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GHG Mitigation Potential in U.S. Transportation

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Interim Report IR-09-045

GHG Mitigation Potential in U.S. Transportation

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Contents

Abstract

This study used GAINS Annex I transportation data for the U.S. to quantify carbon dioxide mitigation potential in the on-road transport sector for a range of aggressive fuel-efficient vehicle technology penetration scenarios focusing on 2020 and 2030. A cost-benefit sensitivity analysis was also conducted to determine each penetration scenario's "net extra cost" sensitivity to uncertainties in future fuel prices and technology investment costs. Results showed carbon dioxide reductions from increased vehicle fuel-efficiency of up to 7 percent relative to 2006 U.S. fossil fuel emissions levels, were achievable in 2030 for the technology scenarios analyzed. The net extra costs for the entire on-road vehicle fleet in all scenarios were negative, and cost-benefit sensitivity analysis showed that the on-road fleet is surprisingly robust againstuncertain future fuel prices and investment costs. A break-even endpoint analysis revealed the on-road fleet could experience up to a 60 percent increase in investment costs, or up to a 40 percent decrease in fuel prices and still maintain negative or break-even net extra costs in 2020, in other words conclusions and recommendations are very robust.

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About the Authors

This work was carried out at IIASA though collaboration between Jens Borken-Kleefeld, researcher in the Atmospheric Pollution and Economic Development (APD) program, and Erica Bickford, PhD student from the Nelson Institute's Center for Sustainability and the Global Environment (SAGE) at the University of Wisconsin-Madison, USA. This collaboration was conducted as part of IIASA's Young Scientist Summer Program (YSSP).

GHG Mitigation Potential in U.S. Transportation

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1 Introduction

The devastating global effects of climate change, already beginning to be observed (IPCC, 2007) have made climate change—and by extension, curbing the greenhouse gases responsible—one of the largest international issues of the current century. Several countries have acted swiftly and decisively to reign-in national emissions in accordance with the Kyoto Protocol of 1997, however many countries, including the United States of America, have not. This inaction is significant because the U.S. is the second largest global emitter of fossil-fuel Carbon Dioxide (CO_2) after China, and accounts for 20 percent of global emissions (CDIAC, 2009).

As of 2009, the U.S. federal government has begun to take steps at implementing climate policy. In June 2009 the U.S. House of Representatives passed the American Clean Energy and Security Act (H.R. 2454)—which includes legislation to establish a greenhouse gas cap-and-trade system and additional measures to mitigate climate change and expand clean energy. If passed into law, this act proposes a step-down emissions cap requiring 17 percent reductions of 2005 emissions levels by 2020, and a 42 percent reduction of 2005 emissions levels by 2030. Additionally, in December of 2009, the United Nations Framework Convention on Climate Change (UNFCCC) is convening in Copenhagen, Denmark to negotiate a global climate agreement to take effect when the Kyoto Protocol expires in 2012 (UNFCCC, 2009).With both the U.S. federal government and the international community recognizing the need to limit greenhouse gas emissions and proposing reduction targets, it is essential to know in what sectors reductions are possible and what are the associated costs.

The on-road transportation sector in the U.S. accounts for more than 25 percent of total U.S. fossil-fuel CO_2 emissions and is the second-largest emitting sector after electricity generation. Compared to other developed countries, the U.S. has historically had relatively low fuel prices (IEA, 2008), creating little incentive for fuel-efficiency in vehicle manufacturing. This means significant reductions in greenhouse gas emissions may be possible from this sector by implementing more fuel-efficient vehicle technologies. The purpose of this study is to analyze a variety of penetration scenarios for implementing more fuel-efficient technologies starting in model year 2010, and calculate the associated change in fuel consumption and costs.

In recent years, a few studies have similarly endeavored to quantify emissions reduction potential in the U.S. as well as associated costs. A 2007 report by McKinsey & Company (Creyts, Derkach et al, 2007) presented a detailed analysis estimating reduction potentials and costs for reducing greenhouse gas emissions in the U.S. The study included analysis of all sectors using projected emissions data to 2030, setting the "societal cost" of CO_2 abatement at \$50 per ton. They reported that through increasing fuel-efficiencies and use of diesel in light-duty vehicles, between 240 and 290 megatons of carbon could be abated from the on-road transport sector (Creyts, Derkach et al, 2007). Lutsey (2008) similarly took a whole sector approach to examining carbon mitigation potential in the U.S., by comparing the cost-effectiveness of different abatement technologies across sectors, also for 2030. Lutsey examined cost-effective technologies for carbon (and carbon equivalent) prices of \$30 and \$50 per ton, determining that reductions of 13-29 percent of baseline 2030 emissions were possible, with the transportation sector comprising a large share of the most cost-effective technologies through efficiency improvements in passenger vehicles and commercial trucks.

Compared to the McKinsey & Company and Lutsey reports, this study presents a more in-depth analysis of fuel-efficient technologies in the on-road vehicle sector, examining technologies by fuel-type and vehicle class with penetration starting in 2010. Similar to McKinsey, this report applies a range of penetration scenarios for new technologies, however unlike both McKinsey and Lutsey, this report also includes a sensitivity analysis to account for uncertain future fuel prices and technology investment costs. The results of this sensitivity analysis show the robustness of the on-road transport sector to fluctuations in future fuel prices and technology investment costs, for a range of aggressive technology penetration scenarios as well as quantifying greenhouse gas mitigation potential.

2 Methods

This study used U.S. on-road transportation data from IIASA's Greenhouse Gas–Air Pollution Interaction Synergies (GAINS) model database (Amann, Bertok et al, 2009; Borken-Kleefeld, 2009; Borken-Kleefeld, Cofala et al, 2009) and future fuel consumption projections from the World Energy Outlook (WEO) 2008 (IEA, 2008) for years 2000-2030 in five year increments to conduct a cost-benefit sensitivity analysis of several fuel-efficiency technology penetration scenarios for the U.S. transport sector. Detailed descriptions of data calibration and sensitivity analysis methods are provided below.

2.1 GAINS Data Calibration

The first task of this project was optimization of road transport variables (fuel efficiency, vehicle mileage, number of vehicles in fleet) in the GAINS database such that calculated annual fuel consumption values wouldmatch the annual fuel consumption predictions from the WEO 2008. Total annual fuel consumption is given by

$$(1) \qquad FC_{GAINS} = \sum_{fc} (vehno_{fc} * vkm_{fc} * sFC_{fc}) \neq FC_{WEO}$$

where FC is total fuel consumption (J), vehno is number of vehicles in fuel category f and vehicle category c, vkm is annual mileage of vehicles in fuel category f and vehicle category c (km/yr-vehicle), and sFC is specific fuel consumption (fuel efficiency) of vehicles in fuel category f and vehicle category c (J/km). The FC values calculated by the GAINS data differed from the WEO FC values by between one and ten percent. Thus, the GAINS data variables were calibrated simply by applying a multiplicative adjustment factor, Δ.

$$\Delta = \frac{FC_{WEO}}{FC_{GAINS}} \tag{2}$$

$$FC_{GAINS_{optimized}} = \Delta * \sum_{fc} (vehno_{fc} * vkm_{fc} * sFC_{fc}) = FC_{WEO} \tag{3}$$

The adjustment factor was applied to each of the transportation variables (vehno, vkm, sFC) by weighting Δ by an exponent of each variable's normalized uncertainty relative to the other triplet variables, a_i, where $a_1+a_2+a_3=1$.

$$FC_{GAINS_{optimized}} = \sum_{fc} ((vehno_{fc} * \Delta^{a1}) * (vkm_{fc} * \Delta^{a2}) * (sFC_{fc} * \Delta^{a3})) = FC_{WEO} \tag{4}$$

These adjusted transportation variables comprise the "optimized" GAINS data for vehicle models before 2010. Prior to 2010, fuel-vehicle classes were not differentiated by vehicle technology. Beginning with 2010, penetration of new technologies were considered such that

$$sFC_{fc_{2010+}} = \sum_{t} pen_{fct} * sFC_{fct} \tag{5}$$

where pen is the penetration rate and t indicates the technology, e.g., reduced vehicle weight, hybrid, fuel cell, etc. (see Borken-Kleefeld,Cofala et al, 2009 for descriptions of vehicle technologies). Optimized penetration rates were calculated by dividing the optimized product of pen_{fct} and sFC_{fct} by sFC_{fct}, and normalizing.

$$pen_{fct_{optimized}} = normalized \left[\frac{(pen_{fct} * sFC_{fct})_{optimized}}{sFC_{fct}} \right] \tag{6}$$

Optimized sFC_{fct} was calculated by dividing the optimized product of pen_{fct} and sFC_{fct} by the optimized penetration rates.

$$sFC_{fct_{optimized}} = \left[\frac{(pen_{fct} * sFC_{fct})_{optimized}}{pen_{fct_{optimized}}} \right] \tag{7}$$

These optimized GAINS transportation variables were used to conduct the cost-benefit sensitivity analysis for penetration of fuel-efficient vehicle technologies described in detail in the following sections. Cost-benefit was determined by calculating the net extra investment costs associated with each penetration scenario using the formula below.

(8) Net Extra Investment Costs = {Annualized Investment Costs + Operation and Maintenance} – Fuel Savings

2.2 Sensitivity Testing

The economic viability of implementing potentially expensive, fuel-efficient vehicle technologies in this study depended on several factors: the degree of technology penetration, cost of technology investment, and price of fuel. Future projections of each of these factors involve significant levels of uncertainty. Uncertainty in technology investment costs is due to uncertainties in manufacturing efficiencies of vehicle technologies, future supply and demand for technologies, and potential for government incentives. Fuel price uncertainties stem from uncertainty of the future global supply of crude oil as well as the state of the future global economy. In an effort to capture some of that uncertainty and account for a variety of future circumstances, this study selected a range of high, middle and low cases for sensitivity testing with each cost factor. In simplified terms, there are four possible cases considering future technology investment costs and fuel consumption in the U.S. on-road transport sector (see Figure 1). Two cases involve improved fuel efficiency, and two cases involve reduced investment costs. The sensitivity analyses conducted here investigate the trade-offs between increased investment in fuel-efficient vehicle technologies and fuel savings, as a function of investment costs and fuel price.

Figure 1. Simplified future cases for Net Costs-Fuel Consumption in the U.S. on-road transportation fleet.

The sensitivity analyses described in detail below incorporated several broad assumptions. The principal assumption for this analysis was that transport demand in the U.S. remains constant. That is, the analysis assumed no change in transport behavior, or in distribution of vehicles in the on-road fleet—just their fuel efficiency. The analyses further assumed a payback period of 12 years on investment costs and a four percent social investment rate for technology investments costs.

2.2.1 Penetration rates of new technologies

Sensitivities to penetration of new technologies in the U.S. on-road fleet were analyzed by comparing a range of aggressive technology penetration scenarios to the optimized Baseline penetration rates given in GAINS. The central case was derived from the "Maximum Feasible Penetration" values given in the GAINS database, beginning with maximizing penetration rates for the most fuel-efficient technologies and distributing the remainder percents to less fuel efficient technologies. High and low cases were developed from the central case by increasing penetration rates by 50 percent in the high case, and decreasing penetration rates by 50 percent in the low case (beginning with the most fuel efficient technologies and distributing the remainder percents to less fuel efficient technologies).

2.2.2 *Fuel price and investment costs*

Sensitivities to future fuel price increases and decreases were analyzed by comparing a range of fuel price scenarios. The WEO 2008 (IEA, 2008) crude oil fuel prices, projected to 2030, were used as a central case (see Table 1.), with high and low cases derived by increasing or decreasing the per barrel crude oil price by 20 percent.

Crude Oil Prices ($/barrel)

WEO 2008	2010	2015	2020	2025	2030
	94.19	94.19	103.61	109.26	114.91

Fuel Prices (€/GJ)

	2010	2015	2020	2025	2030
Heavy Fuels	6.64	6.64	6.64	6.64	6.64
Diesel	21.16	21.16	22.65	23.54	24.43
Gasoline	20.56	20.56	22.05	22.94	23.83
Liquid Petroleum Gas	20.56	20.56	22.05	22.94	23.83
Natural Gas	12.54	12.54	13.68	14.37	15.05
Hydrogen	12.21	12.21	12.21	12.21	12.21
Electricity	13.89	13.89	13.89	13.89	13.89

Table 1. Crude oil price predictions from WEO 2008 in US dollars per barrel, and prices for vehicle fuels. Prices for Heavy Fuels, Hydrogen and Electricity were taken from GAINS for 2020 and used for all years. Prices for Diesel, Gasoline, Liquid Petroleum Gas and Natural Gas were derived from WEO crude oil prices. Note units for fuel price are Euro/GJ, and all prices are in 2005 dollars or Euros.

Sensitivities to a range of investment costs were analyzed for 2020 and 2030, using GAINS technology cost values for 2020 and McKinsey technology cost values for 2030 (Creyts, Derkach et al., 2007). High and low ranges were generated for each year, using the GAINS and McKinsey data as central values with high and low cases derived by increasing and decreasing the central values by 33 percent. A summary of the sensitivity testing parameters is shown in Table 2.

Parameter	Low	Central	High
Fuel Costs	-20% of Central	WEO 2008	+20% of Central
Investment Costs	-33% of Central	GAINS values 2020, McKinsey for 2030	+33% of Central
Penetration Rates	-50% of MFP	Maximum Feasible Potential, MFP (relative to Baseline in GAINS)	+50% of MFP

Table 2. Ranges for testing cost sensitivities to fuel prices, investment costs, and penetration rates of new fuel-efficient vehicle technologies.

Because one can easily predict the outcomes from increasing fuel costs while decreasing investment costs, and decreasing fuel costs while increasing investment costs, the sensitivity analyses in this study focused on the outcomes of less certain cases where both fuel and investment costs increase, and where both fuel and investment costs decrease.

2.2.3 Net Extra Costs

Costs and benefits of technology penetration, fuel price and investment cost scenarios were evaluated by calculating "Net Extra Costs" for each scenario. Net extra costs are the difference between the total costs for a given penetration scenario, and the total costs in the Baseline case. The Baseline case represents the "Business as Usual" scenario and used the Baseline penetration rates given in GAINS. "Total Costs" are quantified as the sum of "Annualized Costs" (including investment costs and operation and maintenance costs), and "Fuel Costs." The difference between fuel costs in the Baseline scenario and fuel costs in the penetration scenario gives the "Fuel Savings" (see section 2.1).

3 Analysis Results

The following sections present sensitivity testing results for the dominant fuel-vehicle classes in the U.S. on-road fleet: gasoline cars, gasoline light trucks and diesel heavy-duty trucks, as well as results for the total fleet.

3.1 Penetration Scenarios

Vehicle technology distributions for each penetration scenario used for gasoline cars in this analysis are presented in Figures 3a-3b and 4a-4b. See Appendix for penetration scenario figures for the remaining dominant fuel-vehicle classes.

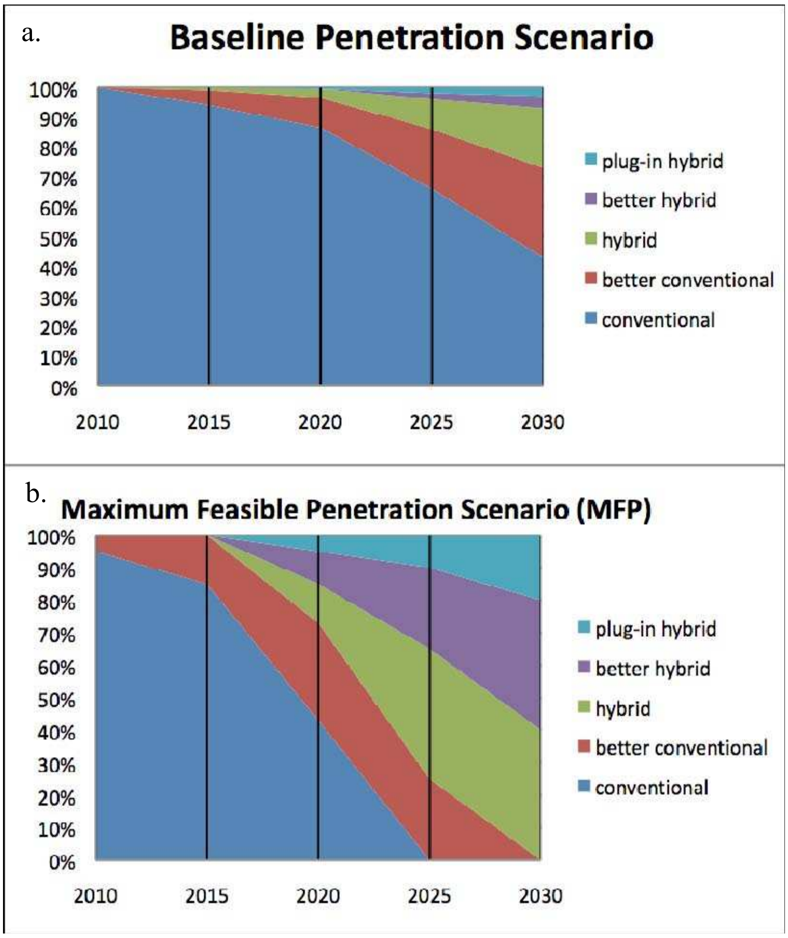


Figure 1a and 2b. Baseline (business as usual) (2a) and Maximum Feasible Penetration (MFP) (2b) scenarios for fuel-efficient technologies in gasoline cars. Data labels are generalist terms, see Borken-Kleefeld, Cofala et al. (2009) for detailed descriptions of technology packages.

As described in the methods section, the Baseline penetration case for fuel-efficient technologies represents “Business as Usual” behavior (see Figure 3a). Conventional vehicles dominate the gasoline car fleet through 2030, with only small percentages of more fuel-efficient technologies in 2030. Conversely, in the Maximum Feasible Penetration Scenario (MFP) (see Figure 3b), conventional vehicles are mostly phased out of the fleet by 2025, and completely by 2030 with various hybrid technologies replacing them.

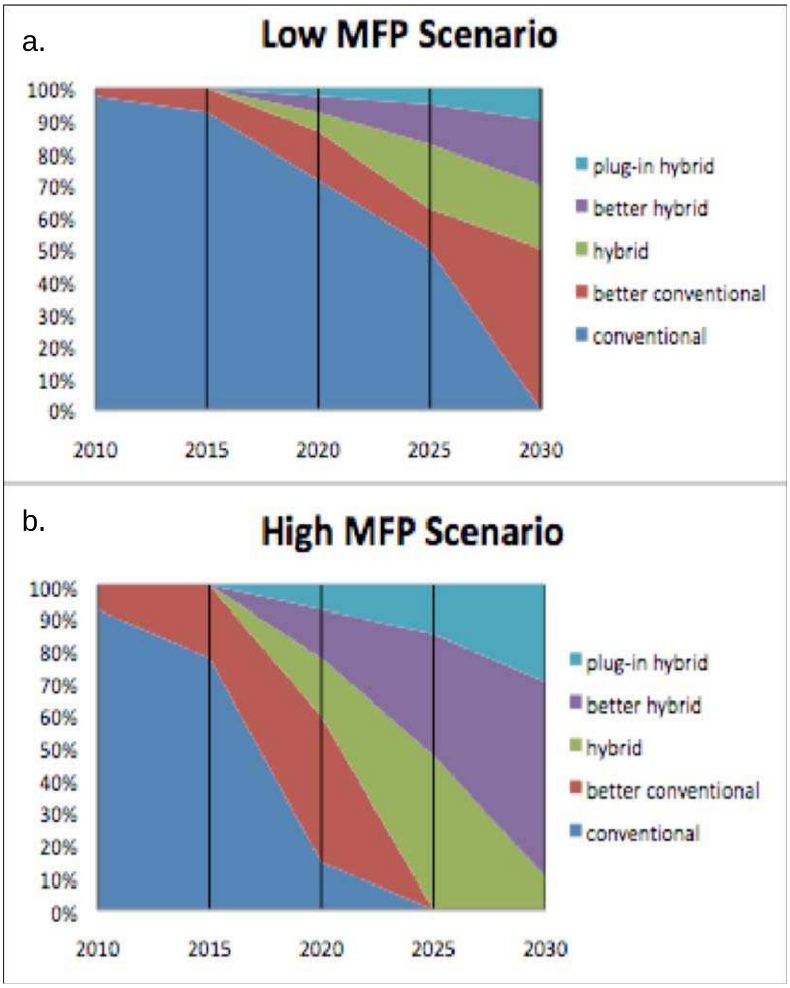


Figure 4a and 4b. The Low (4a) and High (4b) MFP scenarios for penetration of fuel-efficient technologies in gasoline cars.

The Low MFP scenario (see Figure 4a) presents a penetration scenario less aggressive than MFP, and tends more toward the Baseline scenario with conventional vehicles remaining present through 2030 with less than 50 percent penetration of hybrid technologies. The High MFP scenario (see Figure 4b) presents an even more aggressive penetration scenario than MFP with conventional vehicles completely phased out of the fleet by 2025 and the 2030 fleet comprised entirely of hybrid technology equipped vehicles. Together, Low MFP, MFP and High MFP make-up the spectrum of aggressive fuel-efficient technology penetration scenarios (relative to Baseline) analyzed in this study. The effect of these penetration scenarios on fuel consumption and costs are presented in the following sub-sections.

3.2 Fuel Consumption and Extra Costs

The purpose of this research is to investigate potential for reducing fuel consumption in the U.S. transportation sector and calculate investment costs and fuel savings for each technology penetration scenario. This section presents the fuel consumption reductions, and extra costs for each penetration scenario, for each major fuel-vehicle category and the entire on-road fleet. Due to differences in fuel and vehicle efficiency, fuel consumption is presented in units of energy (Joules). In addition, because the data used in this study comes from a European institute, all costs are given in 2005 Euros.

3.2.1 Gasoline cars

The total fuel consumed by gasoline cars in 2020 and 2030 under each technology penetration scenario is shown in Figure 5. Not surprisingly, the highest fuel consumption reductions are found in the scenario with the highest penetration rates (High MFP) for advanced fuel-efficient technologies. Fuel consumption reductions of 4-17 percent are possible in 2020, and reductions of 19-35 percent are possible in 2030 for the gasoline car fleet and these penetration scenarios.

The net extra costs of these technology penetration scenarios are shown in Figures6a-6c. As previously mentioned, net extra costs are the sum of the extra investment costs for the technology plus the fuel savings. For the Central Costs case, in 2020, net extra costs for all scenarios are negative, with the highest negative costs in the most aggressive penetration

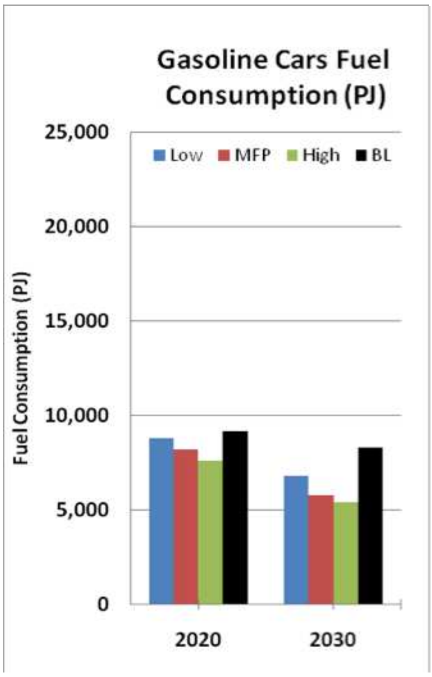


Figure 5. Gasoline consumption by cars in 2020 and 2030 for each penetration scenario. The Baseline (BL) penetration scenario is shown in black.

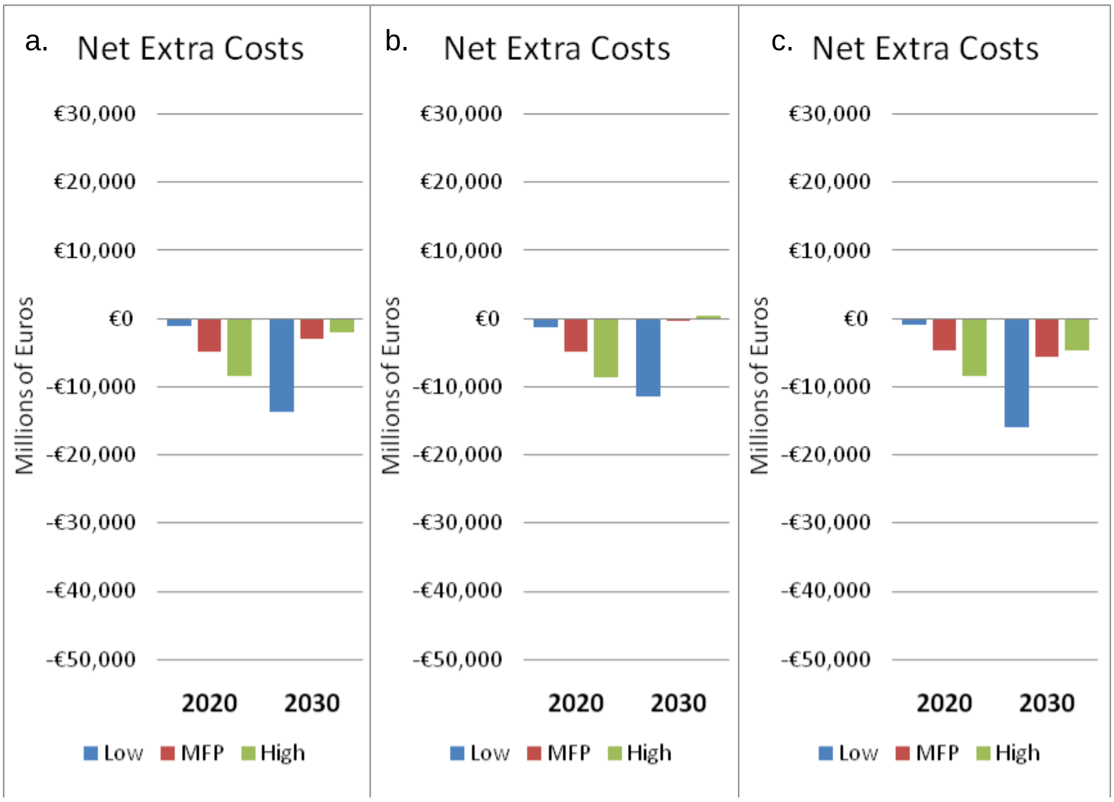


Figure 6. Gasoline Cars Net Extra Costs, the difference between annualized costs and fuel savings relative to the baseline penetration scenario for the case where (a) Fuel Price and Investment costs are at central values, (b) Fuel Price and Investment Costs are Low and (c) Fuel Price and Investment Costs are High.

scenario (High MFP). In 2030, net extra costs for all scenarios are still negative, however the most negative costs are associated with the least aggressive penetration scenario (Low MFP). The drastic increase in the negative costs associated with Low MFP and the decrease in negative costs for the MFP and High MFP scenarios occur because in 2020, fuel savings from the more aggressive scenarios outweigh the added investment costs. By 2030, the "low-hanging fruit" investment options have been exhausted. Much smaller gains in fuel efficiency are achievable such that in the least aggressive penetration scenario (Low MFP), fuel savings from the few new technologies included outweigh the much smaller extra investment costs for this scenario.

For the Low Costs case, where fuel prices and technology investment costs are low, results are very similar to the Central Costs case with negative extra costs in all scenarios and the most negative costs for the most aggressive penetration scenario (High MFP). In 2030, we again see that the last aggressive penetration scenario yields the most negative costs (though less negative than the Central Costs case)while the MFP and High MFP scenarios are at about the break-even point with MFP slightly negative and High MFP at slightly positive net extra costs.

In the High Costs case, where fuel prices and technology investment costs are high, the trend in 2020 is again very similar to what was seen in the Central and Low costs cases. In 2030, the net extra costs for all scenarios are more negative than in the Central and Low Costs cases, with the most negative net extra costs again falling to the least aggressive penetration scenario. These results show that across a range of future fuel price and investment cost uncertainty, the net extra costs for each gasoline car technology penetration scenario are negative orbreaking-even, and more aggressive investments in new technologies (MFP and High MFP) yield greater negative costs in 2020 than can be achieved in 2030.

3.2.2 Gasoline light trucks

Fuel consumption reductions achievable from fuel-efficient technologies in the gasoline light truck vehicle class are shown in Figure 7.and are very similar—though slightly higher—to the fuel consumption reductions found for gasoline cars. Fuel consumption reductions of 6-24 percent are found in 2020, and reductions of 22-38 percent are found in 2030. The greatest fuel consumption reductions are found in the most aggressive technology penetration scenarios (MFP, High MFP).

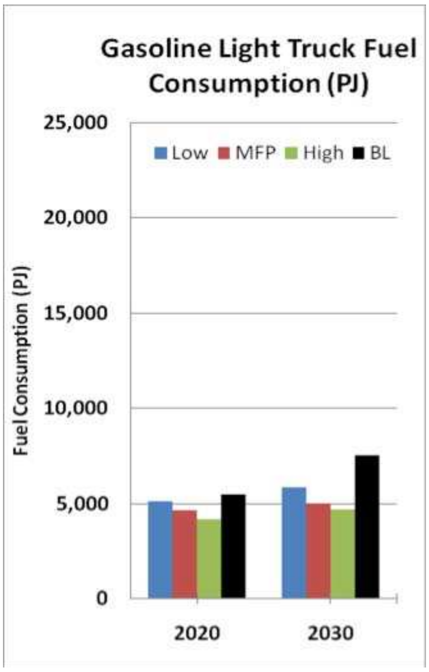


Figure 7. Gasoline consumption by light trucks in 2020 and 2030. Baseline (BL) scenario is shown in black.

Net extra costs for each penetration scenario for 2020 and 2030 are shown in Figures 8a-8c. Similar to what was observed for gasoline cars, across all cost cases, results in 2020 are fairly consistent. Inall technology penetration scenarios net extra costs are negative (at slightly smaller magnitudes than for gasoline cars), with more negative costs associated with more aggressive penetration scenarios (MFP, High MFP). In

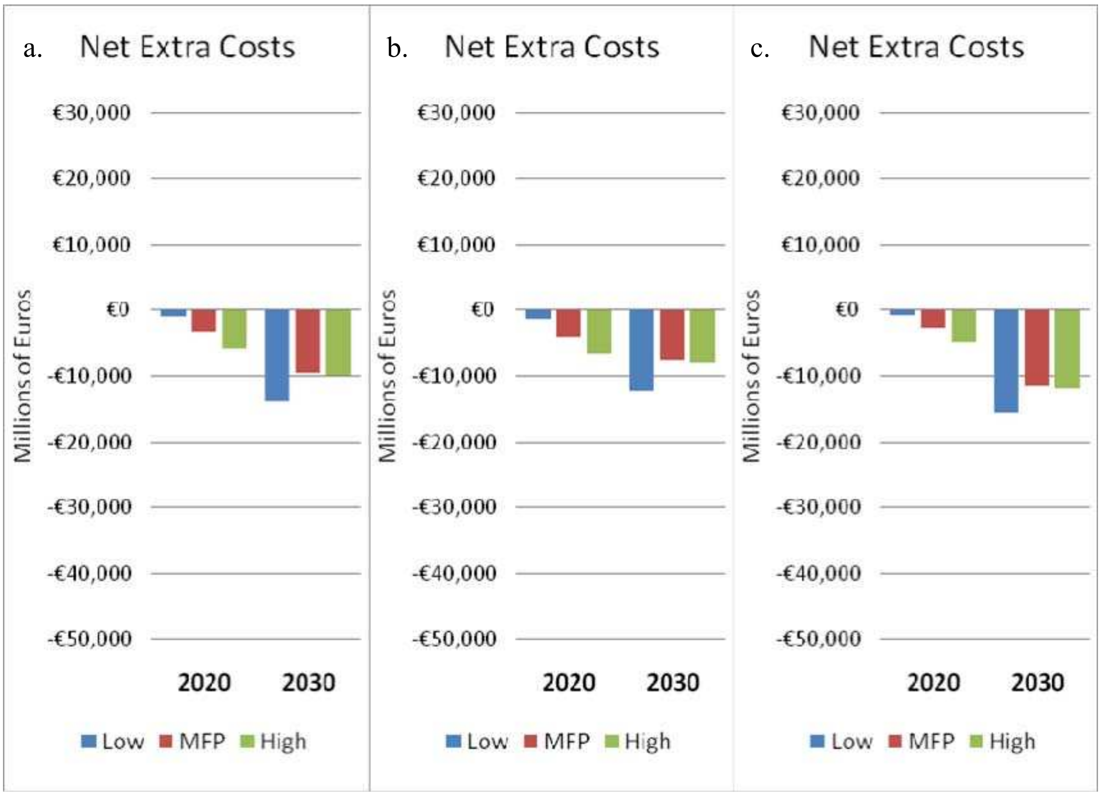


Figure 8. Net Extra costs from costs sensitivity analysis for Gasoline Light Trucks for the case where (a) Fuel Price and Investment Costs are at central values, (b) Fuel Price and Investment Costs are Low and (c) Fuel Price and Investment Costs are high.

2030, across all cost scenarios, the results are somewhat different. The least aggressive penetration scenario (Low MFP) maintains the most negative net extra costs—but there are much smaller differences between the Low MFP, MFP and High MFP penetration scenarios than observed for gasoline cars. With gasoline light trucks we again see that across a range of uncertain future fuel prices and investment costs, net extra costs remain negative. In 2030, greater negative costs are achieved in the least aggressive technology penetration scenario, however, converse to what was observed for gasoline cars, magnitudes of negative costs for more aggressive technology penetration scenarios *increase* from 2020 to 2030 indicating that fuel savings from fuel-efficient technologies for light duty trucks are much greater than extra investment costs. This difference is reasonable considering greater savings in fuel efficiency are possiblefor larger vehicles (trucks) through relatively inexpensive improvements such as reducing vehicle weight and increasing aerodynamics, thanin smaller vehicles like cars.

3.2.3 Diesel heavy trucks

Diesel heavy trucks—also known as Heavy-Duty Diesel Vehicles (HDDV)—make-up a majority of the U.S. on-road freight truck fleet (AASHTO, 2007). Diesel engines are more fuel-efficient than gasoline. As freight transport is a business with large fuel costs, freight operators have added incentive to upgrade trucks to be as fuel efficient as possible. The heavy-duty diesel truck fleet already operates more efficiently than the gasoline passenger vehicle fleet, such that fewer additional fuel-efficiency improvement technologies are available. In this study, only two fuel-efficient technology improvements involving improved aerodynamics and electric auxiliaries were considered because only currently available technologies were included and hybrid diesel engines for long-haul freight trucks are still in development stages (Borken-Kleefeld, Cofala et al., 2009). The limited technology options available for diesel heavy trucks accounts for their relatively small fuel consumption reductions in Figure 9. In 2020, fuel consumption reductions of 1-10 percent are observed, and in 2030, reductions of 6-8 percent for the MFP and High MFP scenarios are found while fuel consumption increases 9 percent in the Low MFP scenario. This increase is due to the methods used to generate the penetration scenarios. With fewer technologies, the Low MFP scenario for diesel heavy trucks results in higher penetration of less fuel-efficient conventional vehicles than in the Baseline scenario (see Appendix, Figure 2c). This accounts for the increase in 2030 fuel consumption for Low MFP.

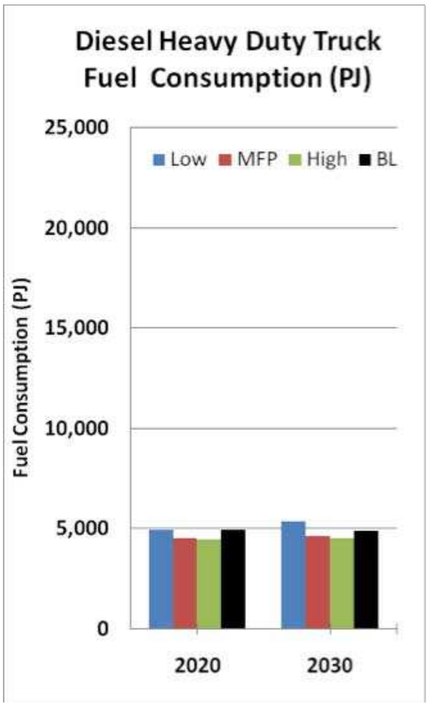


Figure 9. Diesel consumption for heavy trucks for each technology penetration scenario. The baseline (BL) case is shown in black.

Net extra costs for diesel heavy trucks for a range of future cost scenarios are shown in Figure 10a-10c. Again, in 2020 net extra costs for all penetration scenarios across all cost cases are negative with the largest magnitudes in the more aggressive penetration

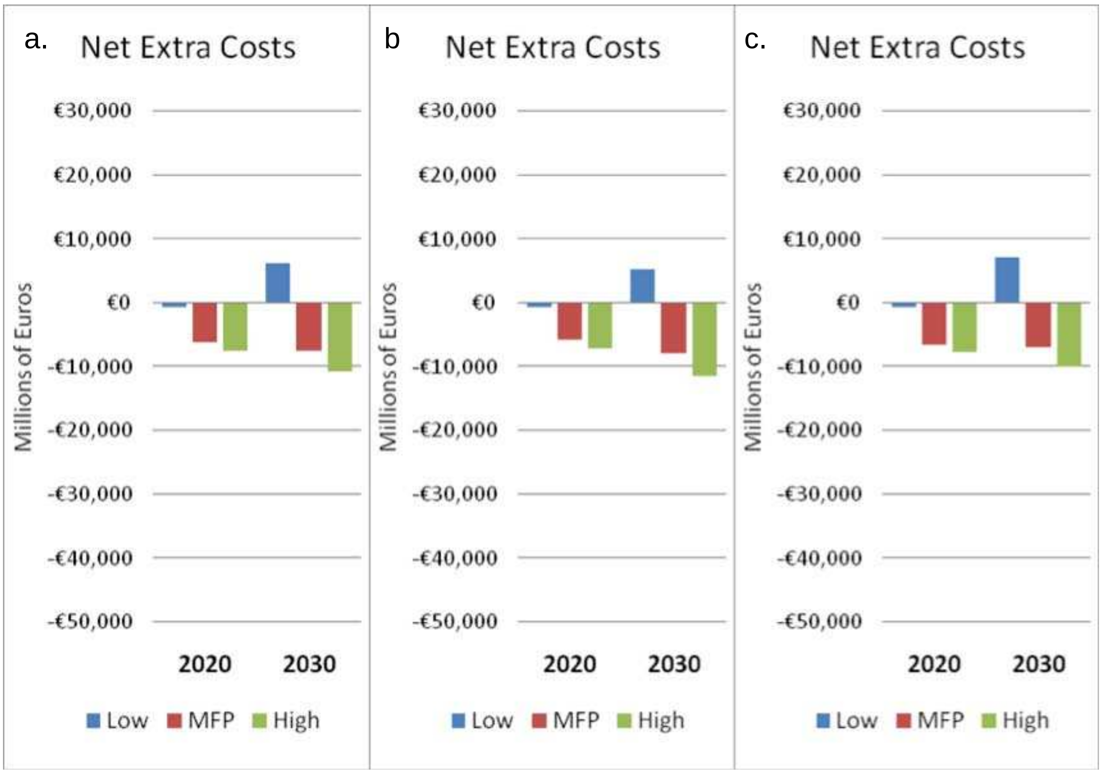


Figure 10. Net Extra costs from costs sensitivity analysis for Diesel Heavy Trucks for the case where (a) Fuel Price and Investment Costs are at central values, (b) Fuel Price and Investment Costs are Low and (c) Fuel Price and Investment Costs are high.

cases. In 2030, for the first time, net extra costs are significantly positive for the least aggressive penetration case. This is the opposite trend than was found for gasoline cars and trucks where the least aggressive penetration scenarios consistently had the most negative net extra costs in 2030. This again is due to the higher penetration rates for conventional vehicles in the Low MFP scenario relative to the Baseline. In the more aggressive penetration scenarios (MFP, High MFP), the magnitudes of net extra costs increase from 2020 to 2030, as they did for light trucks. Therefore, while fuel consumption reductions are small, investment in these technological improvements is still economical for the MFP and High MFP scenarios.

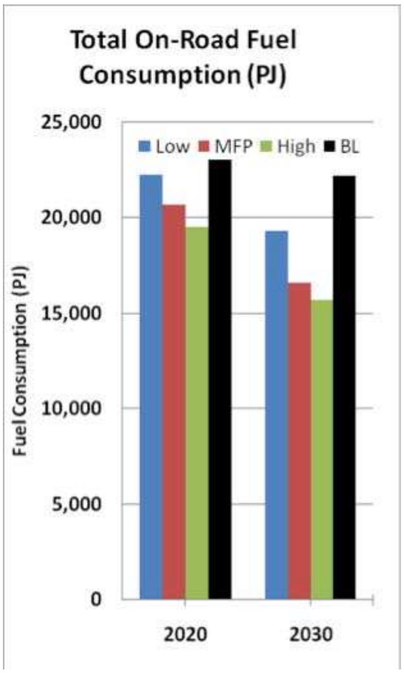


Figure 11. Total on-road fuel consumption for each technology penetration scenario. Baseline (BL) consumption levels are shown in black.

3.2.4 *Entire on-road fleet*

Although gasoline cars, gasoline light trucks and heavy diesel trucks together comprise most of the U.S. on-road vehicle fleet, it is useful to examine the on-road transport sector as a whole to get a sense of scale. Figure 11. shows the total on-road fuel consumption for each penetration scenario in 2020 and 2030. Potential fuel consumption reductions in 2020 are 3-15 percent, and reductions in 2030 are 13-29 percent,

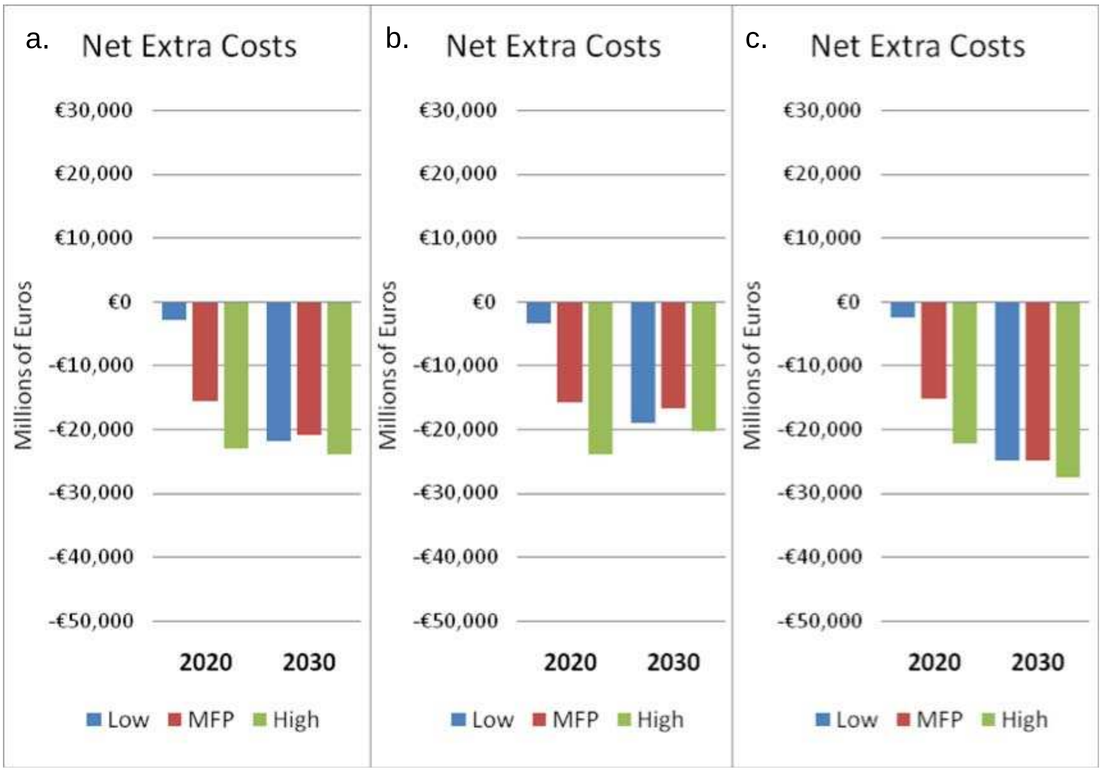


Figure 12. Net Extra costs from costs sensitivity analysis for the entire on-road fleet for the case where (a) Fuel Price and Investment Costs are at central values, (b) Fuel Price and Investment Costs are Low and (c) Fuel Price and Investment Costs are high.

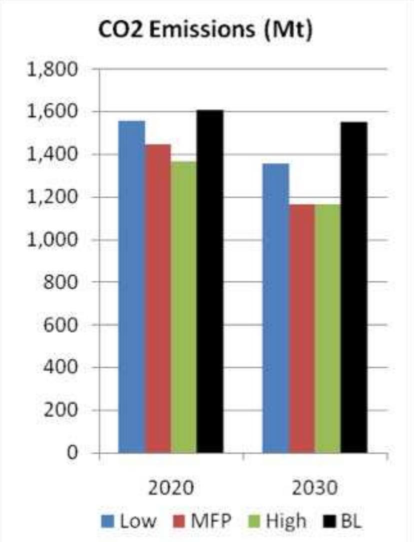
again with greater reductions from the more aggressive fuel-efficient technology penetration scenarios.

Figures 12a-12c. show the net extra costs for each cost case and penetration scenario for the entire on-road fleet. As consistently observed in 2020, net extra costs for all cost cases are negative with the largest magnitudes in the most aggressive penetration scenarios. In 2030, with all fuel-vehicle classes incorporated, the net extra costs are still negative for all penetration scenarios. However, the most aggressive penetration scenario (High MFP) maintains the largest magnitudes for all cost scenarios. This result is due to the positive net extra costs in the Low MFP case for diesel heavy trucks diminishing the negative net extra costs from gasoline cars and gasoline trucks—a potentially unreasonable result due to the increase in conventional diesel heavy trucks between the Baseline scenario and the Low MFP penetration scenario.

In the U.S. on-road transportation sector, across a range of penetration scenarios, the more aggressively fuel-efficient technologies penetrate the fleet, the greater the fleet fuel economy and the more fuel savings outweigh added investment costs over the vehicle lifetimes. Further, these savings are sustained from 2020 to 2030, and in some fuel-vehicle categories, savings increase from 2020 to 2030. These results lead to the conclusion that the cost-effectiveness of increased investment in fuel-efficient technologies is robust against significant uncertainty in investment costs and fuel prices.

3.3 CO_2 Emissions

As the title of this report suggests, the goal of this study is to investigate greenhouse gas mitigation potential, yet thus far only fuel consumption reductions and costs have been addressed. Fuel consumption has been used as proxy for greenhouse gas emissions due to differences in carbon content for vehicle fuels and the convenience of comparing and combining fuel consumption in a common energy unit. Figure 13. shows the total CO_2 emissions and reduction potential for each technology penetration scenario for the entire on-road fleet of vehicles. In 2020, reductions of 53-244 megatons are possible and reductions of 194-384 megatons are possible in 2030, however at most this amounts to 7 percent of total U.S. fossil-fuel CO_2 emissions in 2006 (CDIAC, 2008).



Reductions in 2020 from 53-244 Mt CO2 possible. Reductions in 2030 from 194-384 Mt CO2 possible.

Figure 13. Entire on-road fleet carbon dioxide emissions from fuel consumption for each technology penetration scenario, with the Baseline (BL) case in black.

3.4 Break-even Costs

In the net extra costs part of this study, three ranges of costs cases were considered in an effort to account for the uncertainty of future fuel prices and investment costs. Somewhat surprisingly, even across a broad range of costs and penetration scenarios, net extra costs remained largely negative. This suggests that at least for the technology

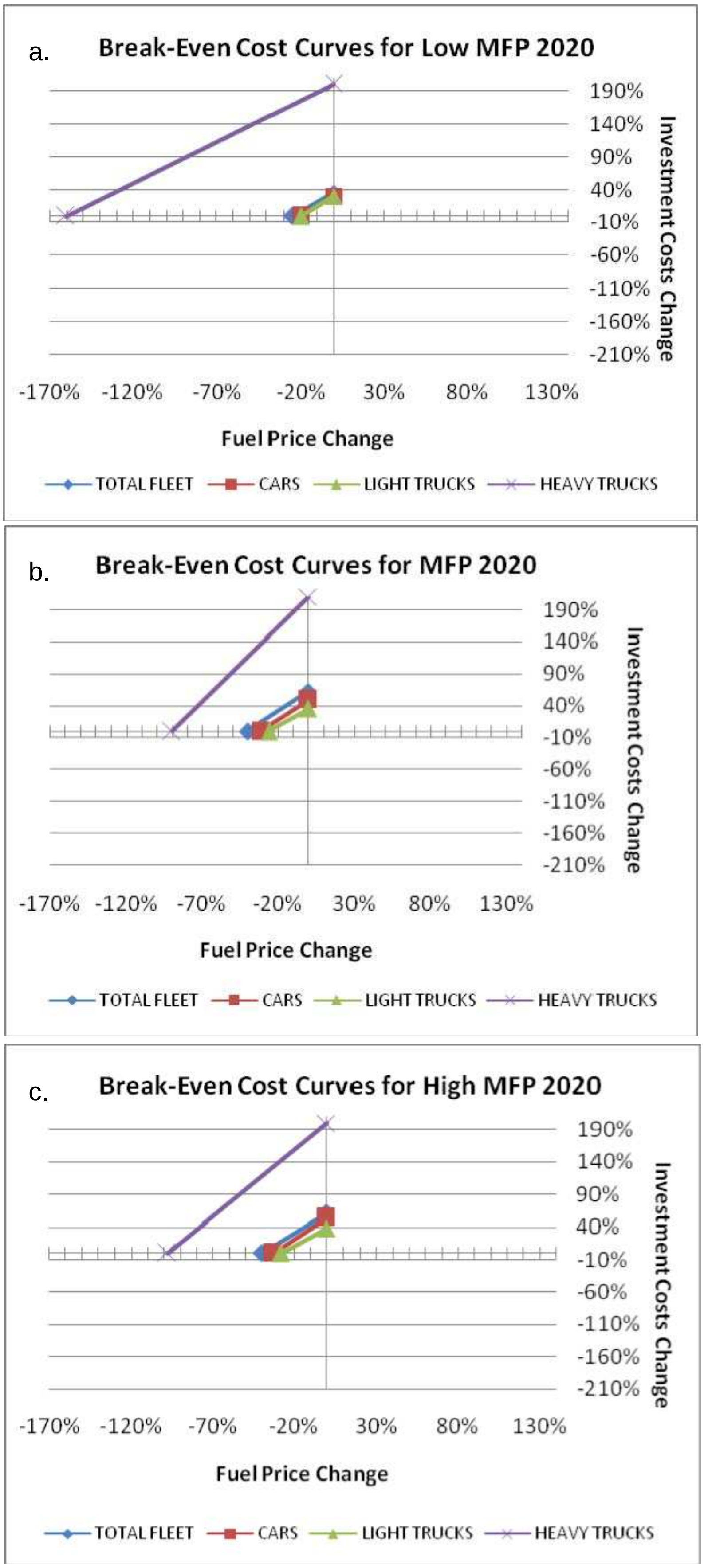


Figure 14a-14c. Break-even cost curves for major fuel-vehicle classes and entire on-road fleet in 2020 for each technology penetration scenario.

penetration scenarios examined in this study, there is a broader range of costs than expected where net extra costs remain negative or break-even. Figures14a-14c.show the "break-even cost curves" for the dominant fuel-vehicle categories and entire on-road fleet in 2020, for each penetration scenario. The curves are not true curves, but merely give the break-even endpoints for the percentchanges in fuel price and investment costs that may occur while still maintaining negative or zero net extra costs.

Clearly, diesel heavy trucks show the most elasticity in terms of fuel price and investment costs allowing for a 90-170 percent decrease in fuel price (a negative price for fuel), and a 200 percent increase in investment costs. Results for the entire on-road fleet, gasoline cars and gasoline trucks are much less elastic, and more similar to one another, allowing for a 20-40 percent decrease in fuel price, and a 30-60 percent increase investment costs while maintaining negative or break-even net extra costs. Across penetration scenarios, the break-even points for gasoline cars, gasoline trucks and the entire on-road fleet differ by only a few percentage points, suggesting that the endpoints for the break-even cost curves depend very little on penetration scenario. Since these curves were generated as endpoints only, results reflect changes in either fuel price or investment costs. Additional work to create more complete curves, allowing for simultaneous changes in fuel price and investment costs is in progress. Results for 2030 are similar and not shown here.

4 Summary and Conclusions

This study used GAINS database on-road transport data to analyze greenhouse gas mitigation potential and costs in the U.S. on-road transport sector through penetration of fuel-efficient vehicle technologies. The GAINS transport data was first calibrated to match the WEO 2008 fuel consumption estimates for 2000-2030, at five-year intervals. Three aggressive technology penetration scenarios were derived from the Maximum Feasible Penetration (MFP) scenario given by GAINS to quantify a range of fuel-consumption reduction possibilities. Net extra costs, defined as the sum of extra technology investment costs (relative to the Baseline) and fuel savings were calculated for each scenario, for each dominant U.S. fuel-vehicle category (gasoline cars, gasoline light trucks, and diesel heavy trucks) as well as for the entire on-road fleet. A cost-benefit sensitivity analysis, conducted to capture costs of fuel-consumption mitigation given uncertainties in future fuel prices and investment costs,showed that across a variety of aggressive technology penetration scenarios, net costs for technology penetration remainlargely negative. A break-even cost threshold analysis further showed the elasticity of the on-road transport sector to uncertain fuel price and investment costs to be rather high, with the entire on-road fleet accommodating up to a 40 percent decrease in fuel price and up to a 60 percent increase in investment costs while maintaining negative of zero net extra costs in 2020.

Caveats to this analysis include not accounting for life-cycle carbon emissions for manufacture of fuel-efficient vehicle technologies (eg. batteries for hybrid and electric vehicle technologies), as well as assuming an investment payback period proportional to vehicle lifetime (12 years), rather than investor holding time (3-5 years). In addition, this study only considered fuel-efficient vehicle technologies for new vehicles starting in 2010. Incorporating retrofit technologies, particularly in diesel heavy trucks is planned for future work. Also planned for future work is a comparison of the U.S.'s cost-benefit robustness—where fuel efficiency gains can be achieved at low cost—to other countries with much tighter cost structures, such as Europe and Japan. Finally, unlike McKinsey (Creyts, Derkach et al, 2007) and Lutsey (2008), a "carbon price" or tax was not included in the cost-benefit analysis. If a carbon price were applied, investment in fuel-efficient vehicle technologies becomes even more cost-effective.

Although the most aggressive technology penetration scenario considered in this study showed at best a 7 percent reduction in U.S. fossil fuel carbon emissions relative to 2006 levels by 2030— meeting only one sixth of the reductions called for by the American Clean Energy and Security Act—these reductions are solely due to penetration of new vehicle technologies excluding behavior changes, and occurred at negative net extra costs. The break-even cost threshold analysis revealed that under a range of uncertain future fuel prices and investment costs, greater reductions are possible at zero or negative net extra costs. This is an important policy result, because it demonstrates that the on-road transport sector is robust against large uncertainties in future costs. Even more aggressive penetration scenarios than considered in this study could be used to achieve greater reductions in carbon emissions, while still maintaining negative or zero net extra costs making the on-road transport sector a very viable sector to target for least-cost carbon emissions mitigation.

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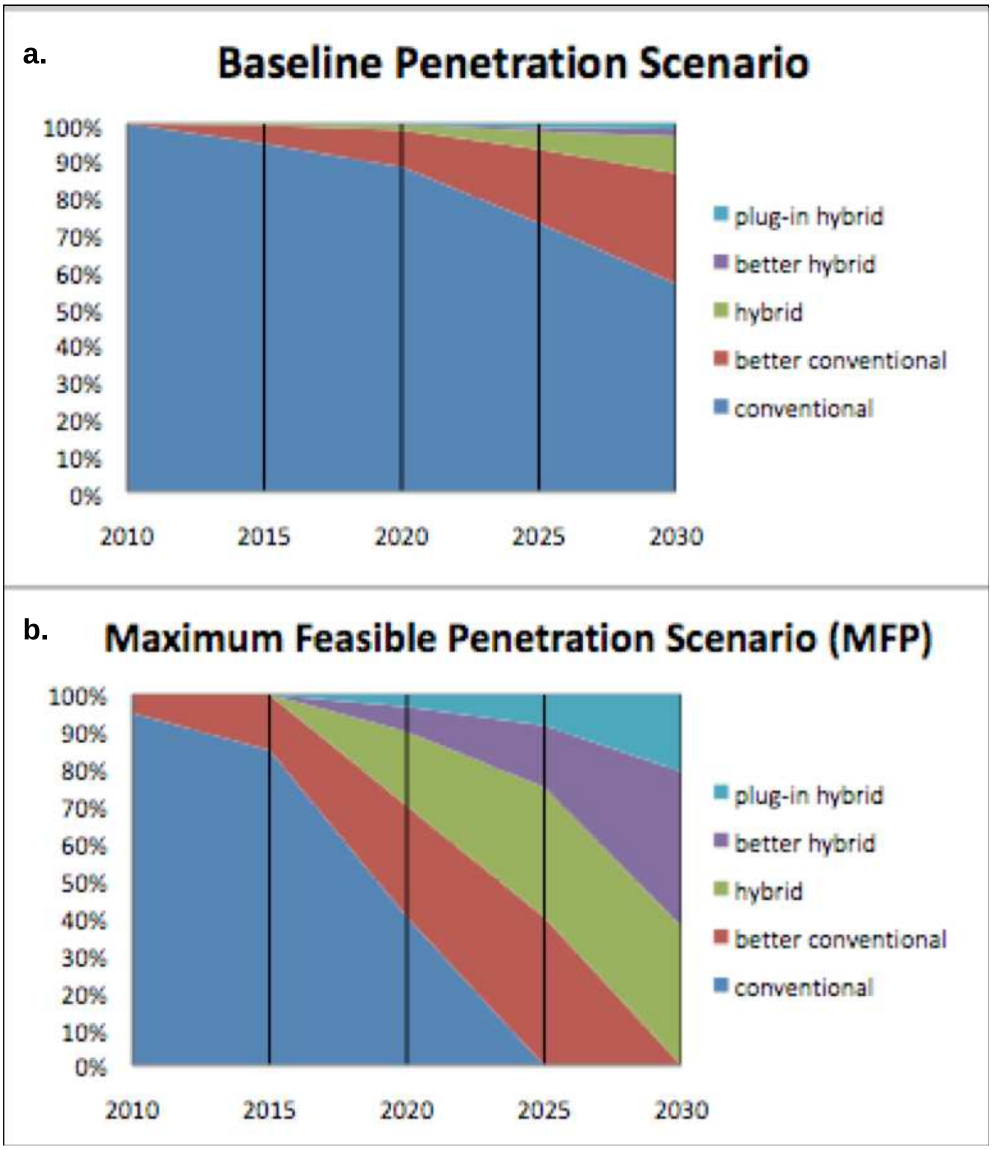
Appendix - Penetration Scenarios

Figure 2a – 1d. Gasoline Light Duty Truck fuel-efficient vehicle technology penetration scenarios. The Baseline scenario constitutes "Business as usual," while the MFP, low MFP and high MFP present a range of scenarios for aggressive technology penetration.



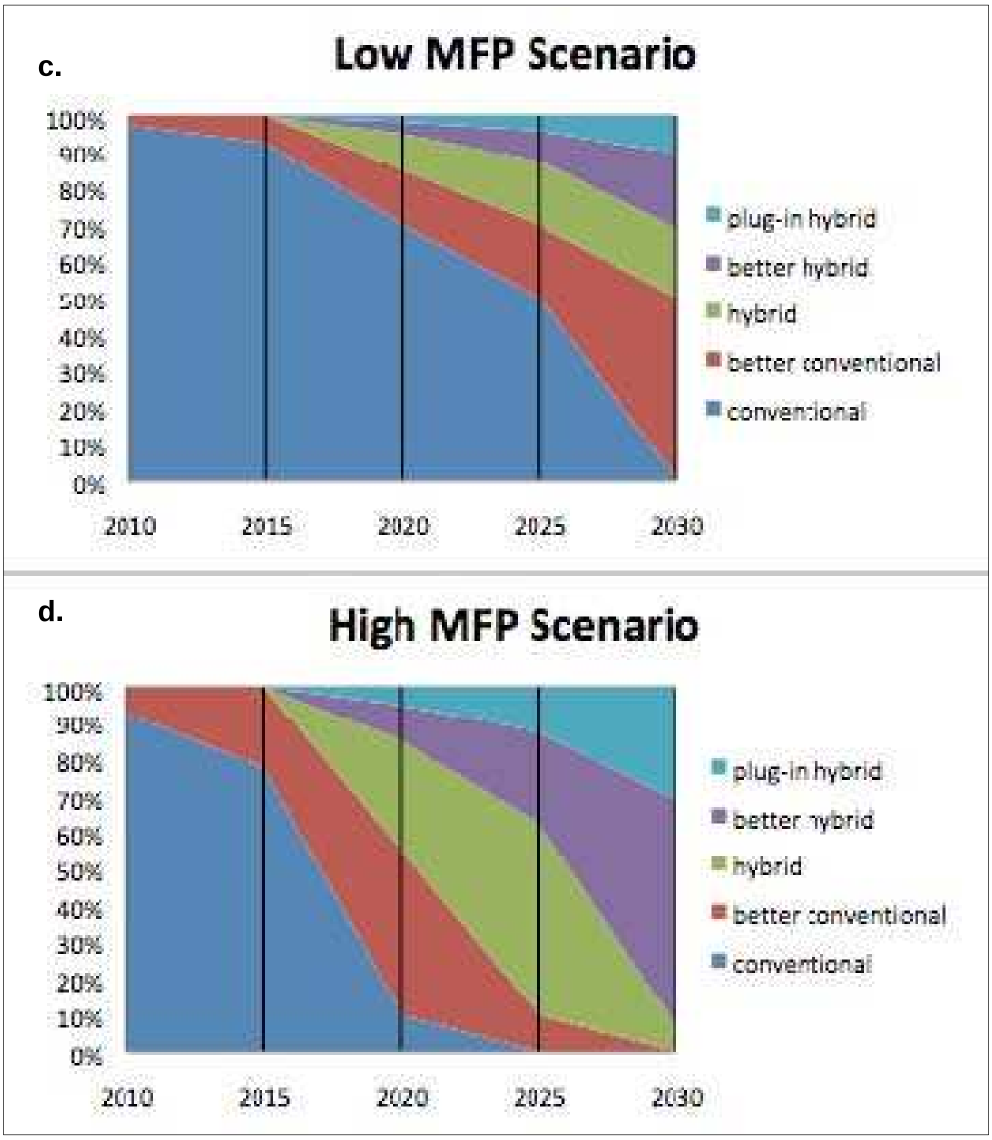
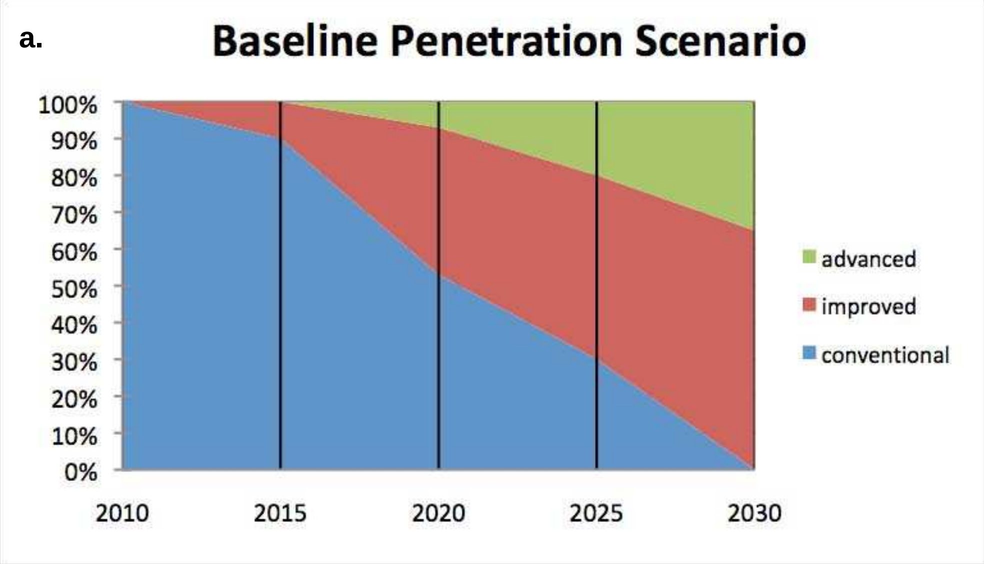
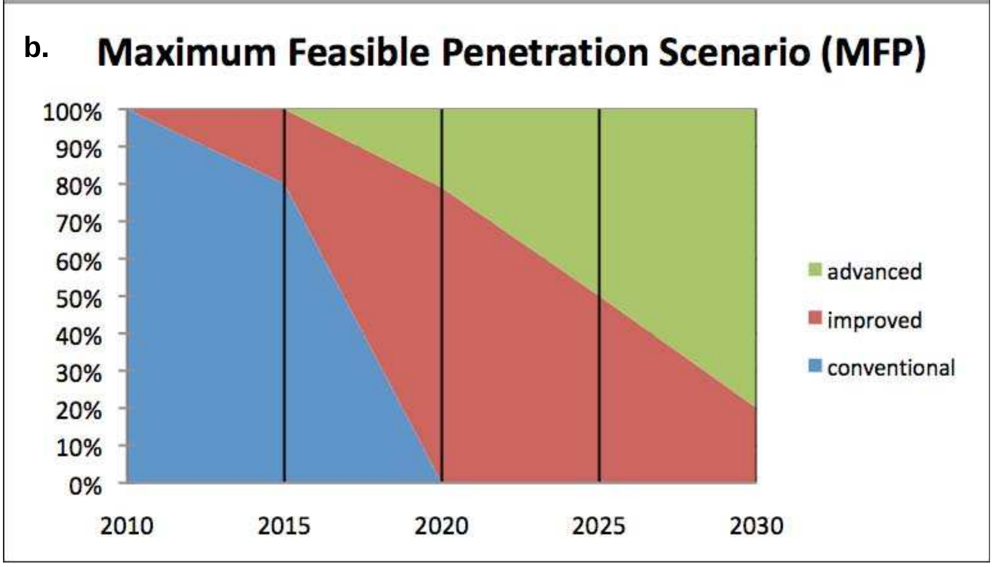
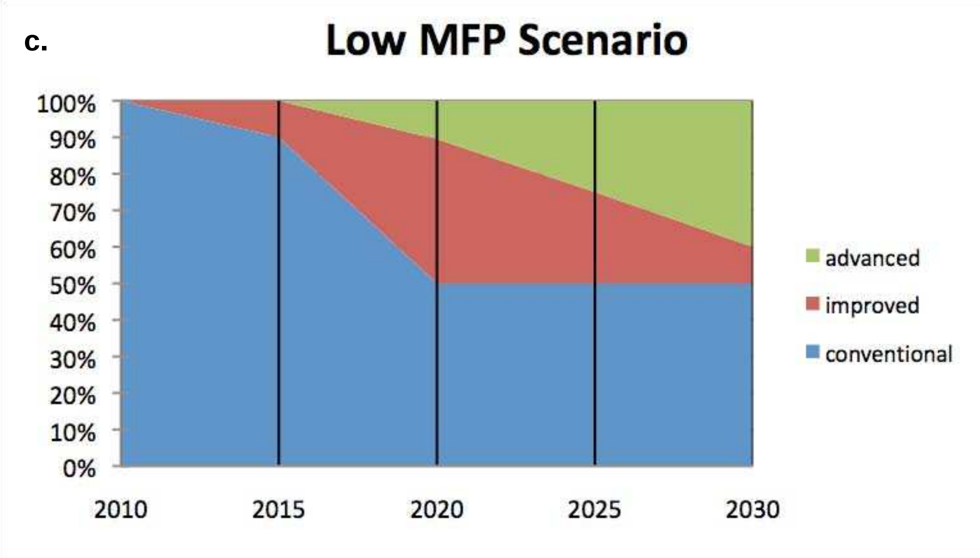

c.
Low MFP Scenario
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
2010
2015
2020
2025
2030
plug-in hybrid
better hybrid
hybrid
better conventional
conventional
d.
High MFP Scenario
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
2010
2015
2020
2025
2030
plug-in hybrid
better hybrid
hybrid
better conventional
conventional

Figure 2a -2d.Diesel Heavy Duty Truck fuel-efficient vehicle technology penetration scenarios. (See Borken-Kleefeld (2009) for detailed descriptions of technology packages.)






c.
Low MFP Scenario
100%
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2010
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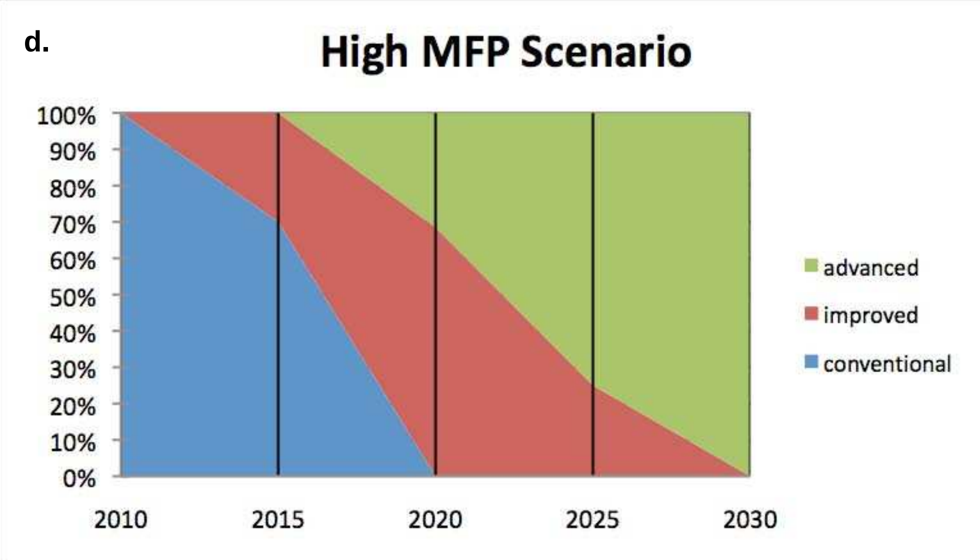
2025
2030
advanced
improved
conventional


d.
High MFP Scenario
100%
90%
80%
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2010
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advanced
improved
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