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Regional climate impact of aerosols emitted by transportation modes and potential effects of policies on demand and emissions

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ABSTRACT

The transportation system is one of the main sectors with significant climate impact. In the U.S. it is the second main emitter of carbon dioxide. Its impact in terms of emission of carbon dioxide is well recognized. But a number of aerosol species have a non-negligible impact. The radiative forcing due to these species needs to be quantified. A radiative transfer code is used. Remote sensing data is retrieved to characterize different regions. The radiative forcing efficiency for black carbon are $396 \pm 200\ W/m^2/AOD$ for the ground mode and $531 \pm 190\ W/m^2/AOD$ for the air transportation, under clear sky conditions. The radiative forcing due to contrail is $0.14 \pm 0.06\ W/m^2$ per percent coverage. Based on the forcing from the different species emitted by each mode of transportation, policies may be envisioned. These policies may affect demand and emissions of different modes of transportation. Demand and fleet models are used to quantify these interdependencies. Depending on the fuel price of each mode, mode shifts and overall demand reduction occur, and more fuel efficient vehicles are introduced in the fleet at a faster rate. With the introduction of more fuel efficient vehicles, the effect of fuel price on demand is attenuated. An increase in fuel price of 50 cents per gallon, scaled based on the radiative forcing of each mode, results in up to 5% reduction in emissions and 6% reduction in radiative forcing. With technologies, significant reduction in climate impact may be achieved.

Introduction

As concern about climate impact of anthropogenic emissions grows, discussions on regulations and policies gain momentum, exemplified by the Kyoto protocol or the European Emission Trading Scheme. The focus of climate impact studies and policies has been mainly on greenhouse gases especially carbon dioxide so far (Hivin et al., 2014; Hofer et al., 2010; Tol, 2007). However concern is growing on the effect of non-CO_2 climate impacts (Krammer et al., 2013), including short-lived aerosol species such as black carbon (Shindell et al., 2011). Aerosols account for a large portion of transportation impact, and black carbon (BC) is viewed as the second most significant warming species (Bond et al., 2013). The inclusion of these short-lived species into climate policy is increasingly advocated (Jackson, 2009). Short-lived species have been the focus of air quality issues, but need to be integrated into climate change studies (Garderet and Emmet, 2009). They have short-term and local effects. A number of challenges for BC climate impact remain, such as the significant variability in

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List of acronyms

AOD	aerosol optical depth
BC	black carbon
IR	Infra Red
LW	longwave
RF	radiative forcing
RFE	Radiative Forcing Efficiency
RPM	Revenue Passenger Mile
SCC	social cost of carbon
SW	shortwave
SZA	solar zenith angle
TOA	top of the atmosphere
VMT	Vehicle Miles Traveled

emission factors of different vehicles as well as the variability in the impact of BC on the Earth energy budget based on location and time of emission. The latter will be explored in this paper.

The Earth receives radiation from the sun and radiates back longwave radiation. The amount of radiation that is reflected and transmitted determines the energy balance of the planet. Changes in atmospheric composition create 'forcing' which is an external factor that affects climate. Both gaseous and aerosol species have a significant impact on the energy budget of the planet. Greenhouse gases change the radiative balance by trapping outgoing infrared (IR) radiation. Aerosols affect the radiation balance of the Earth-Atmosphere system by reflecting sunlight back into space, absorbing sunlight, and absorbing and emitting IR radiation (Liou, 2002). Radiative transfer codes are used to quantify the effects of gaseous and aerosols emissions. Forcing efficiencies (radiative forcing per unit of emission) and uncertainties of the different species can be determined.

The transportation system is a potential target for climate policies, as it is one of the main sectors resulting in radiative forcing. In the United States, it is one of the main emitter of greenhouse gases, with 27% of total emissions (U.S. Environmental Protection Agency, 2011). Most of these emissions come from road transport. Aviation is responsible for 10% of these emissions, but its impact has been growing significantly in the past years. The concern about this growth motivated the first sector specific assessment from the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change, 1999). Decision makers need to know the impact of different species, as well as associated uncertainties to appropriately estimate transportation activity and impact, and achieve desired goals. They need Integrated Assessment Models (IAM) capable of forecasting future demand and impacts under different scenarios. IAMs are a set of models that integrate different aspects of a system, including socio-economics, technologies, and policies. They use approximations of the system's behavior in order to allow fast comparison of policy scenarios with relatively simple and transparent tools (Edwards, 1996). IAMs date back to the club of Rome models in the 1970s. One of the first models is the World Dynamics developed by system dynamicist Jay Forrester following a meeting with the club of Rome. System Dynamics is a suitable technique for IAMs as showed by Fiddaman (1997) with the Feedback-Rich Energy-Economy (FREE) model. Fiddaman compares model purpose and characteristics for a number of state of the art IAMs including the Dynamic Integrated model of Climate and the Economy (DICE) model and the Integrated Climate Assessment Model (ICAM) model. IAMs are widely used for climate impact assessment by researchers and decision makers in a wide variety of disciplines. Spatial and sectoral resolutions need to be chosen wisely for each study in order to facilitate scenario exploration. Integrated assessments can help with the analysis of different policy and technology scenarios. However most IAMs are ill suited to examine potential travel demand changes and travel mode shifts given climate policies and changes in fuel prices (Daly et al., 2012). They rarely establish the link between demand and its drivers such as fuel price and technology investment. A tool that integrates travel demand, fleet forecast, and main climate impacts is needed in order to appropriately assess the effect of climate policies on the U.S. transportation system.

The uncertainty associated with future transportation climate impact is significant and predicting the future transportation system's demand and performance is challenging. Efforts are being made by the current two main industries (aircraft and automobiles) to improve their efficiencies. New modes of transportation may also be considered (Lewe et al., 2014b). Significant mode shift may be observed. Multiple scenarios need to be envisioned to account for uncertainties on new technologies implementation, new modes introduction date and resulting impact. Due to the interactions and competition between different modes of transportation, a multimodal approach is necessary. The tool should allow for multiple scenarios, efficiently track their environmental impact and assess the impact of different technologies and policies. It may be used for studies on co-modality, which, as introduced by the European commission, is the use of multiple modes of transportation in the most efficient way. The Ground and Air Mode Explorer (GAME) model (Lewe et al., 2012) integrated with the Integrated Dynamics Environmental Analysis (IDEA) (Pfaender and Mavris, 2012) quantifies fuel burn from different modes of transportation. The effects in terms of emissions and climate impact are the focus of this research, resulting in the environmental GAME (eGAME) simulation environment, which integrates demand and fleet models and quantifies climate impact to perform policy and technology scenario exploration.