless all fossil fuels would be replaced by biofuels, the passenger aviation and freight sectors still remain dependent on fossil fuels. The technological and economic optimization leads to there being ongoing use of fossil fuels in the transport sector, mainly for international aircraft, and that negative emissions are thus required to balance this usage in order to meet the temperature goals. As shown in the figure 7 of emissions by sector, CO_2 emitted by the transport sector will not decrease to zero, and emissions from the agriculture, land use, and energy sectors will decrease to negative values. To analyze the uncertainties of various socioeconomic factors and the robustness of the policy simulation using coupled CGE and transport models, we adopt SSP1 parameters to

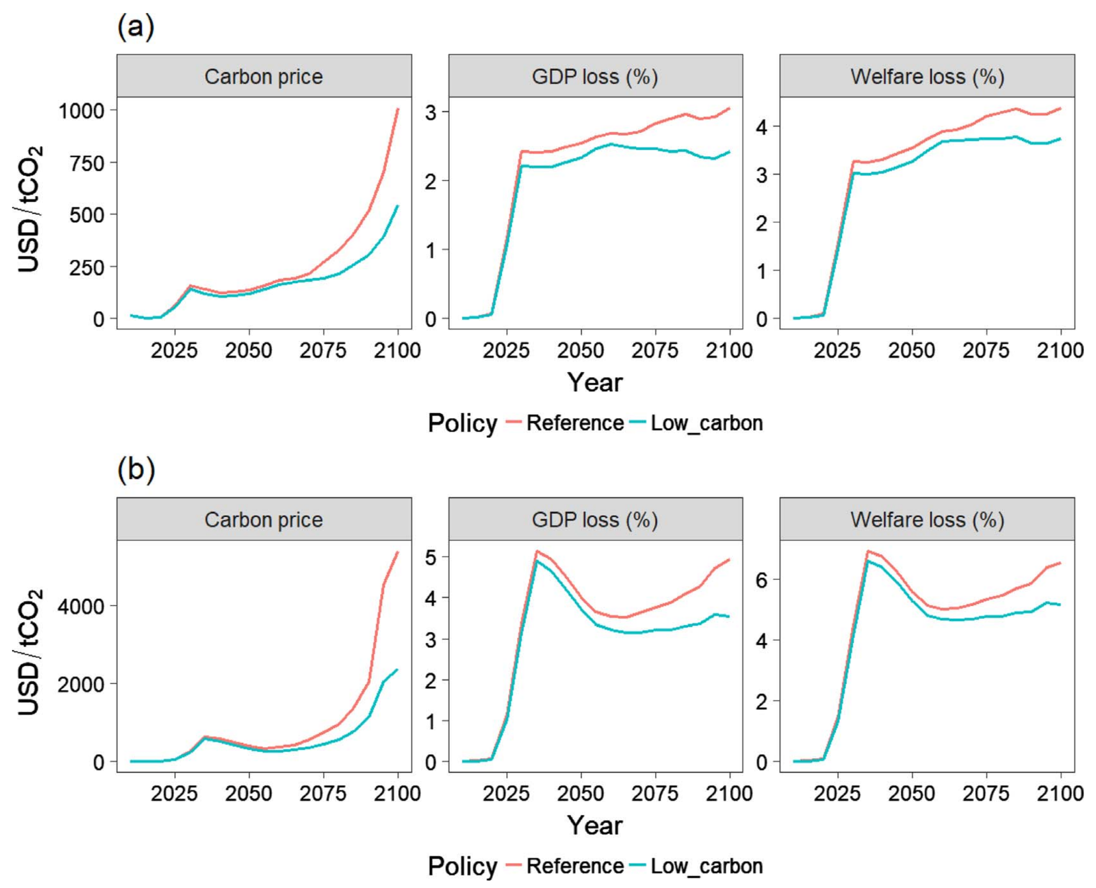

Figure 8. Mitigation cost metrics for the 2 °C (*a*) and 1.5 °C (*b*) targets.

assess the reduction potential and emission trajectories under the SSP1 socioeconomic assumptions. We selected SSP1 among five SSPs because 1.5 °C scenarios are attainable only for the SSP1 and SSP2 scenarios. The SSP1 results of reduction potential and emission trajectories are provided in figure S15 (supporting information available at stacks.iop.org/ERL/13/054008/mmedia), indicating that SSP1 assumptions generate the results similar to SSP2.

3.3. Mitigation cost

With respect to the economic effect of transport policies, figure 8 shows that carbon price, GDP loss rate, and welfare loss rate can be reduced in the Low_Carbon scenario. The mitigation cost including carbon price, GDP loss, and welfare loss were calculated by AIM/CGE according to the emission constraint given by a Dynamic Integrated Climate–Economy (DICE)-type intertemporal model [61]. The indicators of GDP loss and welfare loss can be employed to analyze how a carbon pricing policy will reduce GDP and welfare as compared with a BaU scenario. The maximum reduction in GDP loss rate occurred in 2100 with decreases from 3.1%–2.4% and 5.0%–3.6% for the 2 °C and 1.5 °C scenarios, respectively. The GDP and welfare loss rate can be lowered because the low-carbon transport policies are conducive to decreasing the CO_2 emissions in the transport sector, which helps alleviate the economic losses generated by stringent carbon tax imposition. This implies that technological innovation and behavioral changes in the transport sector do exert positive influences on mitigation costs for achieving climate change mitigation targets.

It also can be seen in figure 8 that the reduction in carbon price, GDP loss rate, and welfare loss rate in the 1.5 °C scenario is more than that in the 2 °C scenario. To more clearly detect how the effects of decarbonization due to transport policies vary with climate change mitigation polices, the reduction in GDP loss rate from 2005–2100 was determined for the 2 °C and 1.5 °C scenarios (figure 9). The values of the reduction in GDP loss rate in the 1.5 °C scenario are higher than those in the 2 °C scenario after 2030, implying that the contribution to the reduction in GDP loss is relatively more significant in the 1.5 °C target. The degree of contribution of transport policies is more effective for stringent climate change targets.

4. Discussion and conclusion

4.1. Interpretations and policy implications

This study investigated the impacts on mitigation potential and cost using a global transport model AIM/Transport coupled with a computable general equilibrium model AIM/CGE. The integration of the

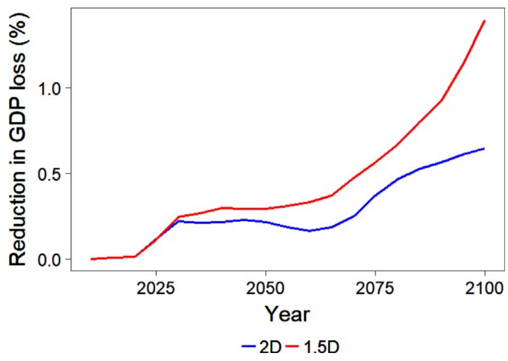

Figure 9. Reductions in gross domestic product (GDP) loss rate for the 2 °C and 1.5 °C targets.

transport model and CGE model can enrich transport representation in an integrated assessment model and capture mode and technological factors. Simulation results show that transport policy interventions such as technological development (vehicle technology innovations, energy efficiency improvements), transport behavioral changes (public transport development, increasing the vehicle occupancy rate) alter global transport-related energy consumption composition and emission trajectories. Cumulative emissions can be reduced by 46% and 54% for 2 °C and 1.5 °C reduction goals by integrating transport policies and a carbon tax. This study therefore provides a comprehensive and multidimensional policy tool for long-term decision making in transport decarbonization. Combinations of technological innovations, social transformation, and human behavioral changes are conducive to a drastic reduction in transport-related emissions. Implementation of transport policies combining technological innovation and changes in transport behaviors is required to achieve both the 2 °C and 1.5 °C goals.

Although technological policy interventions have more significant positive effects on emission reduction, technological transformations such as deep electrification in the transport sector are long-term in nature and will require profound changes to the energy, infrastructure, and national macroeconomic systems. For example, the promotion of electric vehicle use cannot be simply achieved unless these vehicles were to occupy the whole market, because consumer preferences for conventional gasoline-powered vehicles would not easily switch to electric vehicles in the short term due to behavioral inertia and economic issues, such as purchasing cost; thus, immediate actions to improve efficiency in conventional internal combustion engine-driven vehicles deserve more attention in the next decade. In contrast, a decarbonized transport system is a concept that can be applied both to technological improvements in the transport sector, and to social transformation. Social transformations such as lifestyle change and low-carbon urban reorganization could be effective supplementary policy tools. Therefore, balanced technological and social transformations can mitigate risks that may not be fully addressed via technological innovation alone, for developing an energy-efficient decarbonized transport system.

Because the feedback between the AIM/Transport and AIM/CGE models helps detect the effects of transport sector dynamics on the macroeconomy, these analyses convince us that transport policies provide an effective contribution to modifying the mitigation cost. Importantly, the GDP and welfare loss for meeting the 2 °C and 1.5 °C targets in the long term can be reduced via low-carbon transport policies, which can contribute to the deep global transformation needed to achieve climate change mitigation targets. Because this methodology of transport modeling overcomes the limitations of linking the CGE model and the transport model, it may be used by transport planners to analyze how mitigation options would affect the dynamics of the macroeconomy. Interestingly, the maximum reduction in GDP loss rate in the 1.5 °C scenario (1.4%) is higher than that in the 2 °C scenario (0.6%). The greater effectiveness of transport policies was well demonstrated in the 1.5 °C scenario, indicating that the transport sector deserves more attention for achieving stringent climate change mitigation targets. There is significant potential for reducing emissions assuming even relatively slow evolution of transportation technology and the reduction potential has an optimistic outlook with aggressive technological development.

Policy implications can be drawn from the scenario simulations. First, the liquid fuel savings can be realized directly by the deployment of hybrid vehicles, which is likely to become a significant fraction of new vehicle sales in the interim before becoming fully electric. The costs of electric vehicles are assumed to continue to decline over the coming decades (see supporting information), which allows an optimistic perspective regarding the electrification of road transportation, which will contribute to climate change mitigation. Then substantial numbers of fully battery electric-powered vehicles can be strongly promoted to achieve the goal of deep decarbonization in the transport sector. Second, because of the trend of increasing urbanization in the world, it would be most useful and cost effective to prioritize public transport and build a transit-oriented society for emission reduction in urban areas. It is necessary to establish a public transit system with better accessibility, security, and comfort to influence households' preference on transport modes. The transit net density, station coverage rate, and departure frequency need to be increased to provide an appealing physical environment and public transit service. Specifically, investing in public transport infrastructure such as dedicated corridors for buses and railways, and high-speed trains such as maglev, can assist in shifting more travelers from carbon-intensive modes to a transit-oriented movement. If investment is directed to a low-carbon infrastructure and transit-oriented city planning, it is possible to move towards low-carbon transport development. Third, decarbonization in the transport sector requires innovative policy strategies for lifestyle transformations. The government needs to launch a scheme to promote car sharing and carpooling, to increase the car occupancy rate and cut the number of commuters.

4.2. Limitations and future work

There are three main limitations that should be addressed. First, due to the lack of reliable efficiency and technology cost data, the current modeling effort does not consider some advanced transport technologies (e.g. electric bus and truck, self-driven cars and trucks, personal airfoils, drone package delivery, dirigibles) that have not yet been fully tested and do not seem likely to be more than niche services in the near-term. In consideration of the behavioral mechanism and cost minimization, the technological transformations are assumed relatively moderate. However, faster and more aggressive targets of technological improvement also need to be simulated to offer an optimistic outlook for the electrification of road transportation. Second, meeting electric vehicle promotion targets will require simultaneous construction of a publicly accessible charging infrastructure. Third, for behavioral changes, the detailed relationship between land use, urban structure, and the transport sector has not been incorporated. Transport behaviors depend on urban spatial structures and organizations. A compact city and pedestrian-friendly street design are usually considered an optimum and effective policy tool for low-carbon transport development. Another concern is behavioral transformations due to communication technologies, such as teleworking and teleshopping. Transport demand is likely to be reduced as a result of decreases in commuting and shopping trip frequency. Therefore, infrastructure, land use, urban structure, communication technologies, and advanced transport technologies need to be incorporated into the AIM/Transport model. While this study has limitations, they mainly concern issues of how the transport sector evolves in the future that are largely unknowable. What has been shown is that there are a number of policy actions that can assist in reducing CO_2 emissions from the sector, especially with regard to cars, that are more effective than other actions and identified areas for further work.

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ORCID iDs

Runsen Zhang https://orcid.org/0000-0001-9841-8453
Shinichiro Fujimori https://orcid.org/0000-0001-7897-1796

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