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Global emission projections for the transportation sector using dynamic technology modeling

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Table of Contents

S.1 Region definitions

We assign emission characteristics for 17 world regions by following the divisions of IMAGE: 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, as shown in Table S1. The corresponding region names in the other models are also shown, and they are used when the results in this work are compared with the other models.

Table S1. Regrouped region names and corresponding region names in each model.

Regrouped region name	**IMAGE**	**EDGAR**	**QUANTIFY**	**IEA/SMP**
North America	Canada, U. S.	Canada, U. S.	NAM	OECD North America
Latin America	Central America, South America	Mexico, Rest Central America, Brazil, Rest South America	LAM	Latin America
Africa	Northern Africa, Western Africa, Eastern Africa, Southern Africa	Northern Africa, Western Africa, Eastern Africa, Southern Africa	AFR	Africa
Europe	OECD Europe, Eastern Europe	OECD Europe, Central Europe	EU15, CEC	OECD Europe, Eastern Europe
Former USSR	Former USSR	Ukraine+, Asia-Stan, Russia+	CIS	FSU
Middle East	Middle East	Turkey, Middle East	MEA	Middle East
South Asia	South Asia	India+	SAS	India
East Asia	East Asia	Korea, China+	EAS	China
Southeast Asia	Southeast Asia	Southeastern Asia, Indonesia+	SEA	Other Asia
Pacific	Oceania, Japan	Oceania, Japan	OCN	OECD Pacific

S.2 Data sources and assumptions about historical and future fuel consumption

In this work, 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 (van Vuuren et al., 2006) such as Integrated Model to Assess the Global Environment (IMAGE) (RIVM, 2001; MNP, 2006), so that the emission estimates are driven by the same "big picture" factors as other energy-related emission scenarios (Nakicenovic et al., 2000).

Though fuel use for on-road vehicles is presently available to 2010 from IEA, we apply fuel data in IEA only until 2005 in order to be consistent with Yan et al. (2011). We grow gasoline and diesel use based on the growth rate of fuel in IMAGE from 2006 to 2050. In year 2010, the gasoline consumption for on-road vehicles from IEA falls within the range of adjusted projections (-2%–+3%), while the diesel consumption from IEA is 6% lower than the projected ones. For other transportation modes, we apply historical regional and global fuel consumption data from IEA from 1980 to 2010. Similar to our treatment of future fuel consumption for on-road vehicles, we also project fuel consumption for non-road engines based on IPCC scenarios in IMAGE. Non-road gasoline and diesel engines used in agriculture, construction and mining, and industry are included in this category. We project 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. (2005). Future aviation fuel growth rates are from Owen et al. (2010).We exploit the growth of GDP to project diesel oil growth for rail.

Tables S2, S3, S4, and S5 show the key information, assumptions, and major data sources of fuel consumption for on-road vehicles, shipping, aviation, and rail.

Table S2. Key information, assumptions and major data sources for on-road fuel consumption

Variable (unit)	Symbol [a]	Period	Data Source	Data Type	Flow/Product or calculation
Gasoline consumption (ktonne/year)	$FC_{IEA, gasoline, road, k}(t)$	1971-2005	IEA [b]	raw	ROAD/GASDIES
Diesel consumption (ktonne/year)	$FC_{IEA, diesel, road, k}(t)$	1971-2005	IEA [b]	raw	ROAD/MOTORGAS
Energy by transportation light liquid oil (PJ/year)	$FC_{IMAGE, LLO, trans, k, i}(t)$	2005-2050	IMAGE [c]	raw	Transportation/Light Liquid Oil
Energy by transportation heavy liquid oil (PJ/year)	$FC_{IMAGE, HFO, trans, k, i}(t)$	2005-2050	IMAGE [c]	raw	Transportation/Heavy Liquid Oil
Fuel consumption ratio of light-duty diesel and gasoline	$R_{d/g, k}$	constant	IEA/SMP [d]	raw	-
Gasoline consumption by light-duty vehicles (ktonne/year)	$FC_{gasoline, LD, k, i}(t)$	1971-2050	IEA; IMAGE	calculated	$FC_{gasoline,LD,k,i}(t)=\begin{cases} FC_{IEA,gasoline,road,k}(t) & (t \le 2005) \\ FC_{IMAGE,LLO,trans,k,i}(t)\times\frac{FC_{IEA,gasoline,road,k}(2005)}{FC_{IMAGE,LLO,trans,k,i}(2005)} & (t > 2005) \end{cases}$
Diesel consumption by light-duty vehicles (ktonne/year)	$FC_{diesel, LD, k, i}(t)$	1971-2050	IEA; IMAGE; IEA/SMP	calculated	$FC_{\text{diesel},LD,k,i}(t)=FC_{gasoline,LD,k,i}(t)\times R_{d/g,k}$
Diesel consumption by heavy-duty vehicles (ktonne/year)	$FC_{diesel, HD ,k ,i}(t)$	1971-2050		calculated	$FC_{diesel,HD,k,i}(t)=\begin{cases} FC_{IEA,diesel,road,k}(t) - FC_{diesel,LD,k,i}(t) & (t \le 2005) \\ FC_{IMAGE,HLO,trans,k,i}(t)\times\frac{FC_{IEA,diesel,road,k}(2005)}{FC_{IMAGE,HLO,trans,k,i}(2005)} - FC_{diesel,LD,k,i}(t) & (t > 2005) \end{cases}$

[a] FC = Fuel Consumption;. subscripts i, and k represent scenario (A1B, A2, B1, and B2), region (1-17); variable t represents calendar year
[b] IEA (2012a, b)
[c] RIVM (2001); MNP (2006)
[d] Fulton and Eads (2004)

Table S3. Key information, assumptions and major data sources for shipping fuel consumption.

Variable (unit)	**Symbol**[a]	**Period**	**Data Source**	**Data Type**	**Flow/Product or Calculation**
Marine distillate oil (MDO) by international marine bunkers (ktonne/year)	$FC_{IEA,MDO,int,k}(t)$	1971-2010	IEA[b]	raw	MARBUNK/GASDIES[e]
Marine distillate oil (MDO) by domestic navigation (ktonne/year)	$FC_{IEA,MDO,dom,k}(t)$	1971-2010	IEA[b]	raw	DOMESNAV/GASDIES[e]
Marine distillate oil (MDO) by fishing (ktonne/year)	$FC_{IEA,MDO,fishing,k}(t)$	1971-2010	IEA[b]	raw	FISHING/GASDIES[e]
Heavy (residual) fuel oil (HFO) by international marine bunkers (ktonne/year)	$FC_{IEA,HFO,int,k}(t)$	1971-2010	IEA[b]	raw	MARBUNK/RESFUEL+ other heavy fuel oil[e,]
Heavy (residual) fuel oil (HFO) by domestic navigation (ktonne/year)	$FC_{IEA,HFO,dom,k}(t)$	1971-2010	IEA[b]	raw	DOMESNAV/RESFUEL+ other heavy fuel oil[e]
Heavy (residual) fuel oil (HFO) by fishing (ktonne/year)	$FC_{IEA,HFO,fishing,k}(t)$	1971-2010	IEA[b]	raw	FISHING/RESFUEL+ other heavy fuel oil[e,f]
Global fuel consumption by shipping	$FC_{global,i}(t)$	1971-2050	IEA[b]; Eyring et al. (2005)	calculated	$FC_{global,i}(t)=\begin{cases}\sum_l\sum_m\sum_k FC_{IEA,l,m,k}(t) & (t\le 2010)\\ FC_{global,i}(2010)\times\beta_i(t) & (t>2010)\end{cases}$ [f]
Regional fuel growth rate	$\alpha_{l,m,k,i}(t)$	2011-2050	IEA\SMP[c]; IMAGE[d]	calculated	$\alpha_{l,m,k,i}(t)=\left(\frac{GDP_{k,i}(t)}{GDP_{k,i}(t-1)}-1\right)^{\gamma_{k,m}}+1$ [g]
Regional fraction of fuel consumption	$f_{l,m,k,i(t)}$	2011-2050	-	calculated	$f_{l,m,k,i}(t)=\frac{f_{l,m,k}(2010)\times\alpha_{l,m,k,i}(t)}{\sum_l\sum_m\sum_k f_{l,m,k}(2010)\times\alpha_{l,m,k,i}(t)}$
Regional fuel consumption (ktonne/year)	$FC_{l,m,k,i}(t)$	2011-2050	-	calculated	$FC_{l,m,k,i}(t)=FC_{global,i}(t)\times f_{l,m,k,i}(t)$

[a] FC = Fuel Consumption; int = international marine bunker (MARBUNK), dom = domestic navigation (DOMESNAV); subscripts i, k, l, and m represent scenario (A1B, A2, B1, and B2), region (1-17), fuel type (MDO and HFO), and shipping category (int, dom, and fishing); variable t represents calendar year.

[b] IEA (2012a, b)

[c] Fulton and Eads (2004)

[d] RIVM (2001); MNP (2006)

[e] The integration is the same as Bond et al. (2004); GASDIES and RESFUEL represent gas/diesel and fuel oil.

[f] β is annual growth rate for global fuel consumption from Eyring et al. (2005); it is distinguished by scenario and calendar year. For years 2011-2020, β is 2.08%, 1.65%, 1.94%, and 1.85% per year for A1B, A2, B1, and B2, respectively; for years 2021-2050, the values are 1.93%, 1.14%, 1.59%, and 1.40% per year, respectively.

[g] GDP = Gross Domestic Product, from IMAGE (RIVM, 2001; MNP, 2006);γ, taken from IEA\SMP model (Fulton and Eads, 2004), is elasticity and represents the relative growth rate of fuel consumption to GDP

Table S4. Key information, assumptions and major data sources for aviation fuel consumption.

Variable (unit)	Symbol[a]	Period	Data Source	Data Type	Flow/Product or Calculation
Aviation fuel consumption (ktonne/year)	$FC_{IEA,air,k}(t)$	1971-2010	IEA[b]	raw	DOMESAIR+AVBUNK/AVGAS+JETGAS+JETKERO[e]
Global fuel consumption by aviation (ktonne/year)	$FC_{IEA,air,k,i}(t)$	2011-2050	-	calculated	$FC_{global,i}(t)=\begin{cases}\sum_k FC_{IEA,air,k}(t) & (t\le 2010)\\ FC_{global,i}(2010)\times\beta_i(t) & (t>2010)\end{cases}$ [f]
Regional fuel growth rate	$\alpha_{air,k,i(t)}$	2011-2050	IEA\SMP[c]; IMAGE[d]	calculated	$\alpha_{air,k,i}(t)=\left[\left(\frac{GDP_{k,i}(t)}{GDP_{k,i}(t-1)}-1\right)^{\gamma_k}+1\right]\times(1+\mu)$ [g]
regional fraction of fuel consumption	$f_{air,k,i(t)}$	2011-2050	-	calculated	$f_{air,k,i}(t)=\frac{f_{air,k}(2010)\times\alpha_{air,k,i}(t)}{\sum_k f_{air,k}(2010)\times\alpha_{air,k,i}(t)}$
Regional fuel consumption (ktonne/year)	$FC_{air,k,i}(t)$	2011-2050	-	calculated	$FC_{air,k,i}(t)=FC_{global,i}(t)\times f_{air,k,i}(t)$

[a] FC = Fuel Consumption; Air = Aviation, including domestic air (DOMESAIR) and international aviation bunkers (International aviation bunkers); subscripts *i* and *k* represent scenario (A1B, A2, B1, and B2) and region (1-17); variable t represents calendar year.
[b] IEA (2012a, b)
[c] Fulton and Eads (2004)
[d] RIVM (2001); MNP (2006)
[e] The integration is the same as Bond et al. (2004); AVGAS, JETGAS, and JETKERO represent aviation gasoline, gasoline type jet fuel, and kerosene type jet fuel, respectively.
[f] β is an annual growth rate for global fuel consumption from Owen et al. (2010); it is distinguished by scenario and calendar year. For years 2011-2020, β is 3.55% per year for all the four scenarios; for years 2021-2050, the values are 2.78%, 1.12%, 0.79%, and 0.86% per year, for A1B, A2, B1, and B2, respectively.
[g] GDP = Gross Domestic Product, from IMAGE (RIVM, 2001; MNP, 2006);γ, taken from IEA\SMP model (Fulton and Eads, 2004), is elasticity and represents the relative growth rate of revenue passenger kilometers (RPK) to GDP; μ is the improvement rate of energy intensity, it is also taken from IEA\SMP model (Fulton and Eads, 2004)

Table S5. Key information, assumptions and major data sources for rail fuel consumption.

Variable (unit)	**Symbol**[a]	**Period**	**Data Source**	**Data Type**	**Flow/Product or Calculation**
Rail oil consumption (ktonne/year)	$FC_{IEA,rail,Oil,k}(t)$	1971-2010	IEA[b]	raw	RAIL/GASDIES+RESFUEL+ other heavy fuel oil[e]
Rail coal consumption (ktonne/year)	$FC_{IEA,rail,Coal,k}(t)$	1971-2010	IEA[b]	raw	RAIL/ANTCOAL + COKCOAL+ other kinds of coal[e]
Regional energy growth rate	$\alpha_{rail,m,k,i}(t)$	2011-2050	IEA\SMP[c]; IMAGE[d]	calculated	$\alpha_{rail,m,k,i}(t)=\left[\left(\frac{GDP_{k,i}(t)}{GDP_{k,i}(t-1)}-1\right)^{\gamma_{m,k}}+1\right]\times\left(1+\mu_{m,k}\right)$ [f]
Regional oil consumption (except East Asia) (ktonne/year)	$FC_{rail,Oil,k,i}(t)$	2011-2050	IEA\SMP[c]	calculated	$FC_{rail,Oil,k,i}(t)=FC_{IEA,rail,Oil,k}(2010)\times\alpha_{rail,k,i}$ [g] (where $\alpha_{rail,k,i}=f_{frt,k}\times\alpha_{rail,frt,k,i}+f_{pass,k}\times\alpha_{rail,pass,k,i}$)
East Asia oil and coal consumption (ktonne/year)	$FC_{rail,l,EastAsia,i}(t)$	2011-2050	-	calculated	$FC_{rail,l,EastAsia,i}(t)=\frac{\left(\sum_{l=coal,oil}FC_{IEA,rail,l,East(2010)}\times Q_l\right)\times\alpha_{rail,EastAsia,i}\times X_l(t)}{Q_l}$ [h]

[a] FC = Fuel Consumption; subscripts *i*, *k*, and *m* represent scenario (A1B, A2, B1, and B2), region (1-17), subgroup of railway (freight and passenger rail transport); variable t represents calendar year.
[b] IEA (2012a, 2012b)
[c] Fulton and Eads (2004)
[d] RIVM (2001); MNP (2006)
[e] The integration is the same as Bond et al. (2004); GASDIES, RESFUEL, ANTCOAL, and COKCOAL represent gas/diesel, fuel oil, anthracite, and coking coal, respectively.
[f] GDP = Gross Domestic Product, from IMAGE (RIVM, 2001; MNP, 2006); γ, taken from IEA\SMP model (Fulton and Eads, 2004), is elasticity and represents the relative growth rate of total passenger-km of travel for passenger rail or total tonne-km of travel for freight rail to GDP; μ is an improvement rate of energy intensity, it is also taken from IEA\SMP model (Fulton and Eads, 2004)
[g] f is the fraction of energy by passenger and freight rail, coming from IEA\SMP model; frt = freight, pass = passenger; middle distillate and residual fuel are treated in the same way, so that the growth rate of energy is also the growth rate of oil consumption
[h] *l* represents coal or oil; Q_l is energy content of coal or oil; $X_l(t)$ is the fraction of coal or oil in calendar year t, and estimated by transition curve in Bond et al. (2007):

$X_{coal}(t)=\left(X_{coal,0}-X_{coal,f}\right)e^{\left[-(t-t_0)^2/2s^2\right]}+X_{coal,f}$, where X_0 and X_f are the initial and final values of the energy fraction by coal; t_0 is the time at which the transition begins, and *s* is the rate. Here $X_{coal,0}=0.65$, $X_{coal,f}=0$, $t_0=2010$, and s = 12 years. Then $X_{oil}(t)=1-X_{coal}(t)$.

S.3. Timing of emission standards

Two emission standards sequences—"Tier" in the U.S., and "Euro" in Europe—capture most of the regulatory transitions observed around the world. The coefficients of GDP per capita were found in Yan et al. (2011) to be not significant in the study of Cox proportional-hazard regression (Cox, 1972) if only technology-following countries were included, and were only significant if the technology-forcing countries were included. Therefore, an empirical method is applied to estimate the implementation dates of standards in different world regions for past and future years. Tables S6, S7, and S8 show the detailed assumptions and projected adoption dates of emission standards.

Table S6. Assumptions for regional adoption dates of emission standards.

Regions	Description	Assumptions
Canada, U.S. , Former USSR, South Asia, East Asia, Japan, Oceania	Regions in which a single country has the highest population	Use the dominant country to provide the timing of standard implementation
Middle East, Southeast Asia, South America, and Eastern Europe	Regions which are quite heterogeneous in terms of standard adoption	Use the average of the implementation year in each country to represent the region
Central America, Northern Africa, Southern Africa	Regions which contain large countries that committed to standard implementation shortly after 2000, but the remaining countries in the region have not committed to such standards even now.	Use the average implementation timing that is the leading country plus 10 years
Eastern Africa and Western Africa	Regions which have no current plans for standards	Assume that they will adopt standards when they reach a level of GDP per capita similar to the average of other technology-following world regions

Table S7. Emission standards adoption dates for light-duty vehicles in different regions under scenario A1B.

Region Name	Euro I [Tier 1][a]	Euro II [Tier 2-2004][a]	Euro III [Tier 2-2006][a]	Euro IV [Tier 2-2007][a]	Euro V	Euro VI
Canada	[1994]	[2004]	[2006]	[2007]	-	-
U.S.	[1994]	[2004]	[2006]	[2007]	-	-
Central America	2011	2017	2019	2022	2026	2031
South America	-	2004	2007	2009	2013	2018
Northern Africa	-	2012	2016	2019	2023	2028
Western Africa	2047	2052	2056	2059	2063	2068
Eastern Africa	2048	2053	2057	2060	2064	2069
Southern Africa	2015	2018	2022	2025	2029	2034
OECD Europe	1992	1996	2000	2005	2009	2014
Eastern Europe	1996	200	2005	2008	2012	2017
Former USSR	1999	2006	2008	2014	2018	2023
Middle East	2001	2005	2007	2009	2013	2018
South Asia	2000	2005	2010	2013	2017	2022
East Asia	2000	2003	2007	2010	2014	2019
Southeast Asia	1998	2003	2006	2012	2016	202
Oceania	1995	2002	2005	2006	2010	2015
Japan	1997	-	2002	2005	2009	2014

[a] Standards in [] are U.S. standards and years in [] are corresponding timing for adoption of U.S. standards.

Table S8. Emission standards adoption dates for heavy-duty vehicles in different regions under scenario A1B.

Region Name	Euro I [HDSTD88]	Euro II [HDSTD91]	Euro III [HDSTD93]	Euro IV [HDSTD94]	Euro V [HDSTD96]	Euro VI [HDSTD98]	[HDSTD04]	[HDSTD07]	[HDST10]
Canada	[1988]	[1991]	[1993]	[1994]	[1996]	[1998]	[2004]	[2007]	[2010]
U.S.	[1988]	[1991]	[1993]	[1994]	[1996]	[1998]	[2004]	[2007]	[2010]
Central America	-	[2003]	2013	2018	2021	2026	-	-	
South America	1995	2000	2005	2008	2011	2016	-	-	
Northern Africa	-	2016	2020	2024	2027	2032	-	-	
Western Africa	2047	2051	2055	2059	2062	2067	-	-	
Eastern Africa	2052	2056	2060	2064	2067	2072	-	-	
Southern Africa	-	2020	2024	2028	2031	2036	-	-	
OECD Europe	1992	1996	2000	2005	2008	2013	-	-	
Eastern Europe	1995	1999	2003	2007	2010	2015	-	-	
Former USSR	1999	2006	2008	2014	2017	2022	-	-	
Middle East	2001	2005	2009	2013	2016	2021	-	-	
South Asia	2000	2005	2010	2014	2017	2022	-	-	
East Asia	2000	2003	2008	2010	2012	2017	-	-	
Southeast Asia	1999	2005	2009	2013	2016	2021	-	-	
Oceania	1995	2000	2002	2007	2010	2015	-	-	
Japan	1995	1997	-	2003	2005	2009	-	-	

[a] Standards in [] are U.S. standards and years in [] are corresponding timing for adoption of U.S. standards.

S.4. Emission intensity of CO and THC for non-road engines

CO and THC emissions are constantly increasing from non-road engines, 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. Tables S9 and S10 provide regional emission intensities of CO and THC for non-road engines. While regional emission intensity for gasoline or diesel engines decreases with time, overall emission intensity, which largely depends on the ratio between gasoline and diesel, may not decrease.

Table S9. Emission Intensity (g/kg-fuel) of CO for non-road engines under scenario A1B

Year	North America	Latin America	Africa	Middle East	Europe	Former USSR	South Asia	East Asia	Southeast Asia	Pacific
					Gasoline					
2010	589	902	932	917	713	854	861	893	877	732
2030	500	707	969	758	482	712	623	653	730	543
2050	502	77	808	581	472	553	554	565	578	527
					Diesel					
2010	15	27	27	27	23	31	28	26	28	23
2030	8	20	28	24	11	19	12	14	19	13
2050	7	11	20	13	9	12	10	10	11	9
					Overall					
2010	117	97	236	41	170	170	166	166	151	142
2030	97	121	226	52	134	317	196	207	156	116
2050	94	101	166	47	114	291	265	276	137	108

Table S10. Emission Intensity (g/kg-fuel) of THC for non-road engines under scenario A1B.

Year	North America	Latin America	Africa	Middle East	Europe	Former USSR	South Asia	East Asia	Southeast Asia	Pacific
					Gasoline					
2010	39	138	159	139	35	114	117	127	123	65
2030	33	84	159	82	24	74	70	75	79	45
2050	37	77	110	74	25	67	67	70	73	48
					Diesel					
2010	3	7	7	7	5	7	8	7	8	6
2030	1	4	8	5	1	4	2	2	4	2
2050	1	1	4	2	1	1	1	1	1	1
					Overall					
2010	9	18	42	9	11	25	25	26	24	15
2030	7	16	39	8	7	34	22	24	18	10
2050	7	13	24	6	6	35	32	34	17	10

S.5 Regional emission projections and fuel consumption

In the main content, Fig. 2 shows the estimated global emission consumption and emissions. In this supplement, Tables S11, S12, S13, S14, and S15 show regional emission projections in years 2010, 2030, and 2050 under scenarios A1B, A2, B1, and B2. Table S16 shows fuel consumption by region and by mode in years 2010, 2030, and 2050 under four scenarios. This table is consistent with the information in the right panel of Fig. 2.

Table S11. CO emission projections for different regions in years 2010, 2030, and 2050 (Unit: Tg/year).

Region	2010	2030				2050			
		A1B	A2	B1	B2	A1B	A2	B1	B2
Canada	1.84	1.68	1.52	1.38	1.30	1.66	1.59	1.18	1.00
U. S.	11.4	11.3	9.19	9.63	8.19	10.7	8.36	7.64	5.71
Central America	14.5	5.51	4.88	4.76	4.21	4.42	4.02	3.31	2.25
South America	11.0	5.67	5.17	4.86	4.43	5.15	4.97	4.06	2.98
Northern Africa	8.00	5.77	5.18	5.51	4.91	5.97	4.53	4.68	3.64
Western Africa	7.24	21.4	15.0	18.2	13.7	33.5	21.2	24.8	14.7
Eastern Africa	0.89	3.42	2.17	2.98	2.04	10.4	5.35	7.46	3.57
Southern Africa	6.38	4.08	3.18	3.55	3.12	2.93	1.81	2.07	1.47
OECD Europe	9.31	7.55	7.09	6.20	5.96	6.79	7.19	4.99	4.06
Eastern Europe	2.21	1.67	1.09	1.20	1.17	1.44	1.08	1.03	0.86
Former USSR	10.6	14.1	9.39	8.58	9.39	12.5	8.74	7.11	7.68
Middle East	11.5	6.73	6.24	5.72	5.30	8.26	8.43	5.57	5.53
South Asia	6.84	15.1	8.99	11.9	13.0	29.2	15.3	17.8	16.5
East Asia	20.5	20.7	12.9	17.6	17.5	22.2	11.0	15.3	16.7
Southeast Asia	11.0	10.0	6.67	7.78	7.77	10.7	7.14	7.24	6.49
Oceania	1.46	1.11	0.83	0.92	0.79	0.98	0.73	0.72	0.60
Japan	2.19	1.81	1.58	1.49	1.50	1.57	1.34	1.15	1.01
Total	137	138	101	112	104	168	113	116	95

Table S12. NO_x emission projections for different regions in years 2010, 2030, and 2050 (Unit: Tg/year).

Region	2010	2030				2050			
		A1B	A2	B1	B2	A1B	A2	B1	B2
Canada	0.80	0.52	0.47	0.46	0.46	0.58	0.46	0.43	0.41
U. S.	5.89	4.65	4.13	4.09	3.99	5.69	4.38	3.95	3.87
Central America	2.78	1.99	1.81	1.81	1.61	1.93	1.59	1.59	1.26
South America	4.45	3.21	3.01	2.92	2.77	3.39	2.82	2.78	2.31
Northern Africa	1.67	2.11	1.75	1.89	1.57	2.07	1.45	1.50	1.13
Western Africa	1.02	2.86	2.06	2.47	1.90	5.15	3.33	3.86	2.34
Eastern Africa	0.26	0.95	0.61	0.83	0.58	2.89	1.47	2.06	1.01
Southern Africa	1.22	1.63	1.26	1.44	1.21	1.48	0.96	1.13	0.90
OECD Europe	8.50	6.30	5.76	5.76	5.55	7.24	5.90	5.76	5.40
Eastern Europe	1.23	1.02	0.75	0.80	0.79	0.99	0.70	0.73	0.67
Former USSR	2.84	2.52	1.85	1.90	1.90	2.33	1.61	1.60	1.58
Middle East	5.49	4.86	4.59	4.48	4.15	5.78	5.03	4.60	4.09
South Asia	2.74	2.76	1.86	2.26	2.38	3.43	1.76	2.43	2.18
East Asia	8.71	9.81	7.41	8.46	8.81	12.3	7.59	9.24	9.48
Southeast Asia	6.31	6.82	5.56	5.97	6.25	8.23	5.85	6.59	6.69
Oceania	0.72	0.54	0.47	0.47	0.46	0.54	0.42	0.38	0.38
Japan	1.46	0.96	0.90	0.88	0.87	1.09	0.91	0.85	0.84
Total	56.1	53.5	44.2	46.9	45.2	65.1	46.2	49.5	44.5

Table S13. THC emission projections for different regions in years 2010, 2030, and 2050 (Unit: Tg/year).

Region	2010	2030				2050			
		A1B	A2	B1	B2	A1B	A2	B1	B2
Canada	0.19	0.16	0.14	0.13	0.13	0.17	0.14	0.12	0.11
U. S.	1.08	1.09	0.88	0.94	0.83	1.17	0.82	0.87	0.67
Central America	2.01	0.77	0.70	0.68	0.61	0.69	0.62	0.54	0.39
South America	1.64	0.85	0.78	0.74	0.69	0.83	0.76	0.67	0.51
Northern Africa	1.13	0.98	0.89	0.95	0.84	0.88	0.69	0.71	0.57
Western Africa	0.76	2.25	1.59	1.92	1.46	3.65	2.32	2.72	1.62
Eastern Africa	0.11	0.43	0.28	0.38	0.26	1.32	0.69	0.95	0.46
Southern Africa	0.72	0.58	0.45	0.51	0.45	0.44	0.28	0.33	0.24
OECD Europe	1.20	0.97	0.87	0.85	0.80	1.01	0.88	0.81	0.68
Eastern Europe	0.34	0.25	0.17	0.19	0.19	0.23	0.17	0.17	0.14
Former USSR	1.45	1.69	1.14	1.07	1.15	1.65	1.15	0.97	1.03
Middle East	1.77	1.10	1.03	0.97	0.91	1.37	1.32	0.98	0.94
South Asia	1.10	1.89	1.14	1.50	1.62	3.76	1.97	2.33	2.15
East Asia	3.09	3.18	2.12	2.72	2.76	3.64	1.96	2.62	2.79
Southeast Asia	1.75	1.63	1.18	1.33	1.35	1.92	1.31	1.40	1.31
Oceania	0.22	0.16	0.12	0.14	0.12	0.14	0.11	0.11	0.09
Japan	0.26	0.20	0.17	0.17	0.17	0.20	0.16	0.16	0.14
Total	18.8	18.2	13.6	15.2	14.3	23.1	15.3	16.5	13.8

Table S14. PM emission projections for different regions in years 2010, 2030, and 2050 (Unit: Tg/year).

Region	2010	2030				2050			
		A1B	A2	B1	B2	A1B	A2	B1	B2
Canada	0.06	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
U. S.	0.33	0.25	0.23	0.24	0.23	0.30	0.24	0.25	0.23
Central America	0.16	0.15	0.14	0.14	0.13	0.15	0.13	0.13	0.11
South America	0.35	0.25	0.24	0.24	0.23	0.25	0.22	0.22	0.18
Northern Africa	0.16	0.20	0.17	0.18	0.16	0.15	0.12	0.12	0.10
Western Africa	0.06	0.15	0.12	0.14	0.11	0.32	0.20	0.24	0.15
Eastern Africa	0.02	0.09	0.06	0.08	0.05	0.27	0.14	0.20	0.10
Southern Africa	0.09	0.14	0.11	0.13	0.11	0.12	0.08	0.09	0.08
OECD Europe	0.54	0.45	0.42	0.43	0.41	0.52	0.44	0.47	0.42
Eastern Europe	0.10	0.07	0.05	0.06	0.05	0.06	0.04	0.05	0.04
Former USSR	0.25	0.21	0.16	0.16	0.16	0.18	0.12	0.12	0.12
Middle East	0.44	0.40	0.38	0.38	0.35	0.43	0.37	0.37	0.32
South Asia	0.29	0.28	0.19	0.24	0.25	0.41	0.21	0.28	0.25
East Asia	0.82	0.96	0.71	0.85	0.87	0.91	0.57	0.73	0.74
Southeast Asia	0.55	0.61	0.51	0.55	0.57	0.73	0.52	0.62	0.62
Oceania	0.06	0.04	0.03	0.04	0.03	0.03	0.02	0.03	0.02
Japan	0.10	0.07	0.07	0.07	0.06	0.08	0.07	0.07	0.07
Total	4.37	4.36	3.62	3.93	3.80	4.94	3.53	4.02	3.58

Table S15. BC emission projections for different regions in years 2010, 2030, and 2050 (Unit: Gg/year).

Region	2010	2030				2050			
		A1B	A2	B1	B2	A1B	A2	B1	B2
Canada	23	10	8	9	8	9	7	7	6
U. S.	113	67	52	58	52	75	51	57	44
Central America	61	56	52	50	47	48	41	39	29
South America	152	100	95	90	88	84	72	67	55
Northern Africa	75	95	83	88	76	84	60	63	48
Western Africa	25	72	52	63	48	149	94	111	67
Eastern Africa	12	46	30	41	29	149	76	108	53
Southern Africa	38	62	49	55	48	51	31	37	30
OECD Europe	151	89	73	78	73	96	73	78	64
Eastern Europe	46	34	25	27	27	28	20	21	18
Former USSR	116	88	64	64	66	62	44	41	41
Middle East	170	140	134	127	121	133	123	100	93
South Asia	139	124	87	104	109	161	82	112	99
East Asia	265	283	208	244	253	179	114	129	135
Southeast Asia	171	154	125	132	138	146	101	110	107
Oceania	24	16	13	14	13	11	8	9	8
Japan	27	11	10	10	10	13	10	10	9
Total	1608	1447	1160	1254	1206	1478	1005	1100	906

Table S16. OC emission projections for different regions in years 2010, 2030, and 2050 (Unit: Gg/year).

Region	2010	2030				2050			
		A1B	A2	B1	B2	A1B	A2	B1	B2
Canada	17	8	7	7	7	7	6	6	5
U. S.	74	48	42	44	41	53	41	43	37
Central America	35	34	32	31	29	32	29	27	23
South America	74	59	57	54	52	51	46	43	35
Northern Africa	42	52	47	50	44	51	40	42	34
Western Africa	12	32	24	28	22	66	42	50	31
Eastern Africa	5	17	12	15	11	54	29	39	20
Southern Africa	17	28	22	25	22	27	16	20	17
OECD Europe	90	64	58	59	56	68	59	59	52
Eastern Europe	22	16	12	13	13	12	9	9	8
Former USSR	69	82	57	55	58	67	47	39	42
Middle East	83	76	73	71	67	72	66	59	53
South Asia	72	118	75	98	103	211	107	140	127
East Asia	160	259	178	227	233	188	104	143	151
Southeast Asia	97	110	87	96	98	118	83	93	91
Oceania	15	12	10	11	10	9	7	8	7
Japan	18	10	9	9	9	11	9	9	9
Total	902	1025	803	894	876	1097	740	830	740

Table S17. Fuel consumption (unit: Pg yr^{-1}) by region and transport mode under four scenarios (A1B, A2, B1, and B2) in years 2010, 2030, and 2050

Year	Variable	Region	Mode	Scenarios			
				A1B	A2	B1	B2
2010	Fuel	North America	On-road	0.557	0.550	0.541	0.542
2010	Fuel	North America	Off-road	0.045	0.045	0.045	0.045
2010	Fuel	North America	Shipping	0.030	0.030	0.030	0.030
2010	Fuel	North America	Aviation	0.072	0.072	0.072	0.072
2010	Fuel	North America	Rail	0.010	0.010	0.010	0.010
2010	Fuel	Latin America	On-road	0.164	0.160	0.157	0.154
2010	Fuel	Latin America	Off-road	0.023	0.023	0.023	0.023
2010	Fuel	Latin America	Shipping	0.020	0.020	0.020	0.020
2010	Fuel	Latin America	Aviation	0.014	0.014	0.014	0.014
2010	Fuel	Latin America	Rail	0.002	0.002	0.002	0.002
2010	Fuel	Africa	On-road	0.071	0.067	0.069	0.066
2010	Fuel	Africa	Off-road	0.015	0.015	0.015	0.015
2010	Fuel	Africa	Shipping	0.006	0.006	0.006	0.006
2010	Fuel	Africa	Aviation	0.009	0.009	0.009	0.009
2010	Fuel	Africa	Rail	0.000	0.000	0.000	0.000
2010	Fuel	Europe	On-road	0.333	0.316	0.319	0.315
2010	Fuel	Europe	Off-road	0.029	0.029	0.029	0.029
2010	Fuel	Europe	Shipping	0.061	0.061	0.061	0.061
2010	Fuel	Europe	Aviation	0.050	0.050	0.050	0.050
2010	Fuel	Europe	Rail	0.003	0.003	0.003	0.003
2010	Fuel	Former USSR	On-road	0.074	0.065	0.067	0.064
2010	Fuel	Former USSR	Off-road	0.020	0.020	0.020	0.020
2010	Fuel	Former USSR	Shipping	0.004	0.004	0.004	0.004
2010	Fuel	Former USSR	Aviation	0.013	0.013	0.013	0.013
2010	Fuel	Former USSR	Rail	0.002	0.002	0.002	0.002
2010	Fuel	Middle East	On-road	0.123	0.120	0.120	0.117

2010	Fuel	Middle East	Off-road	0.019	0.019	0.019	0.019
2010	Fuel	Middle East	Shipping	0.023	0.023	0.023	0.023
2010	Fuel	Middle East	Aviation	0.014	0.014	0.014	0.014
2010	Fuel	Middle East	Rail	0.000	0.000	0.000	0.000
2010	Fuel	South Asia	On-road	0.052	0.045	0.047	0.050
2010	Fuel	South Asia	Off-road	0.021	0.021	0.021	0.021
2010	Fuel	South Asia	Shipping	0.002	0.002	0.002	0.002
2010	Fuel	South Asia	Aviation	0.006	0.006	0.006	0.006
2010	Fuel	South Asia	Rail	0.003	0.003	0.003	0.003
2010	Fuel	East Asia	On-road	0.138	0.124	0.125	0.134
2010	Fuel	East Asia	Off-road	0.043	0.043	0.043	0.043
2010	Fuel	East Asia	Shipping	0.050	0.050	0.050	0.050
2010	Fuel	East Asia	Aviation	0.028	0.028	0.028	0.028
2010	Fuel	East Asia	Rail	0.012	0.012	0.012	0.012
2010	Fuel	Southeast Asia	On-road	0.088	0.080	0.080	0.087
2010	Fuel	Southeast Asia	Off-road	0.022	0.022	0.022	0.022
2010	Fuel	Southeast Asia	Shipping	0.046	0.046	0.046	0.046
2010	Fuel	Southeast Asia	Aviation	0.017	0.017	0.017	0.017
2010	Fuel	Southeast Asia	Rail	0.000	0.000	0.000	0.000
2010	Fuel	Pacific	On-road	0.101	0.098	0.098	0.097
2010	Fuel	Pacific	Off-road	0.013	0.013	0.013	0.013
2010	Fuel	Pacific	Shipping	0.011	0.011	0.011	0.011
2010	Fuel	Pacific	Aviation	0.014	0.014	0.014	0.014
2010	Fuel	Pacific	Rail	0.001	0.001	0.001	0.001
2010	Fuel	Global	On-road	1.701	1.625	1.623	1.626
2010	Fuel	Global	Off-road	0.251	0.250	0.250	0.251
2010	Fuel	Global	Shipping	0.252	0.252	0.252	0.252
2010	Fuel	Global	Aviation	0.237	0.237	0.237	0.237
2010	Fuel	Global	Rail	0.034	0.034	0.034	0.034
2030	Fuel	North America	On-road	0.534	0.472	0.447	0.363
2030	Fuel	North America	Off-road	0.053	0.051	0.045	0.048

2030	Fuel	North America	Shipping	0.036	0.035	0.035	0.034
2030	Fuel	North America	Aviation	0.131	0.112	0.108	0.109
2030	Fuel	North America	Rail	0.016	0.014	0.015	0.014
2030	Fuel	Latin America	On-road	0.326	0.268	0.279	0.208
2030	Fuel	Latin America	Off-road	0.027	0.030	0.024	0.025
2030	Fuel	Latin America	Shipping	0.031	0.029	0.031	0.027
2030	Fuel	Latin America	Aviation	0.027	0.023	0.022	0.022
2030	Fuel	Latin America	Rail	0.003	0.003	0.003	0.003
2030	Fuel	Africa	On-road	0.218	0.153	0.182	0.135
2030	Fuel	Africa	Off-road	0.021	0.018	0.020	0.017
2030	Fuel	Africa	Shipping	0.010	0.009	0.010	0.009
2030	Fuel	Africa	Aviation	0.017	0.015	0.014	0.014
2030	Fuel	Africa	Rail	0.001	0.001	0.001	0.001
2030	Fuel	Europe	On-road	0.446	0.357	0.355	0.317
2030	Fuel	Europe	Off-road	0.028	0.028	0.023	0.024
2030	Fuel	Europe	Shipping	0.075	0.072	0.073	0.070
2030	Fuel	Europe	Aviation	0.092	0.079	0.076	0.076
2030	Fuel	Europe	Rail	0.005	0.004	0.005	0.004
2030	Fuel	Former USSR	On-road	0.200	0.113	0.130	0.124
2030	Fuel	Former USSR	Off-road	0.029	0.021	0.018	0.021
2030	Fuel	Former USSR	Shipping	0.007	0.005	0.006	0.006
2030	Fuel	Former USSR	Aviation	0.025	0.021	0.021	0.021
2030	Fuel	Former USSR	Rail	0.006	0.004	0.005	0.005
2030	Fuel	Middle East	On-road	0.272	0.244	0.219	0.190
2030	Fuel	Middle East	Off-road	0.022	0.023	0.022	0.020
2030	Fuel	Middle East	Shipping	0.035	0.033	0.035	0.031
2030	Fuel	Middle East	Aviation	0.027	0.023	0.023	0.022
2030	Fuel	Middle East	Rail	0.000	0.000	0.000	0.000
2030	Fuel	South Asia	On-road	0.143	0.077	0.099	0.102
2030	Fuel	South Asia	Off-road	0.063	0.035	0.048	0.055
2030	Fuel	South Asia	Shipping	0.005	0.003	0.005	0.004

2030	Fuel	South Asia	Aviation	0.012	0.010	0.010	0.010
2030	Fuel	South Asia	Rail	0.010	0.006	0.009	0.008
2030	Fuel	East Asia	On-road	0.274	0.158	0.174	0.198
2030	Fuel	East Asia	Off-road	0.066	0.041	0.058	0.061
2030	Fuel	East Asia	Shipping	0.088	0.068	0.079	0.081
2030	Fuel	East Asia	Aviation	0.052	0.044	0.043	0.043
2030	Fuel	East Asia	Rail	0.042	0.026	0.035	0.037
2030	Fuel	Southeast Asia	On-road	0.191	0.114	0.128	0.140
2030	Fuel	Southeast Asia	Off-road	0.034	0.024	0.028	0.029
2030	Fuel	Southeast Asia	Shipping	0.075	0.063	0.070	0.072
2030	Fuel	Southeast Asia	Aviation	0.032	0.027	0.026	0.026
2030	Fuel	Southeast Asia	Rail	0.001	0.000	0.000	0.000
2030	Fuel	Pacific	On-road	0.105	0.095	0.086	0.082
2030	Fuel	Pacific	Off-road	0.012	0.011	0.010	0.010
2030	Fuel	Pacific	Shipping	0.013	0.013	0.013	0.013
2030	Fuel	Pacific	Aviation	0.026	0.023	0.022	0.022
2030	Fuel	Pacific	Rail	0.001	0.001	0.001	0.001
2030	Fuel	Global	On-road	2.708	2.052	2.099	1.859
2030	Fuel	Global	Off-road	0.355	0.280	0.294	0.308
2030	Fuel	Global	Shipping	0.375	0.332	0.357	0.348
2030	Fuel	Global	Aviation	0.442	0.376	0.364	0.366
2030	Fuel	Global	Rail	0.085	0.059	0.075	0.075
2050	Fuel	North America	On-road	0.401	0.405	0.275	0.215
2050	Fuel	North America	Off-road	0.052	0.050	0.037	0.038
2050	Fuel	North America	Shipping	0.045	0.041	0.041	0.040
2050	Fuel	North America	Aviation	0.229	0.141	0.127	0.130
2050	Fuel	North America	Rail	0.024	0.019	0.020	0.019
2050	Fuel	Latin America	On-road	0.313	0.287	0.242	0.145
2050	Fuel	Latin America	Off-road	0.025	0.030	0.019	0.020
2050	Fuel	Latin America	Shipping	0.048	0.039	0.045	0.037
2050	Fuel	Latin America	Aviation	0.046	0.028	0.025	0.026

2050	Fuel	Latin America	Rail	0.006	0.005	0.006	0.005
2050	Fuel	Africa	On-road	0.434	0.288	0.302	0.171
2050	Fuel	Africa	Off-road	0.033	0.020	0.023	0.017
2050	Fuel	Africa	Shipping	0.018	0.014	0.017	0.014
2050	Fuel	Africa	Aviation	0.030	0.018	0.017	0.017
2050	Fuel	Africa	Rail	0.003	0.002	0.003	0.002
2050	Fuel	Europe	On-road	0.339	0.329	0.254	0.197
2050	Fuel	Europe	Off-road	0.025	0.026	0.020	0.019
2050	Fuel	Europe	Shipping	0.093	0.080	0.086	0.080
2050	Fuel	Europe	Aviation	0.161	0.098	0.089	0.091
2050	Fuel	Europe	Rail	0.008	0.005	0.007	0.006
2050	Fuel	Former USSR	On-road	0.199	0.142	0.130	0.133
2050	Fuel	Former USSR	Off-road	0.026	0.019	0.015	0.017
2050	Fuel	Former USSR	Shipping	0.012	0.008	0.010	0.009
2050	Fuel	Former USSR	Aviation	0.043	0.026	0.024	0.025
2050	Fuel	Former USSR	Rail	0.014	0.007	0.011	0.009
2050	Fuel	Middle East	On-road	0.352	0.392	0.235	0.226
2050	Fuel	Middle East	Off-road	0.015	0.017	0.014	0.014
2050	Fuel	Middle East	Shipping	0.057	0.046	0.053	0.043
2050	Fuel	Middle East	Aviation	0.047	0.029	0.026	0.027
2050	Fuel	Middle East	Rail	0.001	0.001	0.001	0.001
2050	Fuel	South Asia	On-road	0.219	0.119	0.136	0.107
2050	Fuel	South Asia	Off-road	0.092	0.043	0.051	0.056
2050	Fuel	South Asia	Shipping	0.010	0.005	0.009	0.007
2050	Fuel	South Asia	Aviation	0.021	0.013	0.012	0.012
2050	Fuel	South Asia	Rail	0.024	0.010	0.020	0.016
2050	Fuel	East Asia	On-road	0.285	0.188	0.158	0.161
2050	Fuel	East Asia	Off-road	0.052	0.027	0.037	0.047
2050	Fuel	East Asia	Shipping	0.135	0.086	0.112	0.112
2050	Fuel	East Asia	Aviation	0.089	0.055	0.050	0.051
2050	Fuel	East Asia	Rail	0.089	0.042	0.067	0.068

2050	Fuel	Southeast Asia	On-road	0.224	0.151	0.137	0.128
2050	Fuel	Southeast Asia	Off-road	0.036	0.027	0.026	0.028
2050	Fuel	Southeast Asia	Shipping	0.115	0.083	0.101	0.103
2050	Fuel	Southeast Asia	Aviation	0.055	0.033	0.030	0.031
2050	Fuel	Southeast Asia	Rail	0.001	0.001	0.001	0.001
2050	Fuel	Pacific	On-road	0.074	0.078	0.055	0.048
2050	Fuel	Pacific	Off-road	0.010	0.009	0.007	0.008
2050	Fuel	Pacific	Shipping	0.016	0.014	0.015	0.014
2050	Fuel	Pacific	Aviation	0.046	0.028	0.025	0.026
2050	Fuel	Pacific	Rail	0.002	0.002	0.002	0.002
2050	Fuel	Global	On-road	2.841	2.379	1.925	1.530
2050	Fuel	Global	Off-road	0.367	0.268	0.248	0.264
2050	Fuel	Global	Shipping	0.549	0.416	0.489	0.460
2050	Fuel	Global	Aviation	0.766	0.469	0.426	0.435
2050	Fuel	Global	Rail	0.171	0.092	0.139	0.128

S.6 Assumption details

Retirement rates depend on regional income rates and on-road vehicle age or non-road engine cumulative service hours. Retirement rate can be converted from survival rate by the function shown in the footnote of Table 1. Fig. S1 (a) shows two examples of survival rate for HDDVs in the U.S. and South Asia. It shows that survival rate of vehicles decreases with vehicle age. It also shows the rate at different income levels. U.S. has lower survival rates than South Asia. In the U.S., because the price of new vehicles is low relative to the income level, people can afford new cars and old ones are replaced more quickly.

Based on our assumption of transition rate, in each calendar year the remaining normal vehicles of all model years have the possibility to develop to superemitters, depending on their ages. Fig. S1(b) shows the pattern of superemitter transition rate, which represents the rate at which normal vehicles become superemitters. Fig. S2 shows equilibrium superemitter fractions of HDDVs in different regions between 2010 and 2050. The number of superemitters in the vehicle fleet at a given time, like any component of the vehicle population, depends on the balance between introduction and retirement. Based on our assumptions about transition rate, in each calendar year some fraction of vehicles of all model years has the possibility to develop into superemitters, depending on their ages. This determines the rate of introduction of superemitters into the vehicle fleet. And, just like for normal vehicles, superemitters retire from the fleet at a rate determined by regional income level and vehicle age. Thus, the number of existing superemitters in a given year depends on the survived superemitters from the previous year, as well the introduction and retirement of superemitters in the study year. We use a term called “equilibrium superemitter fraction” to represent the total contribution of superemitters in all model years, no matter which emission standards they originally come from.

Fig. S1(c) presents an example of PM emission factor degradation for on-road LDDV under the Euro I standard, showing three phases: new engine (constant), degradation (increasing linearly), and stabilized (maintaining constant at the maximum level). Fig. S1 (c) also shows a similar example of emission degradation for non-road agricultural medium diesel engine with Stage I standard. The degradation curve for non-road engine also has three patterns: first, increasing slowly to emission standard level, then increasing to maximal level, and finally flattening out.

The interplay among degradation rate, retirement rate, and timing of new emissions standards varies among regions and therefore leads to regionally differentiated average emission factors in any given year, as shown in Fig. S1(d), which presents average PM emission factors of all LDDVs following Euro I standards in OECD Europe and East Asia, excluding superemitters.

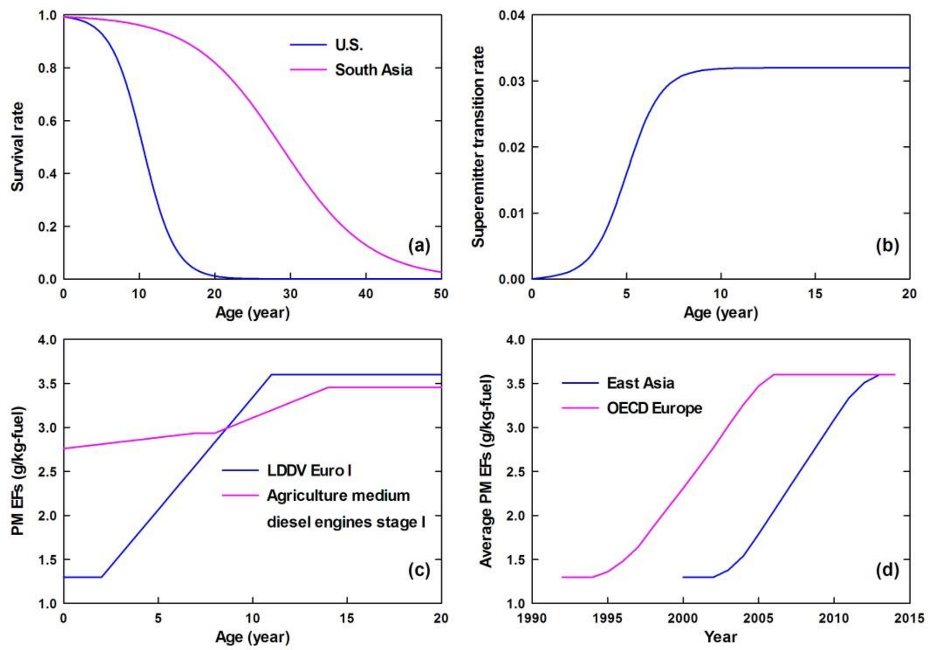


Fig. S1. (a) Survival rate of HDDVs in the U.S. (rgdp = 4.11) and South Asia (rgdp = 0.27) in year 2030 under scenario A1B; (b) superemitter transition rate; (3) degradation of emission factors for LDDV Euro I and agriculture medium diesel engines Stage I; (d).average PM emission factors (unit: g/kg-fuel) of all LDDVs following Euro I standards in OECD Europe and East Asia, excluding superemitters.

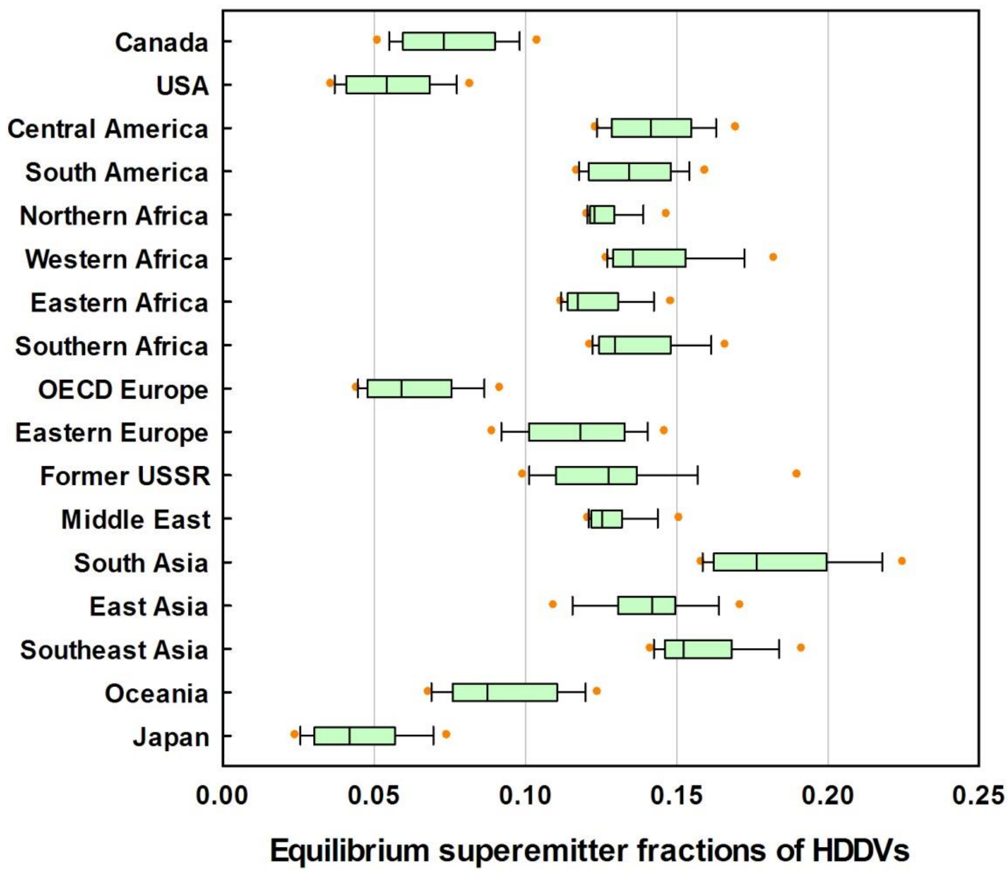


Fig. S2. Equilibrium superemitter fractions of HDDVs in different regions between 2010 and 2050. The two dots outside of the box refer to 5th and 95th percentiles, the two whiskers refer to 10th and 90th percentiles, the two edges of the box refer to 25th and 75th percentiles, and the line inside the box refers to median.

S.7 Additional results

The middle panel of Fig. 2 presents fuel consumption and emissions by transport mode under scenario A1B; these depictions for the other three scenarios are shown in Fig. S3.

Fig. S4 shows the contributions of LDGVs, LDDVs, and HDDVs to fuel consumption, and emissions of CO, NO_x, THC, and PM under scenario A1B. Of all the CO and THC emissions from on-road vehicles, LDGVs contribute over 80%. Though HDDVs consume less than half of the total on-road fuel, they dominate emissions of NO_x and PM from on-road vehicles and lead to 60-80% and 80-90% of the total, respectively.

The right panel of Fig. 2 presents the fractions of each transportation mode in 10 regrouped world regions, as well as regional contribution to the global emissions in year 2050 under scenario A1B. Regional estimates in other years are shown in Fig. S5.

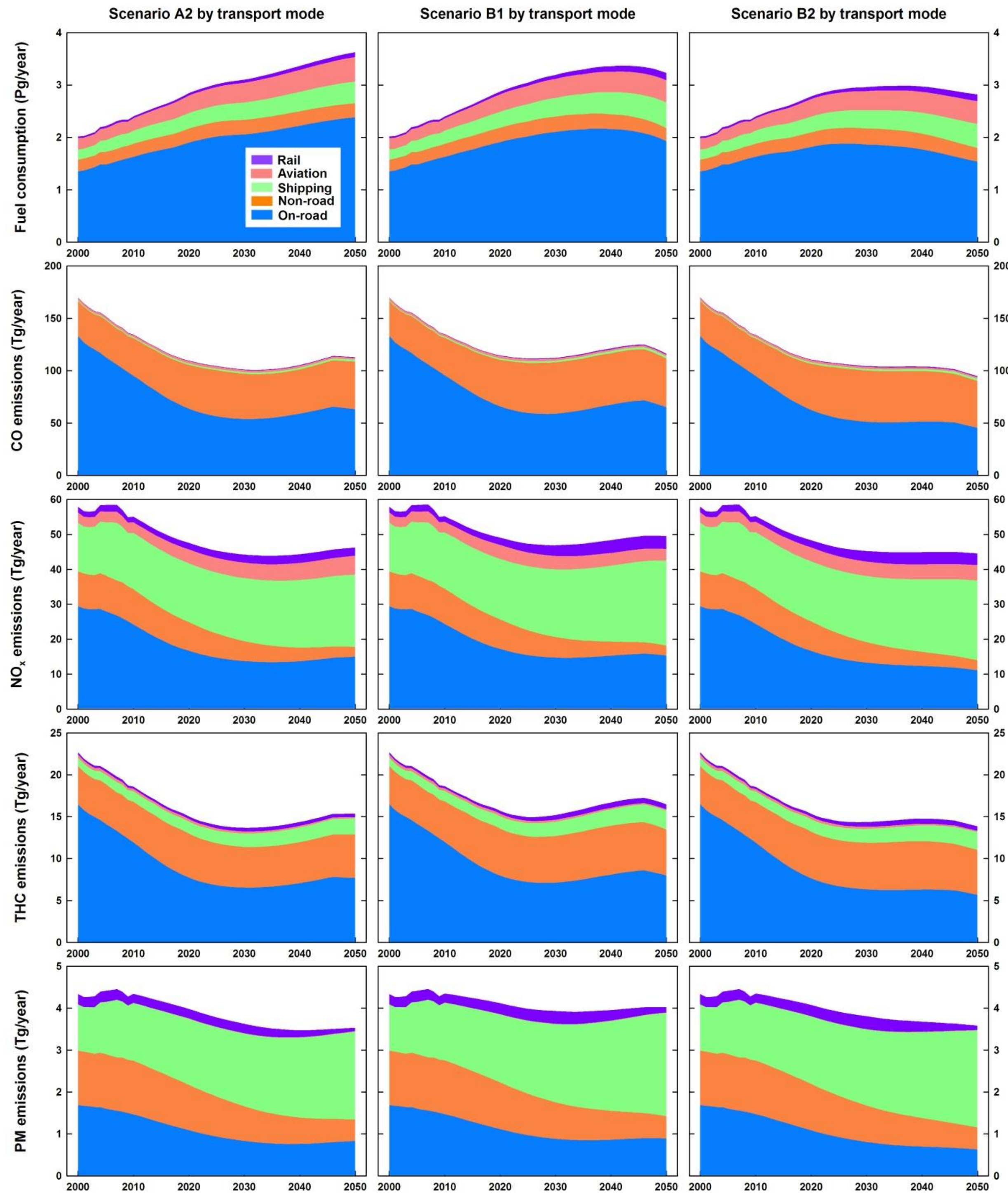


Fig. S3. Estimated global fuel consumption and emissions of CO, NO_x, THC, and PM segregated by transport mode under scenarios A2 (left), B1 (middle), and B2 (right).

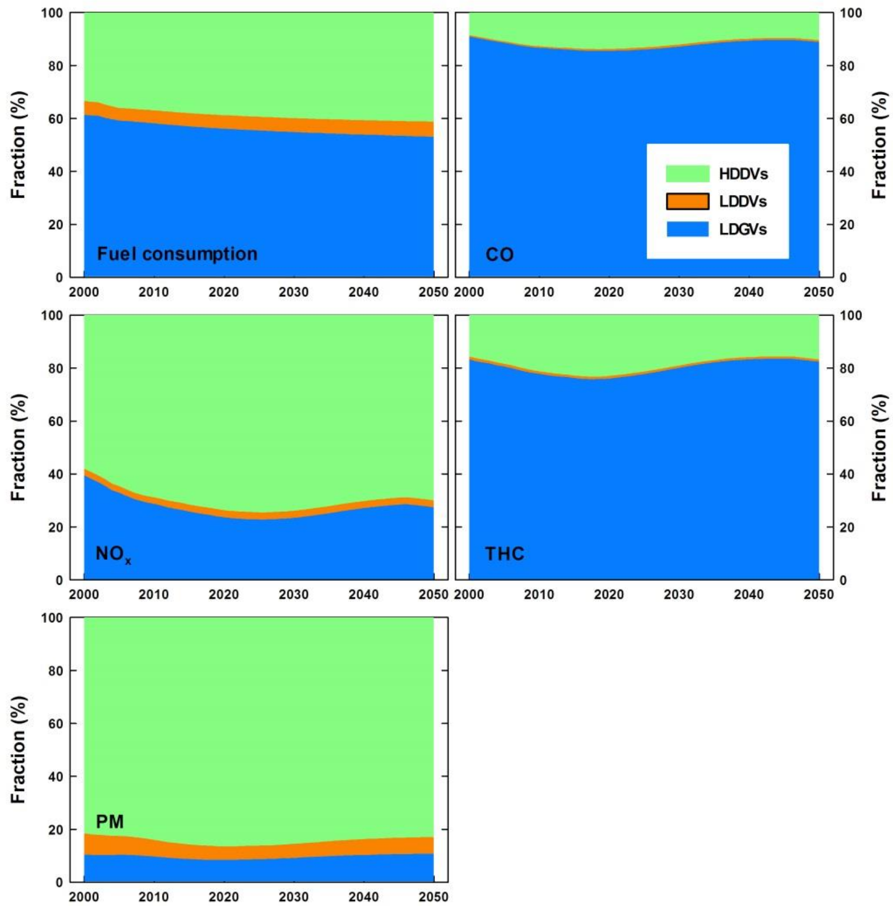
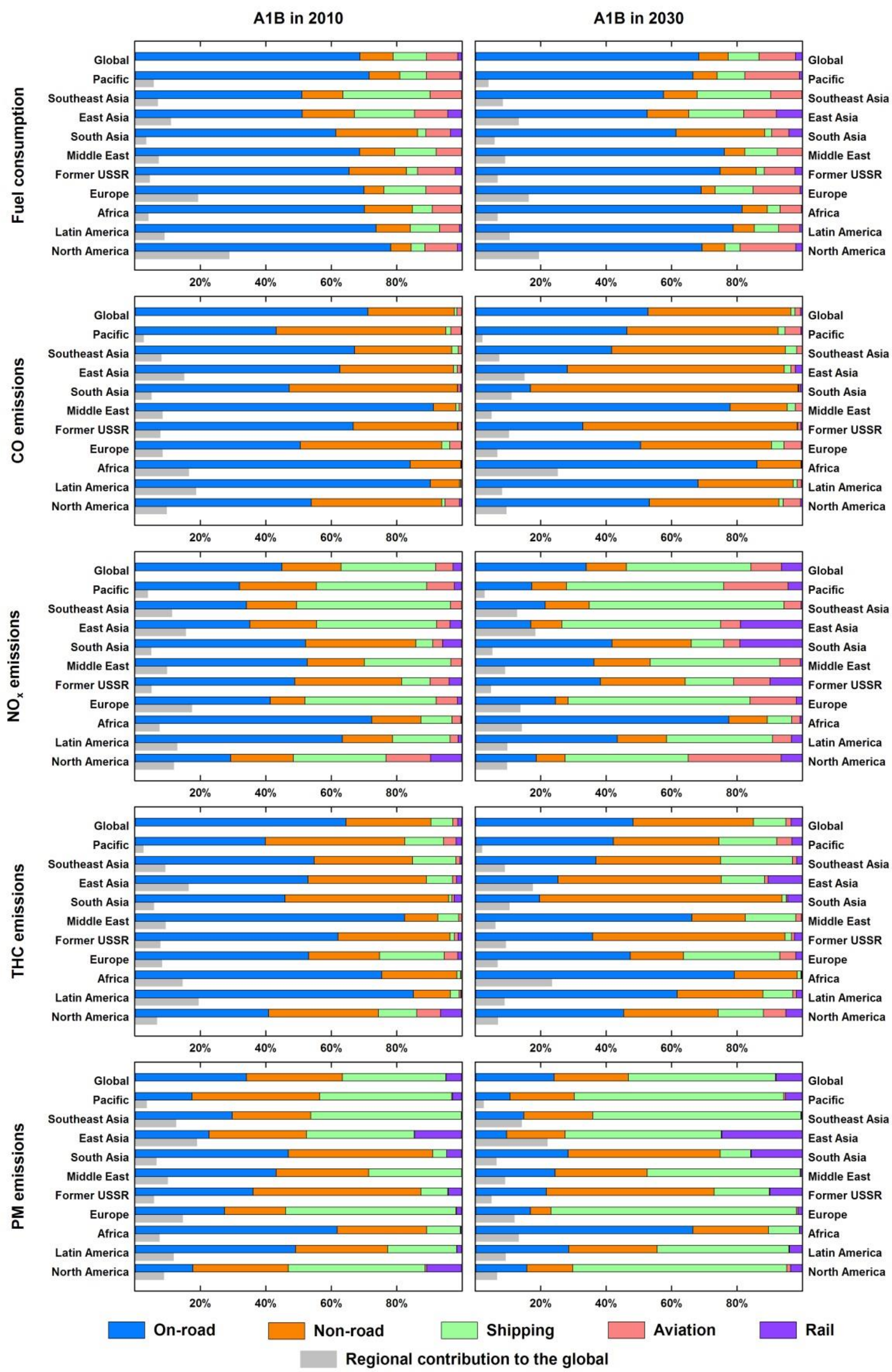


Fig. S4. Contributions of LDGVs, LDDVs, and HDDVs to fuel consumption and emissions of CO, NO_x, THC, and PM under scenario A1B.

212



A1B in 2010
A1B in 2030
Fuel consumption
CO emissions
NO_x emissions
THC emissions
PM emissions
Global
Pacific
Southeast Asia
East Asia
South Asia
Middle East
Former USSR
Europe
Africa
Latin America
North America
20%
40%
60%
80%
On-road
Non-road
Shipping
Aviation
Rail
Regional contribution to the global

Fig. S5. Transport mode contributions to fuel consumption and emissions of CO, NO_x, THC, and PM under scenario A1B in years 2010 (left) and 2030 (right). The gray bars represent the regional contributions to the global emissions.

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