Atmos. Chem. Phys. Discuss., 13, 23373–23419, 2013
www.atmos-chem-phys-discuss.net/13/23373/2013/
doi:10.5194/acpd-13-23373-2013

Atmospheric Chemistry and Physics
Discussions
Open Access

Global emission projections for the transportation sector using dynamic technology modeling

F. Yan[1,2], E. Winijkul[3], D. G. Streets[1,2], Z. Lu[1,2], T. C. Bond[3], and Y. Zhang[4]

[1]Decision and Information Sciences Division, Argonne National Laboratory, Argonne, IL 60439, USA
[2]Computation Institute, University of Chicago, Chicago, IL 60637, USA
[3]Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
[4]Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, USA

Received: 31 July 2013 – Accepted: 24 August 2013 – Published: 5 September 2013

Correspondence to: F. Yan (fangyan@anl.gov)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

In this study, global emissions of gases and particles from the transportation sector are projected from the year 2010 to 2050. The Speciated Pollutant Emission Wizard (SPEW)-Trend model, a dynamic model that links the emitter population to its emission characteristics, is used to project emissions from on-road vehicles and non-road engines. Unlike previous models of global emission estimates, SPEW-Trend incorporates considerable details on the technology stock and builds explicit relationships between socioeconomic drivers and technological changes, such that the vehicle fleet and the vehicle technology shares change dynamically in response to economic development. Emissions from shipping, aviation, and rail are estimated based on other studies so that the final results encompass the entire transportation sector. The emission projections are driven by four commonly-used IPCC scenarios (A1B, A2, B1, and B2). We project that global fossil-fuel use (oil and coal) in the transportation sector will be in the range of 3.0–4.0 Gt across the four scenarios in the year 2030. Corresponding global emissions are projected to be 101–138 Tg of carbon monoxide (CO), 44–54 Tg of nitrogen oxides (NO_x), 14–18 Tg of total hydrocarbons (THC), and 3.6–4.4 Tg of particulate matter (PM). At the global level, a common feature of the emission scenarios is a projected decline in emissions during the first one or two decades (2010–2030), because the effects of stringent emission standards offset the growth in fuel use. Emissions increase slightly in some scenarios after 2030, because of the fast growth of on-road vehicles with lax or no emission standards in Africa and increasing emissions from non-road gasoline engines and shipping. On-road vehicles and non-road engines contribute the most to global CO and THC emissions, while on-road vehicles and shipping contribute the most to NO_x and PM emissions. At the regional level, Latin America and East Asia are the two largest contributors to global CO and THC emissions in the year 2010; this dominance shifts to Africa and South Asia in the future. By the year 2050, for CO and THC emissions, non-road engines contribute the greatest fraction in Asia and the Former USSR, while on-road vehicles make the largest contribution in Latin America,

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Africa, and the Middle East; for NO_x and PM emissions, shipping controls the trend in most regions. These forecasts include a formal treatment of the factors that drive technology choices in the global vehicle sector and therefore represent a more realistic projection of what future emissions are likely to be. These results have important implications for emissions of gases and aerosols that influence air quality, human health, and climate change.

1 Introduction

1.1 Emission projections

Global emission projections are critical elements in understanding future climate impacts at global and regional scales. They provide support to forecasts of future climate change ,intercontinental transport of air pollutants, and the evolution of the entire Earth system, and they are the basis of determination of the benefits of possible mitigation strategies (Levy et al., 2008; Shindell et al., 2011; Streets et al., 2004, 2009). Such projections must cover emissions at multinational scale and be consistent across different world regions (Borken et al., 2007). The requirement of consistency across time and space makes the projection of emissions challenging, because it means applying the most current understanding of the factors that drive emissions at local and regional scales to world regions.

Unlike emission projections of energy-related species, such as carbon dioxide (CO_2), which depend to a large extent only on the amounts of fuel consumed and the carbon content of the fuel (Nakicenovic et al., 2000; Smith, 2005), emission projections of other important anthropogenic species such as nitrogen oxides (NO_x), carbon monoxide (CO), total hydrocarbons (THC), and particulate matter (PM) require consideration of technology choices, because different technologies can yield widely varying emission rates (Cooke and Wilson, 1996; Bond et al., 2004, 2007; Streets et al., 2004; Cofala et al., 2007; Klimont et al., 2002, 2009; van Aardenne et al., 1999; Ohara et al.,

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2007). "Technology" here is defined as a piece of hardware or an operating procedure that influences the emission factor of an emitter. The net change of emissions over time can then be characterized by changes of technology shares. Emission factors depend on technology improvements, which in turn may be related to economic growth, but a more important factor is environmental legislation. The latter can be a key factor in determining the penetration of abatement measures and consequently the evolution of emission factors (Dentener et al., 2010).

The deficiency of current emission projections is that they lack a clear or explicit relationship between socioeconomic factors and projected technology change. Earlier studies (e.g., Streets et al., 2004; Rao et al., 2005; Ohara et al., 2007) realized that emission factors would change with time, but they did not explicitly account for the contribution of technological changes in determining emissions. In previous studies, emissions have often been estimated by combining fuel consumption with an averaged emission factor that represents the whole emitter population. Technology shares are usually assembled by expert judgment and their changes over time are ignored. Such emission estimates cannot well represent the continuous influence of economic development or emission control strategies. Therefore, it is essential to differentiate emitters by their emission characteristics, and demonstrate the evolution of technology dynamically and consistently across model years and world regions.

This work presents a new set of global projections of gaseous and particle emissions from the whole transportation sector. These projections emphasize the role of combustion practice and emission control technology in the determination of emissions and reflect the dynamics of technology change. This paper is an extension of the work by Yan et al. (2011) and Winijkul et al. (2013). It not only broadens the treatment of on-road vehicle emissions from PM to gases, but also includes emissions from non-road engines and adds emissions from shipping, aviation, and rail to provide a comprehensive treatment of transportation sector emissions.

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1.2 Importance of emissions from the transportation sector

As a key component of economic development and human welfare, transportation activity is increasing rapidly around the world (Uherek et al., 2010; Wang et al., 2006; ICAO/FESG, 2008; Arora et al., 2011; Dargay et al., 2007; Ribeiro et al., 2007). Robust growth in the transportation sector is expected to continue over the next several decades. If there is no major shift away from current patterns of energy use, global energy use from transportation is projected to increase at the rate of about 2 % per year.

This steady growth in energy use makes the transportation sector a crucial driver of future global anthropogenic emissions. On-road vehicles and non-road engines together contribute as much as 41 % of anthropogenic NO_x emissions (JRC/PBL, 2011). While most sectors decreased their greenhouse gas (GHG) emissions from 1990 to 2010, emissions from transportation increased by nearly 21 % (EEA, 2012). However, emissions of pollutants closely related with the combustion process, such as NO_x, CO, THC, PM and sulfur dioxide (SO_2), have increased at a lower rate than fuel consumption or CO_2 emissions, because of improved emission control technologies and fuel quality (Cofala et al., 2007; Rao et al., 2005; Fulton and Eads, 2004; Smith et al., 2005; Lu et al., 2011; Klimont et al., 2009; Zhang et al., 2009).

Emissions from the transportation sector have important effects on air quality, climate, and public health. Several studies have investigated this interaction by specifically isolating the climate forcing from transportation (Fuglestvedt et al., 2008; Berntsen and Fuglestvedt, 2008; Unger et al., 2010; Koffi et al., 2010; Shindell et al., 2011; Saikawa et al., 2011; Balkanski et al., 2010). For example, Fuglestvedt et al. (2008) showed that the transportation sector contributes significantly to man-made radiative forcing (RF) and that current emissions from transportation are responsible for 16 % of the integrated net forcing from all current anthropogenic emissions over the next 100 yr. Berntsen and Fuglestvedt (2008) estimated that the global average temperature will rise by 0.23 K if the emissions from the transportation sector remain constant at year

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2000 levels. Unger et al. (2010) concluded that on-road vehicles exert the largest net positive RF among all economic sectors in the near term and the second largest in the long term.

The results of this work will provide an improved foundation to better understand future climate and air quality. More importantly, though, this work should help identify the benefits of making alternative technology and policy choices, under a variety of socioeconomic futures, to mitigate the adverse effects of anthropogenic emissions on the global environment.

This paper focuses on the exhaust emissions of gaseous and particles from the combustion of fossil fuels (oil and coal) in the transportation sector. It includes indirect GHG, such as CO, NO_x, and THC, which are precursors of tropospheric ozone (O_3) and affect the oxidation capacity of the atmosphere. It also includes emissions of primary PM, black carbon (BC), and organic carbon (OC) (results for the two carbonaceous species are shown in the SI).

The paper is organized as follows: in Sect. 2, we discuss the general approach used to project emissions and describe the Speciated Pollutant Emission Wizard (SPEW)-Trend model. Section 3 describes information concerning the fuel-use projections, technology shares, and emission factors for each transport mode: on-road vehicles, non-road engines, shipping, aviation, and rail. In Sect. 4, we present the model results and compare them with other studies. Section 5 summarizes the major findings and makes recommendations for future research.

2 Modeling approach

2.1 General methodology

The basic modeling approach in this paper is similar to earlier work (Bond et al., 2004, 2007; Streets et al., 2004), in which emissions are determined by apportioning fuel use among different emitting technology types. An emission factor is assigned to each

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technology, and the net emissions in any given year are determined by the mix of technologies. Yan et al. (2011) provide a full description of how the mix of technologies is determined dynamically by deriving explicit relationships among socioeconomic factors and technological changes. The schematic methodology is shown in Fig. 1. This process is handled by the SPEW-Trend model and is described in detail in Yan et al. (2011) and Winijkul et al. (2013). In this paper, the SPEW-Trend model is applied to emission estimates from on-road vehicles and non-road engines. The general equation to represent emissions for scenario "i", species "j", and region "k" is as follows:

$$\mathrm{Em}_{i,j,k}(t) = \sum_{l}\sum_{m}\sum_{n}\sum_{p} \mathrm{FC}_{i,k,l,m,n}(t)\,\mathrm{EF}_{j,l,m,p,0}\,\mathrm{DR}_{j,l,m,n,t-p} \tag{1}$$

where subscripts "i", "j", "k", "l", "m", "n", and "p" represent scenario, species, region, fuel type (diesel or gasoline), engine type (light-duty or heavy-duty for on-road vehicles; small, medium, or large for non-road engines), technology (or emission standards), and vehicle or engine model year (defined as the year it is manufactured), respectively. Em (t) is emissions in calendar year t. FC is fuel consumption. EF_0 is the emission factor specific to each species/fuel/technology at vehicle age zero. DR_{t-p} is the degradation rate of the emission factor of the vehicle at age ($t-\mathrm{p}$), and DR = 1 for vehicle at age zero; here, the degradation rate is defined as the relative increase rate in emission factor with time or usage (Ubanwa et al., 2003).

As shown in Fig. 1, historical fuel consumption estimates are based on fuel statistics, e.g. as compiled by the International Energy Agency (IEA). Estimates of future fuel consumption are based on exogenous scenarios that have been simulated in integrated assessment models such as Integrated Model to Assess the Global Environment (IMAGE) (RIVM, 2001; MNP, 2006) and the Global Change Assessment Model (GCAM) (Smith and Wigley, 2006; van Vuuren et al., 2006), so that the emission estimates are driven by the same "big picture" factors as other energy-related emission scenarios (Nakicenovic et al., 2000). Socioeconomic variables from exogenous scenarios are used to derive the relationships that affect technological changes. Both historical and future fuel use are disaggregated by the SPEW-Trend model (in the dashed rectangular

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box in Fig. 1) into heterogeneous emitter groups based on fuel, engine type, technology, and age. The details of fuel projections and technology splits have been discussed in Yan et al. (2011) and Winijkul et al. (2013), and we summarize them in Sects. 2.2 and 3.

For shipping, aviation, and rail, many studies have described future emission scenarios (e.g. Eyring et al., 2005a, b, 2010; Corbett et al., 2010; Endresen et al., 2007; Buhaug et al., 2009; Paxian et al., 2010; Lee et al., 2009, 2010; Owen et al., 2010; Sausen and Schumann, 2000; Eyers et al., 2004; Bek and Sorenson, 1998; Berghof et al., 2005; EEA, 2012a; Uherek et al., 2010). We estimate emissions from these three transport modes by combining information on fuel consumption and emission factors from a variety of published data sources. We assume that the technology shares are the same as in the previous studies, and no details about technological changes are provided, thus only time-dependent, fleet-average emission factors are considered. Trends toward cleaner technologies are represented as changes of average emission factors with time. Emissions from shipping, aviation, and rail are estimated by:

$$\mathrm{Em}_{\mathrm{i,j,}}(t) = \sum_{\mathrm{l}} \mathrm{FC}_{\mathrm{i,k,l}}\mathrm{EF}_{\mathrm{avg,j,l}}(t) \qquad (2)$$

We assign emission characteristics for 17 world regions: Canada, USA, Central America, South America, Northern Africa, Western Africa, Eastern Africa, OECD Europe, Eastern Europe, Former USSR, Middle East, South Asia, East Asia, Southeast Asia, Oceania, and Japan. They are sometimes regrouped to 10 regions for ease of presentation or for comparison with other studies (Table S1). Emissions are projected from 2010 to 2050 and presented annually. Available data of historical fuel consumption ends in 2010. In order to evaluate and compare with other studies, past emissions from 1990 are also shown in some figures.

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2.2 Dynamic technology model: SPEW-Trend

As shown in Fig. 1 and introduced in Sect. 2.1, we estimate emissions from on-road vehicles and non-road engines within the framework of the SPEW-Trend model. As a hybridization of a bottom-up engineering model and a top-down economic model, SPEW-Trend can be driven by any economic model, as long as it provides the required inputs, e.g. fuel consumption, population, and GDP. In this work, we apply four scenarios (A1B, A2, B1 and B2), developed for the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) (Nakicenovic et al., 2000), as formulated by the IMAGE group (RIVM, 2001). These scenarios were used as the basis of the IPCC Third Assessment Report (TAR) and the fourth (AR4).

Emissions decrease with introduction of advanced technology and implementation of more-stringent environmental regulations (Cofala et al., 2007; Klimont et al., 2002; Bond et al., 2004; Streets et al., 2004; Rao et al., 2005). In SPEW-Trend, we group vehicles built to a single emission standard as one "technology". Although different control approaches are sometimes used to meet the same emission standard, they have the same effect on emission factor. Emissions may also increase with aging (Ubanwa et al., 2003), or even achieve extreme high values under malfunctioning conditions ("superemitters"). Superemitters refer to vehicles that are responsible for a relatively large fraction of air pollutant emissions from the transportation sector, even though they may only represent a small portion of the vehicle fleet (Lawson et al., 1993; Hansen and Rosen, 1990; Zhang et al., 1995; Ban-Weiss et al., 2009; Bluett et al., 2008; Wang et al., 2011). These issues are also treated as technology variants in this work.

Major features of the SPEW-Trend model are summarized here, and equations that describe each of the governing relationships are given in Table 1. (1) Future annual fuel consumption is set by exogenous scenarios; (2) new vehicle demand is set by growth in fuel consumption and the need for vehicle replacement; (3) retirement rates depend on regional income rates and on-road vehicle age or non-road engine cumulative service hours (see Table 1, "Retirement rate/survival rate"); (4) the technology for new vehicles introduced in any year is set by the emission standard in force in that year, so that the time at which vehicles with advanced emission standards enter the population is region-dependent (Table 1, "Adoption of emission standards"); (5) the fraction of normal emitters that become superemitters is based on vehicle age (Table 1, "Superemitter transition rate"); and (6) the emission factors of individual vehicles (except superemitters) change as the vehicle ages and experiences three phases: first no change (for on-road vehicles) or increasing slowly to emission-standard level (for non-road engines), then increasing to maximal level, and finally flattening out (Table 1, "Degradation rate").

3 Fuel projections, technology divisions, and emission factors

3.1 On-road vehicles

3.1.1 Fuel and technology

This work applies the same set of fuel use and socioeconomic variables as used in Yan et al. (2011) to estimate gaseous emissions from on-road vehicles. On-road vehicles are divided into three categories: light-duty gasoline vehicles (LDGV), light-duty diesel vehicles (LDDV), and heavy-duty diesel (HDDV) vehicles. Within these three broad categories, the vehicle fleet is further disaggregated by the applicable emission standards (Yan et al., 2011).

3.1.2 Emission factors

Because of the complexity of ensuring representative vehicle samples and driving conditions, obtaining appropriate emission factors for vehicles with different technologies is difficult, even with extensive measurement programs. Dynamometer tests are widely used to measure vehicle emissions, but their disadvantage is that they only measure a few vehicles over a small range of conditions which may not be representative of the

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in-use fleet and actual driving cycles. Traffic tunnel and remote sensing measurements are valuable, but they only catch a snapshot of many vehicles at limited locations, where all of the tested vehicles are operated at similar speeds and acceleration profiles (Yanowitz et al., 2000). There is no procedure that measures the full spectrum of vehicles and conditions. In spite of the fact that dynamometer tests can be biased toward lower emissions by excluding high emission conditions, driver behavior, and heavily loaded vehicles (Bond et al., 2004; Subramanian et al., 2009), this work mostly relies on emission factor measurements from dynamometer tests. Measurements from tunnel testing and remote sensing are not used directly due to their constraints on locations and circumstances.

Our basic approach to resolving emission factors consists of the following four steps: (1) determining emission factors for new vehicles based on measurements from regions where the stringent US or European emission standards have already been implemented; (2) if measurements under the more advanced standards (e.g. Euro V and VI and US standards after 2010) are not available, then estimation of emission factors is based on the assumption that the ratio between two standards represents an achievable emission reduction (Ntziachristos and Samaras, 2008; Yan et al., 2011); (3) deriving degradation rates from measurements that take into account vehicle age or model year; and (4) estimating emission factors for superemitters by averaging the emission factors of “smokers”, poor-maintenance vehicles, or the emission factors of the highest 5–10 % of vehicles.

Tables 2, 3, and 4 summarize gaseous emission factors and degradation rates for on-road vehicles under US and European emission standards, based on measurement programs and compiled reports (Cadle et al., 1999; Durbin et al., 1999; EEA, 2012a; Maricq et al., 1999; McCormick et al., 2003; Ntziachristos and Samaras, 2008; US EPA, 2009, 2011, 2012; Yan et al., 2011; Yanowitz et al., 2000). Emission factors for PM were previously presented in Yan et al. (2011), so they are not shown in this paper. Since there is inadequate information about gaseous emissions, we assume that (1) the years that emission factors for CO, NO_x, and THC start to increase or stabilize

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are the same as for PM (Ubanwa et al., 2003; Yan et al., 2011), but the degradation rates are different; (2) CO, NO_x, THC, and PM share the same fraction of superemitters, but a particular vehicle is not necessarily a superemitter of all pollutants; (3) the degradation rates for HC and CO are the same for LDGV because they are related products of incomplete combustion; and (4) NO_x emission factors for LDDV and HDDV do not degrade beyond the level of opacity standards, but do degrade after implementation of the most advanced current standards such as Tier 2 and Euro VI that require vehicles to be equipped with aftertreatment devices.

3.2 Non-road engines

3.2.1 Fuel consumption

Similar to fuel consumption for on-road vehicles, we use historical fuel consumption for non-road engines from IEA (2012a, b) and project future fuel consumption based on IPCC scenarios. Non-road gasoline and diesel engines used in agriculture, construction and mining, and industry are included in this category. To allocate historical and future fuel consumption to different sectors and subgroups by engine type and size, this study follows methods described in Winijkul et al. (2013).

3.2.2 Technology divisions

Because emissions from non-road engines are highly related to their power (or engine size), non-road engines are grouped into three subgroups for both diesel engines (large, medium, and small engines) and gasoline engines (4-stroke high power, 4-stroke low power, and 2-stroke engines). These groups are consistent with the categories used in US and European Union emission standards (Dieselnet, 2012; US EPA, 2012b; Winijkul et al., 2013). Each group by engine size follows emission control standards from Tier/Phase 0 (US standards) and Stage 0 (European Union standards) – where engines have no controls and their emission factors are the highest among normal emitters – to the most stringent planned standards. As also described for on-road vehicles, superemitters are included to represent unusual high-emitting engines existing in non-road engine fleets. Progression in emission standards in each region is based on planned emission standard implementation (if any) or estimated by assuming lag years between on-road and non-road standards in any regions where data are not available (Winijkul et al., 2013).

3.2.3 Emission factors

There are very limited emission testing data available for non-road engines. Moreover, most available emission factor measurements are for engines without emission standards (EEA, 2009; US EPA 2010a, b); those for future engines with advanced emission standards are mostly not available. We follow the same four-step approach as in Sect. 3.1.3 to develop current and future emission factors for non-road engines.

Similar to on-road vehicles, emission factors for non-road engines (except superemitters) are separated into three phases including durability, degradation, and stabilizing phases. The difference for non-road engines is that the first phase (durability phase) includes periods when emission factors increase from new-engine emission levels to the highest level without exceeding the standards, because these engines are still under emission warranty (US EPA, 2012b) and non-road emission standards require emissions of aged engines to be lower than standards during specific periods (US EPA, 2010a, b). Emission factors for on-road vehicles, however, remain the same as those for new engines in the first phase. In the degradation phase, non-road engines degrade at either the same or a higher rate. Finally, emission factors stabilize until they reach the maximal values for normal engines. Emission factors for superemitters are assumed to be much higher than normal engines and constant throughout the study period. Emission factors and their degradation rates for non-road engines are shown in Winijkul et al. (2013).

3.3 Shipping

3.3.1 Fuel consumption

The IEA database contains records of regional demand for (or sale of) heavy fuel oil (HFO) and marine distillate oil (MDO) in three categories: international marine bunkers, domestic navigation, and fishing. However, recent studies that have focused on activity-based estimates of energy and power demands from fundamental principles (Eyring et al., 2005a, 2010; Buhaug et al., 2009; Corbett and Koehler, 2003; Endresen et al., 2007) questioned the validity of relying on the statistics of marine and fuel sales. Buhaug et al. (2009) compared world fleet fuel consumption from different activity-based estimates (Corbett and Koehler, 2003; Endresen et al., 2007; Eyring, 2005a, b) and statistics (EIA, 2012; IEA, 2012a, b), and noted that IEA substantially underreports shipping fuel consumption. By comparing country and regional levels over time, Smith et al. (2011) argued that the energy discrepancies among different estimates can be explained by the IEA "standard error" category. There is no other consumption category in the IEA data that is large enough to include the difference between the regional fuel consumption estimate and the IEA reported bunker fuel use. While we presume that the difference is unreported consumption, no adjustment to the IEA consumption data has been made for historical emission estimates.

We grow global shipping fuel consumption (including international shipping, domestic shipping, and fishing, but excluding military vessels) from current to future by applying information in Eyring et al. (2005b). Their work determined future ship traffic demand from the economic growth forecasts according to the IPCC SRES storylines. In Eyring et al. (2005b), fuel consumption is projected through extrapolations of historical trends in economic growth, total seaborne trade, and number of ships, as well as the average installed power per ship. Despite the inconsistency of historical fuel estimates between activity-based studies and IEA statistics, we employ the annual-average growth rates of global shipping fuel consumption in years 2030 and 2050 from Eyring et al. (2005b) to construct trajectories from current IEA fuel use, which vary by

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region. We distribute the global fuel use to the 17 world regions by applying a simple linear relationship between growth of fuel and regional GDP (Fulton and Eads, 2004; MNP, 2006; RIVM, 2001). Data sources and major equations to project shipping fuel consumption are summarized in Table S2.

3.3.2 Emission factors

Emission estimates must take into account the variation in operational and technical changes over the years (Eyring, 2005a, b; Eyring et al., 2010; Endresen et al., 2007). Ships need to meet an increasing number of rules, regulations, and voluntary appeals from international, national, and local regulatory bodies, such as MARPOL (International Convention for the Prevention of Marine Pollution from Ships) Annex VI by the IMO (International Maritime Organization) (IMO, 2009).

Emission reduction technologies are mainly available for exhaust pollutants. The highest NO_x reduction can be achieved with Selective Catalytic Reduction (SCR). Significant reduction of SO_2 emissions can be achieved through limitations on the sulfur content of fuels and an exhaust-gas scrubbing system. Emissions of PM can be reduced by scrubbing with seawater and/or by optimizing combustion conditions. After-treatment technologies that are used for on-road and non-road engines to reduce PM emissions, such as diesel particle filters, are not suitable for marine fuels due to their high sulfur content (Buhaug et al., 2009). Engine exhaust emissions of methane (CH_4) and non-methane volatile organic compounds (NMVOC) are relatively low, and they can be reduced by optimizing the combustion process and oxidation catalysts. Technologies that reduce these pollutants can interact with other technologies. For example, when SCR technology is adopted to reduce NO_x emissions, low-sulfur fuels are required and PM emissions are reduced as well (Eyring et al., 2005b).

In this paper, we use fleet-average emission factors to estimate emissions. We do not distribute shipping engines by vessel speed, engine power, duty cycle, or emission control technologies, but rely on integrated fleet information from other studies. Eyring et al. (2005b) presented four technology scenarios; we choose the business-as-usual

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scenario (TS4), which represents a future in which the sulfur content of marine fuels is still rather high, NO_x emission standards are adopted in all new engines according to current IMO regulations, but there is no shift to alternative fuels. In this work, we assume that changes of fleet composition are the same as TS4, and the average reductions of emission factors due to introduction of cleaner technologies are the same as well. As shown in Table 5, emission factors in 2000 and before are back-calculated with fuel consumption and total emissions from Table 3 of Eyring et al. (2010), which summarized information from a variety of sources (Buhaug et al., 2009; Corbett and Koehler, 2003; Endresen, 2003; Endresen et al., 2007; Eyring, 2005a, b; Fearnleys, 2007).

3.4 Aviation

Historical and current emissions from aviation have previously been assessed in terms of the construction of three-dimensional gridded inventories, such as those constructed for the early 1990s air traffic and reviewed by Henderson et al. (1999). Other inventories have been developed recently, such as AERO2k (Eyers et al., 2004), FAST (Lee et al., 2005), and SAGE (Kim et al., 2007). Lee et al. (2010) summarized recent results from these and older models for 1990s emissions.

Future emission scenarios were first constructed by Henderson et al. (1999) based on GDP projections under older IPCC scenarios. Following similar methods, Owen and Lee (2006) as well as Berghof et al. (2005) for CONSAVE projected emissions with updated scenarios. Lee et al. (2009) showed that IEA fuel sales data consistently indicate larger CO_2 emissions than are implied by "bottom up" inventories, which include less or no information about military aviation, aviation gasoline, non-scheduled traffic, holding patterns, and the effect of winds (Lee et al., 2009; Owen et al., 2010). The most recent aviation emission scenarios were developed by Owen et al. (2010), which relied on air traffic projections of ICAO/CAEP(ICAO/FESG, 2008) and a simple econometric model based on global GDP growth as the principle driver (Olsthoorn, 2001; Vedantham and Oppenheimer, 1998).

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In this work, we apply historical regional and global fuel consumption data from IEA (2012a, b) and future global fuel growth rates from Owen et al. (2010). The details are summarized in Table S3. Similar to fuel consumption for shipping, future global aviation fuel use is distributed among world regions based on regional fuel fractions as well as a linear relationship between fuel growth and GDP (Baughcum et al., 1999; Fulton and Eads, 2004; MNP, 2006; RIVM, 2001). Table 5 shows fleet-average emission factors for aviation in the years 2000, 2020, and 2050. Emission factors for NO_x are back-calculated using emissions and fuel consumption in Owen et al. (2010) and they are assumed to be constant in the year 2000 and before, as there was no consideration of NO_x control in this period. We take historical emission factors for THC and CO from the emission inventory of Baughcum et al. (1999) and fit them with an exponential curve to estimate emission factors in the other years. Emission factors of PM and SO_2 are taken directly from Lee et al. (2010).

3.5 Rail

Rail is likely to play a key role in future transportation policies. This is because rail has lower emissions and higher energy efficiency per passenger and per quantity of freight carried compared to other modes (Uherek et al., 2010; EEA, 2004). Studies in Europe have shown that rail emissions make up only 1–3 % of total emissions (EEA, 2004; European Commission, 2007). Electricity shares about 30 % of the global rail energy use; and this share is 50 % in the European Union. The remaining energy sources are fossil fuels, such as coal, middle distillate oil, and residual fuel oil. With the transition from coal to oil, coal-driven trains are only common in China these days, and their number is declining there as well. Global coal consumption by rail has been reduced from 49 Mt in 1980 to 6 Mt in 2010 (Uherek et al., 2010; IEA, 2012a, b).

Rail fuel data are available for all world regions at the country level from IEA during 1971 and 2010. For future fuel use, we exploit the growth of GDP to project diesel oil growth. Passenger and freight rail are considered separately, due to their different elasticity to GDP and energy intensity. Information about passenger and freight fuel

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share, fuel growth elasticity to GDP growth, annual energy intensity improvement, and electricity fraction comes from Fulton and Eads (2004). Because coal still contributes significantly in China, we apply a transition curve between coal and oil to split energy for rail, by applying the same parameters as in Bond et al. (2007). We assume that oil contributes 100 % to rail fuel demand in other regions after 2010. Table S4 lists detailed information, assumptions, and data sources about fuel consumption from rail.

Rail diesel engines produced after 1990 emit substantially less NO_x and PM compared to older engines, particularly in the US and European countries (Bergin et al., 2012; UIC/CER, 2006). In the US, the first set of emission standards, named Tier 0, applied to rail engines manufactured from 1973 through 2001, then followed by Tier 1 for engines manufactured from 2002 to 2004, and Tier 2 for those after 2005. Within Europe, emissions from rail engines are regulated by the non-road mobile machinery (NRMM) directives. The GAINS model provides diesel emission factors for rail by different control levels, as shown in Table 5. Instead of distributing rail engines by emission standards or control technologies, we use the fleet average emission factors from GAINS to combine with fuel consumption to estimate total emissions. As GAINS only provides emission estimates at five-year intervals to 2030, fleet-average emission factors are interpolated to get annual estimates. We assume that all rail engines will achieve more stringent control levels in the year 2050 than 2030. Coal emission factors are taken from IPCC, Uherek et al. (2010), and Bond et al. (2004) and are summarized in Table 5.

4 Results and discussion

4.1 Global emissions

Estimated global fuel consumption and emission of CO, NO_x, THC, and PM from 2000–2050 from the entire transportation sector under all scenarios are shown in the left panel of Fig. 2. The middle panel of Fig. 2 presents fuel consumption and emissions

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by transport mode under scenario A1B; these for the other three scenarios are shown in Fig. S1. Table 6 summarizes the estimates for the years 2010, 2030, and 2050. Global fuel consumption is projected to be 3.0–4.0 Gt and 2.8–4.7 Gt across the four IPCC scenarios (A1B, A2, B1, and B2) in the years 2030 and 2050, respectively. The corresponding emissions are 101–138 Tg and 95–168 Tg for CO, 44–54 Tg and 46–65vTg for NO_x, 14–18 Tg and 14–23 Tg for THC, and 3.6–4.4 Tg and 3.5–4.9 Tg for PM, respectively.

Despite the increasing global fuel use, especially under scenarios A1B and A2, emissions under all scenarios decrease in the next one or two decades before starting to increase again. The major reason for the decrease in near-term emissions is the implementation of stringent emission standards, particularly for on-road vehicles (Yan et al., 2011), which contribute more than 60 % of the total fuel use. The increase in emissions after about 2030 can be explained by (1) significant growth in on-road vehicle emissions in Africa, which is projected to experience rapid growth in the number of vehicles having no or lax emission controls (Yan et al., 2011); (2) a relatively constant increase of CO and THC emissions from non-road engines after 2030, because emission control of non-road gasoline engines is not as stringent as for on-road and there is greater use of non-road gasoline engines; and (3) a greater contribution of shipping to total NO_x and PM emissions.

CO and THC emissions are dominated by emissions from on-road vehicles at the beginning of the period (Fig. 2, middle panel). However, emissions from non-road engines have the potential to become the leading contributor as time goes on. Though on-road vehicles consume about seven times as much fuel as non-road engines, their net CO and THC emissions become comparable, especially after 2030. This is because on-road vehicles have been required to use increasingly advanced emission control technologies in order to comply with more stringent emission standards. On the other hand, on-road vehicles and shipping govern the emission trends of NO_x and PM, and they contribute 66–83 % to the total. The constant increase of NO_x and PM emissions from shipping makes it play a more significant role in future years; this is can be

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explained by the growth in the world economy, which necessitates the movement of an increasing amount of goods by sea, and the absence of further tightening of emission regulations for ships.

4.2 Regional emissions

The right panel of Fig. 2 presents the fractions of each transport mode in 10 regrouped world regions (Table S1), as well as regional contribution to the global emissions. We show fractions of fuel consumption and the emissions of the four species in the year 2050 under the A1B scenario. Regional estimates in other years are shown in Fig. S2. As shown in Fig. 2, Table S5, and Fig. S2, there is a significant shift in the regional distribution of CO emissions, with an increasing proportion of emissions coming from Africa and South Asia. Until the year 2010, emissions are dominated by Latin America and East Asia, which together account for 34 % of total CO emissions (Fig. S2). After 2010, the emissions from Africa and South Asia increase more rapidly than those from other regions and contribute to 31 and 17 %, respectively, of global CO emissions by the year 2050 (Fig. 2). THC emissions show similar changes in regional contributions, but NO_x and PM emission contribution do not alter much.

The regional composition of future emissions by transport mode varies with species and year. Non-road engines are the dominant contributor to CO emissions in many regions by the year 2050, particularly Asia (those in South Asia, East Asia, and Southeast Asia together account for 70 %) and the Former USSR (61 %). On-road vehicles and non-road engines contribute about equally in North America (51 and 40 %), Europe (53 and 35 %), and the Pacific (47 and 43 %). In the Middle East (86 %), Africa (89 %), and Latin America (69 %), emissions from on-road vehicles continue to contribute large shares of total emissions because of the combined effects of a large fraction of fuel use and lax emission standards. The sources of THC are somewhat similar to CO, except that shipping has more influence in some regions, particularly Europe (35 %), Southeast Asia (25 %), and the Pacific (21 %). Shipping drives NO_x and PM emissions in most regions by the year 2050. In Africa, there is a large contribution (over 70 %) from

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on-road vehicles to all pollutants, due to the delayed introduction of advanced emission standards.

4.3 Comparison with other studies

4.3.1 Global emissions

Other estimates of future emissions of CO, NO_x, THC, and PM for the purposes of studying future air quality and climate change, have used global emission projections such as GAINS (Klimont et al., 2009), IEA/SMP (Fulton and Eads, 2004), QUANTIFY(DLR, 2009), and the new IPCC AR5 Representative Concentration Pathways (RCP) database (Moss et al., 2010). Historical and present-day global emissions, which are used as the baseline for future emissions, often rely on the EDGAR database (JRC/PBL, 2011), RETRO (Schultz et al., 2007), or a combination of several existing emission databases (Lamarque et al., 2010; Zhang et al., 2012). In this section, we compare our results with some of these widely used datasets, none of which consider dynamic technological change.

Because on-road vehicles represent a significant contribution to total emissions, especially for CO and THC, we first compare our global on-road emission estimates with previous work in Fig. 3 (right panel). Except for this work, the other studies do not explicitly model the influence of superemitters, which may contribute over 50 % of total emissions (Yan et al., 2011), thus two extra scenarios that do not include any consideration of superemitters (dashed lines) are constructed for comparison purposes. Emissions of PM from on-road vehicles have already been compared with other studies in Yan et al. (2011), so they are not discussed here. The historical EDGAR emission estimates show a similar trend and magnitude for NO_x emissions up to the year 2010; however, EDGAR estimates for CO and THC emissions are higher. Estimates from the GAINS model are generally within the bounds of our estimates across multiple scenarios, though they are slightly larger before 2010. The IEA/SMP model shows much higher emissions for CO and THC in the first 20 yr of the forecast, because their model

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assumes that light-duty gasoline and diesel vehicles have the same emission factors, while we use measured emission factors and differentiate them by not only fuel type but also emission standard and vehicle age. Since their model is more optimistic with regard to emission standard implementation, even in Africa, emission projections in the future are lower than our estimates even without consideration of superemitters after around 2025.

RCPs have been developed for AR5, but they provide climate forcing pathways rather than prescribed changes in socioeconomic conditions. They are consistent sets of projections of the components of radiative forcing that are meant to serve as inputs for climate modeling, pattern scaling, and atmospheric chemistry modeling. A specific emission scenario for each RCP is identified from the peer-reviewed literature as a plausible pathway towards reaching the target radiative forcing trajectory (Moss et al., 2010). Figure 4 shows a comparison of global emission estimates for the transportation sector as a whole, including on-road vehicles, non-road engines, shipping, aviation, and rail. The annual global emissions estimated in this work have trends that are similar to other work up to 2010 but of somewhat different magnitude. In part due to the high growth of the shipping contribution, our estimates of NO_x emissions under scenario A1B tend to exceed RCP8.5 after 2040 and PM emissions show comparable or even higher emissions than RCPs. Between 2010 and 2030, emission projections of CO, NO_x, and THC in this work are consistently lower than RCPs, especially for THC, but higher than QUANTIFY. If emissions from shipping are excluded from the total, our projections of PM emissions are also lower than the ranges of RCPs. The main reason for higher estimates in RCP scenarios is that, in general, only one emission factor is assigned to each subsector, e.g. on-road gasoline engines, and such treatment of emission factors cannot reflect technology shares or changes in shares, which tends to lead to overestimation of emissions. Whether differences of emission projections may also be due to differences in energy consumption or socioeconomic assumptions such as GDP and population is beyond the scope of this paper and will not be discussed here.

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4.3.2 Regional emissions

As an illustration of regional emissions, the middle and left panel in Fig. 3 compare emission estimates from on-road vehicles in North America and East Asia. These two regions are selected for the purpose because they play key roles in the determination of current and future emissions. Due to the fact that aviation and shipping are more international activities, they are not compared at the regional level. Regional comparisons of PM emissions from on-road vehicles and all emissions from non-road engines are discussed in Yan et al. (2011) and Winijkul et al. (2013), respectively.

In general, emission estimates for North America in this work are consistent with other studies in terms of emission trends, yet our estimates have lower magnitudes and a faster decline especially for CO and THC between 2000 and 2020. Emissions from the IEA/SMP model are overestimated, particularly before 2010, because of its emission factor choice (as explained in Sect. 4.3.1 for global emissions. Emissions from GAINS are higher than our estimates. Though fuel use in GAINS is closer to or even lower than our work, their net emission factor or emission intensity is much higher because of the slower phase-in of advanced emission standards and the use of emission factors for European emission standards instead of measured ones as in this work.

Emission estimates for East Asia show wide variation. EDGAR represents a good match with our study for past emissions of CO and NO_x, while their emissions are higher for THC and lower for PM. This close match is partly due to use of the same IEA fuel data. The GAINS model tends to have higher emission estimates for CO, THC, and PM before the year 2000 due to greater shares of vehicles without emission standards. Emission projections between the years 2010 and 2030 in this work show a continuous decrease in East Asia, unlike in the GAINS model where emissions increase after 2020. Such an increase is caused by their higher estimates of the growth rate of vehicle activity and slower adoption of Euro VI emission standards. Emission projections after the year 2020 from the IEA/SMP model and QUANTIFY lie within the range of the sce-

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narios from this work, and their emissions are approaching or lower than the scenarios without superemitters in year 2050. This highlights the importance of separating superemitters from other emitters so that future emissions are not underestimated. It also indicates that the potential environmental issues caused by superemitters must be addressed specifically by policy makers, because such vehicles make a highly significant contribution to total emissions.

5 Conclusions and recommendations

5.1 Conclusions

This paper presents projections of exhaust emissions of CO, NO_x, THC, and PM from the transportation sector, consisting of on-road vehicles, non-road engines, shipping, aviation, and rail. It presents emissions from 2010 to 2050 annually under four IPCC scenarios. Future emissions from on-road vehicles and non-road engines are estimated within the framework of the SPEW-Trend model, incorporating dynamic representation of the dependence of technology choice on socioeconomic and other variables. For completeness, emissions from shipping, aviation, and rail are compiled from other related studies. Our emission trends and magnitudes are somewhat different from previous work, the most important reason for which is that we account for the explicit relationship between socioeconomic factors and technological change, and other studies do not.

At the global level, the effects of tighter emission standards for on-road vehicles in many parts of the world offset the growth in fuel consumption during the first one or two decades of projections, and therefore the emissions of all pollutants decrease. As time goes on and particularly after 2030, however, emissions from on-road vehicles in Africa and emissions from non-road engines and shipping comprise an ever-increasing share of total emissions and lead to an increase in emissions in some scenarios. On-road

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vehicles and non-road engines dominate global CO and THC emissions, while on-road vehicles and shipping contribute most to NO_x and PM emissions.

At the regional level, emissions from Latin America and East Asia contribute most to global CO and THC emissions in the year 2010; this dominance shifts to Africa and South Asia in the future. By the year 2050, for CO emissions, non-road engines contribute the greatest fraction in Asia and the Former USSR, while on-road vehicles make the greatest contribution in Latin America, Africa, and the Middle East. For NO_x and PM emissions, shipping controls the trend in most regions.

One of the major goals of this work is to build a new dataset of potential future emissions to support climate modeling. In previous studies (Berntsen and Fuglestvedt, 2008; Unger et al., 2010), present-day or historical emissions have often been used to drive climate models, because regional and global projections of the emissions of appropriate species were not available. Some studies simply extrapolated current emissions into the future with linear assumptions about the relationship between emissions and economic growth. These methods are not satisfactory because they neglect the fact that emission factors are strongly dependent on in-use technology and applicable regulatory standards, both of which vary dramatically around the world today and will undergo transition at different rates in the future. These factors that govern technology change will dramatically influence the trajectory of future emissions. This dynamic technology model can also help identify the major emission contributors by technology type, transport mode, and world region, and thereby allow policymakers to design more efficient and effective emission control policies.

5.2 Recommendations for future research

5.2.1 Updates of scenarios

It is important that the socioeconomic drivers and fuel use are periodically updated when new scenarios are developed. This work is based on four IPCC scenarios, which were developed for the SRES (Nakicenovic et al., 2000). These four scenarios were

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used in the third (TAR) and fourth (AR4) IPCC assessments of climate change and have been widely applied by other groups for global projections of greenhouse gases, but they are now outdated. Although we have updated the SRES scenarios with actual data from IEA for fuel use and the World Bank for GDP and population, these variables after the year 2010 (or 2005 for on-road vehicles) still follow the trends that were originally formulated in the IMAGE model. These trends therefore do not reflect factors that will have influenced socioeconomic development within the past decade or two. Though work is underway to back-calculate socioeconomic forecasts consistent with the RCP, this is not a very satisfactory solution, as there could be many different ways to achieve the same climate forcing pathway. In principle, SPEW-Trend can be driven by the forecasts of any macroeconomic model, but those forecasts need to provide the basic socioeconomic parameters that govern emissions. In order to generate climate and air pollution projections that are both consistent and widely used, greater integration among technology-rich models such as SPEW-Trend, scenario-defining macroeconomic models, and climate pathway models needs to be developed.

5.2.2 Dynamic technological changes in shipping, aviation, and rail

Unlike emissions from on-road vehicles (Yan et al., 2011) and non-road engines (Winijkul et al., 2013), the emissions from shipping, aviation, and rail in this work are based on fuel consumption and emission factors gathered from a variety of other studies (e.g. Eyring et al., 2005b; Owen et al., 2010; Uherek et al., 2010). These studies have considered technology development and fleet turnover to some extent, yet these changes are not dynamic. In some cases, they are simply based on expert judgment. The methodology used here for on-road vehicles and non-road engines is readily transferable to other sectors with availability of required information, and it is recommended that the approach be adapted in future work to shipping, aviation, and rail. In order to represent dynamic changes in these three modes and make them consistent with on-road vehicles and non-road engines, we need more information about the factors

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that drive technology preference and retirement decision-making for ships, aircraft, and locomotives.

5.2.3 Uncertainty analysis

It is not possible to apply the traditional approaches to characterizing uncertainties for estimates of future emissions. We clearly cannot measure the emission rates of 2050 vehicles in the laboratory, and we have no way of knowing the relative likelihood of particular future pathways of human development. For this reason, few studies of future emissions have even addressed the question of uncertainty. Nakicenovic et al. (2000) suggested that the scenario approach to describe the range of possible future emissions developed by complex systems that are "either inherently unpredictable, or that have high scientific uncertainties". Some estimates of historical and present-day emissions (Bond et al., 2004; Lu et al., 2011; Smith et al., 2011; Zhao et al., 2011) have coupled uncertainties in activity rates, fuel use, and emission characteristics to give an indication of the uncertainty in the final emission estimate. However, in addition to the uncertainty in these factors, the relationships that link socioeconomic factors and technological change to determine future technology shares are another significant source of uncertainty in this work. Many of the relationships involved in the SPEW-Trend model, such as retirement rates, are only loosely constrained by observations. Yan et al. (2013) demonstrated how uncertainties in model input parameters affect projected emissions from on-road vehicles and found that the emission uncertainty caused by lack of knowledge about technology composition is about the same as the uncertainty demonstrated by alternative economic scenarios. The results presented in this paper must be understood in the context of these uncertainties.

Supplementary material related to this article is available online at: http://www.atmos-chem-phys-discuss.net/13/23373/2013/acpd-13-23373-2013-supplement.pdf.

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Acknowledgements. This work is supported by the US Department of Agriculture, National Institute of Food and Agriculture, through the award number 2012-67003-30192 to the University of Chicago and by the National Science Foundation EaSM program, through the award number AGS-1049200 at NCSU. We are grateful for the support of the USDA Project Officer, Luis M. Tupas, and the NSF Program Director, Anjuli S. Bamzai. Argonne National Laboratory is operated by UChicago Argonne, LLC under Contract No. DE-AC02-06CH11357 with the US Department of Energy.

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Table 1. Relationships and parameters used in the SPEW-Trend model for on-road vehicles and non-road engines (Winijkul et al., 2013; Yan et al., 2011).

Relationship	Parameter	Description	Functional Description
Survival rate (Su)[a]	s[b]	age (or cumulative service hours)	
	α_{ret}	intercept, shape factor related to the onset of significant retirement	$\mathrm{Su}\,(s) = \frac{1}{1+\exp[-\alpha_{ret}(1+\beta_1\times s+\beta_2\times rgdp\times s)]}$ (3)
	β_1	age coefficient	
	β_2	income[d] coefficient	
Adoption of emission standards	adoption dates of first advanced standards	–	Depends on regions, emission standards in neighboring countries, and vehicle size
	lag years between advanced standards	–	Constant
Superemitter transition rate (Tr)[c]	α_{sup}	shape factor; determines slope of the curve	
	$L_{50,sup}$	vehicle life at which the rate becomes half of the maximum	$\mathrm{Tr}(s) = \frac{\mathrm{gain}}{1+\exp[\alpha_{sup}(1-s/L_{50,sup})]}$ (4)
	gain	maximum rate of superemitter transition	
Degradation rate (DR)	$\mathrm{EF_{new}}$	emission factor for new vehicles	
	$\mathrm{EF_{es}}$	emission factor, the same as emission standard	$\mathrm{DR_{on\text{-}road}}(s) = \begin{cases} 1, & \text{if } s \le s_{deg} \\ \frac{\mathrm{EF_{max}}-\mathrm{EF_{new}}}{s_{stab}-s_{deg}} \times \frac{s-s_{deg}}{\mathrm{EF_{new}}} + 1, & \text{if } s_{deg} < s < s_{stab} \\ \frac{\mathrm{EF_{max}}}{\mathrm{EF_{new}}}, & \text{if } s \ge s_{stab} \end{cases}$ (5)
	$\mathrm{EF_{max}}$	maximum emission factor	
	s_{deg}	age that emission factor starts to degrade	$\mathrm{DR_{non\text{-}road}}(s) = \begin{cases} \frac{\mathrm{EF_{es}}-\mathrm{EF_{new}}}{\mathrm{EF_{new}}} \times \frac{s}{s_{deg}} + 1, & \text{if } s \le s_{deg} \\ \frac{\mathrm{EF_{max}}-\mathrm{EF_{es}}}{\mathrm{EF_{new}}} \times \frac{s-s_{deg}}{s_{stab}-s_{deg}} + \frac{\mathrm{EF_{es}}}{\mathrm{EF_{new}}}, & s_{deg} < s < s_{stab} \\ \frac{\mathrm{EF_{max}}}{\mathrm{EF_{new}}}, & \text{if } s \le s_{stab} \end{cases}$ (6)
	s_{stab}	age that emission factor starts to stabilize	

[a] Survival rate can be converted to a retirement rate by Re $(s) = 1\,\frac{\mathrm{Su}(s+1)}{\mathrm{Su}(s)}$.

[b] s represents vehicle age of on-road vehicles or cumulative service hours of non-road engines.

[c] The transition rate is defined as the fraction of normal vehicles that become superemitters in any given year.

[d] Income level is represented by the ratio of local and global GDP per capita, rgdp.

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Table 2. Gaseous emission factors (unit: $g\,kg^{-1}$) and degradation rates for light-duty gasoline vehicles (LDGV).

Emission Standards	CO			THC			NO_x		
	EF_{new}	$DR_{max}^{l,m,n}$	EF_{max}	EF_{new}	$DR_{max}^{l,m}$	EF_{max}	EF_{new}	$DR_{max}^{l,m}$	EF_{max}
Tier 1	19.6[d]	3.15	61.9	1.35[o]	3.15[p]	4.27	1.97[o]	2.20[j]	4.33
NLEV[a]	10.3[e]	3.72	38.3	1.13[j]	3.72[p]	4.21	1.19[q]	2.02[q]	2.41
Tier 2-2004	7.07[e]	3.17	22.4	0.39[q]	3.17[q]	1.23	0.52[q]	2.26[q]	1.17
Tier 2-2006	6.43[e]	3.17	20.4	0.34[q]	3.17[q]	1.09	0.34[q]	2.26[q]	0.77
Tier2-2007	6.39[e]	3.17	20.3	0.36[q]	3.17[q]	1.13	0.26[q]	2.26[q]	0.59
Euro I	39.1[f]	3.15	123	4.73[f]	3.15[r]	14.91	4.45[f]	2.20[r]	9.80
Euro II	24.4[f]	3.15	76.8	2.40[f]	3.15[r]	7.56	2.35[f]	2.20[r]	5.18
Euro III	25.6[f]	3.15	80.8	1.41[f]	3.15[r]	4.45	1.39[f]	2.20[r]	3.06
Euro IV	9.85[f]	3.17	31.2	0.87[f]	3.17[s]	2.75	0.80[f]	2.26[s]	1.81
Euro V	9.85[g]	3.17	31.2	0.87[g]	3.17[s]	2.75	0.60[g]	2.26[s]	1.36
Euro VI	9.85[g]	3.17	31.2	0.87[g]	3.17[s]	2.75	0.60[g]	2.26[s]	1.36
None	408[h]	1.28	521	39.0[h]	1.28[t]	49.8	25.6[h]	2.20[j]	56.3
OPAC	159[h]	2.59	413	21.5[h]	2.59[t]	55.7	18.1[h]	2.20[j]	39.8
Super1[b]	521[i,k]	–	–	63.9[i,k]	–	–	56.3[i, k]	–	–
Super2[c]	123[j,k]	–	–	29.1[j,k]	–	–	9.80[j,k]	–	–

[a] National Low Emission Vehicle program. [b] refers to superemitters turned from vehicles without regulation (None) and with opacity standards (OPAC). [c] refers to superemitters turned from vehicles with US Tier I and II, and Euro I-VI standards. [d] Maricq et al. (1999); US EPA (2011). [e] US EPA (2011). [f] Ntziachristos and Samaras (2001); EEA (2012). [g] based on emission standard reduction rate (Ntziachristos and Samaras, 2001;Yan et al., 2011). [h] EEA (2012); US EPA (2012a). [i] Durbin et al. (1999); Cadle et al. (1999). [j] Durbin et al. (1999). [k] maximal of references and highest emission factors for corresponding vehicle groups. [l] $DR_{max} = EF_{max}/EF_{new}$. [m] ages that vehicles start to degrade and stabilize are the same as for PM (Yan et al., 2011). [n] the same as THC. [o] Maricq et al. (1999); US EPA (2011, 2012a). [p] US EPA (2011, 2012a). [q] US EPA (2011). [r] the same as Tier 1. [s] the same as Tier 2. [t] US EPA (2012a).

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Table 3. Gaseous emission factors (unit: $g\,kg^{-1}$) and degradation rates for light-duty diesel vehicles (LDDV).

Emission Standards	CO			THC			NO_x		
	EF_{new}	$DR_{max}^{i,j}$	EF_{max}	EF_{new}	$DR_{max}^{i,j}$	EF_{max}	EF_{new}	$DR_{max}^{i,j}$	EF_{max}
Tier 1	11.5[d]	1.17[k]	13.4	1.52[d]	1.31[k]	2.00	10.5[d]	1.00[l]	10.5
NLEV[a]	11.5[d]	1.17[k]	13.4	1.52[d]	1.31[k]	2.00	10.5[d]	1.00[l]	10.5
Tier 2-2004	11.5[d]	1.17[k]	13.4	1.52[d]	1.31[k]	2.00	10.5[d]	1.00[l]	10.5
Tier 2-2006	3.70[d]	1.17[k]	4.32	0.17[d]	1.31[k]	0.22	3.71[d]	1.00[l]	3.71
Tier2-2007	3.70[d]	1.17[k]	4.32	0.17[d]	1.31[k]	0.22	3.71[d]	1.80[m]	6.65
Euro I	8.03[e]	1.17[k]	9.37	1.68[e]	1.31[k]	2.20	9.52[e]	1.00[l]	9.52
Euro II	7.42[e]	1.17[k]	8.65	1.69[e]	1.31[k]	2.22	9.70[e]	1.00[l]	9.70
Euro III	5.45[e]	1.17[k]	6.35	0.98[e]	1.31[k]	1.28	8.95[e]	1.00[l]	8.95
Euro IV	4.74[e]	1.17[k]	5.53	0.51[e]	1.31[k]	0.66	5.34[e]	1.00[l]	5.34
Euro V	2.59[f]	1.17[k]	3.02	0.25[f]	1.31[k]	0.32	4.84[f]	1.00[l]	4.84
Euro VI	2.59[f]	1.17[k]	3.02	0.14[f]	1.31[k]	0.18	1.55[f]	1.80[m]	2.78
None	17.1[g]	1.17[k]	20.0	6.15[g]	1.31[k]	8.07	12.9[g]	1.08[k]	13.9
OPAC	12.1[g]	1.17[k]	12.5	2.56[g]	1.31[k]	3.36	11.1[g]	1.08[k]	12.0
Super1[b]	20.0[h]	–	–	8.07[h]	–	–	13.9[h]	–	–
Super2[c]	13.4[h]	–	–	2.22[h]	–	–	10.5[h]	–	–

[a] National Low Emission Vehicle program. [b] refers to superemitters turned from vehicles without standards (None), and with opacity, Tier 1 and Euro I standards. [c] refers to superemitters turned from vehicles with US Tier 2 and Euro II-VI standards. [d] US EPA (2011). [e] Ntziachristos and Samaras (2001); EEA (2012). [f] EEA (2012). [g] EEA (2012); US EPA (2011, 2012a). [h] maximal value of highest emission factors for corresponding vehicle groups. [i] $DR_{max} = EF_{max}/EF_{new}$. [j] ages that vehicles start to degrade and stabilize are the same as PM (Yan et al., 2011). [k] US EPA (2012a). [l] no degradation. [m] the same as emission factor for HDDV Euro VI standard.

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Table 4. Gaseous emission factors (unit: $g\,kg^{-1}$) and degradation rates for heavy-duty diesel vehicles (HDDV).

Emission Standards	CO			THC			NO_x		
	EF_{new}	$DR_{max}^{h,i}$	EF_{max}	EF_{new}	$DR_{max}^{h,i}$	EF_{max}	EF_{new}	$DR_{max}^{h,i}$	EF_{max}
1988	14.5[c]	3.34[j]	48.5	2.02[c]	4.00[j]	8.09	36.1[c]	1.00[q]	36.1
1991	10.1[c]	4.00[k]	40.4	2.43[c]	4.00[k]	9.73	34.8[c]	1.00[q]	34.8
1993	8.06[c]	4.00[k]	32.2	1.28[c]	4.00[k]	5.12	29.9[c]	1.00[q]	29.9
1994	6.43[c]	4.00[k]	25.7	1.27[c]	4.00[k]	5.09	36.9[c]	1.00[k]	36.9
1996	7.87[c]	4.00[k]	31.5	0.23[c]	4.00[k]	0.93	27.9[c]	1.00[k]	27.9
1998	7.87[d]	4.00[k]	31.5	0.23[d]	4.00[k]	0.93	22.3[d]	1.00[k]	22.3
2004	7.87[d]	2.50[k]	19.7	0.23[d]	2.50[k]	0.58	13.4[d]	1.00[k]	13.4
2007	7.87[d]	2.50[k]	19.7	0.02[d]	2.50[k]	0.06	6.69[d]	1.00[k]	6.69
2010	7.87[d]	1.33[k]	10.5	0.02[d]	1.33[k]	0.03	1.12[d]	1.80[k]	2.00
Euro I	7.01[e]	4.00[l]	28.0	2.46[e]	4.00[l]	9.85	34.9[e]	1.00[l]	34.9
Euro II	6.11[e]	4.00[l]	24.4	1.65[e]	4.00[l]	6.59	36.3[e]	1.00[l]	36.3
Euro III	6.57[e]	4.00[l]	26.3	1.56[e]	4.00[l]	6.24	28.3[e]	1.00[l]	28.3
Euro IV	0.48[e]	2.50[m]	1.19	0.07[e]	2.50[m]	0.18	19.9[e]	1.00[m]	19.9
Euro V	0.48[e]	2.50[m]	1.19	0.07[e]	2.50[m]	0.18	9.96[e]	1.00[m]	9.96
Euro VI	0.48[e]	1.33[n]	0.63	0.07[e]	1.33[n]	0.09	1.92[e]	1.80[n]	3.45
None	17.5[c]	2.94[j]	51.5	6.91[o]	1.84[j]	12.7	45.7[o]	1.04[q]	47.7
OPAC	16.0[c]	3.12[j]	50.0	4.47[o]	2.33[j]	10.4	40.6[o]	1.02[q]	41.3
Super1[a]	62.7[f,g]	–	–	12.7[f]	–	–	55.5[f]	–	–
Super2[b]	31.5[c,g]	–	–	6.59[c]	–	–	55.5[p]	–	–

[a] refers to superemitters turned from vehicles without standards, and with opacity, US HDDV 1988–1993 and Euro I standards. [b] refers to superemitters turned from vehicles with US HDDV 1994–2010 and Euro II-VI standards. [c] Yanowitz et al. (2004). [d] based on emission standard reduction rate (Ntziachristos and Samaras, 2001;Yan et al., 2011). [e] EEA (2012). [f] Yanowitz et al. (2000); McCormick et al. (2003). [g] maximal of references and highest emission factors for corresponding vehicle groups. [h] $DR_{max} = EF_{max}/EF_{new}$. [i] ages that vehicles start to degrade and stabilize are the same as PM (Yan et al., 2011). [j] estimated by applying average of emission degradation ($g\,kg\,yr^{-1}$) for US HDDV standards in 1991 to 1998. [k] US EPA (2009). [l] the same as emission factor for US HDDV 1991 standard. [m] the same as emission factor for US HDDV 2004 standard. [n] the same as emission factor for US HDDV 2010 standard. [o] EEA (2012); Yanowitz et al. (2000). [p] the same as emission factor for Super1. [q] US EPA (2012a).

Table 5. Emission factors (unit: $g\,kg^{-1}$) for shipping, aviation, and rail.

Transport modes		CO	NO_x	THC	PM
Shipping (Oil)[n]	2000[a,b]	4.72	71.0[d]	5.12[e]	5.6
	2020[c,b]	4.72	56.8[d]	4.89[e]	5.32
	2050[c,b]	4.72	49.7[d]	4.66[e]	5.04
Aviation (Oil)[n]	2000	10.0[f]	13.6[g]	1.80[f]	0.025[i]
	2020	6.54[f]	11.9[g]	0.91[f]	0.025[i]
	2050	3.44[f]	9.79/11.5/7.98/10.1[g,h]	0.33[f]	0.025[i]
Rail (Oil)[j]	No control	11.8	69.5	8.95	4.62
	Stage I	11.2	34.2	5.81	3.08
	Stage II	9.89	31.1	4.74	2.31
	Stage IIIA	5.30	28.6	3.58	0.69
	Stage IIIB	4.24	20.3	3.58	0.14
	Stage IV	4.24	13.4	3.40	0.28
Rail (Coal)[k]	–	4.20[l]	8.40[l]	0.84[l]	15.0[d]

[a] Estimated by fuel consumption and emissions in Table 3, Eyring et al. (2010). [b] emissions factors before 2000, are the same as these in 2000 except NOx; emission factors in 2000–2020 and 2020–2050 are interpolated linearly. [c] emission factors in 2020 and 2050 and estimated by emission factors in 2000 and technology reduction factors in scenario TS4 in Eyring et al. (2005b). [d] NO_x emission factor before 1999 is the same as the one in 1995 (80.4 $g\,kg^{-1}$); it decreases linearly from 1995 to 2000. [e] no HC emissions from crude oil transport. [f] emission factors in 1976, 1984, and 1992 from NASA emission inventories in Baughcum et al. (1999) are applied to fit an exponential curve [$y = \exp(ax + b)$], where x is calendar year and y is emission factor, and then use the estimated parameters to model emission factors in other years. The parameters for CO are $a = -0.0214$, and $b = 45.082$; those for THC are: $a = -0.0338$, and $b = 68.198$. [g] estimated by emissions and fuel consumption in Owen et al. (2010); emission factors in year 2050 are distinguished by scenarios due to different trends of technology. [h] for scenario A1B, A2, B1, and B2, respectively. [i] Table 1 in Lee et al. (2010). [j] GAINS (Klimont et al., 2009). [k] coal emission factors are assumed to be constant; as coal makes a small contribution in the future rail energy use, this assumption will not affect the total transportation emission much. [l] IPCC (1995); Uherek et al. (2010). [m] Bond et al. (2004). [n] fleet average emission factors.

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Table 6. Fuel consumption (Unit: $Pg\,yr^{-1}$) and emissions (Unit: $Tg\,yr^{-1}$) from different transport modes in year 2010, 2030, and 2050.

Variable	Mode	2010	2030				2050			
			A1B	A2	B1	B2	A1B	A2	B1	B2
Fuel[a]	On-road	1.7	2.71	2.05	2.1	1.86	2.84	2.38	1.93	1.53
	Non-road	0.25	0.35	0.28	0.29	0.31	0.37	0.27	0.25	0.26
	Shipping	0.25	0.37	0.33	0.36	0.35	0.55	0.42	0.49	0.46
	Aviation	0.24	0.44	0.38	0.36	0.37	0.77	0.47	0.43	0.44
	Rail	0.03	0.09	0.06	0.08	0.07	0.17	0.09	0.14	0.13
	Total	2.47	3.97	3.1	3.19	2.96	4.69	3.62	3.23	2.82
CO	On-road	97.4	72.8	53.8	58.8	51.2	93	63.2	65.1	45.3
	Non-road	35.9	59.9	43.2	49	48.8	69.1	45.4	46.4	44.9
	Shipping	1.19	1.77	1.57	1.69	1.64	2.59	1.96	2.31	2.17
	Aviation	1.92	2.33	1.98	1.92	1.93	2.64	1.61	1.47	1.5
	Rail	0.35	0.84	0.56	0.73	0.73	1.08	0.57	0.89	0.79
	Total	137	138	101	112	104	168	113	116	95
NO_x	On-road	25.2	18.1	13.7	14.7	13.3	21.9	14.9	15.3	11.1
	Non-road	10.1	6.58	5.7	5.87	5.87	3.84	2.9	2.86	2.91
	Shipping	16.2	20.4	18.1	19.4	18.9	27.3	20.7	24.3	22.8
	Aviation	3.02	4.95	4.42	3.85	4.14	7.5	5.4	3.4	4.4
	Rail	1.59	3.48	2.32	3.05	3.04	4.52	2.33	3.65	3.33
	Total	56.1	53.5	44.2	46.9	45.2	65.1	46.2	49.5	44.5
THC	On-road	12.1	8.77	6.52	7.09	6.3	11.4	7.66	7.96	5.65
	Non-road	4.87	6.7	4.85	5.57	5.56	8.11	5.19	5.48	5.36
	Shipping	1.26	1.8	1.6	1.72	1.68	2.56	1.94	2.28	2.14
	Aviation	0.3	0.29	0.24	0.24	0.24	0.25	0.16	0.14	0.14
	Rail	0.25	0.64	0.43	0.56	0.56	0.73	0.39	0.6	0.54
	Total	18.8	18.2	13.6	15.2	14.3	23.1	15.3	16.5	13.8
PM	On-road	1.49	1.05	0.83	0.88	0.8	1.26	0.82	0.89	0.62
	Non-road	1.28	0.99	0.83	0.87	0.87	0.75	0.51	0.53	0.52
	Shipping	1.38	1.96	1.74	1.87	1.82	2.77	2.1	2.47	2.32
	Aviation	0.006	0.011	0.009	0.009	0.009	0.019	0.012	0.011	0.011
	Rail	0.21	0.35	0.23	0.3	0.31	0.15	0.08	0.13	0.1
	Total	4.37	4.36	3.62	3.93	3.8	4.94	3.53	4.02	3.58

[a] Fuel for on- and non-road, shipping, aviation is oil; that for rail is oil and coal.

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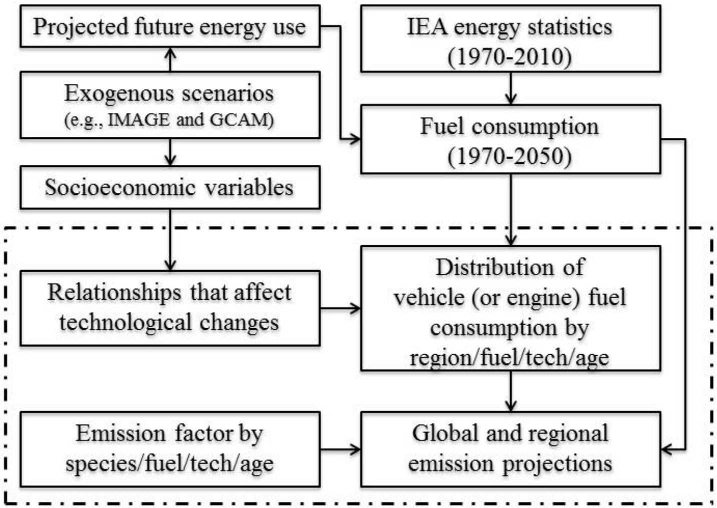

Fig. 1. Schematic methodology for developing projections of exhaust emissions from on-road vehicles and non-road engines. Parts in the dashed rectangular box are handled by Speciated Pollutant Emission Wizard Trend (SPEW-Trend) (Sect. 2.2, Yan et al., 2010, and Winijkul et al., 2013). The exogenous scenarios are from integrated assessment model framework.

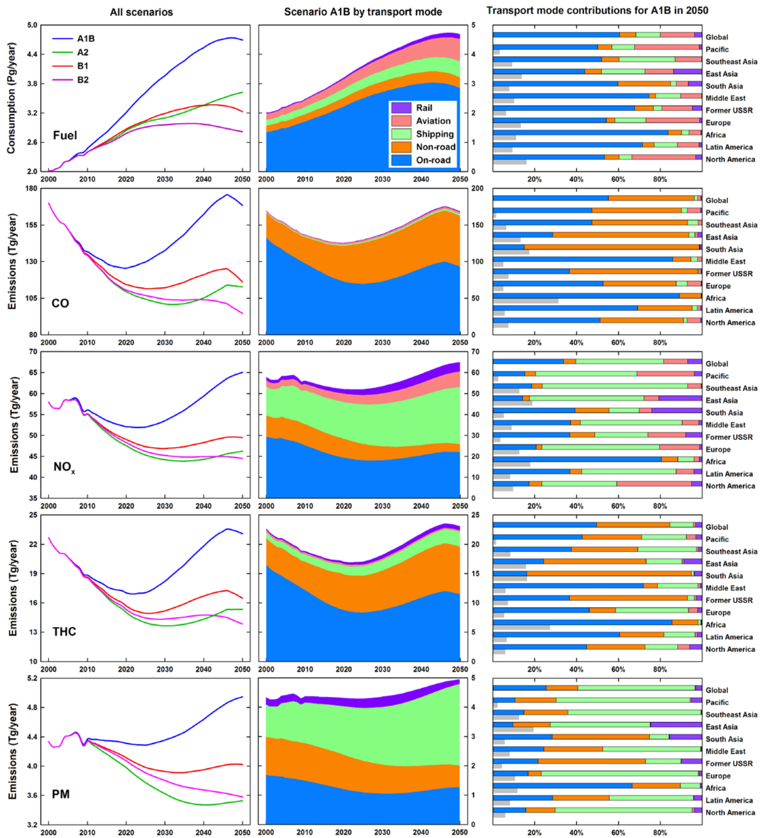

Fig. 2. Estimated global fuel consumption and emissions of CO, NO_x, THC, and PM from the transportation sector under all scenarios (A1B, A2, B1, and B2) (left), by transport mode under scenario A1B (middle), and by transport mode fractional contribution in different regions under scenario A1B in year 2050 (right). The grey bars in the right panel represent regional contributions to the global emissions.

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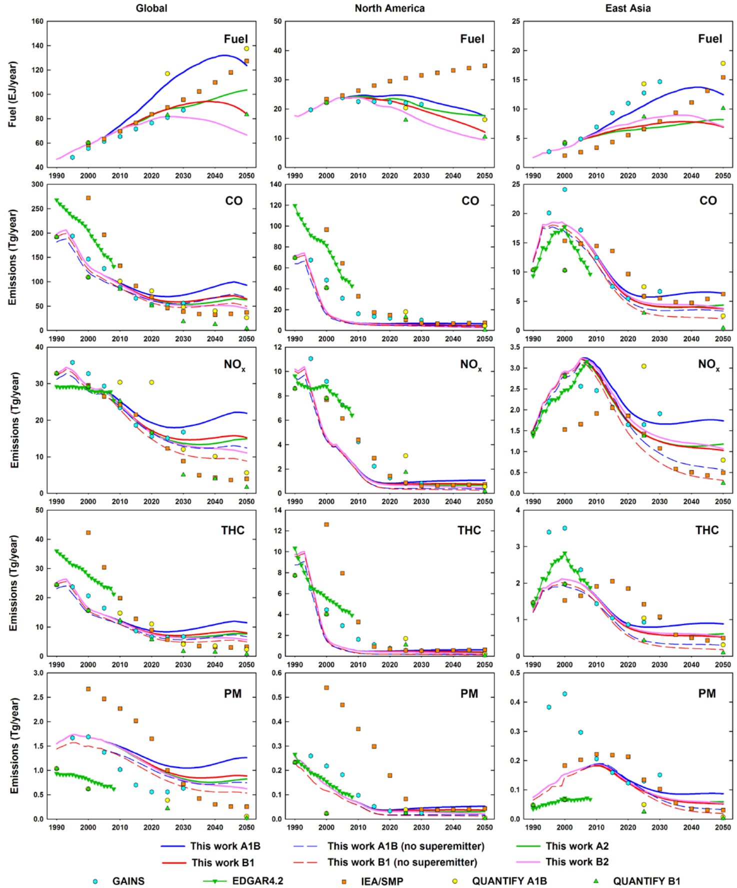

Fig. 3. Comparison of global (left) and regional (North America, middle; East Asia, right) fuel and emission estimates for on-road vehicles in this work with previous studies: GAINS (scenario: BL_WEO_2010) (Klimont et al., 2009), EDGAR (version 4.2) (JRC/PBL, 2011), IEA/SMP (Fulton and Eads, 2004), and QUANTIFY (DLR, 2009).

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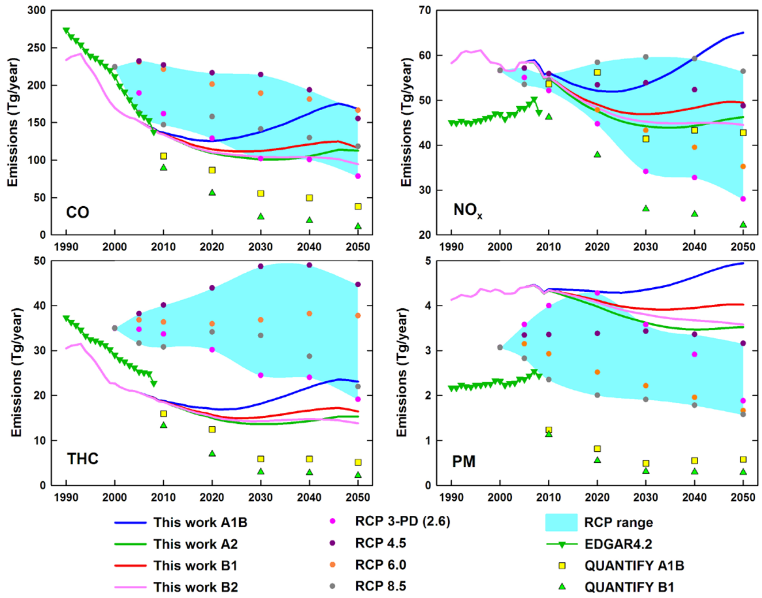

Fig. 4. Comparison of global emission estimates from the whole transportation sector. The solid lines are total emissions estimated in this work under scenarios A1B, A2, B1, and B2, including on-road vehicles, non-road engines, total shipping (domestic and international), total aviation (domestic and international), and rail. RCP (Moss et al., 2010) includes emissions from surface transportation, aviation, and international shipping. EDGAR (JRC/PBL, 2011) includes emissions from road transport, inland navigation, international shipping, domestic and international aviation, and rail. QUANTIFY (DLR, 2009) includes emissions from road, maritime shipping, inland navigation, aviation, and rail. For the comparison of PM, this work shows emissions of total PM, EDGAR shows emissions of PM_{10}, QUANTIFY and RCP show the sum of the emissions of BC and OC.

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