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Contribution of the transport sector to climate change mitigation: Insights from a global passenger transport model coupled with a computable general equilibrium model

Runsen Zhang[a,*], Shinichiro Fujimori[a,c], Hancheng Dai[b], Tatsuya Hanaoka[a]

[a] Center for Social and Environmental Systems Research, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba 3058506, Japan
[b] College of Environmental Science and Engineering, Peking University, Beijing 100871, China
[c] International Institute for Applied Systems Analysis, Schlossplatz-1, 2361 Laxenburg, Austria

HIGHLIGHTS

- Model structure and mathematical formulation of AIM/Transport.
- Iterative simulation for coupling AIM/CGE and AIM/Transport.
- Interaction between transport sector, energy consumption, GHG emissions, and macro-economy.

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ABSTRACT

A passenger transport model, Asia-pacific Integrated Model (AIM)/Transport, incorporating travelers' mode of choice and transport technological details was developed in this study. This AIM/Transport was coupled with the AIM/Computable General Equilibrium (AIM/CGE) to capture interactive mechanisms between the transport sector, energy consumption, greenhouse gas (GHG) emissions, and the macro-economy. This paper presents the model structure and mathematical formulation of AIM/Transport, and explains how it was integrated with the CGE model by an iterative algorithm, taking into consideration the feedback between AIM/Transport and AIM/CGE. A numerical simulation proved that the integration of AIM/CGE and AIM/Transport can achieve a convergence after 13 iterations. A business-as-usual (BaU) scenario and a mitigation scenario were created to test the robustness of the model integration and how the mitigation potential and cost would be modified by coupling AIM/Transport. The key finding was that the carbon price and mitigation cost were modified with the coupled CGE-Transport model.

1. Introduction

Transport accounted for around 23% of carbon emissions in 2013, which cannot be ignored in terms of global greenhouse gas (GHG) emissions and climate change [1]. In the transport sector, light-duty passenger vehicles are the major contributor to transport-related GHG emissions. With levels of urbanization and motorization increasing rapidly worldwide, carbon emitted in the transport sector, especially passenger traffic, is projected to keep growing [2,3]. Without the implementation of aggressive and sustained policy interventions, transport-related GHG emissions could increase at a faster rate than emissions from the energy end-use sectors, with the potential to double by 2050. Because the continuing growth in traffic activities could outweigh all mitigation measures unless transport emissions can be strongly decoupled from gross domestic product (GDP) growth, decarbonizing the transport sector will be more challenging than for other sectors [4,5]. It has been proposed that transport-related GHG emissions are bound up with economic development, technological change, travel behavior, transport policy, and energy efficiency improvements [2,6–11]. Therefore, the key factors influencing global passenger transport, including travel mode and technological details, need to be taken into account to estimate long-term transport-related GHG emission pathways.

Integrated assessment models (IAMs), which integrate economic, energy, agriculture, land use, water, climate, and health factors with GHG emissions are widely used in the environmental sciences and in environmental policy analysis [12–17]. The transport sector has been taken into consideration in bottom-up integrated assessment models

* Corresponding author.
E-mail address: zhang.runsen@nies.go.jp (R. Zhang).

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such as Asia-pacific Integrated Model/Enduse (AIM/Enduse), MARKAL, and the International Energy Agency (IEA) Mobility Model (MoMo) to evaluate the GHGs emitted in the transport sector [18–21]. In these models, the travel demand is computed with linear or quadratic correlations between traffic activities and GDP per capita, or an exogenously determined modal share, and therefore it is not suitable to incorporate behavioral and technological factors to assess their influences on passenger transport and mitigation potential. Compared with the bottom-up type model, in top-down integrated assessment models such as AIM/Computable General Equilibrium (AIM/CGE), which has been widely used for climate change mitigation and impact assessment [22–28], travel demand is dynamically estimated with relative prices and the elasticity of substitution. However, AIM/CGE represents transport at a highly aggregated level, but technological details and behavioral determinants such as travel cost, travel time, modal split, and preference are not incorporated. This implies that current models cannot be applied to investigate global transport dynamics and the mitigation potential of transport technological and behavioral options.

The choice of transport mode for a personal trip is determined by various attributes, such as travel cost, travel time, personal preference, and individual socioeconomic characteristics. This determines travel behavior and can affect the travel demand and transport-related GHG emissions [29–31]. Thus, a transport mode decision model provides a methodology to estimate the travel demand and modal split, and is commonly applied to transport planning and policy analysis. Several studies have used a discrete choice model to analyze an individual's travel behavior based on choices made regarding the mode, technology, and individual attributes [32–36]. In a transport mode decision model, the traveler's utility associated with alternative travel modes is modeled by computing variables that describe the features of different travel modes and a traveler's preference among them. Transport mode decision models using multinomial logit type equations have been linked with 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), and IMACLIM-R. to estimate the travel demand and modal share for climate mitigation analysis from the perspectives of transport policy and behavior [37–45]. The MESSAGE-Transport model creates a triangular arrangement of three soft-linked models to incorporate transport mode choices and individual vehicle technologies into the partial-equilibrium model MESSAGE. A larger-scale economic-engineering model for passenger and freight transport PRIMES-TREMOVE was linked with the GEM-E3T, which has been enhanced based on the standard GEM-E3 for modelling the transport sector [44]. The IMACLIM-R model offers a detailed representation of passenger and freight transportation for the energy-economy-environment (E3) IAM, taking into account the deployment of transport infrastructure. It was found that the GDP loss with a fixed carbon emission trajectory can be reduced by the deployment of infrastructure for roads and air travel [46]. It is difficult to deal with the interactive impacts of transport policy interventions on the macro-economy because the dynamic feedback or interplay between the transport sector and CGE models are seldom taken into consideration.

To improve the transport sector representation in CGE models, this study developed a global passenger transport model, AIM/Transport, which was coupled with AIM/CGE. AIM/Transport can provide an elaborate technological description of the transport sector and evaluate the technological feasibility of transport policies, whereas individual transport models are not able to investigate the interaction between the transport sector and the macro-economy, and the response of other sectors to transport policy interventions. Coupling with AIM/CGE overcomes this shortcoming of AIM/Transport because the CGE model covers all goods and service transactions; thus, an interactive analysis of the transport sector and other sectors becomes possible. The transport representation in AIM/CGE is also enriched because the CGE model uses either a production function or price elasticity to represent the aggregated transport sector and, therefore, lacks an explicit transport representation, including mode and technological details.

In this context, this study of the use of AIM/Transport, which has a detailed representation of transport technologies and is coupled with the CGE model, had three objectives: (1) to demonstrate how to couple a transport model within a CGE model; (2) to provide detailed transport representation for a global CGE model; and (3) to create a better understanding of the interactive mechanism between the transport sector and macro-economic system.

The paper is organized as follows. Section 2 describes the model structure, iterative algorithm, formulations, data source, and scenario settings. Section 3 presents the model integration and convergence of coupling for the CGE-Transport model and how the feedback of AIM/Transport updates the transport representation in AIM/CGE, followed by an analysis of results for the BaU and mitigation scenarios. Section 4 provides a discussion of the interpretation and the implications of the simulation results. Section 5 is a conclusion that summarizes the findings, with a roadmap for future research tasks.

2. Methodology

2.1. Model interaction

In this study, a global passenger transport model, AIM/Transport, was developed to analyze the transport sector representation by incorporating travelers' modes of choice and technological details, and then estimating the resulting energy consumption and GHG emissions. AIM/Transport was coupled with AIM/CGE to capture interactive mechanisms between the transport sector, energy consumption, GHG emissions, and the macroeconomic system. AIM/CGE is a one-year interval recursive-type, dynamic, general equilibrium model that covers all regions of the world. This CGE model consists of 17 regions and 42 industrial classifications. Details of the model structure and mathematical formulas are provided in the AIM/CGE manual [47].

To integrate AIM/CGE and AIM/Transport, an iterative procedure was used to obtain the convergence between AIM/Transport and AIM/CGE. As shown in Fig. 1, if the energy consumption calculated in AIM/Transport differs from that consumed by the transport sector in AIM/CGE, the travel demand, energy consumption, and capital cost from the transport model is fed back into AIM/CGE to re-estimate the related parameters of the transport sector in AIM/CGE. AIM/CGE then passes the updated energy prices and carbon prices to AIM/Transport. This loop continues until the energy consumed in AIM/CGE and AIM/Transport reaches a convergence.

2.2. AIM/Transport

2.2.1. Overview

AIM/Transport for global passenger travel simulation was developed for 17 regions, which is consistent with AIM/CGE (Fig. S1 and Table S1 in Supporting Information). Fig. 2 shows the overall framework of AIM/Transport. The passenger travel demand for each region is computed based on GDP, population, and generalized transport cost, which is calculated from the outcomes of the energy and carbon price determined from AIM/CGE, and travel time cost estimated from the wage rate and vehicle velocity. The total travel demand is divided into different distances, modes, vehicle sizes, and technologies by mode choice models using multinomial logit equations based on the generalized transport cost of each category. Then the shares of different distances, modes, vehicle sizes, and technologies also can impact the total passenger transport demand by modifying the generalized transport cost. The energy consumed by passenger trips in each region can be evaluated according to the travel demands of each technology category and technology-wise energy intensities. GHG emissions produced by the