Effects of mitigation policies on future PM emissions from on-road vehicles

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Abstract

The purpose of this work is to provide an understanding of the potential benefits of policies in addressing global and regional particulate matter (PM) emissions in the future. A dynamic model of vehicle population linked to emission characteristics, SPEW-Trend, is used to make the emission projections and policy evaluations.

Two mitigation measures, scrappage of vehicles and retrofit to advanced control technology, are explored to examine potential PM emission reductions from on-road vehicles. The simulations show that scrappage can provide more emission reduction as soon as the measure begins, while retrofit reduces more emissions in later years when very advanced technology becomes available in most regions. With the consideration of uncertainties, scrappage and retrofit reduce emissions by 22-49% and 9-23%, respectively, within 90% confidence interval under medium scenarios in the year 2030.

1. Introduction and rationale

1.1 Black carbon reduction

After carbon dioxide (CO_2) and perhaps methane (CH_4), black carbon (BC) provides the second or third largest positive radiative forcing (RF) [*Jacobson*, 2000; *Sato et al.*, 2003; *Ramanathan and Carmichael*, 2008], which makes it a significant contributor to global warming and responsible for about 0.3^{o}C of historical warming [*Jacobson*, 2004; *Bice et al.*, 2009]. Thus, BC reductions may help to cool the climate. Further, BC reduction has substantial benefits in the sensitive snow-covered regions, e.g., Arctic, and the Himalayas, and could avoid great premature deaths and loss of global food product [*UNEP*, 2011]. Because BC is a component of particulate matter (PM), BC reductions have been historically approached by PM control programs [*Arctic Council*, 2011].

There are several reasons to consider BC reduction in mitigation policy. BC has a shorter lifetime (days to weeks, compared with 30-95 years for CO_2) and does not accumulate in the atmosphere, thus its removal can change global temperature rapidly and it presents a mitigation opportunity with very short delay between action and effects [*Bond*, 2007; *Ramanathan and Carmichael*, 2008; *Baron et al.*, 2009; *Kandlikar et al.*, 2010]. Reducing BC can also improve air quality so that benefit human health, largely in the developing world [*Grieshop et al.*, 2009]. Thus**,** it is a 'win-win' strategy to mitigate BC emissions. However, this does not mean that BC can substitute for CO_2 as the only target in mitigation policies; it will still be necessary to reduce CO_2 emissions in the long term. BC mitigation is a relatively quick opportunity to limit global warming and may buy time for research and development (R&D) to deliver cheaper options for CO_2 emission reduction.

Diesel vehicles and engines are ideal candidates for black carbon control. The reasons are: (1) the exhaust PM emissions from diesel vehicles has very low OC/BC which means a greater warming effect per unit mass of BC ; (2) technologies to control diesel emissions are available, for example, diesel particulate filter can reduce PM up to 90%; (3) reducing emissions from diesel vehicles can achieve substantial co-health benefit.

However, there is deficiency in the determination of emission reduction potential from on-road diesel vehicles in the future, especially with consideration of uncertainty.

1.2 Mitigation policies

Although regulatory steps have been taken to make new vehicles cleaner and these steps have managed to decrease emissions in spite of growth in fuel use [*Yan et al.*, 2011], the previous work has shown that it is the older vehicles and the superemitters that make by far the greatest contribution to total PM emissions. From the point of view of PM emissions, vehicles built to the most advanced emission standards (e.g., Euro VI and US Tier 2007) are almost as clean as any of the new alternatively-fueled vehicles mentioned above (e.g., hybrid or electric vehicles). Therefore, although mitigation measures that involve new technologies and new fuels for new vehicles may have significant advantages in other areas, they may not lead to a greater decline in PM emissions in the future. For this reason, we examine the effects of two mitigation measures that focus on reducing the emissions from the existing stock of older, polluting vehicles: scrappage and retrofit.

1.2.1 Scrappage

A program of scrappage, also known as accelerated retirement, refers to the replacement of old or high-emitting vehicles with newer ones that emit less pollution, before their owners would otherwise retire them from use. Several countries, states, and local agencies have adopted accelerated vehicle retirement programs [*Dill*, 2001; *Van Wee et al*, 2011]. Scrappage programs typically target older vehicles, yet replacement of newer vehicles that have been poorly maintained and that become superemitters may provide more benefits if those vehicles are used often [*Bice et al.*, 2009].

Scrappage programs that aim to eliminate old and high-emitting vehicles at national and local levels have been evaluated by several studies [*Lenski et al.*, 2010; *Lumbreras et al.*, 2008; *Van Wee et al.*, 2000; *Lelli et al.*, 2010]. However, few studies have addressed PM emissions [*Lumbreras et al.*, 2008], and none have done so at global level. This work will fill that gap by studying global PM emission reductions that could be generated by hypothetical scrappage programs. It is the first attempt to evaluate the effects of a long-term scrappage program at global scale.

1.2.2 Retrofit

The term "retrofit" is broadly defined to include any technology, device, fuel, or system that, when applied to an existing engine, achieves emission reductions beyond that required by regulations at the time of a vehicle's or engine's certification. Different retrofit technologies (e.g., Diesel Particle Filter (DPFs) and Diesel Oxidation Catalysts (DOCs)) play different roles in emission reductions. The selection should be based on the desired reduction in emissions, applicability, and cost. Retrofit programs have been implemented in some countries or states and have proved to be an efficient way to reduce PM emissions from diesel vehicles [e.g., *CARB*, 2008]. This requires retrofit or replacement of older in-use engines.

The purpose of this work is to provide an understanding of the potential benefits of policies in addressing global and regional PM emissions from on-road vehicles in the future. Although both the global economic trajectories and the assumptions of mitigation policies are simplified, the modeling results will be used to address the following questions:

(1) What contribution can scrappage and retrofit programs make to improvements in global emissions over the coming decades?

(2) In what regions are such programs most and least effective in reducing emissions, and what features of the vehicle fleet cause these results?

(3) Given uncertainties in the parameters describing the dynamic vehicle fleet in the coming decades (which have been discussed in *Yan et al.*, [2011] and [2012]), what is the level of confidence in the projected emission reductions due to these potential policies?

2. *Method*

2.1 SPEW-Trend model

We calculate future emissions and their uncertainties within the framework of the Speciated Pollutants Emission Wizard (SPEW)-Trend model [*Yan et al.*, 2011], which represents population dynamics and categorizes emitters into different groups by technologies. Although different control approaches are sometimes used to meet the same emission standard, they are grouped as one technology in this work, since they cause similar changes in emission factors. As used in this work, the term "technology" encompasses not only measures (e.g., emission standards) that can reduce emission factors, but also the contributions of poorly tuned or defective vehicles (e.g., superemitters) that can increase emission factors. SPEW-Trend keeps track of technology stock over time, including fuel consumption growth rates, vehicle retirement rates, timing of emission standards, emission degradation rates, and the transition of old vehicles to superemitters. Equations and detailed description about each of the governing relationships are given in *Yan et al.* [2011].

2.2 Policy assumptions

The analysis in this work does not aim to identify emission reductions by exact mitigation policies that will be taken in the future, as both policies and future economic trajectories are unknown; nor does it explore policies to achieve fixed target values of reduction. Rather, it seeks to identify programs that are the most promising, even in the face of uncertainty and varying economic circumstances.

Scrappage and retrofit programs have been implemented in some countries or states. However, unlike emission standards, complete information about the program targets, implementation dates, accelerated retirement rate or retrofit rates are neither available nor discernible from program data. Yet these parameters are key inputs needed to analyze potential emission reductions caused by mitigation policies. Further, the exact situation may depend on factors such as government R&D effort and enforcement, cost effectiveness of each program, and pressure from global climate policies. We therefore adopt an approach similar to that of scenario developers: we make reasonable assumptions that simulate the goals of mitigation programs. These assumptions will be represented as changes in model parameters.

2.2.1 Scrappage

The principle of scrappage programs is that new technologies with lower emissions replace older technologies with higher emissions, so that low-emitting technologies gain a greater share of fuel consumption and the fleet-average emission is reduced. Traditionally, scrappage programs are adopted only during a specific period, targeting old vehicles or "clunkers"; but the effect of emission reduction would decrease with the gradual disappearance of target vehicles.

For that reason, we include multi-stage programs in this work. Here “multi-stage” implies a series of program components that are successively implemented, that target the remaining highest emitters. For example, the retirement rates of both uncontrolled vehicles and vehicles with advanced emission standards would be accelerated during successive periods.

Scrappage policies will be described using four major parameters in this work: (1) vehicle targets, which mean levels of technology or emission standard in this work, (2) gap-year, which refers to the timing difference between adoption of more advanced emission standards and adoption of scrappage; (3) start year (calendar year), which determines the timing of policy adoption, and (4) rate of accelerated retirement.

2.2.2 Retrofit

We treat only diesel vehicles as targets of retrofit program. This is because PM emission factors of gasoline vehicles are much lower, so retrofit technologies (e.g., DPFs and DOCs) are mainly developed for diesel vehicles. Besides fuel, another limitation of retrofit is the existing engine. Verified on-road diesel retrofit technologies promoted by U.S. EPA and CARB are only applicable to vehicles produced after 1993 in the USA [*U.S. EPA*, 2011; *CARB*, 2008]. Older vehicles might have emissions that are high enough to overwhelm the control devices, or they may not be able to support operation of the retrofit devices for other reasons. Therefore, it is assumed that diesel vehicles with older engines cannot be retrofitted. “Old engines” here are consistent as that defined in *Yan et al.* [2011] and refer to vehicles before Tier I for LDDVs or before 1993 standards for HDDVs under U.S. standards, and vehicles before Euro I under European standards.

The targeted vehicles could be retrofitted to Euro V or VI under European emission standards, or to 2007 standards under U.S. emission standards. Aftertreatment technologies begin to penetrate after Euro IV and become prevalent when Euro V and VI, or 2007 U.S. standards are required. Thus retrofit technology would be adopted only when these highly advanced emission standards are available.

Similar to scrappage programs, the gap-year concept is also used for retrofit program to indicate how long retrofit programs are delayed after the adoption of advanced emission standards. The combination of lag-year (the timing difference between emission standards) and gap-year (the timing difference between adoption of more advanced emission standards and adoption of retrofit policy) ensures that new vehicles are not retrofitted until they reach a certain age.

There is very little information on the penetration of retrofits through the old vehicle fleet, since such programs have not been applied in entire nations with unlimited capacity. As the purpose of this work is to estimate the quantity and rate of emission reductions, we assume the retrofit rate to be 0.2, 0.5 and 0.8 for three different cases in order to compare with our scrappage program assumptions. Here “retrofit rate” means the probability that the targeted vehicles are recognized and retrofitted to desired emission standards. In the model world, if both retrofit and scrappage programs are operating, then the scrapped vehicles are removed from the population before the retrofits occur.

2.3 Scenarios chosen for policy analysis

Based on variations in policy assumptions mentioned above, the scrappage policy is described by four major parameters: vehicle targets, start calendar year, gap-year and accelerated retirement rate. The retrofit policy is described by five major parameters: vehicle targets, start calendar year, gap-year, retrofit rate and equivalent retrofit vehicle, where the first three parameters are similar to those in the scrappage programs.

Four scenarios will be compared for scrappage programs and five for retrofit policies in scenario analysis. The baseline scenario has no defined scrappage or retrofit policy. “Best” and “Worst” scenarios refer to the most and least aggressive programs, and “Medium” scenarios (one for scrappage and two for retrofit) are intermediate between the two. Table 1 and Table 2 provide an overview of the cases for scenario and sensitivity analyses. Fast scrappage policy scenarios are designated with the prefix FS_ (e.g. “FS_Best”) and retrofit policy scenarios have the prefix Retro_ (e.g. “Retro_Worst”).

Table 1. Parameters in scenario analyses for fast scrappage (FS) policy

Case Name	Description	Vehicle targets	Start Year	Gap-Year (Gy)	Accelerated Retirement Rate
Baseline	without any policy	-	-	-	-
FS_Best	Best case for scrappage	All vehicles	2010	0	0.8
FS_Medium	Medium case for scrappage	All vehicles	2010	5	0.5
FS_Worst	Worst case for scrappage	Superemitters only	2015	10	0.2

Table 2. Parameters in scenario analyses for retrofit (Retro) policy

Case Name	Description	Vehicle targets	Start Year	Gap-Year (Gy)	Retrofit Rate	Equivalent retrofit vehicle
Baseline	without any policy	-	-	-	-	-
Retro_Best	Best case for retrofit	All diesel vehicles with new engines	2010	0	0.8	Euro VI
Retro_Medium1	Medium case 1 for retrofit	only HDDVs with new engines	2010	5	0.5	Euro VI

Retro_Medium2	Medium case 2 for retrofit	only HDDVs with new engines	2010	0	0.2	Euro VI
Retro_Worst	Worst case for retrofit	Only HDDV superemitters with new engines	2015	10	0.2	Euro V

Yan et al. [2012] showed that the absolute value of emissions and relative growth rates are also uncertain due to uncertainties in vehicle fleet, even in the absence of mitigation policies. In order to examine the effectiveness of mitigation policies in light of this uncertainty, each member of the Monte Carlo simulations described in *Yan et al.* [2012] is repeated, but the medium scenario mitigation policy is applied to the program-related parameters. Scenario parameters remain fixed (deterministic).

3. *Results and discussion*

3.1 Scenario analysis

3.1.1 Scrappage

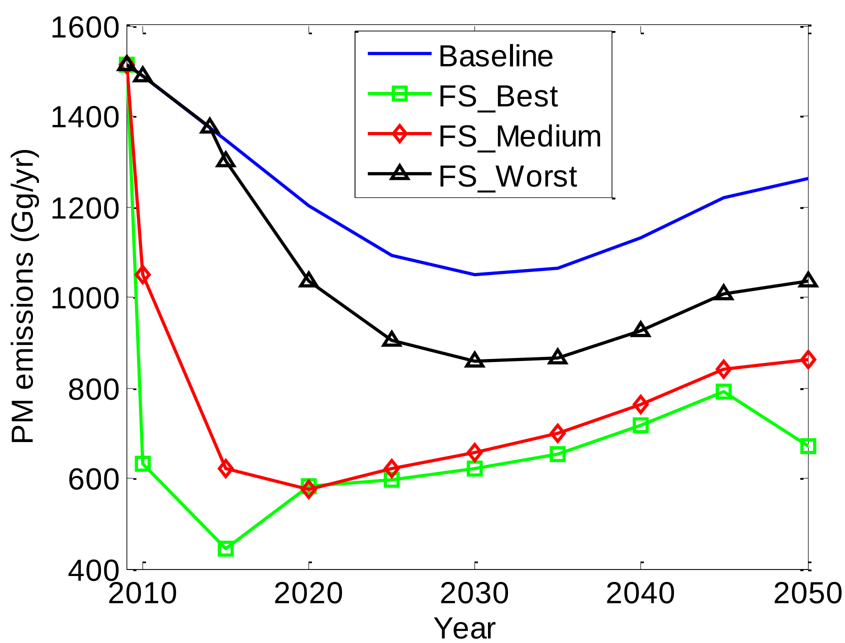

Figure 1. Emission projections with three scrappage policy scenarios in A1B. The scenarios FS_Best, FS_Medium and FS_Worst are defined in Table 1. The “best” or “worst” means best or worst for emission reduction

Figure 1 shows emission projections with the three scrappage policy scenarios described in Table 1. These policies represent varying degrees of aggressiveness ("Best" is most aggressive and "Worst" is least aggressive.) The mitigation policies do not change the general shape of the emission projection curve, as each curve still shows first a decreasing and then an increasing trend. Emissions begin to reduce from the baseline immediately after the start-year of the policy, which is the year 2010 for the FS_Best and FS_Medium scenarios, and year 2015 for FS_Worst scenario. With the scrappage policy, global emissions in 2030 can drop to as low as 620 Gg under the FS_Best scenario. Even under FS_Worst scenario, emissions can be reduced to 860 Gg in 2030. Compared with the baseline, the highest emission reduction occurs 5 to 10 years after the adoption of a scrappage policy, ranging from 20% to 70%. One reason is that a large number of uncontrolled and relatively poorly controlled vehicles, as well as superemitters, have accumulated before the policy, and emissions are reduced quite dramatically when they are scrapped at an accelerated rate. Another reason is that most regions have implemented more advanced emission standards before the year 2020 [*Yan et al.*, 2011], and vehicles with earlier standards are replaced more frequently. The sharp emission decrease in FS_Best after 2045 is caused by the quick and immediate removal of uncontrolled vehicles after Euro I implemented in Eastern and Western Africa. Before that time, it is assumed that advanced vehicle technology is not available in those regions.

3.1.2 Retrofit

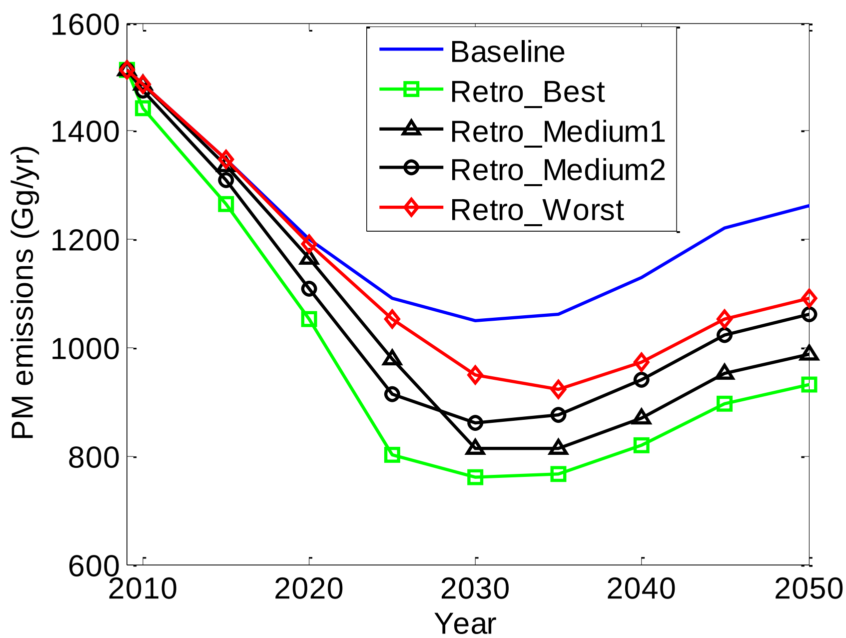

Figure 2. Emission projections with four retrofit policy scenarios in A1B. The scenarios Retro_Best, Retro_Medium1, Retro_Medium2, and Retro_Worst are defined in Table 2

Figure 2 shows emission projections with four different retrofit policies. Different from scrappage, a retrofit policy results in greater emission reductions 20 to 40 years after the policy comes into effect. The greatest emission reduction appears around 2030, when emissions range from 760 Gg to 950 Gg from best to worst scenario; a 10% to 27 % emission reduction is achieved over baseline. The delayed and relatively small emission reduction achieved by the retrofit policy can be explained by the nature of retrofit. (1) Retrofit is applicable only when the highly advanced technology (e.g., Euro V or Euro VI) is available. Except for the developed regions, most regions are projected to adopt Euro V and VI around 2020 or even later, which limits the reductions that can be obtained before 2030. (2) Retrofit can only work on diesel vehicles with newer-technology engines; uncontrolled and poorly controlled vehicles still remain in the market. Because of the assumptions in our retrofit program, it provides emission reduction only when more advanced technologies (e.g. Euro V and Euro VI) are available. Scrappage provides more immediate and higher emission reductions because it begins functioning as soon as slightly advanced vehicles (e.g. Euro II or III) are available.

3.2 Monte Carlo simulations

Monte Carlo simulations are used to examine the uncertainty in the effectiveness of mitigation measures in achieving emission reduction. For each set of fleet parameters used in the Monte Carlo simulations described in *Yan et al.* [2012], the simulation is re-run with the measure scenario applied. These fleet parameters are determined retirement rate and superemitter transition rate. The medium scenarios for scrappage and retrofit are applied to each simulation with deterministic (single-valued) parameters, in order to isolate the effect of uncertainties in the fleet model.

Since each emission sample with measure shares the same random parameters with the corresponding emission under baseline, the probability distribution of emission differences can be obtained by subtracting the paired values. The probability distributions of the differences between emissions with and without measures are shown in Figure 3**.** A 90% confidence interval of the difference between emissions with mitigation measure and emissions under the baseline is estimated and shown in Table 3. This confidence interval is used to represent the emission reduction uncertainties. Within the 90% confidence interval, emissions can be reduced by 22% to 49% by the scrappage measure and 9% to 23% by retrofit measure in 2030.

Table 3. Summary of the three quintiles and 90% confidence interval (CI) of the difference of global emissions with measure (E_2) and under baseline (E_1), and the emission change (%) within 90% CI.

Measure	**Year**	**90% CI of $E_2 - E_1$**	**Changes within 90% CI ($\frac{E_2 - E_1}{E_1}$)**
Scrappage	2015	-683 ± 318	-62%to -41%
	2030	-376 ± 285	-49% to -22%
Retrofit	2015	-40± 36	-4% to -1%
	2030	-166 ± 114	-23% to -9%

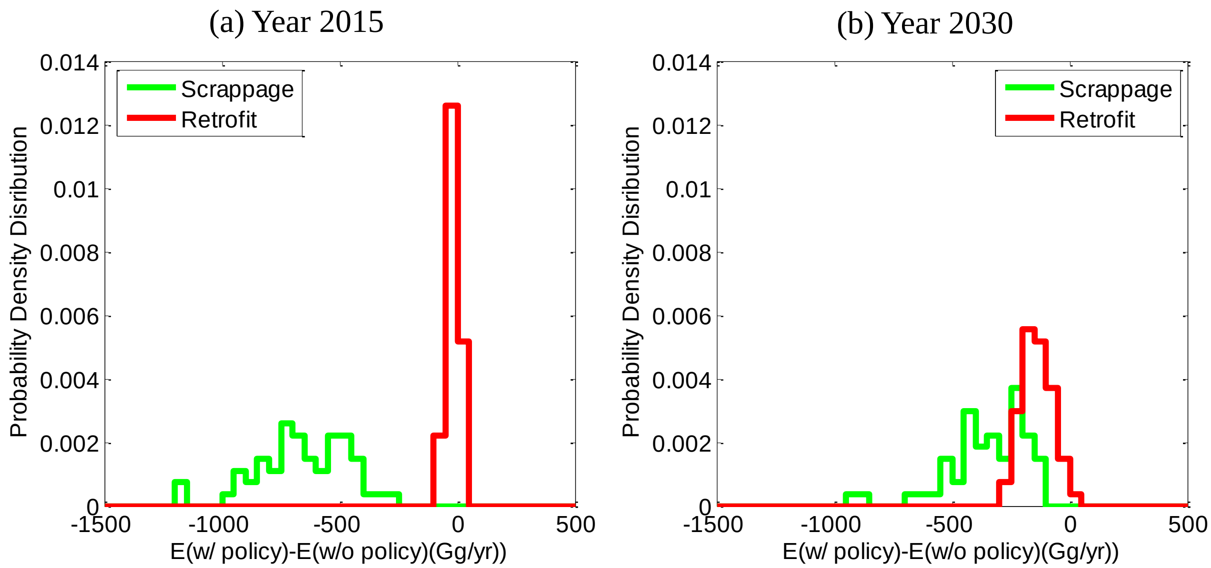

Figure 3. Probability density distributions of differences between global emissions with measure (scrappage in green dashed line, and retrofit in red dashed line) and under baseline in year 2015, 2030.

Figure 4 shows boxplots of emission reductions with scrappage or retrofit over baseline. In year 2015, reductions under scrappage show that East Asia benefits most in the emission reduction (over 80%), followed by South Asia, Southeast Asia, Middle East, Latin America and Former USSR. North America, Africa and Pacific obtain the least emission reductions. There are several reasons that scrappage causes higher emission reduction in Asian regions, Former USSR, Latin America and Middle East. First, in these regions, Euro III and IV with lower emission rate are adopted around year 2010. With five years delay, the first adoption of scrappage happens around 2015. Accumulated vintage vehicles with Euro II and Euro III start to be replaced with vehicles with new standards. Even though North America, Europe, and Pacific also adopt new standards around 2010, their current standards already require low enough emission rate and the newly implemented ones reduce emission insignificantly. Second, we assume that lower retirement rates in these regions due to lower income. Therefore, relatively more old vehicles with higher emission rates have accumulated before the measure. Finally, superemitters have a higher share of fuel consumption in these regions.

Figure 4 (c) and (d) shows emission reduction gained by retrofit. In year 2030, this measure produces highest emission reduction rate in the Middle East and East Asia (around 35%), followed by Southeast Asia, Former USSR, South Asia and Latin America. The reasons for effective emission reduction with scrappage also explain the reductions due to retrofit. The retrofit measure as described in this scenario does not produce emission reductions in Africa, because advanced emission standards are implemented so late that it is not available even in 2030. The low emission reductions in North America, Europe, and Pacific in the year 2030 can be explained by two reasons. First, both highly advanced emission standards and the retrofit measure are adopted earlier (before 2015). By 2030, natural retirement has phased out older vehicles so that fewer measure target vehicles are left in the year 2030. Secondly, the higher retirement rates in these regions help to drive the replacement of old vehicles with less stringent emission standards and minimize the number of vehicles that need to be retrofitted.

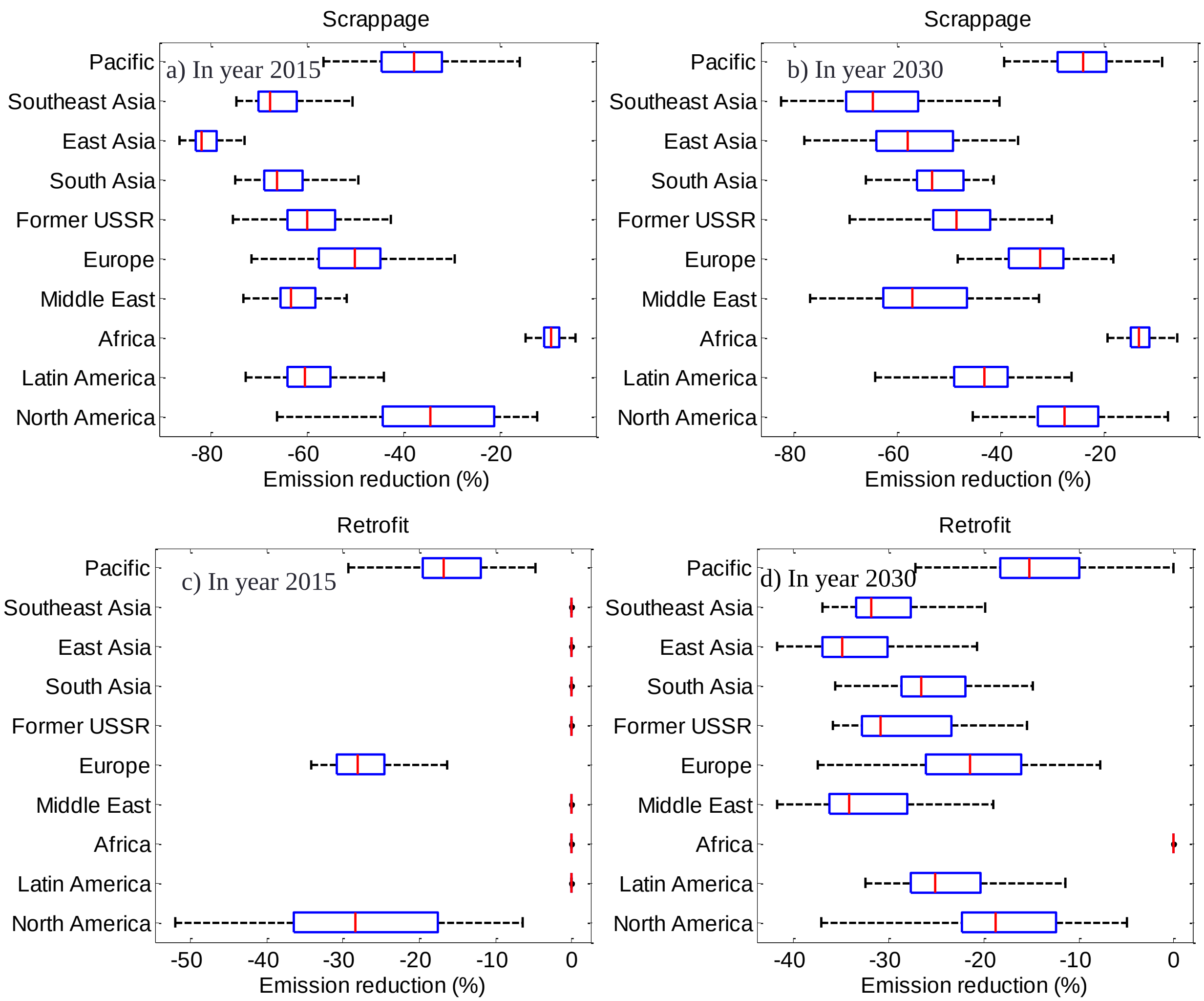

Figure 4. Boxplot of regional emission reduction (a) and (b) with scrappage measure, and (c) and (d) with retrofit in year 2015 and 2030, respectively. The boxplots are based on 54 trials in Monte Carlo simulations. The central red marker is the median (quartile 2 or q2), the edges of the box are the 25th (q1) and 75th (q3) percentiles, and the whiskers extend to the most extreme data points not considered outliers (q1-w(q3-q1) and q3+w(q3-q1), respectively, and w=1.5).

4. Conclusions

This work presents an evaluation of the effectiveness of global emission reductions that can be achieved by applying scrappage and retrofit policies on regional and global levels. Through the scenario analyses, we examined the influence of key parameters for mitigation policies on the reduction of emission projections. Monte Carlo simulations were also used to analyze the probability that emission can be reduced by the application of mitigation policies in light of uncertainties.

Scenario analysis shows that scrappage could provide an immediate and higher emission reduction, while retrofit reduces more emissions only when more advanced technologies are provided (Euro V and Euro VI). The highest emission reductions with scrappage occur 5 to 10 years after the policy adoption, ranging from 20% to 70%; these with retrofit policy happens around 2030, and ranges from 10% to 27 % from the worst to best scenarios.

In light of uncertainties due to retirement rate and superemitter transition rate, global emissions have a high potential to be reduced by mitigation policies, but it is most effective in particular regions. A 90% confidence interval of global emission reductions is 22% to 49% by scrappage policy and 9% to 23% by retrofit policy in 2030. The most effective policy occurs in regions (1) where the policy is implemented in conjunction with the introduction of new technologies with significantly lower emissions, (2) where retirement rate is slower and old vehicles can be accumulated, and (3) where the superemitter fraction is high. The three criteria also apply to retrofit.

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