Review comments on
"Global emission projections for the transportation sector using dynamic technology modeling"
by F. Yan et al., ACPD 13, 23373–23419, 2013

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.

Summary
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).

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.*

Emissions from off-road machines
- 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.

- 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. What evidence do the authors have to assume that by far most "non-road" is unregulated and unabated gasoline powered engines?
  - If most "non-road" is gasoline engines, how come that NOx and PM emission factors are rather comparable to the diesel powered rail engines?
  - 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? Why does the iEF for NOx (and for PM) decrease by a factor 2 and 4 until 2030 and 2050?
- 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 revisions transferred as necessary).

Modeling of emission factors for road vehicles

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 vehicles would turn into super emitters. It is the same approach as in (Yan et al. 2011) and supposedly the same parameters are used. (Please clarify and document in the SI.) The assumptions 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. As the scenario modeling is essential for the results, it is necessary to discuss some issues of consistency and differences in interpretation:

On the use and interpretation of SRES scenarios

- 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 scarce 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).
- The authors note themselves that "environmental legislation" is the "more important factor" determining emission rates (p 23376, 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).

- In all their scenarios the vehicle technology would differ from 2020 onwards from the most advanced standard (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.
- 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 developments as intended by the different scenarios and storyline in SRES.

On the fleet turnover model

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 a. 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 America 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.
- 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?
- 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".
- 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.
- 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

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.

- 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).

On emission deterioration with vehicle age

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.

- 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).
- 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.
- 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. 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,

leading to calculated high emissions. I suggest to review and reduce deterioration rates, and to add a note in the 'caveats' section.

- Please document the assumed age parameters s_deg and s_stab.

On super-emitters

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.

- It is essential to document which share of fuel consumption is allocated to super-emitters in the different regions over time.
- Do assumptions differ between scenarios? If not, why not?
- 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?
- 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.
- 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.
- 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.

- (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.
- 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.
- 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.
- 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.
- Do you also assume super-emitters for the non-road modes? What's the evidence? Please document assumptions.

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.

On rail, shipping and aviation

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.

On scenarios

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.

Review conclusion

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).

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.

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.

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.

Comments and suggestions on presentation:

- 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.
- 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.

- 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.
- Table 1 becomes very small print. Please increase font size or split in two tables.
- 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.
- Fig 3: Add results from QUANTIFY for scenarios A2 and B2 and discuss.

Some detailed questions:

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.

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.

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.

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.

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.

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.

Footnote a: Formula seems to lack a "-".

Implied emission factor

Implied emission factor

		2010	A1B 2030	A2 2030	B1 2030	B2 2030	A1B 2050	A2 2050	B1 2050	B2 2050
CO **g/kg fuel**	On-road	57.3	26.9	26.2	28.0	27.5	32.7	26.6	33.7	29.6
	Non-road	143.6	171.1	154.3	169.0	157.4	186.8	168.1	185.6	172.7
	Shipping	4.8	4.8	4.8	4.7	4.7	4.7	4.7	4.7	4.7
	Aviation	8.0	5.3	5.2	5.3	5.2	3.4	3.4	3.4	3.4
	Rail	11.7	9.3	9.3	9.1	10.4	6.4	6.3	6.4	6.1
	Total	55.5	34.8	32.6	35.1	35.1	35.8	31.2	35.9	33.7
NOx **g/kg fuel**	On-road	14.8	6.7	6.7	7.0	7.2	7.7	6.3	7.9	7.3
	Non-road	40.4	18.8	20.4	20.2	18.9	10.4	10.7	11.4	11.2
	Shipping	64.8	55.1	54.8	53.9	54.0	49.6	49.3	49.6	49.6
	Aviation	12.6	11.3	11.6	10.7	11.2	9.7	11.5	7.9	10.0
	Rail	53.0	38.7	38.7	38.1	43.4	26.6	25.9	26.1	25.6
	Total	22.7	13.5	14.3	14.7	15.3	13.9	12.8	15.3	15.8
THC **g/kg fuel**	On-road	7.1	3.2	3.2	3.4	3.4	4.0	3.2	4.1	3.7
	Non-road	19.5	19.1	17.3	19.2	17.9	21.9	19.2	21.9	20.6
	Shipping	5.0	4.9	4.8	4.8	4.8	4.7	4.6	4.7	4.7
	Aviation	1.3	0.7	0.6	0.7	0.6	0.3	0.3	0.3	0.3
	Rail	8.3	7.1	7.2	7.0	8.0	4.3	4.3	4.3	4.2
	Total	7.6	4.6	4.4	4.8	4.8	4.9	4.2	5.1	4.9
PM **g/kg fuel**	On-road	0.9	0.4	0.4	0.4	0.4	0.4	0.3	0.5	0.4
	Non-road	5.1	2.8	3.0	3.0	2.8	2.0	1.9	2.1	2.0
	Shipping	5.5	5.3	5.3	5.2	5.2	5.0	5.0	5.0	5.0
	Aviation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Rail	7.0	3.9	3.8	3.8	4.4	0.9	0.9	0.9	0.8
	Total	1.8	1.1	1.2	1.2	1.3	1.1	1.0	1.2	1.3

Trend in Implied emission factor vs. 2010

		2010	A1B 2030	A2 2030	B1 2030	B2 2030	A1B 2050	A2 2050	B1 2050	B2 2050
CO	On-road		47	46	49	48	57	46	59	52
g/kg fuel	Non-road		119	107	118	110	130	117	129	120
	Shipping		100	100	99	98	99	98	99	99
	Aviation		66	65	67	65	43	43	43	43
	Rail		80	80	78	89	54	54	54	52
	Total		63	59	63	63	65	56	65	61
NOx	On-road		45	45	47	48	52	42	53	49
g/kg fuel	Non-road		47	50	50	47	26	27	28	28
	Shipping		85	85	83	83	77	76	77	76
	Aviation		89	92	85	89	77	91	63	79
	Rail		73	73	72	82	50	49	49	48
	Total		59	63	65	67	61	56	67	69
THC	On-road		45	45	47	48	56	45	58	52
g/kg fuel	Non-road		98	89	99	92	113	99	113	106
	Shipping		97	96	95	95	92	92	92	92
	Aviation		53	51	53	52	26	27	26	25
	Rail		85	86	84	96	52	52	51	50
	Total		60	58	63	63	65	56	67	64
PM	On-road		44	46	48	49	51	39	53	46
g/kg fuel	Non-road		55	58	59	55	40	37	41	39
	Shipping		96	96	94	94	91	91	91	91
	Aviation		100	95	100	97	99	102	102	100
	Rail		56	55	54	63	13	13	13	11
	Total		62	66	70	73	60	55	70	72

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