We thank the reviewers for very detailed and constructive comments. We have carefully read through those comments and incorporated them to the maximum extent possible into the revised manuscript. Please see our point-by-point replies to general and specific comments.

General response

Model description

This paper describes the application of the dynamic technology model SPEW-Trend and integration of information about emission projections for the whole transportation sector. The model itself has been described extensively in Yan et al. (2011) published in Atmospheric Environment. The purpose of Yan et al. (2011) was to present the relationships and parameters underlying SPEW-Trend and provide detailed model description so that subsequent papers could present the results of its application without repetition.

Though Referee #1 made many comments about the assumptions made in SPEW-Trend, we do not think it appropriate to repeat detailed model descriptions that have already been published; rather, we think it appropriate to include only the essential model details in this paper—which are necessary for the reader to understand the foundations of the modeling—with reference back to the original paper in which the details can be found. It would constitute double publishing as much of this material was already presented. We argue that our treatment here is no different than that of other modeling efforts. This is common practice with all modeling endeavors. For example, one would not expect to find a full description of a climate model in each paper reporting climate modeling results. The main difference is that detailed technological modeling has not previously been used for future global projections and thus this approach may seem novel.

In the original manuscript, we already made efforts to summarize and outline essential assumptions in the model to help readers understand the big picture:
(1) Figure 1 shows the schematic methodology of SPEW-Trend for developing projections;
(2) Section 2.2 summarizes six major features of the model; and
(3) Table 1 presents relationships and parameters used in the model.

To address the reviewers' comments we have added additional material, as follows:
(1) Parameter values for retirement rate and superemitter transition rate in the footnote of Table 1;
(2) Tables S6, S7, and S8 in the supplement to show the assumptions and timing of emission standards in different regions;
(3) More description in section 3.1.1 and Table S2 to provide more detail about the assumptions of historical and future fuel consumption;

(4) Figure S1 to show examples of survival rate, superemitter transition rate, and emission degradation;
(5) Figure S1(d) to show examples of regional differentiation and annual changes of emission factors for a single technology;
(6) Figure S2 to show superemitter fractions by region;
(7) A new subsection in section 3.1 to summarize the assumptions related to on-road vehicles (Appendix A); and
(8) Three new pages in section 3.2 to show the assumptions for non-road engines (which are discussed further below).

Treatment of non-road engines

Reviewers complained that we referred the treatment of non-road engines to an unpublished paper. We agree that it is perhaps not the best approach to cite the manuscript of Winijkul et al., in progress. We have therefore removed all reference to Winijkul et al., and instead added four new pages of text that describe the treatment of non-road engines in this analysis. The revised section 3.2 is shown in Appendix B.

Interpretation of scenarios

Referee #1 commented several times that we did a rather minimal interpretation of the SRES storylines in our different scenarios and did not include aspects of the storylines such as environmental awareness and global technology transfer. Please refer to comments [5a], [5c], and [5d]. We provide below a general response to such comments to avoid repetition later.

We take fuel consumption, GDP, and population from the SRES scenarios to drive the SPEW-Trend model. We do not claim a full analysis of the SRES scenarios. We do not say that our projections are representative of the SRES scenarios. We say that we have used certain parameters from the SRES to outline self-consistent energy and socioeconomic pathways. Of course, there are other attributes of the storylines, many of which are not easy to quantify and indeed are not documented in a quantitative sense in IPCC publications. We do not know how environmental awareness and technology transfer were quantified in the IPCC projections; indeed, we are not aware of any modeling protocol except for ours that explicitly links such concepts to economic and socioeconomic development. We are certain that these concepts have not been included in the vast body of published work that uses IPCC SRES projections for environmental analysis. All we are doing is taking certain energy and socioeconomic features of the SRES scenarios to drive the model and then using our own techniques to calculate the environmental implications of those pathways in a robust and documentable way.

Comparison with other studies

As distinct from emissions comparisons provided in, for example, Lamarque et al. (2010), the task of this work is to compare emissions for the future. Very few studies have addressed future emissions. Some of the relevant studies did not specify on-road and non-road emissions in the published database or papers. This makes comparison more difficult than other studies (Lamarque et al., 2010; Granier et al., 2011). In our original manuscript, we compared the results with emissions from three modeling studies: GAINS, QUANTIFY, and IEA/SMP. The reasons we chose these three models are: (1) they provide both fuel use and emissions, so that the comparison of emissions and their corresponding fuel use is consistent; (2) their estimates are also aggregated from regional level, so it is possible to compare regional and global values at the same time; (3) they clearly separate the transportation sector from other sectors--especially on-road and non-road sources—and they make the comparison much easier and more applicable; and (4) these models have both historical and future emissions. We have also compared with emissions from EDGAR in the original manuscript, though it only has historical emissions, because this emission inventory is widely used and historical emissions can help us to evaluate our model.

As suggested by Referee #2, we add comparisons for three more regions: OECD Europe, Eastern Europe, and South Asia. Besides the four datasets already compared, UNFCCC (no PM emissions) and EMEP (no fuel consumption) for OECD and Eastern Europe are added to show more comparison of historical emissions. We think figures are helpful in presentation and discussion, and they are plotted in Fig. 3. Discussions are added accordingly.

There are also other studies, such as RETRO (for CO and NOx) (Schultz et al., 2007), ACCMIP (Lamarque et al., 2010), REAS (Ohara et al., 2007), and INTEX-B (Zhang et al., 2009). They may be good sources to make total emission comparisons, but they do not specify on-road and non-road components in the published database. Thus we do not compare with them in this work.

Specific response to Referee #1

We thank the reviewer for his/her time and detailed comments. While many of the comments are about relationships in the SPEW-Trend model, which was discussed extensively in Yan et al. (2011), this paper focuses more on application of the model. One of our general responses explained why this paper does not repeat model details. Nevertheless, we have made numerous changes to the manuscript to address the reviewer's comments.

In the response below, the reviewer's comments are given in italics and our responses are in normal font. Numbers indicate the sections with heading (heading levels are not distinguished) in the reviewer's document, and letters indicate the paragraphs. Further splits in one paragraph are marked with [3di], [3dii] and so on.

[1] Preface

Producing emission scenarios for the whole world is substantial work covering many aspects from technologies, the situations in different countries, assumptions about future development etc. Presenting all elements in a succinct form is not easy. As this manuscript covers such a big scope I've tried to address all important elements. This has become a bit long but I hope it is helpful in the open access discussion.

Reply:

We thank the reviewer for understanding the challenges in developing global emission projections. The comprehensive comments in the open access discussion are helpful to us. We have addressed all the comments.

[2] Summary

[2a]*This manuscript presents global pollutant emission scenarios from the transport sector. Results are based on modeling 10/17 world regions, differentiated by 3 road and 4 non-road source sectors.* Covered *are CO, HC, NOx, and PM emissions for the period 2010 to 2050 (with historic data since 1990 given for reference). The regional population and GDP developments from the IMAGE interpretation of four IPCC SRES scenarios (A1B, A2, B1, and B2) are used as input driving a fleet turn-over module. Emission results are differentiated by region, transport mode, and scenario. The authors explicitly represent ageing and malfunctioning of road and off-road vehicles in their emission factors, and model fleet turnover as a function of regional GDP per capita. The authors claim that this is a more realistic projection of future global emissions than previous inventories (p23376, l3ff), necessary for air pollution and climate impact assessments, and informative for policy makers on emission sources (23398, 20).*

[2b]*If I understand correctly the general logic of the modeling is as follows: Emissions are calculated as the product of fuel consumption and emission factor, summed over all vehicle categories and technologies in each region and time step. Fuel consumption data disaggregated by region and road vehicle category are taken from (Yan et al. 2011) for each scenario and region. PM, BC and OC were already presented earlier. Emissions from aviation, shipping and rail modes are collected essentially from other sources. Hence, the work presented here has two novel aspects: The development of the average emission factor for CO, HC and NOx per vehicle category accounting for vehicle ageing and potential malfunctioning, and the addition of off-road machines used in agriculture, construction, mining and industry (23384, 14) into the same modeling framework.*

Reply:

We thank the reviewer for the positive comments and summary of our work. We want to clarify that (1) only on-road exhaust PM emissions were presented in the earlier work (Yan et al., 2011), not BC or OC emissions; (2) emission factors and fuel consumption for aviation, shipping and rail were collected from other sources, but not emissions directly; (3) the novel aspects of this work are not limited to the two listed by the reviewer, the most important one is that this work accounts for the dynamic technological changes in the emission projections.

[3] Emissions from off-road machines

[3a] *Details on the treatment of off-road machines are referred to Winijkul et al., a manuscript "in preparation". The* authors *claim that off-road machinery would make substantial contributions to global CO and HC emissions (e.g., Fig. 2). However, this cannot be reviewed here, and that's a pity: if correct, then this would be an important and new finding. Current emission inventories, for instance the cited GAINS inventory, do not calculate such high shares.*

Reply:

Please refer to our General Response about the treatment of non-road engines.

[3bi]*However, there are* indications *that the modeling of off-road machinery is somewhat questionable:*

From Table 6 you can calculate implied emission factors, that are very useful for comparing the technology assumptions between different modes and over time (see table below): The implied emission factor for "non-road" is for CO as high as LDGV Super2 and for HC as high as LDGV OPAC.

Reply:

A comparison of emission factors of non-road engines with on-road engines found that emission of non-road engines is much higher, which is consistent with other emission inventories, such as

GAINS. The comparison of our emission intensity with GAINS (Scenario: IEA_WEO2011, CP_WEO_2011, Technologies (non-road engines): TRA_OT_ARG + TRA_OT_CNS + TRA_OT_LD2) is shown in Table 1. Table 1 shows that most of the emission intensities are of similar magnitude. Our emission intensities are, however, within the range of GAINS emission intensities for these regions.

Table 1. Comparison of emission intensity (g/kg-fuel) and fraction of diesel between this study (A1B) and GAINS.

Region (source)	Fraction of diesel (2010/2030)	Emission intensity (g/kg-fuel)							
		CO (2010)		THC (2010)		CO (2030)		THC (2030)	
		gasoline	diesel	gasoline	diesel	gasoline	diesel	gasoline	diesel
EU (this study)	0.79/0.74	713	23	35	5	482	11	24	1
EU (GAINS)	0.93/0.94	720	14	241	7	574	8	103	4
US (this study)	0.82/0.82	589	15	39	3	500	8	33	1
US (GAINS)	0.66/0.62	1291	16	39	8	1269	7	39	4

***[3bii]** What evidence do the authors have to assume that by far most “non-road” is unregulated and unabated gasoline powered engines?*

Reply:

Emission standards of non-road gasoline engines are implemented in the U.S. for all engine sizes (U. S. EPA, 2012) and in Europe, Canada, and Australia for small engines. For other regions, we assume that emission standards of non-road gasoline engines will be implemented in the same year as those for diesel engines with the exception of high power 4-stroke gasoline engines. To address the reviewer’s comments, we’ve added a description of emission standards of non-road engines in the revised manuscript. Please refer to the General Response.

The “implied emission factor”, as calculated by the reviewer may lead to the wrong conclusion that non-road engines are unregulated in our model. Please refer to the response to comment [3di] for a detailed explanation.

***[3c]** If most “non-road” is gasoline engines, how come that NOx and PM emission factors are rather comparable to the diesel powered rail engines?*

Reply:

Most non-road engines are diesel engines, as shown in Table 2.

Table 2. The ratio of gasoline and diesel consumed by non-road engines under scenario A1B.

Year	North America	Latin America	Africa	Middle East	Europe	Former USSR	South Asia	East Asia	Southeast Asia	Pacific
2010	0.22	0.09	0.30	0.02	0.27	0.20	0.20	0.19	0.17	0.20
2030	0.22	0.17	0.27	0.04	0.35	0.75	0.43	0.43	0.24	0.24
2050	0.21	0.18	0.23	0.06	0.29	1.07	0.88	0.92	0.29	0.24

***[3di]** Further, the implied emissions for CO and HC increase over time. Why are no emission controls assumed in future? How does this relate to the fact that the role models for all other emission controls, the US and EU, have actually successively tightened controls for these machines as well?*

Reply:

The increasing emission intensity of THC and CO does not mean that no emission controls are assumed in the future. For non-road engines, emission factors of CO and THC for gasoline engines are much higher than these for diesel engines (30-43 times higher on average) (EEA, 2012; U. S. EPA, 2010; U. S. EPA, 2012). Thus, the overall emission intensity is affected essentially by the ratio of gasoline to diesel. Besides, this ratio is not constant over time (Table 2). To address the reviewer's comments, we've added Tables S9 and S10 to show that the emission intensity of CO and THC for gasoline or diesel reduces with time, but overall emission intensity, which largely depends on the changes of the ratio between gasoline and diesel, may not decrease. We also add the following text after line 18 on page 23391:

"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;"

***[3dii]** Why does the iEF for NOx (and for PM) decrease by a factor 2 and 4 until 2030 and 2050?*

Reply:

This is because the emission factors of PM and NOx for gasoline and diesel non-road engines are not as different as those of CO and THC. Thus, the effects of increasing gasoline could not overcome the effects of emission reduction by implementation of emission standards.

***[3e]** I recommend either to cut this part out or to bolster up the documentation on off-road machines. Alternatively, the publication of this manuscript in ACP could be deferred until the review of Winijkul et al. will have been completed (and all necessary revision transferred as necessary).*

Reply:

Please refer to the General Response.

[4] Modeling of emission factors for road vehicles

[4a] *The authors represent the effect of emission standards, of fleet turnover, and of emission degradation explicitly in their modeling. In addition they assume that a certain fraction of vehicle would turn into superemitters. It is the same approach in (Yan et al., 2011) and supposedly the same parameters are used. (Please clarify and document in the SI). The assumption for the first two factors (emission standards and vehicle turnover) are coupled to the regional GDP per capita (growth rates) taken from the IMAGE representation of four SRES scenarios. How the scenarios are modeled is essentially presented in (Yan et al., 2011), and it makes reviewing hard as you need to switch between 4 different documents (2 papers plus SI each) to find the information. In terms of presentation I therefore suggest to assemble all necessary information in the SI of this manuscript.*

Reply:

As we stated in the paper, the emissions from on-road vehicles and non-road engines are estimated within the framework of SPEW-Trend. Assumptions and parameters related to emission standards and fleet turnover are the same as those described in Yan et al. (2011), because these parameters do not change with pollutants. We did not show them in the original manuscript to avoid repetition. Please refer to the General Response. However, the degradation of emissions does differ among pollutants, which is why we show detailed emission factors and degradation in Tables 2-4. It is not possible or necessary to assemble everything in the SI of this manuscript. Please refer to the General Response.

[5] On the use and interpretation of SRES scenarios

[5a] *The implementation of the SRES scenarios seems to differ only in the fuel consumption growth rates, which affects absolute emission levels, and in regional GDP developments, which is translated to a different average emission factor (the lower the rgdp, the higher the fleet average emission factor). However, this is arguably a very scare interpretation of storylines that are supposed to differ e.g. in environmental awareness on the one hand, and global technology transfer on the other hand (Nakicenovic et al., 2000)*

Reply:

Please refer to the General Response.

***[5b]** Authors note themselves that "environmental legislation" is the "more important factor" determining emission rates (p23376, l.5). Hence, this is in conflict with the assumption (spelled out in (Yan et al., 2011)) that only regional GDP would determine the timing of emission controls in E and W Africa (by 2040 at best in A1B)*

Reply:

We do not see the conflict. It is true that environmental legislation, which we refer to as the adoption of emission standards, is an important factor in determining emission rates. This does not necessarily mean that we cannot use regional GDP to determine the timing of emission standards (i.e., environmental legislation) in Eastern and Western Africa.

***[5c]** In all their scenarios the vehicle technology would differ from 2020 onwards from the most advanced standards (Euro 6) in some regions to no controls in other regions. The current formulation is therefore in my opinion rather an interpretation of a A2 type of scenario (fragmented world, little technology transfer). For a B1 type scenario I would expect rather a quicker catch-up of emission controls, potentially even some leapfrogging through global technology transfer. See for instance Uherek et al. 2010 for one transport interpretation of the SRES scenarios.*

Reply:

As we indicated in the General Response, we only used certain aspects of the SRES to guide our energy and socioeconomic pathways in a self-consistent way. We do not claim that our pathways are exact replicas of the SRES storylines. The point of our research is to develop a transparent, documented approach to the treatment of the dynamic drivers of technology change. In due course it may prove necessary to adjust some parameter values, to include additional parameters, or in similar ways to modify the driving forces of the forecasts, as new information becomes available. But at least this can be rigorously done within our model framework and is superior to qualitative expectations. There is presently no evidence that countries introduce emission standards at extremely low GDPs regardless of the level of environmental awareness elsewhere in the world.

It is not explicitly stated, but the reviewer also seems to believe that we did not relate timing of emission standards to economic development or other variables, which was already explained in Yan et al. (2011). We first investigated whether we could project the onset of standard adoption dates based on GDP per capita. We found that, while the coefficients of per-capita GDP were significant when all countries were included, they were not significant when U.S. and European countries were excluded. That is why we chose a more empirical method of introducing standards for past and future years. This method makes the assumptions of emission standards consistent among scenarios.

[5d] *That such differences are not incorporated in (Yan et al., 2011) is no reason not to do them now but rather reason to improve beyond what has already been known. Without such variation the scenarios in their current form are rather pessimist in terms of emission control, and do not span the range of possible development as intended by the different scenarios and storyline in SRES.*

Reply:

This issue has been addressed in the General Response. However, we would like to point out that the term "pessimist" is not an objective one.

[6] On the fleet turnover model

[6a] *The authors employ a simple fleet turnover model that is driven by the growth in fuel consumption assumed for each mode (and vehicle category). This is apparently the model from Yan et al. (2011), where survival functions for cars and trucks were calibrated to historic vehicle stock growth in different countries. However, there are a number of important limitations that could better be addressed:*

The authors note that Asia, Latin American and later Africa will quickly dominate global emissions and hence these regions need to be modeled as good as possible if the projections are supposed to be credible. Have you accounted for data in India (Nesamani 2010; Ramachandra & Shwetmala 2009) or China (Huo & Wang 2012; He et al. 2013; Huo et al. 2011; Zhang et al. 2013), or South East Asia (admittedly, I don't know a good reference). What did you do for Africa and Latin America? Please document assumptions and references.

Reply:

It is an unfortunate fact that, though developing regions make significant contributions to global emissions, insufficient information about the vehicle fleets is available for these regions. This is one of the challenges to modeling global emissions. Hence these regions bring unavoidable uncertainties to the total emissions estimates. We agree and we wish that more data were available to help us better understand vehicle retirement rate. Yet our model integrates the best available observations and projects consistent emissions on multinational scales. Here "consistent" means that assumptions about emission causes and responses to economic growth should be treated similarly in all regions.

We derived the parameters of retirement rate based on observations from different countries, datasets from the International Road Federation, a global compilation of vehicle data, vehicle age distributions from K. G. Duleep, as well as available publications, such as Wang et al. (2006) for China, Baidya and Borken-Kleefeld (2009) for India, and Zachariadis et al. (1995) for European countries. These references were cited in Yan et al. (2011). Please refer to the General Response for why such detail is not discussed in this paper.

Another thing we must point out is that we did not use the actual turnover data for each individual country directly; rather we used those data to develop a relationship between local-to-global GDP per capita ratio and turnover parameter. This allows us to model regions where we could not find any data. As we mentioned above, such data are not easy to obtain. Although many countries have registration data, they are not always appropriate for modeling fleet turnover. For example, despite having a co-author (Winijkul) who had once worked in the vehicle division of Bangkok Pollution Control and still has connections there, we had no appropriate data for Thailand, not to mention other countries in Southeast Asia.

We thank the reviewer for the suggested references. Some of them we were already aware of. Specifically:

(1) For India, we used Baidya and Borken-Kleefeld (2010) to determine vehicle median life as 13 years. This is similar to the assumption in Nesamani (2010), which defined the lifespan of different vehicles in the range of 10-15 years. It is a pity that Ramachandra and Shwetmala (2009) did not show specific information about the vehicle fleet, and we could not evaluate our assumption with their paper.
(2) For China, vehicle fleet information is from Wang et al. (2006). In the suggested references by the reviewer, only Huo et al (2012a) discuss fleet turnover; others applied a similar model without showing specific parameters. Both Wang et al. (2006) and Huo et al. (2012a) share the same data source of vehicle age distribution. Therefore, we decided that there was no need to update the parameters for China.

***[6b]** The same is true for the modeling of trucks that are the dominant emitters of NOx (and PM) in all regions: Yan et al. 2011 noted that the fit was poor. I would argue the modeling approach for trucks needs to be changed, as their development is closely linked to transport work, which in turn is linked to GDP development. What have you done to improve the modeling?*

Reply:

If we understand the comment correctly, it seems the reviewer complains that we did not link fleet turnover of trucks to GDP development. This is not true. In section 2.2. of the original manuscript, we summarized the features of SPEW-Trend, and clearly stated that retirement rates for on-road vehicle (including trucks) and non-road engines depend on regional income and on-road vehicle age or non-road engine cumulative service hours. The relationship is also shown in Table 1.

***[6c]** The same (historic econometric) relations are assumed for the next four decades across all four scenarios? Please justify in the light of scenario storylines, and note these assumptions in a new section "Caveats".*

Reply:

It is impossible to know if the relationships we develop will change in the future. Like most modelers do to project future situations, including those projecting future air pollutant emissions now, we used historical information to derive relationships in the SPEW-Trend model and then used these relationships to project future emissions. The historical information does span a variety of socioeconomic and technology conditions and there is no reason to think that the relationships will not hold into the future, as developing nations approach the conditions that currently prevail in the developed world.

[6d] *I don't find information how you model world regions for which there is not at least one country represented in Yan et al. 2011, e.g. most of Africa except the Republic of South Africa, the former USSR, the Middle East, Central and Eastern Europe. Please document assumptions.*

Reply:

Please refer to the response to comment [6a].

[6e] In Yan et al. 2011 the same relationship for mileage with vehicle age is used worldwide assuming that LDGV and HDDV still have 50% of their initial activity at 15 years of age and more. However, this is significantly higher than the about 33% in the cited reference (Zachariadis et al. 2001); likewise your reference (Van Wee et al. 2000) states that activity of cars in the Netherland has already dropped to 50% at a vehicle age of 9-10 years. Please justify or modify your assumptions. Please search to update with more recent data and enlarge to encompass other 4 countries e.g. China (Huo, Zhang, et al. 2012). In its current form you seem to have a bias towards more miles from older vehicles, hence towards higher emissions.

Reply:

Yan et al. (2011) used data from Zachariadis et al. (2001) for the European average, Van Wee et al. (2000) for the Netherlands, and Davis and Diegel (2008) for U.S. These three data sources were treated as being equally important. In the U.S., the activity of cars drops to 78% at the age of eight years and 50% at the age of 14 years. The three datasets were averaged and modeled by a logistic function. The figure below shows data points from the published literature and the fitted curve for the activity level of cars used in Yan et al. (2011) and this work.

To make the comparison, the normalized activity of cars by age from Huo et al. (2012b) is also shown in the figure. Survey data from two big cities, Beijing and Chengdu, and a final summary for Chinese vehicles are plotted. Vehicle activity in Beijing falls close to the curve in this work after age 10 and the activity level in Chengdu is even higher, with 64% at age 12. The survey by Lin et al. (2009) of more than 400,000 vehicles showed that the annual mileage of cars at age 10 is about 75-80% of the new ones in China. Therefore, we think our estimates of vehicle activity are in the middle of the range of observations, based on the studies of European countries, US, and China.

We agree that the modeling of vehicle activity is based on observations in only a limited number of regions. This does add to uncertainty in the total emissions. We wish that we could distinguish this relationship by region, yet there is nowhere near enough information available to do that.

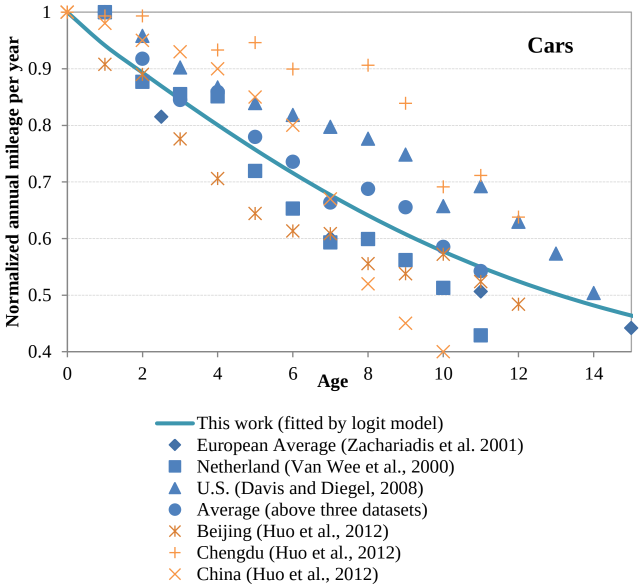

Figure 1. Normalized vehicle activity levels used in this work and other studies.

***[6f]** Table 1 – Formula for Survival rate: If I see correctly, this is the place where you introduce the external data (GDP and population) in form of "ratio of local and global GDP per capita, rgdp". To the extent the ratio between global and regional GDP is different between scenarios, the survival rate differs. Hence, your scenarios are purely driven by GDP and population numbers, although you recognize that "environmental legislation" is the "more important factor" determining emission rates (p 23376, l.5). Please explain how you account for the very different storylines: Global vs. fragmented world (1 vs 2 scenario family) and economically oriented vs environmentally conscious (A vs B family).*

Reply:

We settled for vehicle age and the ratio of regional and global GDP per capita to drive vehicle fleet turnover. We did state that emission legislation is an important factor to determine emission factors. However, it is not appropriate to represent it in the survival rate or the fleet turnover model, because this is not how the fleet evolves. Only incoming emission standards can represent the emission control technologies which determine emission factors, and this is what we rely on.

Yan et al. (2011) discussed why the ratio of local and global GDP per capita and vehicle age were chosen as the drivers of survival rate. Some parts of the discussion are shown below:

"…We settle for representing two of the main factors in retirement decisions: vehicle age and the balance between vehicle cost and repair. The former is retained in our fleet model. The price and labor indices used in retirement rate studies are not available worldwide, so we make a rather bold assumption, namely, that the prices of new vehicles, which can be produced and sold anywhere, are set by the global market, while repair costs are governed by local labor rates. We use the ratio between regional GDP per capita and global GDP per capita as a factor in the retirement decision. This assumption reflects the findings of the studies in Table 3, and is consistent with the conventional wisdom that vehicles are retained longer in lower-income countries."

Again, as stated in the General Response, we chose GDP, population, and fuel consumption as the drivers of different scenarios. These socioeconomic variables are often used by modelers to project future emissions. GDP per capita is an efficient indicator for economic development and reflects the level of convergence in regional development patterns. In Yan et al. (2011), the differences of emission intensities under scenarios A1B and A2 were discussed, and they are caused mainly by economic growth patterns: global vs. regional. The following is cited from Yan et al. (2011), page 4842: "Traditionally, "convergence" of income between developed and developing regions is seen as desirable, but in this case, relatively cheap labor might make clean technology less expensive, facilitating its implementation in areas of rapid growth. Environmental policies should give special attention to vehicle retirement rates and the role of superemitters, because of their inherent importance, but also because they may be affected by regional income diversity in unexpected ways. Finally, we obtained this result because of the way we expressed retirement rates. While this formulation is plausible, it needs further study to confirm the implications for income convergence."

[7]On emission deterioration with vehicle age

[7a] *The authors model the average emission factor per vehicle category as a function of age. This is one step finer than previous models have done.*

Reply:

We thank the reviewer for the positive comment. However, we want to clarify that we do not really use the concept of "average" emission factor in our model, meaning that we do not assign a single emission factor to the whole vehicle fleet averaged by technology or by region. Instead, we study vehicles by age (or vehicle model year) and assume that vehicles in the same age group share the same emission factor, emission standard, degradation rate, retirement rate, and superemitter transition rate.

If the "average" emission factor mentioned by the reviewer is defined as the mass of total emission divided by total fuel consumption, or so called emission intensity as we mentioned in Yan et al. (2011), it is not only a function of age, but also depends on GDP per capita through the fleet turnover model, superemitter fraction through the superemitter transition function, shares of emission control technology through implementation of emission standards, as well as fuel growth which determines the increase in new demand. Except for age, all other factors are differentiated by regions. Thus the "average emission factors" are region-dependent.

[7b] *The key question is however whether the result is accurate or at least whether there is sufficient reliable input data available. Hence, if the mix between ages and technologies that the authors assume is not correct or reliable, their finer modeling level has no advantage. Could the authors show evidence that their average emission factor is more appropriate than others? If not any claim that this is "better than previous work" is not substantiated and should therefore be deleted or better qualified (e.g. 23376-10-19; 23397, 13-19).*

Reply:

We are cautious of claiming that our work is more "accurate" than others. Although our model contains more technological detail than many global inventories, increasing the number of inputs to a model does not necessarily make its results more accurate. However, we believe that our work is "better than previous work" in terms of explicitly differentiating vehicles by their emission characteristics and demonstrating the evolution of technology dynamically and consistently across model years and world regions. That is why we make the statements on page 23376 lines 8-19, and page 23397 lines 13-19. It is our belief that until the factors that determine emission are explicitly represented in emission models, as they are here, there will be little effort to improve them. The framework we present may or may not currently produce improved emissions, but it is the first step toward doing so. The alternative is continuing to use average emission factors without connection to the physical basis of emissions, which we find unacceptable.

Our input data about emission factors and degradation rates are from measurement programs and compliance reports. They are the best available data sources for our purposes. In section 4.3, we compared this work with others at both global and regional level. It shows that the results are comparable, meaning that our emission factors are not unreasonable.

[7c] *Admittedly, the authors do not aim to model finely (see Yan et al. 2011, p4835 concerning country or region emissions) nor in terms of technology: The same emission factors and deterioration rates as for Europe are applied to all other world regions except the US (and probably Canada). Previous inventories (IEA/SMP 2004, QUANTIFY, GAINS) used regionally differentiated emission factors, which is usually considered superior. It is the merit of this approach to draw attention to the fact that emission rates tend to increase with the age/wear of the control equipment. While this can be highlighted, at the same time you need to make clear that here you present first order estimates and no regionally appropriate emission estimates. I suggest to state these limitations clearly in a 'caveats' section.*

Reply:

It seems that the reviewer may have misunderstood how we estimate emission factors. Alternatively, we might misunderstand the reviewer's comment that "the same emission factors and deterioration rates as for Europe are applied to all other world regions except the US (and probably Canada)". To help the reviewer to better understand our model, we provide below more details on how we estimate emission factors and help the reviewer to have a better idea of our model.

(1) Most countries follow European or U.S. emission standards, but the standards are initiated at different times (Dieselnet, 2013). We group vehicles built to comply with 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.
(2) We define "technology" (page 23376, lines 1-2) as a piece of hardware or an operating procedure that influences the emission factor of an emitter over time. In this paper, technology does not only refer to vehicles with stringent emission control, but also vehicles without emission control, or with opacity emission control, or superemitters.
(3) For each technology (except superemitters), we assign an emission factor for a new vehicle (at age zero) and a set of parameters for determining the degradation rate, as shown in Tables 2-4. If the reviewer means that we apply the same emission factors for vehicles at age zero and degradation rate for the same technology meeting the same emission standard in different regions, then that is true.
(4) When vehicles of all ages are accounted for, the average emission factor of a specific technology is regionally differentiated and even annually differentiated for a specific region. We add Fig. S1(d) to show how the average emission factors of a technology are different from region to region. This is because the age distributions are distinguished by retirement rate, which depends on regional income level. Therefore, if the reviewer thought that the same average emission factors for each technology are used in different regions or different years, then that is not true.

[7di] *The assumed deterioration rates for LDGV and HDDV (Tab 2 + 4) are essentially expert judgments, transferred either from HC, or older US technology, or the like. Rates do not decrease over time, hence you do not account for increasing durability in standards and in the field (e.g. durability requirements in the EU were extended from 80'000 km for Euro 2/3 to 160'000 km for Euro 5 onwards for LDVs). Legislative deterioration factors are up to 1.2 (for Euro 3 and 4 and all pollutants) and less than 1.6 for Euro 5 onwards.*

Reply:

Most of the degradation rates in Tables 2 and 4 are not based on expert judgment. They are from measurements and reports, as shown in the footnotes. Some of the data relied on U.S. EPA reports (U.S. EPA, 2009; U.S. EPA, 2011) for development of emission rates for LDVs and

HDVs in the MOVES (Motor Vehicle Emissions Simulator) model. The reports are based on measurements from different programs. We also consulted with AP-42 (compilation of air pollutant emission factors). The report itself was published a long time ago, but it was well documented for old technologies.

Degradation rates generally vary with technologies in our work, but we do not consider rates decreasing for later standards. Measurement data are rare for the new emission standards (e.g., Euro V and VI). Besides, there is no information about emission standards beyond Euro VI or equivalent. Experience shows that emissions from in-use vehicles do not quite follow durability standards. It is quite common for models to assume that new vehicles emit according to the emission standard. However, this assumption is too pessimistic. Manufacturers often target a new-emission rate lower than the standard in order to allow for degradation. Therefore new vehicles emit less than the standard.

[7dii]*In addition, there are OBD requirements for both LDV and HDV, which seem to work (see for instance Ch 5 in (Carslaw & Rhys-Tyler 2013). Similar is true for the US, and data from I/M programs show remarkably increased durability (at least of LDGV, see (Borken-Kleefeld 2013) and primary sources for I/M programs in the US). Hence, the deterioration rates in the current paper are quite speculative, partly in contradiction with other knowledge, and overall strongly biased to the high side, 5 leading to calculated high emissions. I suggest to review and reduce deterioration rates, and to add a note in the 'caveats' section.*

Reply:

In Chapter 5 of Carslaw and Rhys-Tyler (2013), Figures 45, 48, and 51 present the observed mean rates of NO emissions from petrol passenger cars, diesel passenger cars, and diesel light goods vehicles by year of manufacture, measured in years 2008 and 2012. OBD is required to apply to all petrol cars since 2001 and diesel cars since 2004. By using data in the above figures, we calculated the ratio of emission factors for the same manufactured year, measured in years 2008 and 2012, as shown in Figure 2. We observed that the ratio for diesel passenger cars and light goods vehicles is almost constant after 2004, and the ratio for petrol passenger cars is even increasing after 2001. We are not sure that we can make the assumption that OBD works, based on the single study of Carslaw and Rhys-Tyler (2013).

Borken-Kleefeld (2013) summarized the use of remote sensing data to cross-check I/M and OBD performance and cross-check individual I/M results, but did not give any examples. Different opinions about the efficiency of I/M programs still exist. Bishop and Stedman (2008) (as cited in Borken-Kleefeld (2013)) studied on-road remote sensing measurements in multiple cities over a decade, and found that "the majority of on-road emission reductions are the result of continued improvements in function and durability of vehicle emission control systems, and that inspection and maintenance and fuel reformulation programs have only played a minor role." There is not even any evidence that I/M programs hold vehicles to standards in developing countries.

We assumed that vehicle fleet dynamics follow historical patterns in this work. We did not include I/M programs in our model, due to discrepancies in opinions and poor understanding about their effectiveness. Further studies are needed in order to explore the effectiveness of I/M programs. To address the reviewer's comment, we indicate this limitation at the end of section 1.1.:

"This paper assumes that fleet dynamic changes follow historical patterns, in the absence of evidence to the contrary. Any air-quality regulations other than the implementation of emission standards are not considered in this paper. The effectiveness of additional emission reduction programs, such as inspection and maintenance regimes, will be explored in future work."

The degradation rates are from measurements and reports, as shown in the footnotes of Table 2–4. We do not agree with the reviewer's comments on the approach as "speculative" and in "contradiction with other knowledge".

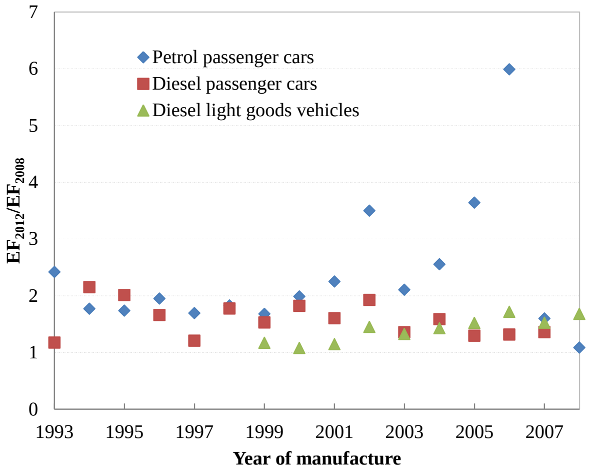

Figure 2. The ratio of emission factors measured in year 2008 and 2012. Data sources: Figure 45, 48, and 51 in Carslaw and Rhys-Tyler (2013).

[7e] Please document the assumed age parameters s_deg and s_stab.

Reply:

We have revised Tables 2-4 and added vehicle ages at which emission factors start to degrade and stabilize, though such information was already shown in Yan et al. (2011).

[8] On superemitters

[8a] The authors assume that as vehicles become old an increasing share of vehicles turns into superemitters. Fig. 3 shows that in this calculation scheme some 50% and more of total emissions are attributed to super-emitters by 2050 in individual regions. Despite this alleged

importance, the modeling of superemitters is least well documented here, and arguably the most speculative element in the whole calculation.

Reply:

As we emphasize in the General Response, Yan et al. (2011) provided a detailed description about the assumptions of the SPEW-Trend model, including the assumptions about superemitters. Thus we did not repeat them in this paper. In the original manuscript, we summarized the main characteristics of superemitters in section 2.2, page 23382, lines 3-4, and presented the function of the superemitter transition rate in Table 1. Please refer to the General Response for the description of material we have added to the revised manuscript.

[8b] *It is essential to document which share of fuel consumption is allocated to super-emitters in the different regions over time.*

Reply:

As will be explained in [8e], we do not simply assume a superemitter fraction, but use a documented superemitter transition rate to estimate the rate at which normal vehicles at a given age develop into superemitters. The fraction is therefore not a constant and cannot be shown for all vehicle types, regions, and years. Figure S2 is added in the supplement and uses HDDV as an example to show distributions of superemitter fractions in different regions between 2000 and 2050.

[8c] *Do assumptions differ between scenarios? If not, why not?*

Reply:

The assumptions about the superemitter transition rate are the same between scenarios. However, superemitter fractions will vary between scenarios since the retirement rate changes with income level in the various scenarios. Please refer to comment [8e] for a detailed explanation.

[8d] *Originally (Bond et al. 2004) estimated PM super-emitter shares of 5% for US and EU, 10% for Eastern Europe and 20% for Asia and Latin America (and probably the rest of the world). These shares were assumed for the year 2004 based on primary data from the 1990'ies, essentially for the US and a few single measurements abroad. Yan et al. 2011 seems to assume these shares for the year 2010. What literature have you consulted to update the old estimates, that were intended to represent PM smokers specifically?*

Reply:

We did not update the estimates in Bond et al. (2004). We want to clarify that Yan et al. (2011) did not assume the superemitter fraction specifically for the year 2010. Parameters in the superemitter transition rate were chosen so that the equilibrium superemitter fractions are approximately the same as those estimated in Bond et al. (2004).

[8e] *Do you assume that shares of superemitters decrease with progressive introduction of more advanced and more durable standards: For instance (McClintock 2007; McClintock 2011) find that US LDGV up to 10 years only very rarely become high-emitters. As they dominate the fleet, the average high emitter rates were calculated as 2-3%, depending on pollutant. To account for this your "gain" parameter in Table 1 needs to depend on the vehicle technology standard and should not be constant for all years. Otherwise you grossly overestimate shares and total emissions.*

Reply:

We do not change the superemitter fraction directly due to introduction of new standards. But as we discuss below, the superemitter fraction is not constant over time for each region.

Studies with sufficient sample size to evaluate superemitter fraction and emission magnitudes are rather scarce. Both McClintock (2007) and McClintock (2011) studied vehicles and high-emitters measured in only one calendar year, 2007 and 2010, respectively. These two studies discussed high-emitter age distributions, instead of changes of high-emitter fraction with time. For example, in McClintock (2011), Fig. 5-2 shows US LDGVs newer than 5 years rarely become high-emitters; this is consistent with our assumption, in which the superemitter transition rate is lower when vehicles are relatively newer. But we could not derive relationships about whether the shares of superemitters for one standard or one model year will change with time or not.

Most important of all, *definitions* about high emitters in McClintock (2007, 2011) are different from this paper. These two studies used cutpoints to identify high emitters. Cutpoint is defined as an emission level used to classify vehicles as having met an emissions inspection requirement, according to McClintock (2011). In our model, we assume that vehicles at any age can transit to superemitters, but the transition rates depend on vehicle age. Once vehicles become superemitters, they follow superemitter emission factors. Due to the different superemitter definitions, we are not able to compare our results with those of the two McClintock studies. We are not aware of any evidence that suggests that our studies overestimate total emissions, especially after the comparison of global and regional emissions with other studies.

It should be noted that the equation for superemitters in Table 1 is the superemitter transition rate, defined as the rate at which normal vehicles develop to superemitters. It is a function of vehicle age. When vehicles are older, they have a higher rate or, alternatively, a higher chance of becoming superemitters. The superemitter fraction depends not only on the superemitter transition rate, but also on the retirement rate. Vehicle retirement rate determines the fraction of existing vehicles which serve as the source of superemitters, and it also determines how quickly superemitters will be out of use. Because retirement rates are not constant for all years or all scenarios, neither are superemitter fractions in our model.

[8f] *In particular you assume that shares in super-emitters for CO, HC and NOx are the same as for PM (23384, 2). However, it is known that the emission performance of different pollutants is not correlated (Mazzoleni et al. 2004). Also (McClintock 2007) found very different shares of high emitters depending on pollutant and on the cut-off threshold.*

Reply:

We agree that the emission performance for different pollutants is not necessarily closely correlated, which is why we state that “a particular vehicle is not necessarily a superemitter of all pollutants” (page 23384, lines 2-3).We intend to explore the development of superemitter fractions that vary with pollutant in future work. However, it is not easy at present to find reliable quantitative data to support a species-specific treatment of superemitter development. Though we did not change superemitter parameters for this work, the reviewer’s comment is important. It is essential to provide some perspective for the reader regarding potential improvements to the model and the direction of our future studies. To address the reviewer’s comments, we’ve added a statement in section 3.1.2:

“(2) CO, NOx, THC, and PM share the same fraction of superemitters, but a particular vehicle is not necessarily a superemitter of all pollutants. The increase of emission factors for superemitters is not the same for all vehicles. Some studies (McClintock, 2007) showed that the fraction of superemitters depends on pollutant. Further studies are needed to refine the parameters in superemitter transition rate;”

[8g] *You refer to superemitters as “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” (23381, 13ff). Technically you characterize them by assigning extreme emission factors that are about 10 times higher than normal emission factors. This definition is however not helpful: It is known that emissions from a vehicle driven a given course are highly skewed, e.g. (Zhang et al. 1994); therefore you always find some percentage of emission records that are much higher than the rest. But as (Smit & Bluett 2011) point out, that there is a certain percentage of high instantaneous emission does not mean that these vehicles are malfunctioning; on the contrary, higher emission events are part of the normal operation of modern vehicles and as such accounted for in the average emission factor.*

[8h] *(Borken-Kleefeld 2013) reviews remote sensing literature and I/M programs, some of which you also consulted. He concludes that the interpretation of the “high tail” of remote sensing as permanent “super-emitters” is likely a misinterpretation, and that numbers in the order that you used are exaggerated, notably for modern vehicles.*

Reply:

The reviewer almost seems to doubt the existence of superemitters (“part of the normal operation of modern vehicles”) and asserts that higher emission events are accounted for in the average emission factor. This seems to run counter to a large literature on the subject of the existence of superemitters as malfunctioning vehicles with average emission rates much higher than typical vehicles. For the developing world this surely cannot be disputed.

The definition of superemitters is not in conflict with a skewed vehicle emission distribution, such as the gamma distribution of Zhang et al. (1994) (as cited by the reviewer). Subramanian et al. (2009) suggest that superemitters can be identified under various distributions. The high skewness and the “long tail” of high emission factors indicate that some vehicles emit far more than others, though their fraction is small. Therefore, using only one average emission factor to represent the whole vehicle fleet is not sufficient. It is necessary to separate superemitters. As admitted by the reviewer, “you always find some percentage of emission records that are much higher than the rest”. We therefore assume that unless the world has changed drastically, superemitters always exist.

The causes of superemitters are various. The high emissions may be due to equipment malfunctioning, incorrect repairs or even tampering (Smit and Bluett, 2011, as cited by the reviewer). But the causes of superemitters are not the concern of this paper. Vehicles with high emission factors are represented by superemitters, no matter what brings about this effect. The representation of superemitters is important, because the policy mechanisms for these vehicles are very different than for other vehicles. We hope that our explicit representation motivates more investigation, a better understanding of causes, and ultimately a better representation of future emissions, but this cannot be accomplished by ignoring the issue.

***[8i]** European vehicles, which are your role model for technologies around the globe do have very low shares of high emitters, different by pollutant, and technology: (Borken-Kleefeld 2012) identified a share of 2% of LDGV emitting about 5 times as much as average. There were NO diesel cars emitting more than 2.5 times NOx than average. Hence, your assumptions on uniform shares and uniform high-emitter level are not valid and needs to be revised.* **.** *Or vice versa, given, that you use a fixed emission factor you need to reduce super-emitter shares strongly for modern technologies.*

***[8j]** Similarly, (Carslaw et al. 2011; Carslaw et al. 2013) note decreasing levels of higher emissions from on-road RS in the UK and conclude on increasing durability of the control equipment.*

Reply:

Again, the definitions of superemitters used by Borken-Kleefeld as well as Carslaw and co-workers are different from our work. Such information is based on the European experience. The situation is very different in many other parts of the world. It should always be borne in mind that the purpose of this study is to develop an approach that is consistently applicable to all regions of the world. Nuanced details about emission rates in Western Europe or other developed regions may be not as important for global emissions as developing robust and realistic methodologies for developing world regions that are likely to drive total global emissions in future years.

Also, again, we did not use uniform shares of superemitters. Pease refer to the response to comment [8e].

[8k] *How do you exclude double counting? You already increase mean emission factors with vehicle age, and these deterioration factors are derived from (mass) samplings. Surely, this will then also include super-emitters (in the sense of your definition), which given their nature, will have a strong influence on the deterioration factor that you assume.*

Reply:

We estimated emission factors of normal vehicles by excluding the highest fraction which was defined as superemitters. There is no possibility for double counting of superemitters and degraded vehicles in our model. We use the superemitter transition rate to estimate the fraction of existing vehicles that develop to superemitters. The rest of the existing vehicles follow the degradation rate. In terms of emission factors, the maximal degraded emission factors are no greater than the emission factors of superemitters.

[8m] *Do you also assume super-emitters for the non-road modes? What's the evidence? Please document assumptions.*

Reply:

Yes, we made similar assumptions about superemitters for non-road engines. Please refer to the General Response and the revised version of section 3.2.

[8n] *In short, I agree that it can be helpful (for policy purposes) to single out super emitters explicitly. And it is possible that existing emission inventories have not accounted for super-emitters in their average emission factors. However, the shares and emission factors assumed here for super-emitters around the globe are not up-to-date, partly in contradiction to observations, and assumptions are inconsistent with technical progress. Therefore, I find that this part needs substantial revision. Any remaining parts should further clearly qualify the speculative nature and include a passage of this kind in the 'caveats' section. Total emission results should always be given with and without assumed super-emitters.*

Reply:

Overall, bearing in mind our responses to comments [8a] to [8m], we think the assumptions about superemitters do agree with observations. No other models have ever treated this topic in as much detail as we do. While it appears that many studies suggested by the reviewer regarding in-use measurements are available, most are unsuitable for the determination of superemitters.

Total emission results with and without superemitters are already shown in Fig. 3 in the original manuscript. Two of four scenarios of emissions without superemitters (A1B and B1) are presented.

[9] On rail, shipping and aviation

[9a] *Given the important reservations on the modeling of the on-road emissions I don't want to go into details for the other modes. If I understand correctly you essentially take over emission factors from other sources. Although you note that these sources have good arguments for recalculating the fuel used for aviation and shipping, you don't take these fuel data over. Please justify and compare your modal emissions with these primary sources, and discuss.*

Reply:

For these transport modes, the differences of emissions from our model and other studies are mainly determined by the differences of fuel consumption, because we apply similar emission factors. Buhaug et al. (2009) and Lee et al. (2009) compared fuel statistics of shipping and aviation, respectively, in their studies. We do not think it is necessary to repeat the discussion of fuel consumption in this paper.

[10a] *Though four scenarios are calculated, their differences in results are not discussed. However as implied emission factors are quite similar with some exception for A2, there seem little differences in technology assumptions, and most differences result from different global and regional fuel consumption rates. As suggested above, please enrich your scenarios – and then discuss consequences.*

Reply:

Emission differences among the four scenarios are not discussed in this paper, because such discussion was part of Yan et al. (2011) (section 4.1 and 4.4) for PM emissions from on-road vehicles. Part of section 4.1 studied the difference of absolute values of global emissions among scenarios. The whole of section 4.4 analyzed the evolution of global and regional emission intensities, which are defined as the ratio between emissions and fuel consumption. Total emission mass and emission intensity of CO, NO_x, and THC are different from PM, yet they share the same technology mix. Therefore, we do not repeat the scenario discussion for on-road emissions in the present paper.

[11] Review conclusion

[11a] *In conclusion, there is a strong but quite questionable bias towards high emission factors in this modeling. Hence, emission results with the current approach are significantly higher than previous calculations. But this does not appear to be based on sound science, and hence the claim that this is better or more realistic than previous emission inventories (p23376, l3ff) is rather unjustified and therefore it is rather misleading instead of "informative for policy makers on emission sources" (23398, 20).*

[11b] *With proper discussion of the caveats and speculative factors this could be a valuable contribution to a discussion, with a somewhat more pessimist approach to technology and emission control. Yet, RCP scenarios assume even higher pollutant emissions from the transport sector, except for PM. Hence, there does not seem the risk that future pollutant emissions from the transport sector are underestimated by the climate science community, rather the contrary.*

[11c] *The merit of this paper could be to delineate an upper limit for transport emissions. To be useful however in the context of the climate-air pollution interactions, and to provide information beyond existing inventories, it would however be necessary to update the current modeling to the RCP input data for GDP, population and fuel use. Whether the results will then however differ significantly from previous work, is uncertain.*

Reply:

Overall, we hope that the revised manuscript and responses to comments [2a] to [10a] would help to provide a better understanding of our work. As stated in the response to comment [7b], we believe that our work is "better than previous work" in terms of explicitly differentiating vehicles by their emission characteristics and demonstrating the evolution of technology dynamically and consistently across model years and world regions.

It seems that the personal opinions from the reviewer about our work's bias towards high emission factors and significantly higher emissions than previous work are contrary to our comparisons. With the comparisons to other studies (section 4.3), our emission estimates are not significantly higher and are even lower sometimes with similar fuel consumption. We are not sure whether other models make even more pessimistic assumptions about emission controls.

As mentioned by Referee #2 and section 5.2.1., we realize that there is already an effort underway to produce updated socioeconomic pathways, called Shared Socioeconomic Pathways (SSPs) (Kriegler et al., 2012; van Vuuren et al., 2012). When the SSPs are completed and available, it will be possible to compare the emission results with those driven by SRES scenarios.

[12] Overall assessment

- *Does the manuscript represent a substantial contribution to scientific progress: Fair/3*
- *Are the scientific approach and applied methods valid? Are the results discussed in an appropriate and balanced way? Fair/3*
- *Are the scientific results and conclusions presented in a clear, concise, and well-structured way: Good/2*

I recommend resubmission to ACPD (not ACP) after revision. To allow for sufficient time for an opinion to form and for an author's response I suggest the editors keep the discussion open for at least another month.

Reply:

We thank the reviewer for generous consideration of timing issue. We have carefully responded to all the comments and revised the manuscript. We have paid special attention to the modeling approach description. We hope the reviewer will be satisfied with the revised manuscript.

[13] Comments and suggestions on presentation

[13a] *The authors are to be commended for their very informative figures and very comprehensive tables. A lot of useful information is effectively condensed therein. Thank you also for providing e.g. the details of emissions by region for the different scenarios. I'd only wish that you add details on the contributions from HDDV, LDGV and LDDV per scenario.*

Reply:

We thank the reviewer for acknowledging the usefulness of the figures and tables. We added Fig. S4 in the SI to show the contributions of LDGVs, LDDVs, and HDDVs to fuel consumption, and emissions of CO, NO_x, THC and PM in year 2050 under scenario A1B. Please refer to our response to comment [4] for Referee #2 for why we could not show such information by region and by year per scenario.

[13b] *For key modeling assumptions the reader is referred to (Yan et al. 2011), for instance the ages parameters governing degradation, and fractional shares of super emitters. There in turn you have to look-up the SI again. This makes reading and understanding in detail quite hard. Please summarize the information in the SI.*

Reply:

Please refer to General Response.

***[13c]** The reference to Winijkul et al., 2013 is not suitable as a manuscript "in preparation" cannot be consulted for reference. Please remove all occurrences and document assumptions here, e.g. in the SI.*

Reply:

Please refer to General Response.

***[13d]** Table 1 becomes very small print. Please increase font size or split in two tables.*

Reply:

We have revised the table. Please refer to Appendix D.

***[13e]** Fig. 3: Please compare on-road emissions for US and China with national emission inventories (Huo, Wang, et al. 2012; Zhang et al. 2013). Discuss discrepancies.*

Reply:

We projected on-road emissions in North America, instead of the US, so we are unable to compare with the National Emissions Inventory (NEI) in this work. We have carefully checked the two papers listed by the reviewer, and think that they are not appropriate for comparison of on-road emissions in East Asia for the following reasons:

(1) Huo et al. (2012a) projects energy use and greenhouse gas emissions of the road transport sector in China. It does not show emissions of the pollutants studied in this paper.
(2) Zhang et al. (2013) does present emissions of CO, VOCs , NO_x, and PM_{10} from vehicles in China. However, several mistakes seem apparent in the paper and they make us doubt the quality of the data. For example, CO emissions in 2009 in Fig.4 are supposed to be the same, as year 2009 is used as the base year. Fig. 6c is supposed to show NO_x emissions in the AER scenario, but it shows VOCs emissions. Other emissions estimates in China, such as INTEX-B in Zhang et al. (2009), do not specify emissions from on-road and off-road in the transportation sector.

However, we have made comparison with other studies. Please refer to the General Response for which studies we compared in section 4.3 of this paper.

***[13f]** Fig 3: Add results from QUANTIFY for scenarios A2 and B2 and discuss.*

Reply:

We only show A1B and B1 scenarios of QUANTIFY to avoid complexity of the figures. For the same reason, emissions without superemitters from our work are shown with these two scenarios as well.

[14] Some detailed questions

[14a] *One aspect relating to vehicle age are restrictions to the maximum lifetime of vehicles allowed on roads (for instance in Japan, starting in China) or maximum age of imported second hand vehicles (e.g. New Zealand). These are environmental regulations that are not strictly correlated to the relative regional per capita GDP. If I see correctly you do not account for such measures currently in place or possibly being introduced over the course of the next 4 decades, e.g. depending on the environmental awareness assumed in the overall storyline? Please clarify your approach to such policies and options.*

Reply:

As we mentioned in the responses to comments [8h] and [8n], this work presents a business-as-usual scenario. Any air-quality regulations other than the implementation of emission standards are not included in this paper. We are indeed exploring the effects of policies for on-road vehicles, such as scrappage (similar to the restriction on the maximum lifetime of vehicles mentioned by the reviewer). This manuscript is currently in preparation.

[14b] *Do you apply the same survival function to all vehicle categories? (Yan et al. 2011) documented that it's fitting least to trucks. Given that trucks are quite important for NOx and PM emissions, please justify that you are using only a very rough approach here.*

Reply:

We applied a logistic function to estimate the survival rate for on-road vehicles and non-road engines. But the parameter values for each vehicle category are different.

[14c] *According to the table caption you also apply this survival function to non-road engines. This seems to go beyond the work of (Yan et al. 2011) and hence please document and justify assumptions. According to Fig. 2 the non-road engines have an important share in CO and HC emissions, hence it's necessary that your approach is convincing.*

Reply:

Please refer to the General Response.

[14d] *I'm confused by the formula: In (Yan et al. 2011) the coefficient α is negative, hence the whole exponent becomes positive? If so, please delete the leading "-", it is misleading. If the whole exponent is hence positive, then it is increasing with rgdp and with age, thus the survival probability is decreasing with both. Does this mean, the survival probability is decreasing the richer the region is relative to global average? I think in general you are right, though not in the* *details. However, you can get away in pointing to the fact, that it is not the young (=cleanest) vehicles that are important for pollutant emissions, but the oldest. Please add a clarification in this sense.*

Reply:

We changed the equation in the revised version. Please refer to the response to comment [14f].

The equation shows that survival rate is driven by both vehicle age and the ratio of regional and global GDP per capita. Survival rate is lower when a vehicle is getting older or a region's income level is rising. If a decreasing survival probability is observed (as in the example given by the reviewer), it could not be explained by vehicle age or income level alone. This point is reflected by the equation itself.

***[14e]** Hence for the purpose here it is important that you adequately model the share of older vehicles in the fleet. Your formula implies that vehicle age is the higher, the lower the countries are below global GDP. And if they increase their per capita GDP just in the same rate as the global mean, their vehicle fleet will not be renewed but remain as old (in terms of average age) as before when they were say half as rich. Please document the evidence for this assumption.*

Reply:

If we understand this comment correctly, the reviewer seems to assume a situation in which a region changes (may not just increase) its GDP per capita at the same rate with global GDP per capita and doubts that the vehicle fleet will not be renewed. It seems that the other important determinant of survival rate in our model is neglected, that is vehicle age. Old vehicles retire no matter what kind of income level exists in the region.

***[14f]** The formula here is different from (Yan et al. 2011) and neither coefficients nor any parameter like "goodness of fit" are documented here. But when I played with numbers it seems that results are very sensitive to the exact parameters. Is that right? Do you vary coefficients with time? If not, how do you justify the same survival probability for a region over 40 years? Did you perform sensitivity tests – and how certain are you that your coefficients and functional form is the best? Please document coefficients and an indicator for "goodness of fit" in the SI.*

Reply:

The equation of survival rate in the printed version of ACPD is incorrect, which may cause confusion. The correct equation should be:

$$Su(s) = \frac{1}{1 + \exp\left[-\left(\alpha_{ret} + \beta_1 \times s + \beta_2 \times rgdp \times s\right)\right]}$$

We did not delete the negative sign as mentioned in comment [14d], in order to make the equation consistent with other literature:

In Yan et al. (2011), Equation (3) shows the survival rate as a function of vehicle age:

$$Su(s) = \frac{1}{1 + \exp\left[\alpha_{ret}\left(s / L_{50,ret} - 1\right)\right]}$$

In Yan et al. (2011), section 3.2.3 mentioned that "we use a linear regression" between $\alpha_{ret}/L_{50,ret}$ and the value of local-to-global GDP per capita (rgdp) to estimate the parameters governing survival rate in different regions. This means that α_{ret}/L_{50} can be expressed as a function of rgdp, that is:

$$-\alpha_{ret} / L_{50,ret} = \beta_1 + \beta_2 \times rgdp$$

If α_{ret}/L_{50} in Equation (3) in Yan et al. (2011) is substituted by the function of rgdp, the same equation of survival rate in this paper will be achieved.

We did not vary coefficients with time. We could not justify the survival rate in year 2050. As explained in the response to comment [6c], we used historical observations to derive relationships in the SPEW-Trend model. This is what most modelers do to project the future. It seems that the reviewer is concerned whether we include the effect of "time" in the survival rate function. For clarity, the ratio of regional global GDP per capita here changes with both region and time.

We did not include sensitivity or uncertainty analysis, because the goal of this paper is to project future emissions by applying the baseline of SPEW-Trend and such sensitivity or uncertainty analysis is beyond the scope of this work. Please refer to the response to comment [25] from Referee #2.

Specific response to Referee #2

[1]*I have read the paper "Global emission projections for the transportation sector using dynamic technology modeling" by Yan et al. The paper presents estimate for criteria pollutant emissions regionally and globally over the period 1990 through 2050. The underlying working in this paper will be a useful contribution to the literature. The authors expand on previous methodologies by incorporating vehicle purchases, aging (degradation), and superemitters.*

The paper, however, lacks detail in a number of areas and should be revised. The standard for a peer reviewed paper is that enough information needs to be supplied such that researchers with appropriate background could replicate the work. Certainly with respect to the development of emissions data this can't be done literally, however, enough information needs to be supplied so that readers can understand the underlying assumptions (and potentially replicate the work). Overall, however, too much of the methodology is not described sufficiently. There are many assumptions make for uncertain parameters. This if, of course, fine and necessary, but these assumptions needs to be more clearly and completely communicated so that the community can move forward in trying to better quantify some of these key parameters.

Reply:

We thank the reviewer for all the comments. Please refer to the General Response for why we did not show detailed assumptions in the original manuscript and for a description of the material we have added in the revised version to address the reviewer's comments on this.

[2]*Also, the rather small section at the end of the paper that compares with existing estimates needs to be expanded in order to put these results into context. The results are also only presented as sparse summary tables and graphs. More detailed results should be provided in supplemental material (for example as excel spreadsheets) so that these can be actually used.*

Reply:

We have added three more regions: OECD Europe, Eastern Europe, and South Asia to the comparison. Plus, more emissions from other data sources (e.g. UNFCCC and EMEP) are added. Please refer to the General Response.

[3]*The dependence of these results on*

Winijkul, E., et al. : Modeling of current and future global emission from land- based non-road engines, in preparation, 2013

is problematic, since those results form a key part of this work. I do not see a problem with proceeding with review (after revision), but I do not feel this paper should be accepted for peer-reviewed published until Winijkul et al. is accepted. Otherwise, if Winijkul et al. was never published, a portion of the results in this paper would not be documented at all. Alternatively, *the paper could be re-written without including these results, although it would be better if all emissions were included.*

Reply:

Please refer to the General Response. We agree that the reference to Winijkul et al. is not helpful. We have removed all references to this paper and added a description of our approach to non-road engines.

***[4]**Future fuel consumption is a critical assumption. Total fuel consumption and shares should be given (in a supplement is fine) with some summary of these results in the main text (as in Table 6) is fine, but more details need to be provided in the supplement (e.g., at the regional level). It will also be useful to also give values for historical fuel consumption, since the IEA data does not provide information at the technology level, and, thus, can also be interpreted in different ways.*

Reply:

We add Table S17 in the SI to show fuel consumption by region and transport model under four scenarios (A1B, A2, B1, and B2) in the years 2010, 2030, and 2050. In the original manuscript, the right panel of Fig. 2 (transport model contributions for A1B in 2050) does provide shares of fuel consumption and emissions by region and mode. It is not possible to provide detailed data at technology level due to the massive amount of data involved. The information for on-road and non-road technologies consists of 17 regions, more than 50 years (from 2000 or earlier to 2050), and 673 technology levels (49 for on-road and 624 for non-road), amounting to more than 100,000 pages if printed. Even if only one year were to be provided, that still amounts to 2,000 pages. It is better that we share this level of detail by email or ftp to readers and collaborators who are interested in it.

***[5]** pg 23376, line 5 Emission factors depend on technology improvements, which in turn may be related to economic growth, but a more important factor is environmental legislation. – And also enforcement, which should be mentioned here. This is a large uncertainty in all regions, likely even more so in developing countries.*

Reply:

We agree and we have revised this sentence to read:

"Emission factors depend on technology improvements, which in turn may be related to economic growth, but a more important factor is environmental legislation and the degree to which it is enforced. In developing regions, there is no certainty that emission standards will be enforced, and this adds to uncertainty in the emission projections."

***[6]** Pg23379-text on the fuel use*

The use of SRES scenarios is understandable even though these are somewhat dated (now 15 years old!). While a new set of socio-economic scenarios is under development these have not been finalized yet (see further comments below). What is not clear, however, is how newer historical data and trends have been merged with the older SRES IMAGE scenarios used here. I suspect that the near-term trends in the IMAGE scenarios differ in many cases from historical reality. Transportation fuel use is now available to at least 2010 from IEA. Some of the questions that need to be answered (briefly in the text, with further details in the supplement) include: up until what year are historical data used? How are the IMAGE projections modified to be consistent with updated historical trends?

Reply:

We use IEA data for historical fuel consumption up to 2010 for all the transport modes except on-road vehicles and then we use the growth rates in SRES scenarios to estimate future values. For on-road vehicles we use IEA fuel-use data up to 2005, in order to be consistent with Yan et al. (2011). In the supplement, Tables S2, S3, and S4 in the original manuscript show which years of historical data from IEA are used and how we justified the use of SRES scenarios. These tables are for fuel used by shipping, aviation, and rail. We add more description of fuel consumption for on-road vehicles and non-road engines in sections 3.1 and 3.2. Please refer to the General Response.

***[7]**The RCP scenarios are not appropriate for use in this exercise (as suggested by another reviewer) since: 1) they were not designed to span a range of socio-economic conditions, and 2) they span a range of climate polices, not reference (no policy) scenarios as used here (see comments below).*

However, what is not done here, but needs to be done, is to compare road transport fuel use as used here (from IMAGE, perhaps modified?) with long-term projections from other similar models. There are a number of models that are used for this purpose (for example in the RCP scenario process, but there are quite a few others). It is critically important to get a sense of how the fuel consumption trends used in this work compares with other results, since this is a large driver of emission trends.

Reply:

We agree with the reviewer that the fuel use trend is an important driver of the emission trend, which is why Fig.3 (the first row) compares fuel use in this work with GAINS, IEA/SMP, and QUANTIFY. Please refer to the General Response for the reasons why we use these three models.

We are aware of the limitations of RCPs, but we still show them in the comparison of emissions from the whole transportation sector. This is because they are publicly available and an important outlook on future emissions. We want the reader to see how our final results on emissions compare with the RCP emissions. The reference scenario (in the RCP scenario process), as mentioned by the reviewer, is not published and cannot be included. To make it clear to the reader we add a statement before the comparison to clarify that RCPs are climate policy scenarios. Please refer to the response to comment [30].

***[8]** pg 23380, lines 11-12 Meaning of the second part of "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." is not clear. Seems this is trying to make two statements. 1) that "details about technological changes are provided **in this paper**"? (since the previous text emphasizes that the focus of this paper is technological changes over time). Then there is a statement saying something about the use of fleet-average emission factors. It is not clear what "thus only time-dependent, fleet-average emission factors are considered" means. (given the focus of this paper on technology modeling and *not* using just average emission factors!)*

Reply:

We apologize for confusion caused by this sentence. We do not provide details of technological changes of shipping, aviation, and rail in this work. We used fleet-average emission factors derived from other studies, instead of emission factors by technology, to estimate total emissions. The average emission factors change with time and still represent the changes of technology, but in an implicit rather than explicit way. The sentence has been changed to read:

"No explicit technological changes for these three transport modes are considered in this work. Total emissions are estimated by time-dependent, fleet-average emission factors obtained from other studies, which represent technological changes implicitly."

***[9]**23381 – bottom. It would be very helpful if an example of factors (2) – (6) in action could be given. Perhaps a two panel graph with total emissions for 2 example sectors showing all these pieces playing out for the parameters used in the model.*

Reply:

Yan et al. (2011) provided a full description of the SPEW-Trend model with this kind of information in it. To avoid repetition, this paragraph only summarizes the major features of the model. These factors do not generally affect emissions for the whole vehicle fleet, but have impacts on individual vehicles. They determine how much fuel is consumed by new vehicles, which emission standard a new vehicle will follow, whether an old vehicle will retire or transition to a superemitter, or continue to contribute to total emissions as a normal vehicle but perhaps with a higher emission factor because of degradation.

We add the following information into the revised manuscript to partially elaborate on material already presented in Yan et al. (2011):

(1) Factors (3), (5), and (6) can be demonstrated in graphs, and examples are shown in the SI Fig. S1;
(2) Table S6, S7, and S8 show assumptions and schedule of emission standards in each region.

They are also addressed in the General Response.

[10]*23383 - line 29 (bottom) phrase "the years that emission factors for CO, NOx, and THC start to increase or stabilize are the same as for PM " needs more context. Without actually reading Yan et al, it is not clear what this means. (Implementing a graph along the lines as suggested in the previous comment would help with this.)*

Reply:

We add examples of degradation rates for on-road vehicles and non-road engines in Fig. S1. We also add more explanation about degradation in the revised sections 3.1 and 3.2. Please refer to the General Response. In addition, we have added the ages at which emission factors start to increase and stabilize in Table 2-4.

[11]*The discussion about degradation could be clarified. It is not clear what "do not degrade beyond the level of opacity standards," means.*

The phrase "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 after treatment devices." should be re-written to be clearer. I'm guessing this means that, where standards require 'end-of-pipe' treatment, its logical to assume some degradation/ failure rate over time for these devices?

Reply:

This is a good point. We did not explain this assumption well in the original manuscript; we have revised it as follows:

"(4) NOx emission factors for diesel vehicles with standards between opacity and Euro VI (or equivalent) are constant over their lifetime. With the introduction of aftertreatment systems to meet regulatory requirements for Euro VI or other similar standards, tampering and poor maintenance are expected to significantly increase emissions over the vehicle lifetime, as compared with the emissions of a new vehicle (U.S. EPA, 2009). As more observations become available, we will update the degradation rates and overall aging effects. "

***[12]**Again, it would be useful to see a graph showing examples of these emissions factors changing over time for different types of regions (developed, developing) and a few specific vehicle types (perhaps largely in supplement, but at least one figure in the text would be helpful since this is such a key assumption). This would also help quite a bit in explaining the "durability, degradation, and stabilizing phases" concepts, which are a bit murky in the present text.*

Reply:

The degradation rate for one technology depends on pollutant, but not region. However, when all vehicle ages are counted, the average emission factors per technology are regionally differentiated because the vehicles last longer in lower-income regions. The vehicle age distributions and the average emission factors per technology per year by region are determined by the timing of emission standards, the retirement rate of old vehicles, and the demand for new vehicles.

As mentioned in the response to comments [9] and [10], we add a graph to show degradation rate. It is not necessary to plot all vehicle types and pollutants, because they share the same pattern but with different parameters (ages at which emission factors start to degrade and stabilize, and maximal degradation rate). We also add Fig. S1(d) to show the average emission factors of PM for LDDV Euro I in OECD Europe and East Asia. This is an example of how degradation rate interacts with the timing of emission standards, retirement rate, and demand for new vehicles. It shows that the age-averaged emission factor of one technology is regionally differentiated. Hopefully, it will help readers to have a better understanding of how our treatment of degradation rate works.

***[13]**The assumptions actually used for super-emitters are not clear and should be provided (perhaps in a supplement table). In particular, the fraction of vehicles in each class/region that are assumed to be super emitters, and the emissions factors (or perhaps ratio of supper emitter EF to average "normal" EF.)*

Reply:

Please refer to the response to comment [8a] for Referee #1

We do not assume the fraction of superemitters in each class/region. Instead, we apply a superemitter transition rate to define the rate at which normal vehicles develop into superemitters. This transition can occur for vehicles at any age, but is obviously low for newer vehicles. Then we sum up superemitters of all ages and estimate the superemitter fraction.

The reviewer may be unaware that the emission factors of superemitters are already documented in Table 2-4.

[14]*A critical assumption is the assumed mix of vehicles by emissions standard, both at present, and into the future. I presume this is particularly important for road vehicles, but perhaps also for other sectors. An overview of these assumptions (particularly developed vs developing country) needs to be provided, with more detailed information in the supplement*

Reply:

In this work, we do not make simple assumptions about the mixture of vehicles by emission standards. The composition of the vehicle fleet is determined by the growth of fuel use, the retirement rate, the timing of emission standards, and the transition rate to superemitters. When new vehicles come into use to make up for the retirement of old vehicles or the increased demand for new vehicles, they follow the emission standards in force at that time. A fraction of existing older vehicles develops into superemitters, as determined by the transition rate.

Therefore, when we talk about assumptions of the vehicle fleet mix, we are talking about the assumptions of fuel trend, retirement rate, timing of emission standards, and transition rate to superemitters. This is the core of the SPEW-Trend model and is well documented in Yan et al. (2011). A brief summary was presented in this paper in section 2.2, pages 23381 and 23382. We have now added more information in the revised manuscript, as stated in the General Response.

[15] *I assume trucks treated separately from LDVs? If so, it would be useful to see some discussion and results for emissions of cars/light trucks vs freight trucks.*

Reply:

Yes, we have different treatments for LDVs and HDVs. As stated in section 3.1.1, we group on-road vehicles by light-duty gasoline vehicles (LDGVs), light-duty diesel vehicles (LDDVs), and heavy-duty diesel vehicles (HDDVs). LDVs and HDVs are distinguished by a separate treatment of retirement rate, timing of emission standards, and emission factors. Because this paper covers the whole transportation sector, we did not have space to say much about the specific results for LDVs and HDVs.

To comply with the requests of the reviewers, however, we have added Fig. S4 to show the fuel and emission shares of LDGVs, LDDVs, and HDDVs under the A1B scenario. This is discussed briefly in the last paragraph of section 4.1:

"…. Of all the CO and THC emissions from on-road vehicles, LDGVs contribute over 80% (as shown in Fig. S4)… 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%, respectively (Fig. S4). …."

[16]*Page 23384, section 3.2.1 It would be useful to provide slightly more details in this paper about those results. A brief discussion about the uncertainty in current off-road fuel use would be* *helpful, as would a brief description of how fuel use is extrapolated into the future. "and project future fuel consumption based on IPCC scenarios." is not sufficient description.*

Reply:

We have added more description about non-road fuel projections as well as the assumptions for modeling the non-road engine population in the revised manuscript. Please refer to the General Response

[17] *line 14-17 "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." – This is unclear. Should "bunker fuel" be inserted here to read "regional bunker fuel consumption estimate"?*

Reply:

We have changed this sentence to read: "There is no other consumption category in the IEA data that is large enough to include the difference between the regional bunker fuel consumption estimate and the IEA reported bunker fuel use."

[18] *line 17 " While we presume that the difference is unreported consumption, no adjustment to the IEA consumption data has been made for historical emission estimates." – This is a good discussion, but it is unclear, in the end, what was used in this work for bunker fuel consumption estimates. Please clarify. Were IEA base-year data used (which the literature seems to show are underestimates for many countries) or were other data used? If IEA data were used, then shipping emissions would likely be underestimated.*

Reply:

We used IEA data, so that the data source of fuel consumption is consistent with the other transportation modes. This sentence has been revised to read: "While we presume that the difference is unreported consumption, no adjustment to the IEA consumption data has been made for historical emission estimates; we use the IEA datasets to make sure that the source of historical fuel consumption is consistent with the other transportation modes"

[19] *p 23387 line 21 – can oxidation catalysts actually be used with high sulfur bunker fuels?*

Reply:

This sentence has been changed to read: "Engine exhaust emissions of methane (CH_4) and NMVOC are relatively low, and they can be reduced by optimizing the combustion process and oxidation catalysts for low-sulfur fuel (IMO, 2009)."

***[20]** p 23388 line 22 "which the sulfur content of marine fuels is still rather high," – This seems to implicitly assume that the MARPOL standards are not met?*

Reply:

We followed the sulfur content assumptions under scenario TS4 described in Eyring et al. (2005). In Eyring et al. (2005), TS4 is a business-as-usual scenario. The assumptions about future sulfur content and NOx reductions are the same as the IMO compliant scenario (TS3). They defined IMO compliant as a scenario, where future new vessels entering the fleet are equipped with techniques that comply with today's IMO regulations, depending on the rated engine speed.

***[21]** p 23389 line 19 "Electricity shares about 30 % of the global rail energy ..." – on final or primary energy basis? – awkward wording "Electricity shares about"*

Reply:

This sentence has been changed to read: "Electricity contributes about 30% of final energy for the global rail sector;"

***[22]** The statement "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." seems a little problematic given that there is not enough information in the paper to evaluate the assumptions about how stringently emissions controls were assumed to be enforced and the assumed retirement rate of vehicles. (There are equations in Table 1, but no results. A supplement table with age class fractions for historical and future years by region, and fraction of super emitters by region and year would be very helpful in this respect.)*

Reply:

Parameter values for retirement rate have been added to Table 1. New tables S6, S7, and S8 show the assumptions and dates of implementation of emission standards in different regions. We hope this extra information will help the reader to evaluate the assumptions about emission standards and retirement rate.

It is impossible for us to show the age class fractions by region and by year. We model a vehicle for every age, from its initial use to its retirement. In each region and year, there could be vehicles from ages 1 to 30 or even older. The dataset is potentially enormous.

***[23]** It is clear that these factors differ in different parts of the world. Also the effect of older vintages will vary by region. In many developing countries there are clouds of black smoke spewing from nearly every vehicle, most of them old and with effectively no emission controls.*

The retirement rate of vehicles appears to be very low. The bottom line is that sufficient information needs to be provided so that readers can make their own judgment in this respect.

Reply:

Two aspects of the work are pointed out in this comment: long vehicle lifetime (or low retirement rate) and late or no implementation of emission standards in developing regions. We think sufficient information has been provided to the reader. In our model, one of the main drivers of vehicle fleet turnover is the ratio of regional and global GDP per capita (as shown in Table 1), which represents the regional income level. The equation itself shows that when the regional income level is lower, the vehicle survival rate is higher for vehicles at the same age. Higher survival rate means longer vehicle lifetime, and allows old and degraded vehicles to remain in service. The reader can judge the status of emission standard implementation in developing regions with information shown in Tables S7 and S8. We argue that our representation of long vehicle lifetimes in low-income regions, with which the reviewer seems to agree, is important in determining the feasibility of policy mechanisms. Furthermore, we contrast this with the assertion of Reviewer 1 that our assumptions are “pessimistic.”

[24]*The later discussion points out differences between these estimates and GAINS being due to different vintaging assumptions. So more explicit information needs to be given so readers can evaluate this.*

Reply:

To address the reviewer’s comment, we have added the following discussion at the end of the second paragraph in section 4.3.2:

“…For example, while the GAINS model shows that LDGVs under Euro 2 standard still contribute over 50% of fuel consumption in 2010, the dominant LDGVs in our model are vehicles under Tier2-2007 standard. The GAINS model indicates slower retirement rates and more old vehicles in the fleet. ”

[25]*It would be useful in the above paragraph that a bit more discussion about the impact of emissions in developing vs developed countries. A sensitivity study for developed countries with alternative assumptions for vehicle retirement and standards enforcement (or other variables the authors find are important) would be valuable.*

These assumptions are uncertain, and need to be brought out in the literature so that the community can make progress on resolving some of these issue. But in order to do that, more details need to be provided when results are published.

Reply:

In this paper, we focus more on the big picture of emissions from all transportation; thus we do not discuss on-road vehicle emissions in too much detail. Discussion of the regional contributions to total on-road vehicle emissions, as well as the effects of regional income was presented in Yan et al. (2011).

The reviewer raised an important point about uncertainty analysis. We agree that the assumptions we made in the SPEW-Trend model contain uncertainties. That is why we recommended uncertainty analysis for the future study in section 5.2.3. A separate paper (Part II of the AE series [Yan et al. (2013)] is devoted to sensitivity and uncertainty analysis of this methodology. It has been submitted to AE and is presently under review.

***[26]** It appears that the only model assumptions that depend on scenario are fuel use (and, see below, therefore purchase rates)? This needs to be stated in the discussion (and methods) sections where emissions from the different SRES scenarios are presented. In reality, one would expect that emissions enforcement would tend to vary with the level of socio-economic development (with lower incomes societies, in general, lacking the regulatory infrastructure to enforce emission standards). This might add greater spread to the results. (Another way to ask this question is: it seems that, as far as I can guess from the manuscript that, for a given vintage of vehicle, emission factors are constant across the SRES scenarios in this study.)*

Reply:

(1) The model assumptions that depend on scenarios are not only fuel use, but also the socioeconomic variables, like GDP and population. This is already shown in Fig. 1, the schematic methodology for developing emission projections. We also include a brief statement in section 2.2.

(2) As already discussed in Yan et al. (2011), we first tried to investigate whether a Cox regression could be used to project the timing of emission standards based on GDP per capita, because this kind of model has been used to examine the timing of other environmental decisions (Kerr and Newell, 2003; Zahran et al., 2007; Jones and Branton, 2005). We found that the coefficients of GDP per capita were not significant if only technology-following countries were included, and were only significant if the first, technology-forcing countries were included. We therefore chose a more empirical method of estimating the timing of standards. The assumptions and schedule of emission standards are now summarized in Tables S7, S8, and S9.

(3) Emission factors for a given vintage of vehicles are not constant across scenarios. The average emission factors are determined by the composition of vehicle fleet, which depends on the following factors: growth of fuel use, retirement rate, timing of emission standards, and superemitter transition rate. Since these factors are driven by scenarios, the average emission factors change with scenario as well. When old vehicles retire, new vehicles will come into the fleet to make up the replacement and meet the demand of growth. The technology for these new vehicles is set by the emission standards in force in that year. The existing old vehicles degrade

because of aging, and some of them even develop to superemitters. The discussion about emission intensities across SRES scenarios have been made in Yan et al. (2011), section 4.4.

[27] *Higher rates of income growth would tend to lead to higher rates of vehicle purchases and a higher share of vehicles with more up to date emission control equipment. It appears, from reading Yan et al. 2011, that this effect is included in the model. But it this is not clear from the current text. Its an important point, and should be clarified. The extent to which this effect plays a role in the different future trends by scenario should be briefly discussed.*

Reply:

This comment is similar to the first part of comment [25], suggesting discussions about regional emission share and emission intensity. Again, the regional average emission factors, or regional emission intensities for on-road vehicles among scenarios for each region have been compared and discussed in Yan et al. (2011) in section 4.4. This paper does not include detail about regional differences to avoid repetition.

[28] *While it is useful to compare global emissions, more complete comparisons of regional estimates are needed, not just for two sample regions. This could be done in tabular form. The RCP scenarios, for example, are all benchmarked to a common year 2000 estimate (Larmarque et al. 2010). This paper has been widely cited, so a more detailed comparison here is needed. That dataset, for example, uses estimates of emissions from each country's internal inventory values for OECD countries. Are the estimates in this paper different from those? (Actually it would be useful to do this comparison using updated values – which are available in database format from the UNFCCC submissions from 1990- 2010. Look on the UNFCCC web site for "flexible queries") If these values are different, it would imply that country level estimates used for regulatory purposes may not be correct. This would be quite important if true. Alternatively, the differences could stem more from estimates in developing countries, where emissions are more uncertain (see also Granier et al. 2011). This also would be important to know.*

Reply:

Please refer to the General Response. We add the following after page 23393, lines 12:

"In this section, we compare our results with emissions in GAINS, IEA/SMP, and QUANTIFY models, none of which consider dynamic technological change. These three models are chosen because they include both historical and future emissions, provide emissions and corresponding fuel use, specify on-road and non-road in transportation sector, and make consistent assumptions among regions. Additionally, emissions from EDGAR, UNFCCC, and EMEP are compared to provide more insights."

***[29]** The text "RCPs have been developed for AR5, but they provide climate forcing pathways rather than prescribed changes in socioeconomic conditions." Needs to be corrected. The RCP scenarios also, of course, have socioeconomic assumptions. However, the more important point here is that the RCP scenarios, unlike the SRES, were not designed to provide a range of socioeconomic scenarios. So perhaps replace "prescribed changes", with "a range of socioeconomic assumptions". (3 of the four scenarios have very similar "central case" assumptions.) Also, the A2 scenario used in the submitted paper is rather out of date – the RCP4.5 is based on a revised A2 scenario with a lower population. This should probably be pointed out.*

Reply:

We accept the reviewer's suggestion and have changed the text accordingly; please refer to the response to comment [30]. van Vuuren et al. (2011) mentioned that RCP8.5 is based on a revised version of the SRES A2 scenario, but the reviewer said that RCP4.5 is based on a revised A2 scenario with lower population. This is a little confusing. We decided not to mention it in the manuscript.

***[30]**Perhaps even more important, and not mentioned here, is that three of the four RCP scenarios are climate policy scenarios. In some of these scenarios the structure of transportation is changed from reference case conditions, lowering pollutant emissions (see, for example, van Vuuren etal 2011). So they cannot be compared 1:1 with the other reference case scenarios otherwise shown. This needs to be made clear. Reference case emissions from the journal papers that describe the RCP scenarios could be used instead: these would be comparable. (Data could be requested from those authors.)*

Reply:

As mentioned in the response to comment [7], RCPs are publicly available.

To avoid confusion, we clarify that RCPs are climate policy scenarios at the beginning of the second paragraph in section 4.3.1. We have revised the statement as follows:

"RCPs have been developed for AR5. 'Rather than starting with detailed socioeconomic storylines to generate emissions and then climate scenarios', RCPs were developed by a parallel process which "begins with the identification of important characteristics for scenarios of radiative forcings for climate modelling" (Moss et al., 2010). RCPs 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). Note that while the four scenarios used in this work are all reference scenarios, three of the four RCPs are climate policy scenarios, which have the structure of transportation changed from reference case conditions to lower pollutant emissions (van Vuuren et al., 2011). ”

[31] *This statement "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." is not supported by any analysis. Even if one emissions factor is assigned per sector, as defined in the text (I suspect this is, indeed, the case for most if not all of these analyses) this could easily lead to either over or underestimates in trends. The actual direction of any bias would depend on how that emission factor was assumed to change over time.*

Reply:

We agree with the reviewer. We change this sentence to: “Specific details about RCP emission calculation process are not revealed and we do not have adequate information to make further exploration. The emission discrepancies between RCP scenarios and this work may depend on how emission factors are assumed to change over time.”

[32] *The authors state that: "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." I disagree. It would not only be relatively easy to at least compare energy consumption between scenarios, I believe it is rather crucial - given that the underlying scenarios used for this work are now about 15 years old. Once energy consumption is compared, this will give a strong indication if the differences are caused by differences in the trends in fuel consumption or differences in trends in emission factors.*

Reply:

We have deleted this sentence. We compare fuel consumption at global and regional levels in Fig. 3.

[33]*In comparing to other studies, it needs to be noted that for some of these other studies, emissions from non-road vehicles may not be included in the transportation sector. It would be useful to provide regional, annual values in the supplement that do not include non-road vehicles so that these results can be more easily compared to other studies.*

Reply:

As stated in the General Response and response to comment [28], we carefully chose the studies that specify non-road contributions. We are willing to share the regional annual data with readers who are interested, but it is too detailed to include in the supplement.

***[34]** The authors seem to be unaware that there is already an effort well underway to produce updated socio-economic pathways, the so-called SSPs. See Kriegler etal 2012 and Vuuren et al. 2012. This text needs to be updated to reflect these references.*

Reply:

We agree with the reviewer and have deleted the text on page 23398, lines 8-10, and added the following:

"There is already an effort underway to produce updated socioeconomic pathways, called Shared Socioeconomic Pathways (SSPs) (Kriegler et al., 2012; van Vuuren et al., 2012). When the SSPs are completed and available, it will be possible to compare the emission results with those driven by SRES scenarios. "

***[35]** The authors make a point at several places in the text about the assumptions made in order to provide annual data. This data should be supplied annually, at at least the region level, as this would be useful for many readers. (Perhaps in an excel supplement.)*

Reply:

As we state in the paper, we did calculate the emission estimates annually. But even at the regional level, this is a huge dataset with five variables (four pollutants and fuel consumption), 17 regions, more than 50 years, and four scenarios. It is better that we offer to share it with readers via ftp.

***[36]** Need to clarify if Total Hydrocarbons (THC) includes methane. One common nomenclature for this is NMVOC - authors should clarify if THC = NMVOC.*

Reply:

In this paper, we do not include methane in hydrocarbons. We add this clarification at the beginning of the paper when we first define THC.

***[37]** What are the assumptions for the fraction of superemitters? Is this constant over time and vintage?*

Reply:

Please refer to the response to comment [8e] for Referee #1.

***[38]** Is export of vehicles considered? (e.g., secondary markets?) If all new demand in developing countries is assumed to be made up of new vehicles this would likely overestimate emissions.*

Reply:

No, we do not consider the export of second-hand vehicles, simply because we can find no quantitative information about such markets worldwide. Probably, these markets are somewhat surreptitious and are not recognized by country or regional governments/statistical agencies. In our model, we assume that all new demand in both developed and developing regions is made up of new vehicles. If the secondary markets were to be included, we think the emissions would be higher than our current estimates.

We add the following sentences on page 23381, after line 26:

"…Secondary markets are not considered in this work. If they were to be included, the total emissions would be higher than our current estimates because of more effects of vintage vehicles."

fa

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Appendix A. Revised section 3.1 about on-road vehicles

3.1.1 Fuel consumption

To estimate gaseous emissions from on-road vehicles, this work applies the same set of fuel use and socioeconomic variables as was used in Yan et al. (2011) to estimate particulate emissions. 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). On-road vehicles are divided into three categories: light-duty gasoline vehicles (LDGV), light-duty diesel vehicles (LDDV), and heavy-duty diesel (HDDV) vehicles. The following assumptions are made to historical and future on-road fuel consumption: (1) historical fuel use up to 2005 is from IEA and is consistent with Yan et al. (2011); (2) gasoline is consumed by LDGVs, and the growth rate after 2005 follows the growth rate of transportation light oil in IMAGE; (3) diesel is consumed by both LDDVs and HDDVs, and the growth rate after 2005 follows the growth rate of transportation heavy oil in IMAGE; (4) a constant ratio of fuel use by LDDVs and LDGVs is used to estimate diesel use by LDDVs, and the regionally dependent ratios are from the IEA/SMP transport model for the year 2000; (5) HDDVs consume the rest of the diesel. The composition of the light-duty fleet may in fact change and brings uncertainties to the total emissions, especially for CO and THC emissions, which are dominated by LDGV vehicles. We summarize the above assumptions of historical and future fuel use in Table S2 in SI.

3.1.2 Major relationships

While the assumptions about modeling on–road emission projections within the framework of SPEW-Trend were discussed extensively in Yan et al. (2011), this section briefly summarizes the essential details, including: retirement rate, implementation of emission standards, degradation rate, and superemitter transition rate.

Retirement rate

Based on extensive investigations of the literature on vehicle retirement (e.g., Parks, 1979; Greenspan and Cohen, 1999), two main factors are chosen to determine retirement rate: vehicle age and the balance between vehicle cost and vehicle repair. The latter factor is dependent on regional income level and is represented by the ratio of regional and global GDP per capita. The equations used to determine retirement rate are shown in the footnote of Table 1, and the parameters are derived from vehicle fleet information. Fig. S1 (a) shows examples of survival rates corresponding to different income levels.

Implementation 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 first 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 S7, S8, and S9 show the detailed assumptions and projected adoption dates of emission standards.

Degradation rate

The general pattern of degradation rate is modified from Ubanawa et al. (2003). 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). 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 the average PM emission factors of LDDV Euro I in two regions.

Superemitter transition rate

The number of superemitters existing is determined by a superemitter transition rate (shown in the footnote of Table 1 and Fig. S1 (b)), which represents the rate at which normal vehicles become superemitters. The parameters are chosen so that the equilibrium values of superemitter fraction are approximately the same as those used in Bond et al. (2004). Fig. S2 shows equilibrium superemitter fractions of HDDVs in different regions between 2010 and 2050. The number of superemitters, like any component of the vehicle population, depends on the balance between the introduction of new vehicles and the retirement of old vehicles; thus the numbers of superemitters and their fraction of the total fleet are indirectly influenced by income level.

Appendix B. Revised section 3.2 about non-road engines.

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.

Historical diesel consumption until 2010 in agriculture/forestry, industrial, and construction and mining (CM) sectors from IEA (2012a, b) is used. Gasoline consumption, on the other hand, is not available for most countries. We calculate the ratios between diesel and gasoline fuel for each region from countries where both diesel and gasoline fuels are available and use these ratios to estimate gasoline consumption.

For the industrial and CM sectors, future fuel use follows the growth rates from IMAGE after 2010. For the agricultural sector, where future fuel use is subsumed in other sectors in IMAGE, fuel consumption is estimated by developing relationships between agricultural diesel fuel consumption per crop area (diesel fuel intensity) and agriculture GDP per crop area (agricultural productivity).

3.2.2 Population model and emission factors

The principles used in the technology modeling approach for non-road engines are the same as those described by Yan et al. (2011) for on-road vehicles. The derivation of the parameters required for non-road emissions are discussed in this section.

Because emissions from non-road engines are closely 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 (high power 4-stroke, low power 4-stroke, and 2-stroke engines). These groups are consistent with the categories used in U.S. and European Union emission standards (Dieselnet, 2012; U.S. EPA, 2012c).

Retirement rates

Following the approach used to model on-road vehicles, we use a logistic function to fit the scrappage curve provided by U.S. EPA (2005). As listed in Table 1, survival rate (*Su*) is a function of cumulative service (*s*) for non-road engines:

$$Su(s) = \frac{1}{1+\exp\left[\alpha_{ret}\left(s/L_{50}-1\right)\right]} \qquad (3)$$

where α_{ret} is acquired from curve fitting of the scrappage rate in U.S. EPA (2005), and L_{50} is the median service hours for non-road engines. .

Cumulative service (s) is the total engine operation time, in hours, accumulated over the life of the engine (U.S. EPA, 2010a). In SPEW-Trend, we specify the annual service and keep track of the cumulative service as the engine ages. Annual service hours are determined based on engine size (small, medium, large, 2-stroke, low power 4-stroke, and high power 4-stroke) and type (industrial, construction and mining, agriculture). Annual service data are developed based on data in the NONROAD model (U. S. EPA, 2010a) and EEA (2012a).

Median service hours (L_{50}) are the cumulative service at which 50% of the engines have retired. We used the median service hour of different engine sizes in the U.S. (U.S. EPA, 2010a). As for on-road vehicles (Yan et al., 2011), we assume that the median service hour depends on the ratio of regional and global GDP per capita. A linear relationship is derived between median service hours and the ratio of GDP per capita based on available data in several countries (Japan, Korea, India, Brazil, Egypt, Argentina, and U.S.). It is used to estimate the survival rate in regions without observations.

Implementation of emission standards

Few countries have regulated emission standards for non-road engines. Two well-known sets of emission standards for diesel engines are used in the United States (“Tiers”) and Europe (“Stages”).Other regions have elected to follow the United States (Canada, Central America and South Asia) or European (other regions) progression, although with different implementation schedule. For regions without any plans of non-road emission standards, we assume that emission standards for diesel engines will be implemented 20 years after emission standards of HDDVs. The first emission standard for non-road diesel engines is projected to be implemented in 2015 in South America, Eastern Europe, and Oceania (soonest possible considering that no implementation plans exist in these regions in 2013).

Emission standards for non-road gasoline engines have already been implemented for all engine sizes in the U.S. (U.S. EPA, 2012b) and for small engines in Europe, Canada, and Australia. The U.S. standards are known as “Phase 1”, “Phase 2”, and “Phase 3”. In regions without emission standards for non-road gasoline engines, we assume that the standards will be implemented in the same year as that for non-road diesel engines. The exception is that high power 4-stroke gasoline engines are assumed to be regulated 7 years after the first gasoline standard, based on the standard schedule in the U.S.

Emission factors for new engines

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, 2012;

U.S. EPA 2010b); those for future engines with advanced emission standards are mostly not available. For new diesel engines without standards, we average emission factors corresponding to engine sizes from EEA (2012) and U.S. EPA (2010b), while emission factors for Tier 1 and Stage 1 engines are from U.S. EPA (2010b). For new gasoline engines, we estimate emission factors for new engines without standards and for Phase 1 standards based on datasets in U.S. EPA (2012b). We use reduction factors (Ntziachristos and Samaras, 2001) to estimate the appropriate emission factors for new engines under tighter emission standards, using the same methodology that was developed for on-road vehicles in Yan et al. (2011).

Degradation rates

Similar to on-road vehicles, emission factors for non-road engines (except superemitters) are separated into three phases (EEA, 2012; U.S. EPA, 2010b; U.S. EPA, 2010c) including durability, degradation, and stabilizing phases. Fig. S1 (c) shows an example of PM emission factor degradation for agricultural medium diesel engines under the Stage I standard. The difference for non-road engines is that the first phase (durability phase) includes periods when the emission factors increase from new-engine emission levels to the highest level without exceeding the standards, because these engines are still under emission warranty (U.S. EPA, 2012b) and non-road emission standards require emissions of aged engines to be lower than standards during specific periods (U.S. EPA, 2010b, c). 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.

Superemitter Emission Rates

The superemitter transition rate is represented by a logistic function, as shown in the footnote of Table 1. The parameters are chosen by comparing the superemitter population estimated by Bond et al. (2004). We assume that emission factors for non-road superemitters have the same characteristics as those for on-road superemitters, since there has been little emissions testing of non-road engines. The basic assumption is that the emission factor ratio between superemitters and normal non-road engines under the first level of emission standards (e.g., Tier 1 and Stage 1) is the same as that for on-road vehicles.

Appendix C. Revised and added figures

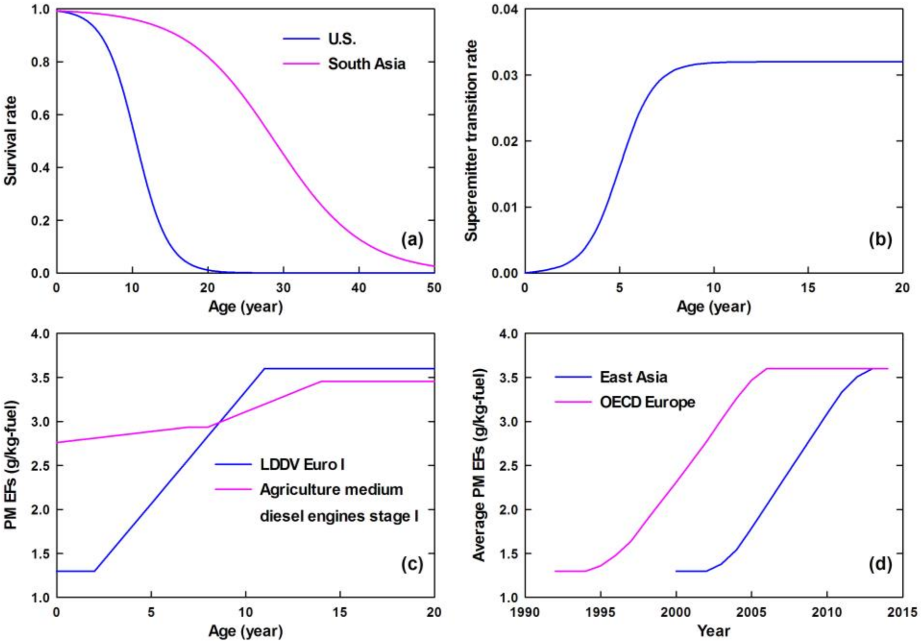

Fig. S1. (a) Survival rate of HDDVs in the U.S. (rgdp =4.11) and South Asia (rgdp = 0.27) in year 2030 under scenario A1B; (b) superemitter transition rate; (3) degradation of emission factors for LDDV Euro I and agriculture medium diesel engines Stage I; (d).average PM emission factors of LDDV Euro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

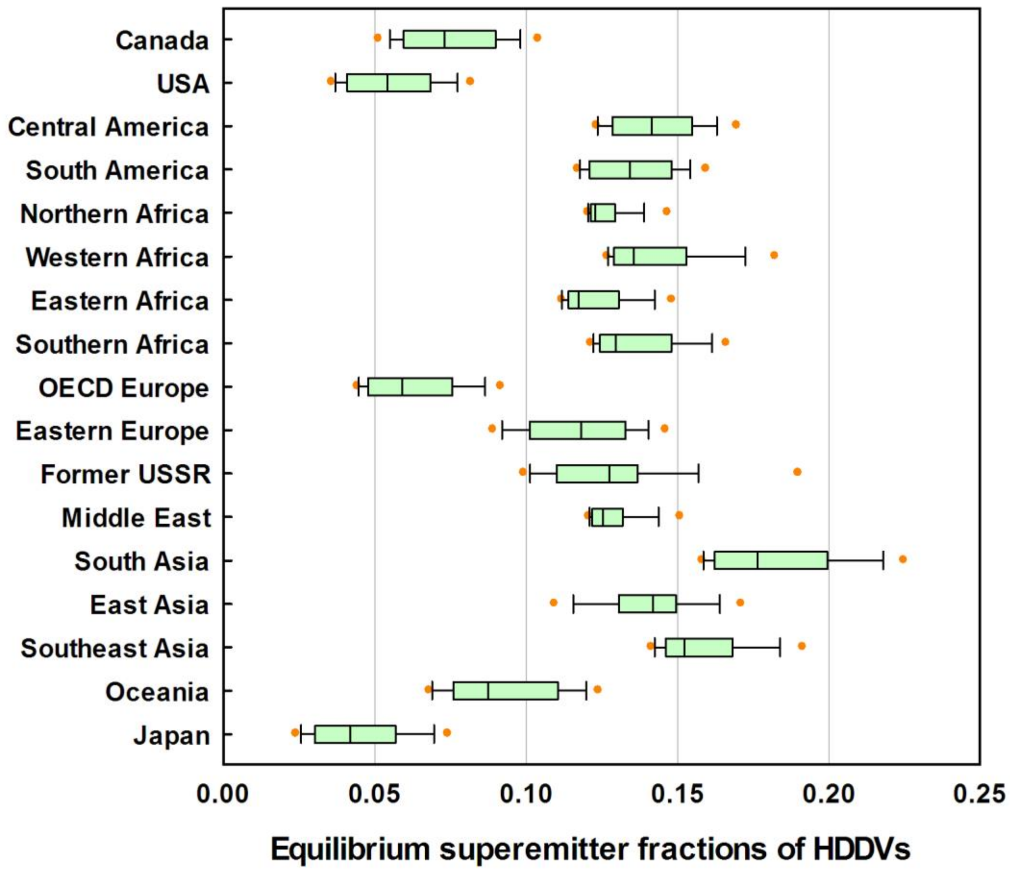

Fig. S2. Equilibrium superemitter fractions of HDDVs in different regions between 2010 and 2050 by varying parameters

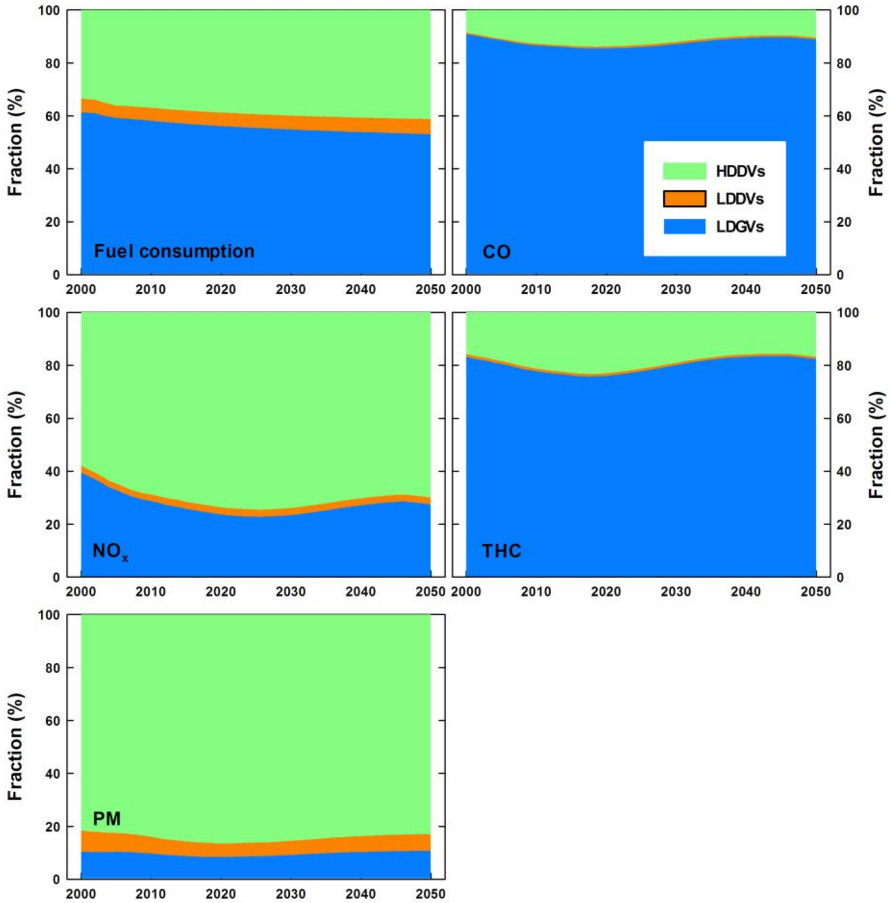

Fig. S4. Contributions of LDGVs, LDDVs, and HDDVs to fuel consumption, and emissions of CO, NOx, THC, and PM under scenario A1B.

Appendix D. Revised and added tables

Table 1. Relationships and parameters used in the SPEW-Trend model for on-road vehicles and non-road engines.

Relationship	Parameter	Description
Survival rate (Su) [a, b]	s [c]	age (or cumulative service hours)
	α_{ret} [d]	intercept, shape factor related to the onset of significant retirement
	L_{50}	Median age or median service hours, at which 50% of the vehicles have retired
	β_1 [d]	age coefficient
	β_2 [d]	income coefficient [e]
Adoption of emission standards	First year when advanced emission standards (Euro I or U.S. Tier 1) are applied	
	Time intervals between emission standard introduction	
Superemitter transition rate (Tr) [f]	α_{sup} [g]	shape factor; determines slope of the curve
	$L_{50,sup}$ [g]	vehicle life at which the rate becomes half of the maximum
	gain [g]	maximum rate of superemitter transition
Degradation rate (DR) [h]	EF_{new}	emission factor for new vehicles
	EF_{es}	emission factor, the same as emission standard
	EF_{max}	maximum emission factor
	s_{deg}	age that emission factor starts to degrade
	s_{stab}	age that emission factor starts to stabilize

[a] $Su(s)=\frac{1}{1+\exp\left[\alpha_{ret}\left(s/L_{50}-1\right)\right]}$; α_{ret}/L_{50} is linearly related with rgdp, and can be expressed as:

$\alpha_{ret}/L_{50,ret}=\beta_1+\beta_2\times rgdp$, then the survival rate function is: $Su(s)=\frac{1}{1+\ \exp\left[-\left(\alpha_{ret}+\beta_1\times s+\beta_2\times rgdp\times s\right)\right]}$

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

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

[d] For LDVs, $\alpha_{ret}=5.34$, $\beta_1=-0.24$, and $\beta_2=-0.029$; For HDVs, $\alpha_{ret}=4.93$, $\beta_1=-0.15$, and $\beta_2=-0.078$;

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

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

$$Tr(s)=\frac{gain}{1+\ \exp\left[\alpha_{\sup}\left(1-s/L_{50,\sup}\right)\right]}$$

[g] $\alpha_{sup}=5.5$, $L_{50,sup}=5.0$, and $gain=0.032$

h

$$DR_{on-road}(\mathrm{s}) = \begin{cases} 1, & \text{if } s \le s_{\deg} \\ \dfrac{EF_{\max} - EF_{new}}{s_{stab} - s_{\deg}} \times \dfrac{s - s_{\deg}}{EF_{new}} + 1, & \text{if } s_{\deg} < s < s_{stab} \\ \dfrac{EF_{\max}}{EF_{new}}, & \text{if } s \ge s_{stab} \end{cases} \quad DR_{non-road}(\mathrm{s}) = \begin{cases} \dfrac{EF_{es} - EF_{new}}{EF_{new}} \times \dfrac{s}{s_{\deg}} + 1, & \text{if } s \le s_{\deg} \\ \dfrac{EF_{\max} - EF_{es}}{EF_{new}} \times \dfrac{s - s_{\deg}}{s_{stab} - s_{\deg}} + \dfrac{EF_{es}}{EF_{new}}, & \text{if } s_{\deg} < s < s_{stab} \\ \dfrac{EF_{\max}}{EF_{new}}, & \text{if } s \le s_{stab} \end{cases}$$

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

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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 dominate 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 I][a]	Euro II [Tier II-04] [a]	Euro III [TierII-06] [a]	Euro IV [TierII-07] [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.

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

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

Table S17. Fuel consumption (unit: $Pgyr^{-1}$) by region and transport mode under four scenarios (A1B, A2, B1, and B2) in year 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