Roads toward a low-carbon future: Reducing CO_2 emissions from passenger vehicles in the global road transportation system

March 2009

McKinsey&Company

Printed in New York City.

Roads toward a low-carbon future: Reducing CO_2 emissions from passenger vehicles in the global road transportation system

Even as automakers and suppliers struggle with the effects of a severe economic downturn, the global movement to reduce greenhouse gas emissions continues to gain momentum. Internationally, key negotiations on a post-Kyoto agreement will take place in 2009 and 2010. In Europe, regulations to limit tailpipe emissions in the passenger vehicle fleet to 130 grams CO_2 per kilometer will take effect as early as 2013,[1] with other regions likely to follow. In North America, the Obama administration is signaling that it intends to tackle climate change vigorously.

Politicians and policymakers are increasing their focus on carbon dioxide (CO_2) emissions from passenger vehicles[2] with reason: these vehicles are a highly visible source of greenhouse gases that has the potential to continue growing steadily through 2030 and beyond. "Well-to-wheel"[3] carbon emissions from these vehicles accounted for about 7 percent of global greenhouse gas emissions in 2006. Unabated annual carbon emissions from passenger vehicles are, however, projected to climb more than 54 percent by 2030, reaching 4.7 gigatonnes (Gt)

1 The European Union proposal would require 65 percent of the European fleet to meet 130 grams CO_2 per kilometer in 2012 and for 100 percent of the fleet to meet that standard by 2015.

2 This report uses "passenger vehicles" inclusively to refer to passenger and other light-duty vehicles up to 3.5 metric tons (tonnes), which are the focus of this research effort. Depending on the context, this report also uses "automotive sector" to refer in a general sense to these vehicles and their emissions or to participants in the sector, which would include automakers, suppliers, consumers, fuel providers, and regulators.

3 Emissions figures in this report, except where noted, represent "well-to-wheel" emissions, which reflect the totality of carbon emissions generated in the drilling, refining, distribution, and consumption of fuel. Tank-to-wheel emissions, or tailpipe emissions, exclude the carbon generated before the energy reaches the vehicle. A "well-to-wheel" emissions perspective enables more accurate comparison of different technologies and more fully reflects the total emissions associated with the sector itself. Note that our well-to-wheel calculations exclude estimates of emissions from the automotive manufacturing process.

CO_2e that year.[4] Underlying this growth is a large expected increase in the number of vehicles on the road – from 730 million to more than 1.3 billion over this period. The growth in carbon emissions contrasts sharply with reductions of up to 50 percent that will be needed, according to the Intergovernmental Panel on Climate Change (IPCC), to stabilize atmospheric concentration of CO_2 at 450 parts per million – the amount estimated as necessary to prevent average global temperatures from rising by more than 2.0 to 2.4 degrees centigrade.[5]

Reducing CO_2 emissions from passenger vehicles will, however, be a highly capital-intensive endeavor. Given the need to reduce such emissions and a severe economic downturn, the outlook for the automotive sector and its consumers is troubled. Could reducing CO_2 emissions be a "nail in the coffin" for the sector, forcing automakers to scale back production, close factories, and shed jobs? Could consumers be forced to drive smaller vehicles, spend more for those vehicles, or even sacrifice the convenience of personal automotive transportation all together? *Or*, could addressing CO_2 emissions ignite demand for new fuel-efficient vehicles and be a catalyst for exciting new products and business models? Answering such questions is a critical and timely task.

This report – based on an 18-month joint effort of McKinsey & Company's Automotive & Assembly Practice and Climate Change Special Initiative – finds that meaningful, cost-effective reductions in carbon emissions from passenger vehicles will entail an integrated approach involving a broad range of measures. These measures could include vehicle upgrades for greater fuel efficiency, broad use of biofuels, swift improvements to road and traffic infrastructure, greater use of public transportation, and driver education to capture the benefits of more fuel-efficient eco-driving.[6] In light of these opportunities, many policymakers are considering such options as fuel-efficiency standards, market price signals, customer incentives and financing, consumer education and behavior change, specialized incentives and/or subsidies for innovative automotive technologies, programs for improving traffic flow and the use of public transportation, and promotion of lower-carbon energy and fuel.

4 CO_2e, or "carbon dioxide equivalent" is a standardized measure of greenhouse gas emissions designed to account for the differing global-warming potentials of these gases. Emissions are typically measured in metric tons (tonnes) of CO_2e per year, i.e., millions of tonnes (megatonnes) or billions of tonnes (gigatonnes).

5 This scenario and its emissions levels were presented as having a probability of greater than 70 percent in "IPCC Fourth Assessment Report: Climate Change 2007." We take the scenario as a useful reference point for the public discussion of greenhouse gas abatement and for the analyses in this report.

6 Eco-driving consists of various techniques to maximize a vehicle's actual fuel efficiency, such as driving at a steady speed and accelerating and decelerating gradually.

Our research suggests that annual carbon emissions from passenger vehicles could be reduced by 2.2 Gt in 2030 (in a scenario involving a variety of propulsion technologies and other measures). The annual incremental investment in 2030 for enhanced vehicle content to improve fuel efficiency – across all regions and all propulsion systems – would exceed €170 billion (≈$230 billion), averaging €1,890 (≈$2,550) per vehicle.[7] Focusing solely on optimizing internal combustion engines would likely be more cost effective, but it would do little to prepare the automotive sector for a transition to new propulsion systems that would enable the additional emissions reductions that the IPCC anticipates in the period from 2030 through 2050.

Under the parameters of our analyses – which reflect theoretical economic and resource factors, not political realities – the rise in emissions could be halted within the next decade, with a continued decline of 11 to 22 percent below 2006 levels by 2030.[8] In 2020, more than 50 percent of CO_2 abatement potential could come from the combined impact of second-generation biofuel, traffic flow, shifts to public transportation, and eco-driving measures. Such measures are essential for near-term abatement because of the potentially shorter time and relatively lower incremental cost associated with their implementation, as well as their applicability to the entire fleet, not just new vehicles. In 2020, technical improvements to enhance the fuel efficiency of vehicles would account for the remainder – slightly less than half – of the identified abatement potential. By 2030, however, improvements to vehicle fuel efficiency could account for more than 70 percent of the total reduction potential, making such improvements key to long-term abatement in the automotive sector.

The goal of this report is to provide a detailed, consistent fact base for the abatement potential and incremental resource costs of key measures to reduce or avoid CO_2 emissions from the use of passenger vehicles.[9] While we refrain from prescribing specific policy solutions, we do explore the implications and potential value of certain types of policy approaches with the hope that the

7 Currency conversions throughout this report assume an exchange rate of $1.35 to €1.00, unless otherwise noted.

8 Emissions abatement potentials in the commercial vehicle and aviation sectors are substantially smaller than in the passenger vehicle sector; as a result, emissions from the transportation sector as a whole are unlikely to peak until later, in the medium to long term.

9 Resource costs reflect the incremental cost of an abatement measure compared to the no-action baseline, annualized over the life of the asset. Thus, resource costs incorporate investment costs, operating costs, and possible savings generated by the measure; they do not include transaction costs, communication or information costs, subsidies, any carbon price or tax, the consequent impact on the economy.

report will enable economically sensible decisions about how best to address the challenge presented by these carbon emissions.

This report identifies key opportunities to reduce carbon emissions from passenger vehicles through the use of proven technologies available today, examines challenges associated with reducing emissions from these vehicles, and explores implications for stakeholders associated with the automotive sector. The report has three sections:

1. Opportunities to reduce passenger vehicle CO_2 emissions by 2030

2. Challenges associated with reducing passenger vehicle CO_2 emissions

3. Proposal for an integrated approach.

Two appendices, “Representative Fuel-Efficiency Measures” (A) and “Regional Abatement Curves for 2030” (B), follow.

1. OPPORTUNITIES TO REDUCE PASSENGER VEHICLE CO_2 EMISSIONS BY 2030

To understand how improving the carbon productivity of passenger vehicles can contribute to the enormous emissions reductions needed globally, we analyzed more than 25 discrete abatement measures across five regions, calculating their abatement potential and resource costs.[10] We also analyzed three paths along which the automotive sector might proceed, based on the types of technology that might be employed. We found:

- A range of positive abatement outcomes is possible
- The benefit from abatement would outweigh the incremental upfront investment
- Second-generation biofuel, traffic improvement, and behavioral measures offer important abatement potential, especially through 2020
- Fuel-efficiency measures would provide the majority of abatement potential in 2030.

10 Appendix B to this report contains abatement curves for regions analyzed in depth: North America, Europe (including Russia), China, and Japan.

The remainder of this section examines these findings in more detail.

Range of positive abatement outcomes possible

The three abatement paths represent different potential approaches to improving the carbon efficiency of passenger vehicles. Presented below as separate scenarios, these paths differ according to the propulsion technology they emphasize:

- Hybrid and electric technologies
- Mixture of hybrid, electric, and internal combustion technologies
- Internal combustion technology.

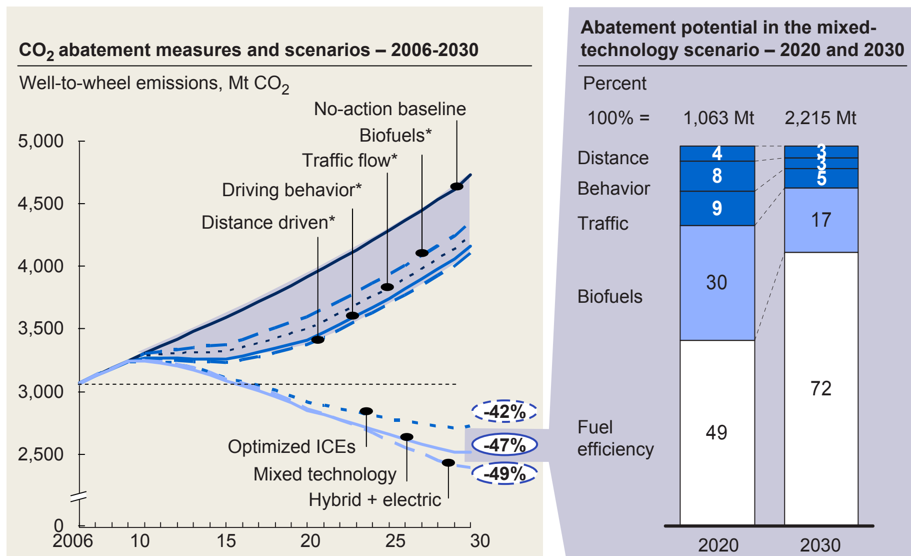
The scenarios differ in the rate and time over which particular technologies penetrate the global vehicle fleet, leading to different penetration levels in 2030. By definition, there is a large difference between the number of new vehicles entering the fleet in any year and the size of the fleet itself. Actions that reduce the carbon emissions of new vehicles therefore have a delayed impact, whereas actions that affect the whole fleet have a more immediate effect. Rather than providing a point estimate of future emissions and abatement, the scenarios offer a range of possible outcomes and reveal the relative advantages and disadvantages of different approaches. We analyzed the abatement potential of each scenario relative to two reference points: projected future automotive sector emissions (assuming no action is taken to reduce emissions) and 2006 emissions figures (Exhibit 1).

It is important to note that calculations of well-to-wheel emissions from the electrification of vehicles assume an aggressive reduction in the carbon intensity of electricity generation, from approximately 600 to 250 tonnes CO_2e per gigawatt-hour. The scenarios share the same assumptions for abatement using other important measures, specifically biofuel, traffic flow, a shift to public transportation, and eco-driving. Many of these additional measures could begin to have meaningful impact relatively quickly, causing emissions from the use of passenger vehicles to begin declining within the next decade.

- **Hybrid-and-electric scenario: 49-percent reduction relative to the no-action emissions baseline; a 22-percent reduction relative to 2006 emissions levels.** This represents a relatively aggressive scenario, assuming a rapid transition toward a world of electricity-based vehicle propulsion systems (Exhibit 2). All remaining ICE-powered vehicles would be optimized for greater carbon efficiency. Average well-to-wheel emissions from new vehicles worldwide in this scenario would decline from 270 grams of CO_2 per kilometer traveled in

Exhibit 1

Global passenger vehicle CO_2 emissions and abatement potential



* Emissions reductions for biofuels, traffic flow, driving behavior and distance driven based on mixed-technology scenario.
Source: McKinsey analysis

2006 to 130 grams of CO_2 per kilometer in 2030.[11] Almost 60 percent of the abatement potential in this scenario depends on the availability of low-carbon sources of electricity generation and assumes an infrastructure will be in place to support the electrified vehicle fleet.

- **Mixed-technology scenario: 47-percent reduction relative to the baseline; 18-percent reduction relative to 2006 emissions.** This scenario assumes a more balanced mix of technological solutions reach the market, including optimized ICEs, hybrids, and electric vehicles. Average well-to-wheel emissions from new vehicles in this scenario would fall to 150 grams of CO_2 per kilometer travelled in 2030.

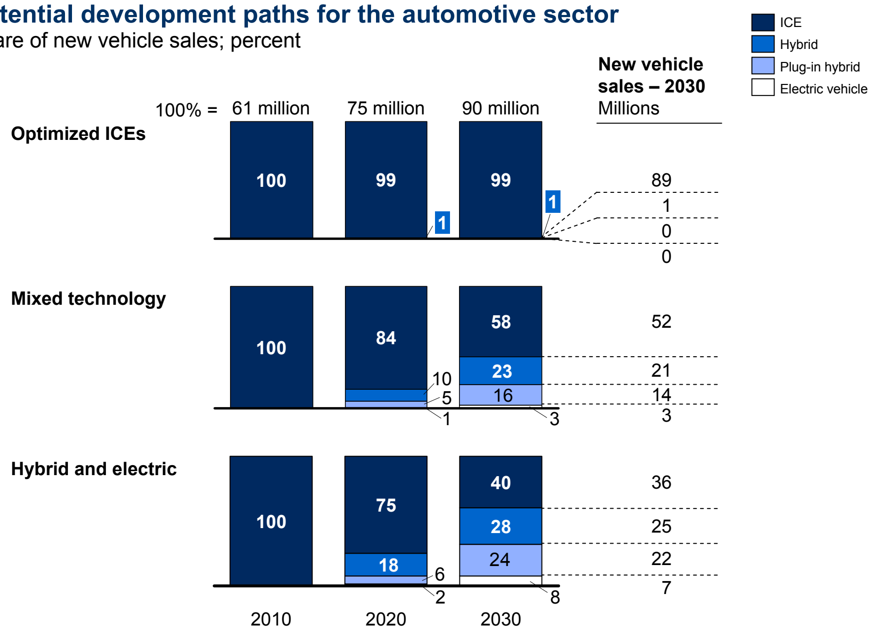
- **ICE scenario: 42-percent reduction relative to the baseline; 11 percent reduction relative to 2006 emissions.** This scenario assumes automakers optimize the fuel efficiency of vehicles powered by internal combustion engines, but the sector does not witness any meaningful global penetration of hybrid or electric vehicles. Average well-to-wheel emissions from new vehicles would decline to 170 grams of CO_2 per kilometer travelled in 2030.

11 Based on 2,371 grams CO_2 per liter of gasoline fuel and 2,640 grams of CO_2 per liter for diesel fuel.

Exhibit 2

Potential development paths for the automotive sector

Share of new vehicle sales; percent



Source: Global GHG Abatement Cost Curve v2.0

Electrification of the vehicle fleet will play an ever-increasing role in reducing carbon emissions from passenger vehicles in the medium to long term. As CO_2 emissions from electricity generation decline through planned investments, Europe and the United States will reach a point at which vehicle electrification will make sense for well-to-wheel carbon abatement, potentially as early as 2017. In the most aggressive case, the hypothetical electrification of the entire global passenger vehicle fleet by 2030 (over four product generations) would likely reduce well-to-wheel carbon emissions from passenger vehicles by 81 percent relative to the no-action baseline. This scenario assumes the carbon intensity of electricity generation in 2030 would be approximately 250 tonnes per gigawatt-hour – a challenging but feasible scenario.[12] We have not detailed such a scenario in this report, as the timing of the transition to such a future state remains unclear and will depend on numerous factors; furthermore, the costs, given today's business models, would be significant. A technical breakthrough that significantly reduces battery system costs and development of an infrastructure that supports vehicle charging on a mass scale will likely

12 See "Pathways to a Low-Carbon Economy: The Global Greenhouse Gas Abatement Cost Curve, version 2," McKinsey & Company, January 2009, chapter 8.1. As of 2009, the carbon intensity of electricity stands at around 600 tonnes CO_2e per gigawatt-hour, and well-to-wheel carbon emissions in some regions would actually increase in the short term with electrification of vehicles.

dictate the timing. Innovation in this area is occurring rapidly as new business models are being developed to address the initial costs of battery systems and the limitations of today's infrastructure.

Benefit from abatement would outweigh incremental upfront investment

For the balance of this report, we focus on the mixed-technology scenario because it envisions a moderately paced transition away from ICEs and depends less on improvements to the carbon intensity of the energy supply. In this scenario, with the average price of oil assumed to be $60 per barrel,[13] the global automotive sector could reduce its annual emissions by 2.2 Gt CO_2e with an average annualized savings of €27 (≈$36) per-tonne CO_2e. It is important to note, however, that fuel savings and incremental costs are measured over the lifetime of the vehicle, without regard for who makes the initial investment and who receives the benefit of the fuel savings.

By arranging the abatement measures, with their potentials, from lowest to highest per-tonne cost, we created a global carbon abatement curve for passenger vehicles. In many cases we aggregated groups of closely related measures into a single entry; this was especially true of fuel-efficiency technologies, which we grouped into separate gasoline and diesel packages of increasing fuel efficiency (labeled "P1" through "P4"),[14] based on how these technologies would likely be introduced by automakers.

We calculated the incremental per-tonne cost shown in the abatement curves as the annualized incremental cost for implementation minus the annualized benefit of implementation, displaying the cost in 2006 real euros. For fuel-efficiency measures, we calculated the per-tonne cost as the difference between the annualized incremental vehicle cost associated with the CO_2 reduction technologies and the annualized fuel savings that result from better fuel economy. If the measure appears on the cost curve below the horizontal axis, the benefits outweigh the costs (a cost-negative measure) on an annual basis.

13 Throughout our analyses, the price of oil is assumed to be $60 per barrel for West Texas Intermediate (WTI), unless otherwise noted.

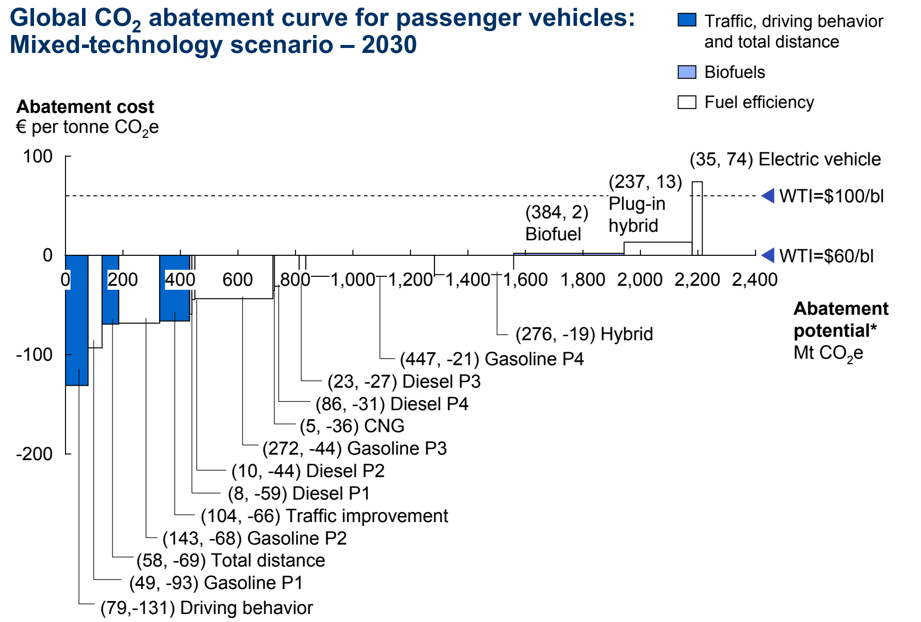
14 Gasoline Package 4 consists of engine downsizing (≈40 percent) with turbo-charging, variable valve control, engine friction reduction, homogeneous direct injection, low rolling resistance tires, weight reduction (≈9 percent), electrification of ancillary components, optimized dual-clutch transmission, improved aerodynamics, and stop-start capability with regenerative braking. Appendix A outlines the contents of this and other fuel-efficiency packages.

If the measure appears above the axis, costs are greater than benefits (a cost-positive measure).[15]

The abatement curve for the mixed-technology scenario in 2030 shows, for example, that the second-generation biofuel, driving behavior, and traffic flow measures would be highly cost effective (Exhibit 3). Reducing the carbon content of fuel by increasing the mix of biofuel to 25 percent could be achieved at a net cost of €2 (≈$3) per tonne CO_2e. By contrast, traffic improvement measures could yield a benefit of €66 (≈$89) per tonne of CO_2e abated and would affect the entire fleet, not only new vehicles.[16]

Exhibit 3

Global CO_2 abatement curve for passenger vehicles: Mixed-technology scenario – 2030



* Calculated on a well-to-wheel basis
Source: McKinsey analysis

15 To make figures comparable across regions, the costs and benefit calculations do not consider regional taxes, subsidies, or other differences from natural market cost and benefits. The figures have also been calculated over the useful life of the assets involved (15 years for automobiles); these figures therefore omit the economics related to first and subsequent owners.

16 Per-tonne CO_2e savings for traffic improvements were calculated based on individual government reports of road construction and the economics of improvement projects, which allocate the capital expense to such benefits as safety and time.

The curve also reveals that improving the fuel efficiency of new vehicles would save modest sums of money for consumers, on average and over the life of the vehicle. With crude oil priced at $60 per barrel, reducing 1 tonne CO_2e from passenger vehicles in the hybrid-and-electric scenario would yield a net benefit of €13 (≈$18) to the average consumer from associated fuel savings. In the ICE and mixed-technology scenarios, consumers would save €38 (≈$51) and €27 (≈$36) per tonne respectively. The benefit to consumers would be even greater if average long-term fuel prices are higher.

It is worth noting that the ICE scenario offers the most cost-effective abatement on a per-tonne basis in 2030, with average per-tonne savings that are 40 percent greater than the mixed-technology scenario and almost 200 percent greater than the hybrid-and-electric scenario. The fuel efficiency for optimized ICEs in our scenarios, however, is near the maximum possible level. Achieving a step-change improvement beyond this would require a fundamental change in the underlying energy supply to lower-carbon sources, such as second-generation biofuels or electricity.

Biofuel, traffic improvement, and behavioral measures offer important abatement potential, especially through 2020

Measures to reduce the carbon content of fuel, improve traffic flow and driving behavior, reduce distances driven, and manage the vehicle stock would provide as much as 630 megatonnes (Mt) of abatement in 2030 in our mixed-technology scenario. Some of these measures, notably improving traffic flow and driving behavior and reducing the carbon content of fuel, are especially important to abatement efforts through 2020.

- **Reducing the well-to-wheel carbon content of fuel and energy.** Reducing the carbon content of fuel by increasing the average biofuel mix in the gasoline supply to 25 percent globally could theoretically yield 380 Mt of abatement (17 percent of the total) at an average cost of €2 (≈$3) per tonne CO_2e in 2030. Blending low-carbon biofuel is an effective way to cut the well-to-wheel carbon content of fuel. Our analysis assumes that a 25-percent biofuel-gasoline mix (the level currently achieved in Brazil) would be possible in all regions using a combination of first-generation feedstock, such as sugarcane, and second-generation ligno-cellulosic sources, such as switch-grass, which are expected to offer substantially greater carbon abatement than corn-based ethanol. For biodiesel, a 25-percent mix is also possible in some regions from such first-generation feedstock as palm oil, rapeseed, soy beans, and recycled cooking oils, but there may also be second-generation feedstocks and processes that would reduce production costs.[17]

Widespread implementation of biofuels would, however, incur additional costs and might not be a viable option in every country. Development of biofuels that more closely resemble gasoline and diesel would help address this challenge. To use ethanol at blending levels above 10 percent,[18] for example, vehicles would need a €225 to €370 ($300 to $500) upgrade to their fuel-delivery systems, due to the corrosive properties of ethanol. Given current and expected future costs for production capacity, the economic attractiveness of biofuels will be driven by some combination of successes in commercial-scale production efficiency, feedstock costs, subsidies, a tax on carbon, and the long-term price of oil.

- **Improving traffic flow and driving behavior.** Improving traffic flow and driving behavior would yield 180 Mt of abatement (8 percent of the total) at an average savings of €94 (≈$127) per tonne in 2030. Improving traffic flow through smarter traffic signals and other related approaches would improve the actual fuel efficiency of vehicles, for example, by reducing the number of starts and stops, reducing the need for acceleration and deceleration, and increasing the average speed. Educating consumers to eco-drive can improve actual fuel efficiency by an average of 17 percent, although it varies from driver to driver; implemented on a mass scale, eco-driving could reduce emissions by about 3 percent globally. Policymakers in many regions generally overlook traffic flow and driving behavior as levers for CO_2 abatement, although our analysis suggests these are among the most cost-effective levers. In fact, improving traffic flow and driving behavior yield a per-tonne benefit to society that is greater than the average benefit from fuel-efficiency measures. A number of these measures could be achieved in relative short order, making them especially attractive for the period from 2010 to 2020.

- **Reducing the distance driven.** Reducing the distance driven would yield 58 Mt of abatement (3 percent of the total), with a savings of €69 (≈$93) per tonne in 2030. Shifting to alternative modes of transportation (e.g., rail, bus, bicycle, foot) and implementing road pricing could help cut distances driven annually.

17 Our model assumes 25-percent biodiesel penetration is possible in North America, China, and Japan, where diesel comprises less than 2 percent of the automotive fuel supply. In Europe, where diesel accounts for a larger share (30 percent in 2006, 40 percent in 2030), our model assumes no growth in biodiesel.

18 Based on reports by U.S. automakers; the threshold in Europe is set lower, at 5.7 percent.

In developing countries where major infrastructure improvements are just under way or planned, efforts to build smart, efficient public transportation systems could reduce the need for passenger vehicles, especially in densely populated metropolitan areas.

- **Managing vehicle stock.** Scrap programs or fuel-efficiency requirements for existing vehicle stock could accelerate the retirement of older, less fuel-efficient vehicles and simultaneously increase demand for more efficient vehicles. These programs can be particularly effective for CO_2 reduction where the stock of old vehicles is large. Germany and France, for example, currently provide subsidies of €2,500 (≈$3,375) and €1,000 (≈$1,350) respectively to consumers who scrap an older vehicle in favor of a new, more fuel-efficient one.[19] Efforts to manage vehicle stock also could provide other benefits, such as improved road safety, while stimulating demand for new fuel-efficient vehicles.

Fuel-efficiency measures would provide majority of abatement in 2030

Increasing fuel efficiency is the single most important abatement lever for 2030 and beyond. More than 70 percent of the total abatement potential in that year could come from fuel-efficiency measures, yielding 1.6 Gt of abatement at an average savings of €25 (≈$34) per tonne. Improving the powertrain efficiency, aerodynamics, and rolling resistance (including weight reduction) of vehicles can enhance their well-to-wheel fuel efficiency by 30 to 85 percent over current levels, depending on the approach:

- **Optimized ICEs.** Technology available today can improve the fuel efficiency of today's ICE gasoline vehicles by about 39 percent at an incremental cost (relative to the cost of an average vehicle without such technologies) of around €3,000 (≈$4,050) per vehicle. Similar changes to diesel vehicles can boost fuel efficiency by 36 percent over current levels at an incremental cost of around €2,600 (≈$3,510) more than today.

- **Hybrid-electric vehicles.** Current hybrid-electric technology can improve vehicle fuel efficiency relative to today's ICE equivalent by about 30 percent; combined with additional vehicle optimization measures like further weight reduction, fuel efficiency would increase by an average of 44 percent relative to today's ICE. The incremental per-vehicle cost is almost €4,000 (≈$5,400) today.

19 In the German program, the vehicle being scrapped must be at least 9 years old, while in the French program the vehicle must be at least 10 years old.

- **Plug-in hybrid-electric vehicles.** PHEV technology combined with vehicle optimization can yield fuel-efficiency improvements of between 65 and 80 percent in some regions relative to current ICE performance, although the incremental cost per vehicle would be almost €16,126 (≈$21,770) today for a vehicle with an electrical driving range of 60 kilometers (≈38 miles).

- **Electric vehicles.** In 2030, EVs could provide well-to-wheel emissions reductions of 70 to 85 percent relative to today's ICE vehicles, with virtually zero tail-pipe emissions. With cost reductions for batteries in the range of 5 to 8 percent per year through 2030, incremental per-vehicle costs are likely to decline from €36,000 (≈$48,500) today to €5,800 (≈$7,800) over the next two decades for vehicles with a driving range of 160 kilometers (≈100 miles). Electric vehicles capable of such distances will remain more costly than their ICE equivalents, suggesting that less costly, lower-range EV derivatives may be more likely to prevail. In addition, infrastructure investments will be required on a large scale to support an electric vehicle fleet of any significance.[20]

In calculating abatement potentials, we focused on proven technologies that can be deployed at a commercial scale in the very near future, so as to provide as realistic an estimate as possible. If important breakthroughs occur in such emerging technologies as high-capacity electricity storage, fuel cells, or third-generation biofuels, then the amount of carbon that can be abated by 2030 could rise dramatically.

Beyond the implementation of electric vehicles and low-carbon energy supply, radical "game-changing" technologies could play an even greater role in abatement over the coming decades. These technologies could include the development and commercialization of a newer and lighter generation of vehicles that break existing paradigms. For example, personal transportation has been dominated for decades by four-wheel vehicles that spend 98 percent of their fuel to move the vehicle itself and not the passengers or cargo. Other game-changing technologies could include advances in traffic control and could create, for example, intelligent traffic management systems in which traditional signals and traffic lanes are not required, or where vehicles communicate with each other, preventing crashes and the carbon-wasting congestion that results.

20 For battery-powered EVs, the evolution of costs and associated payback periods is highly uncertain, because reported costs for batteries differ widely within the industry. For example, per-kilowatt-hour costs for lithium-ion batteries in 2008 ranged from €505 (≈$681) to €1,143 (≈$1,542).

Though we make no attempt to quantify the potential from such opportunities in our abatement curves, these developments could become important if the IPCC's longer-term emissions thresholds, those for 2050, are to be achieved.

2. CHALLENGES ASSOCIATED WITH REDUCING PASSENGER VEHICLE CO_2 EMISSIONS

Abatement of CO_2 emissions in the automotive sector offers a positive net economic benefit of some €27 (≈$36) per-tonne CO_2e in 2030, substantially more per tonne than abatement in most other sectors, including electric power, iron and steel, chemicals, and agriculture.[21] One might expect that the benefit associated with abating passenger vehicle emissions would motivate pursuit of that potential, even though these vehicles account for only 7 percent of global annual greenhouse emissions. Despite the net economic benefit, however, achieving meaningful reductions in passenger vehicle emissions will be a mammoth challenge. Three factors make it especially challenging: first, the upfront investment needed for implementation is exceptionally large; second, there are substantial barriers to changing consumer behavior; and third, the need for timely action is building.

Large upfront investment needed for implementation

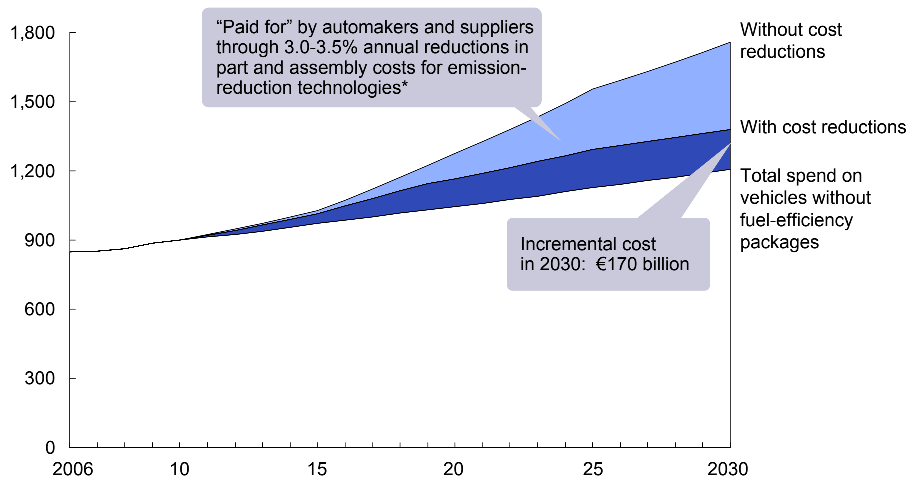
While many of the fuel-efficiency measures would – at a global level – benefit consumers over the life of the vehicles, the incremental upfront investment in content needed for implementation is outstandingly large. The *annual* incremental investment in 2030 for enhanced vehicle content to improve fuel efficiency (Exhibit 4) – across all regions and all propulsion systems – would exceed €170 billion (≈$230 billion), averaging €1,890 (≈$2,550) per vehicle. This amount would represent roughly 14 percent of the total expected industry spend on passenger vehicles that year. The incremental investment per vehicle would vary according to the type of technology deployed to abate carbon emissions. For example, in 2030 an optimized ICE installed in a vehicle that is both lighter and more aerodynamic would have an incremental cost of €1,563 (≈$2,109) over the average vehicle today (Appendix A).

21 See "Pathways" (note 12), chapter 4. Displayed on an abatement curve, the automotive sector would have an average per-tonne cost of abatement of negative €27, while electric power would have an average positive cost of €21 (≈$28), iron and steel €17 (≈$23), chemicals €5 (≈$7), and agriculture €1.20 (≈$2).

Exhibit 4

Additional investment required for global implementation of fuel-efficiency measures – Mixed-technology scenario

€ Billions



* Assuming 83% of total sales based on major automakers COGS in each region. Total market size estimate is based on (new vehicle units sold) x (average vehicle price) in each region

Source: Global Insight; Data monitor; analyst reports; press search; McKinsey analysis

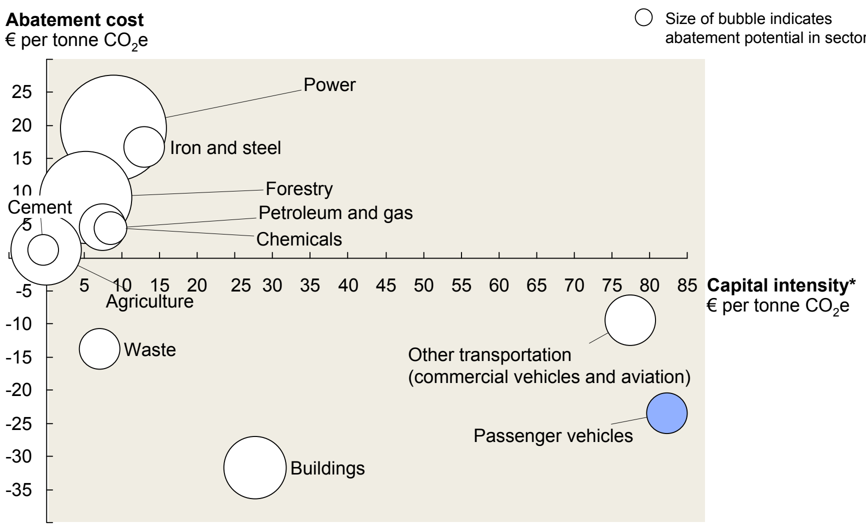
These figures reflect annual cost reductions averaging 3.0 to 3.5 percent for fuel-efficiency-related content included through 2030. In addition, automakers and their suppliers have, in the past, reduced the overall cost of the basic gasoline-powered vehicle by an average of some 2.5 percent per year.[22] Historically, these annual cost reductions have been accompanied by additions of new content (e.g., upgrades to the powertrain, safety improvements, comfort enhancements, and infotainment features). To the extent that future additions of fuel-efficiency content displace or defer other enhancements (e.g., in-car communications), the overall cost of the average vehicle would gradually decline over time, albeit from a higher initial cost. Strong regulatory pressure may ensure that future productivity gains are invested in fuel-efficiency measures, potentially even at the expense of innovations that would enhance other attributes – and therefore, the overall value – of passenger vehicles.

Implementing fuel-efficiency measures in the passenger vehicle sector would demand greater "capital intensity" than would abatement in any other sector (Exhibit 5).

22 See "HAWK 2015: Knowledge-based changes in the automotive value chain," McKinsey & Company, August 2003. This study found that the automotive industry typically reduces per-vehicle costs by €3,000 (≈$4,050) every 13 years. Automakers typically add approximately €4,000 (≈$5,400) of content to vehicles over the same period, leading to gradual increases in the cost of vehicles to consumers.

Exhibit 5

Capital intensity of abatement by economic sector – 2030



* The additional upfront capital investment compared to the baseline case divided by the total amount of emissions avoided during the lifetime of the investment. For measures where upfront investments decrease over time with a learning rate, the weighted average investment over time has been used.

Source: McKinsey Global GHG Abatement Cost Curve v2.0

By "capital intensity" we mean the level of capital required per ton of CO_2e abated over the lifetime of the vehicle; for the passenger vehicle sector, this refers to the incremental investment needed to buy a vehicle with a fuel-efficiency package compared to buying a vehicle without such a package. In fact, the capital intensity of abatement for passenger vehicles is more than nine times the capital intensity of abatement in the power sector, and more than three times that in the buildings sector.

While fuel savings will help offset the large investment requirements, a cash flow analysis of the mixed-technology scenario (calculated as the cash required for new investments in each year minus the fuel savings in each year) indicates that cash requirements for fuel-efficiency measures would peak in 2020 at about €60 billion (≈$81 billion) per year. By 2028, the cumulative impact of fuel-efficiency measures adopted in the mixed-technology scenario would for the first time exceed the required investment, and the fuel-efficiency measures would produce a net benefit for the sector as a whole.

Significant barriers associated with consumer behavior

In our view, three common arguments sometimes underestimate the complications associated with this massive need for incremental capital:

- Even if consumers will not pay today, adding a carbon price to fuel (in the form of taxes or other forms of price increase) will stimulate market forces, causing consumers to drive less and motivating them to buy more fuel-efficient vehicles in the future

- Consumers are becoming increasingly aware of environmental issues and will increasingly "buy green" out of concern for the environment

- Consumers are "rational" and will therefore pay the incremental cost associated with fuel-efficiency measures because their investments will pay back with fuel cost savings.

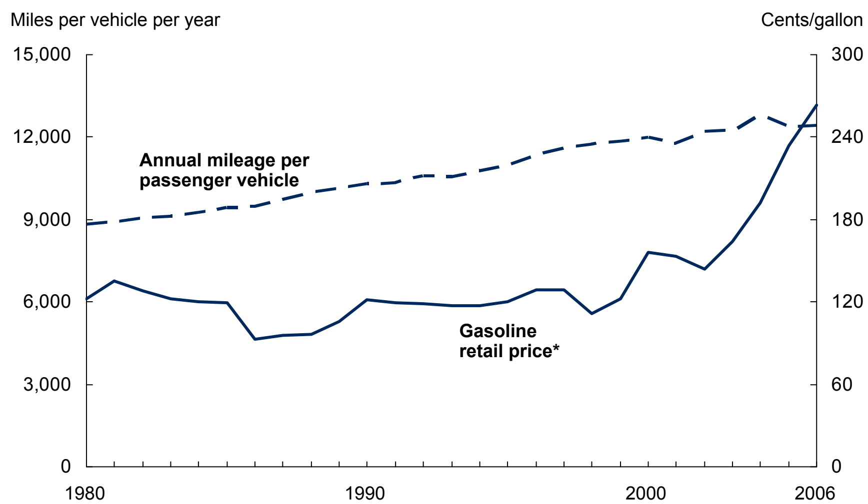
Our analysis suggests that, in the absence of a significant shift from historical patterns, the passenger vehicle sector cannot count on these arguments alone for significant CO_2 reduction in the near term. How the high costs of implementing fuel-efficiency measures will be paid remains an important open question without an obvious or simple answer. This is for three reasons:

1. Relying on increases in fuel prices alone to stimulate abatement in meaningful amounts could have serious negative consequences for the automotive industry. Analysis of retail fuel price changes and miles traveled shows that, over the long-term, sustained high fuel prices may curb driving distance somewhat, but not enough to produce significant long-term abatement. In the short to medium term, the amount of driving does decline slightly in response to sharp rises in the price of fuel (as witnessed by U.S. consumers with the $3.80-per-gallon prices in the summer of 2008), but as consumers adjust to higher prices, distances driven tend to rebound (Exhibit 6). With the exception of a negligible drop in distances traveled in 2007 through 2008, for example, the United States experienced sustained increases in miles traveled by car during the period 2000 to 2008, when retail fuel prices more than doubled.

What *does* happen as fuel prices rise, however, is that individuals spend less on vehicles. Over the past 20 years, consumers have tended to set a fixed share of their wallets for transportation expenses, offsetting higher fuel prices with less spending on vehicles. In 2008, for example, high fuel prices and a significant economic downturn moved some U.S. consumers quickly towards less expensive cars, and away from pricier trucks and SUVs. While sales in all segments plummeted, the drop-off was far deeper for light trucks, SUVs, and vans. U.S. sales of light trucks, SUVs, and vans, for example, dropped 26 percent in 2008 relative to 2007, whereas car sales fell only 10 percent.

Exhibit 6

Retail fuel prices and annual vehicle mileage – 1980-2006



* All types of gasoline; U.S. city average retail price; nominal cents per gallon including taxes
Source: U.S. Energy Information Administration and Department of Transportation

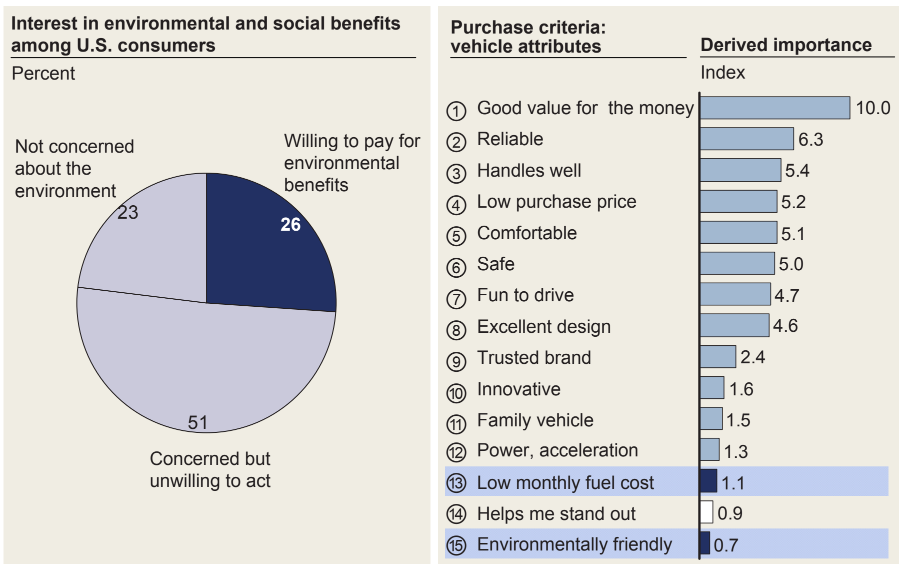
Adding a large carbon tax to fuels could induce abatement through a shift to smaller, more fuel-efficient vehicles, as well as a shift away from vehicle ownership, stimulating a potential shift toward smaller vehicles and shrinkage of the automotive fleet. The result would likely be an overall contraction of the automobile sector, as automakers produce a fleet of vehicles that are on average smaller than those of today for slightly fewer consumers than they would otherwise have served.

2. Analysis of consumer buying trends over the past 2 years shows that "green consumers" have not yet emerged in large numbers, despite the recent increase in awareness of energy security and environmental issues and an increase in fuel prices. It is noteworthy that the recent shift in consumer purchasing behavior described above appears to have been economically motivated, rather than resulting from the emergence of "green" as a buying criterion (Exhibit 7).

Even during the recent two-fold increase in fuel prices, consumers continued to rate attributes associated with fuel efficiency outside their top-10 key buying factors. Despite the record high fuel prices seen in a number of regions in 2008, we may well not have reached the economic tipping-point where higher fuel prices provoke a radical change in consumer buying patterns.

Exhibit 7

Role of CO_2 and fuel efficiency in vehicle purchases



Source: March 2008 McKinsey consumer survey; Synovate Motoresearch's Advanced Propulsion and Fuels Syndicated Study, 12/07, Consumer Survey – "How well does each statement below describe each of these vehicles"

3. The economics of some fuel-efficiency packages are not attractive to buyers of new cars in the absence of tax breaks, subsidies, or other mechanisms to lower initial costs. In fact, for some regions and some fuel-efficiency packages, a "rational" consumer (in a purely economic sense) would opt not to buy a vehicle with some of the more advanced fuel-efficiency measures, such as a plug-in hybrid or electric vehicle. In regions like Japan and China, for example, the relatively low average distances driven annually mean there is less of an opportunity to capture the economic benefit from fuel savings, making the additional cost of fuel-economy features higher than the benefit for the first vehicle owner (Exhibit 8).

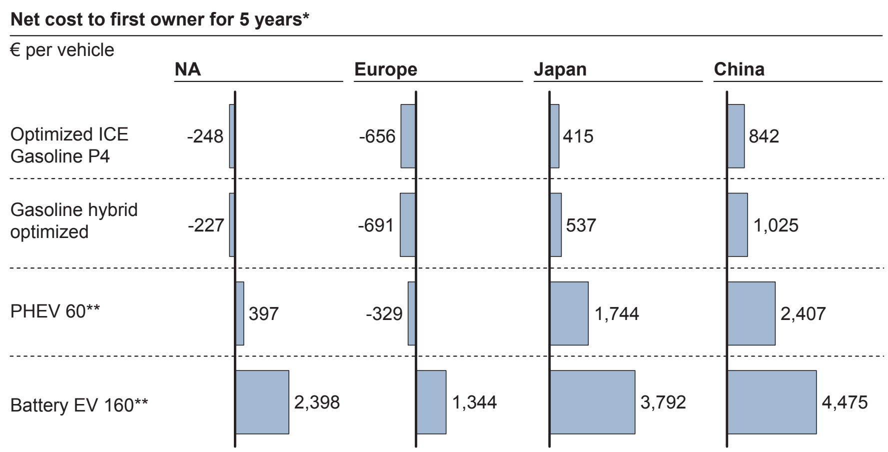
Importance of timely action

If society wants to reduce CO_2 emissions to levels that would have a high probability of achieving global abatement thresholds as set out by the IPCC, time is of the essence. Action in the automotive sector is needed to prevent many more additional years' worth of CO_2 emissions growth and – more importantly – to prevent a high-carbon infrastructure from being locked in for years to come.

Technology choices made today will have an impact for years, if not decades. For sectors like the power sector, the impact of this lock-in effect is dramatic: a coal-fired power plant built in 2009 would likely emit high levels of carbon for 40 to 50 years or longer, unless it were subsequently retrofitted with carbon capture and storage technology, which has yet to be proven feasible at commercial scale.

Exhibit 8

Net Present Value of additional costs/benefits of low-carbon vehicles



* Net cost calculated as 2030 additional vehicle cost compared to normal gasoline vehicle minus NPV of fuel savings over 5 years minus NPV of residual value recovered after 5 years of ownership

** Driving range in kilometers with electric power only

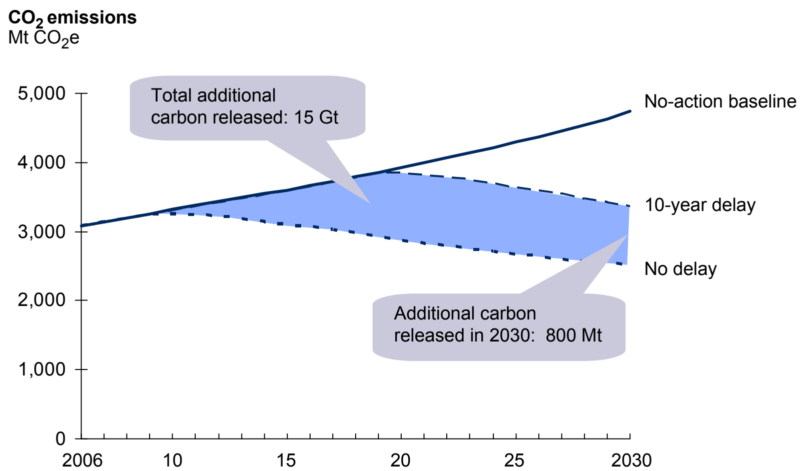
Source: McKinsey analysis

For the automotive sector as well, the lock-in effect could be significant. A fuel-inefficient vehicle bought today will likely stay in the global automotive fleet for an average of 15 years. A typical SUV purchased in North America today will consume about 15 liters (≈4.0 gallons) of gasoline for every 100 kilometers (≈62 miles) it travels, emitting more than 100 tonnes of CO_2 over its lifetime. A similar SUV with just 15 percent higher fuel economy – based on technology commercially available today – would save about 15 tonnes of CO_2 over its lifetime. If less-efficient vehicles predominate in the global fleet, in other words, the lock-in effect would amount to 15 tonnes multiplied by the tens of millions of vehicles sold every year – an amount that would quickly total hundreds of megatonnes of additional carbon emissions per year.

In fact, delaying implementation of all levers by 10 years, from 2010 to 2020, would reduce the 2030 abatement potential in the mixed-technology scenario by 38 percent (≈800 Mt), with the cumulative lost abatement opportunity reaching 15 Gt (Exhibit 9). To put this in perspective, 15 Gt is greater than total annual emissions across all economic sectors in North America.

Exhibit 9

Impact of a 10-year delay on abatement potential – Mixed-technology scenario



Source: McKinsey analysis

The lock-in effect can also work in reverse: accelerated deployment of technology could lock-in CO_2 savings. Compared to the power sector, the "refresh rate" of the global vehicle stock is relatively fast. About 8 percent of the global vehicle fleet is replaced every year with new vehicles; the present fleet is expected to be completely refreshed in only 13 years. In contrast, the global power sector would require decades to achieve a similar degree of turnover. By rapidly deploying existing, proven technologies, such as gasoline ICE turbocharging, the automotive sector can capture significant abatement opportunities. Should the sector accelerate the development cycle of key technologies (a powertrain, for example, typically takes 5 to 8 years to design, develop, and validate), bringing new fuel-efficient designs to market earlier would enlarge the positive lock-in effect.

3. PROPOSAL FOR AN INTEGRATED APPROACH

The outlook for the passenger vehicle sector is indeed troubled. Automakers and suppliers cannot solve the sector's carbon abatement problem on their own. Market evolution by itself will likely take too long to deliver meaningful emissions reductions. Furthermore, our analysis suggests that selective application of one or two policy tools to accelerate market evolution – such as the rapid introduction of a high carbon tax to stimulate changes in consumer behavior – could undermine the industry's economics with potentially serious negative implications for the global economy as a whole.

For the world to have a vibrant automotive sector in the 21st century – one that produces affordable vehicles with high carbon productivity and offers other features that appeal to consumers in a timely way – automakers and their suppliers, consumers, fuel and energy providers, and policymakers will all need to take action in mutually productive ways.

Automakers and suppliers

The underlying propulsion technologies for passenger vehicles will almost certainly undergo a major transition over the next few decades, as various configurations of vehicle electrification penetrate the market. Players in the automotive industry will need to participate actively in defining a path forward. As a group, automakers and suppliers might consider taking the following actions:

- Collaborate with policymakers and other stakeholders in creating a shared, defensible point of view about the industry's potential evolution, one that is economically fact-based and rational, as well as oriented toward future market requirements. This would include, for example, jointly determining a "road map" for the development of infrastructure required to support new propulsion technologies.

- Pursue creative arrangements for accomplishing the necessary R&D work. Given the engineering challenges associated with developing, applying, and validating new automotive technologies, automakers and suppliers may find they have insufficient research and development capacity to bring multiple technologies to market simultaneously. Greater sharing of costs and resources may require both loosening and rethinking the basis of competition in the industry and the nature of financial support from government, e.g., public seed money for R&D consortia. These approaches might also include stimulating the venture capital sector to invest in fuel-efficiency technologies and alternative fuel production technologies.

- Quickly achieve economies of scale with innovations, because scale will be the key to economic viability during and after the transition to new technologies and propulsion systems. Automakers and their suppliers will need to:

  – Design and deliver the right, exciting portfolio of products with appealing attributes – for example, fuel economy (carbon abatement), safety, quality, and convenience. These products will have to appeal to consumers' performance expectations and offer low to zero tail-pipe emissions.

– Bring new products to market in coordination with the evolution of the power and fuel providers' timeline for implementing changes in their industries. Coordination will likely involve linkage to an overall regulatory and abatement framework and pacing that is largely consistent with the commercialization of biofuels and reduction in the carbon intensity of electricity generation and supply.

– Pursue cost reductions to ensure profitability and long-term public good will. It is likely that a relentless, only-the-fittest-will-survive intensity to lower the cost of operations (while ensuring consumer safety and thoughtful decisions about what consumers value) will be necessary to secure and maintain public support for a transition that undoubtedly will take a number of years.

– Actively communicate the benefits of fuel-efficient vehicles, because convincing consumers of the value and reliability of new technologies will be a prerequisite for achieving economies of scale.

Consumers

Consumers can take a variety of actions to accelerate carbon abatement, because significant amounts of abatement depend on their individual choices. Furthermore, consumer choices will heavily influence how the automotive sector changes as it moves through the transition it now faces. Specifically, consumers can:

- Consider carefully the environmental impact of purchasing decisions, particularly the fuel efficiency of a new vehicle. Given the 15-year average life span of an automobile, each new vehicle purchased is an enduring commitment to a certain level of fuel consumption and carbon emissions.

- Adopt eco-driving behaviors to save money immediately. Driver education programs could encourage this transition.

- Choose alternative forms of transportation with higher carbon productivity where feasible, such as rail, bus, bicycle, or foot.

Fuel and energy providers

Biofuel and electricity providers (broadly speaking, participants in production and distribution) will have important roles to play in the long-term effort to reduce carbon emissions from the passenger vehicle sector. Like automakers, biofuel and power companies will need to find ways to participate productively in forward-looking discussions on carbon policy to help shape more productive outcomes for society as a whole. Separately, they will likely have different areas of focus:

- Biofuel companies: Continue efforts to develop, commercialize, and sustainably produce biofuels at scale:
  - Seek to strengthen government and nongovernment funding for research into alternative fuels, such as second- and third-generation biofuels. This would include, for example, seeking ways to stimulate later-stage financing (e.g., possibly including support to minimize financing risks of commercial-scale plants) in these fields.
  - Work with government to ensure sustainable use of land for biofuel feedstock production and seek to establish sustainability standards for biofuel production to prevent the emergence of companies and/or competitors that would seek to produce low-cost biofuel using unsustainable methods (i.e., that damage the environment and work against the goal of CO_2 reduction).
  - Collaborate with governments and automakers to lift the mix of biofuels, scaling up production to maximum levels as soon as possible and helping to create the necessary infrastructure to support increased use. Capturing the abatement potential associated with the 25-percent penetration assumed in our scenarios will require substantially greater volumes in most regions than are now available.
- Electricity providers: Low-carbon sources of electricity will be needed, if the automotive sector is to make a successful transition to electricity-based propulsion systems that abate carbon on a well-to-wheel basis. Electricity providers will need to plan and execute multiple major capital investments across several decades, coordinating these projects with regulatory efforts to increase energy efficiency among users and decouple industry revenues from the volume of electricity sold.

Policymakers

Policymakers have a clear role to play – crafting economically sensible policies tailored to the social, political, economic landscape in their respective regions. While there are multiple options available, policy must balance the desire for quick action to reduce carbon emissions against the danger of economic dislocation and hardship arising from poorly designed programs:

- Carbon pricing. Price signals can play a role in encouraging the global shift from high- to low-carbon energy sources. Our analysis underlines, however, that the near-term introduction of a carbon price high enough to stimulate rapid and significant changes in consumer choices would likely have severely negative consequences for the economics of the automotive sector. Against this background, policymakers in most jurisdictions could employ a form of carbon pricing; however, such measures would likely need to be part of a broader approach.

- Standards and policies. The high capital cost of fuel-efficiency measures and the substantial risk associated with consumer acceptance of the costs have prevented a multitude of fuel-saving technologies from fully penetrating the market. Higher standards for carbon productivity (i.e., fuel-efficiency standards) applied to regional markets could help break the impasse. Standards that push manufacturers to introduce more fuel-efficient vehicles (such as the Corporate Average Fuel Economy standards in the United States) could be complemented by "feebate" systems that push consumers to buy new vehicles.[23] The policy mix will likely reflect the political and economic realities of each jurisdiction.

- Promotion of low-carbon energy and fuel. Abatement in the automotive sector will depend in part on timely progress elsewhere. Reducing the carbon content of automotive fuel, for example, requires continued research and development of biofuels, as well as potential support for commercial-scale production. Abatement with PHEVs and EVs will require that capacity additions to the electricity grid use low-carbon sources. Establishing suitable industry standards in collaboration with automakers, especially for biofuels and electric vehicles, will be an important prerequisite, as will appropriate mechanisms to stimulate advances in the fields of biofuels and low-carbon electricity production.

- Consumer incentives and financing. Fuel-efficiency packages in a number of markets, such as Japan and China, will increase the cost of vehicles for first owners, despite providing substantial fuel savings. Consumers have been reluctant to pay for greater fuel efficiency when faced with trade-offs involving other vehicle attributes. It may be necessary to provide incentives to consumers and support the high initial cost of more fuel-efficient cars; policy options could include subsidies, tax-based programs, scrap incentives, and "feebates."

23 A "feebate" system places a high tax on vehicles with high emissions per kilometer and uses the funds raised to subsidize low-emission vehicles.

- Consumer education and behavior change. Consumers could take a variety of actions to accelerate carbon abatement, because significant quantities of emissions depend on their individual choices. Eco-driving is one such action. Education to increase awareness of the environmental impact of purchasing decisions will also be needed. These efforts might help reinforce some form of price signaling.

- Programs for the improvement of traffic flow and greater use of public transportation. Investments in programs to improve traffic flow are highly cost effective. In fact, our analysis shows that on average such programs will not only abate CO_2, but they will also have a net benefit to society of about €70 (≈$94) per tonne CO_2e.

* * *

With a back-drop of global recession, the automotive industry has come to a defining moment in its history. Though action is needed to avoid immediate collapse, this alone will not be enough: without fundamental reform, the industry will not have an attractive long-term future. Recovery can only come through radical product innovation. Policymakers will play a critical role in this transition, but they too will require a new approach. If changes are made, then recovery can follow, and with it a renewed and thriving automotive sector, restored to its place as a creator of substantial value for the global economy.

Abating carbon emissions from passenger vehicles while meeting the needs and aspirations associated with continued economic growth will be an immense near- and medium-term challenge. Our analysis indicates that the sector, if it develops in line with the mixed-technology scenario, could reverse the steady growth of its emissions within a few years and make significant contributions to overall global abatement, but only if it finds a way to take concerted action to capture the potential available in its many proven abatement measures.

Moreover, the amount of investment needed for abatement in the automotive sector implies a massive business opportunity – one that creative, forward-looking organizations can take advantage of and help create at the same time. Companies that are able to commercialize relevant technologies will face rapid growth in demand, if and when carbon emissions are priced and emission reduction targets are enacted.

We hope that the analyses and perspectives in this report will help all participants connected to the automotive sector move to meaningful action in a timely way and enable the global passenger vehicle sector to take an economically sensible road toward a lower-carbon future.

APPENDIX

A. Representative fuel-efficiency measures

Measure	Description	Incremental cost 2006	Projected incremental cost 2030
Gasoline ICE Package 1	• Variable valve control • Engine friction reduction (mild) • Low-rolling resistance tires • Tire pressure monitoring system • Mild weight reduction (≈2%)	€340 (≈$459)	€185 (≈$250)
Gasoline ICE Package 2	Gasoline Package 1, plus: • Medium displacement reduction ("medium" downsizing ≈20%) • Medium weight reduction (≈4%) • Electrification (steering, pumps) • Optimized gearbox ratio • Improved aerodynamic efficiency • Start-stop system	€1,235 (≈$1,667)	€673 (≈$908)
Gasoline ICE Package 3	• Gasoline Package 2, plus: • Strong displacement reduction ("strong" downsizing ≈40%) • Air conditioning modification • Improved aerodynamic efficiency • Start-stop system with regenerative braking	€1,985 (≈$2,680)	€1,081 (≈$1,460)
Gasoline ICE Package 4	Gasoline Package 3, plus: • Direct injection (homogeneous) • Strong weight reduction (≈9%) • Optimized transmission (including dual clutch, piloted gearbox)	€2,869 (≈$3,873)	€1,563 (≈$2,109)
Gasoline – full hybrid	Gasoline Package 4, plus full hybrid	€3,985 (≈$5,380)	€1,848 (≈$2,495)
Gasoline – plug-in hybrid	• 60 km range, 66% electric share • Energy demand electric drive 150 Wh per km • Battery capacity 14 kWh • Cost/kWh in 2006: €965 (≈$1,302)	€16,126 (≈$21,770)	€3,530 (≈$4,765)
Electric vehicle	• 160 km range • Energy demand 150 Wh per km • Battery capacity 37 kWh • Cost/kWh in 2006: €965 (≈$1,302)	€36,045 (≈$48,660)	€5,764 (≈$7,781)

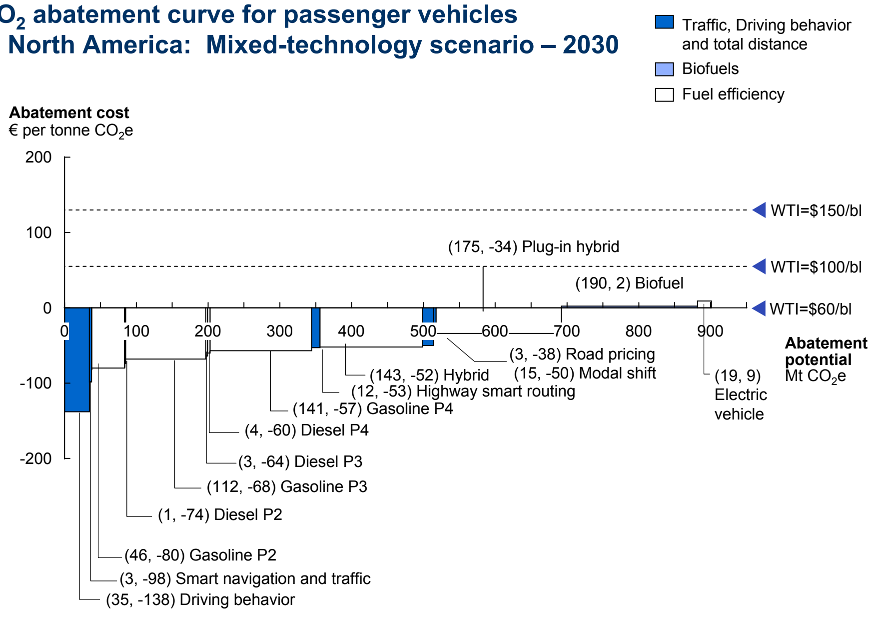
B. Regional abatement curves for 2030

In addition to assessing the abatement opportunities and costs at the global level, we analyzed the opportunities and costs in detail for four key regions: North America, Europe (including Russia), China, and Japan (Exhibits B-1 through B-4).

Our analysis at the regional level revealed significantly different abatement economics (see figures below). The variance in economics was largely driven by differences in the average distance travelled annually in each region; less distance travelled, as in the case of China and Japan, meant that the costs associated with new technologies were necessarily spread over fewer kilometers or CO_2 emissions, increasing the cost per tonne of abatement. Other differences were caused by variations in the existing passenger vehicle fleet, automotive survival rate, projected new vehicle sales, and rate of adoption of various technologies. These differences in abatement economics suggest that a tailored approach to abatement in each region will be more effective than one single global approach.

Exhibit B-1

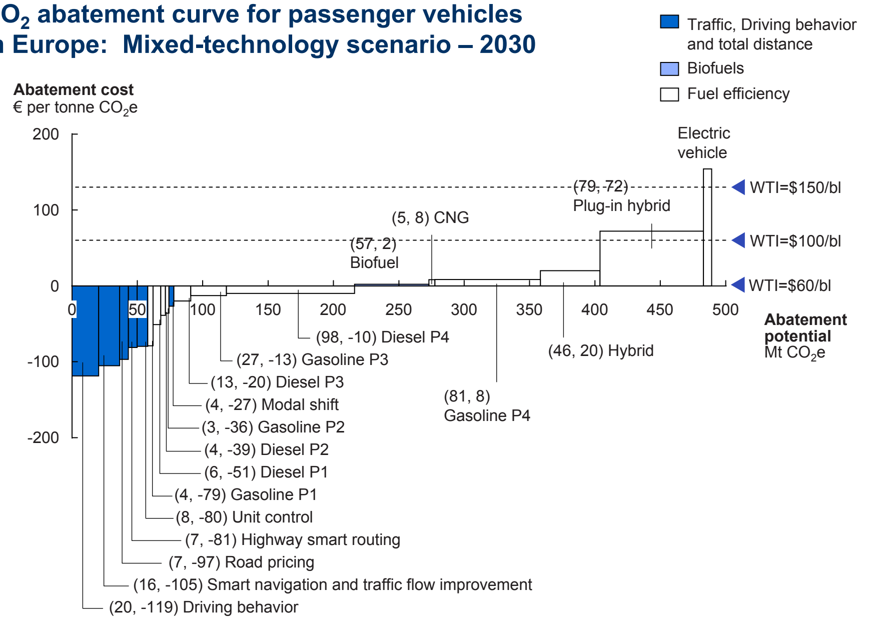
CO_2 abatement curve for passenger vehicles in North America: Mixed-technology scenario – 2030



Source: McKinsey analysis

Exhibit B-2

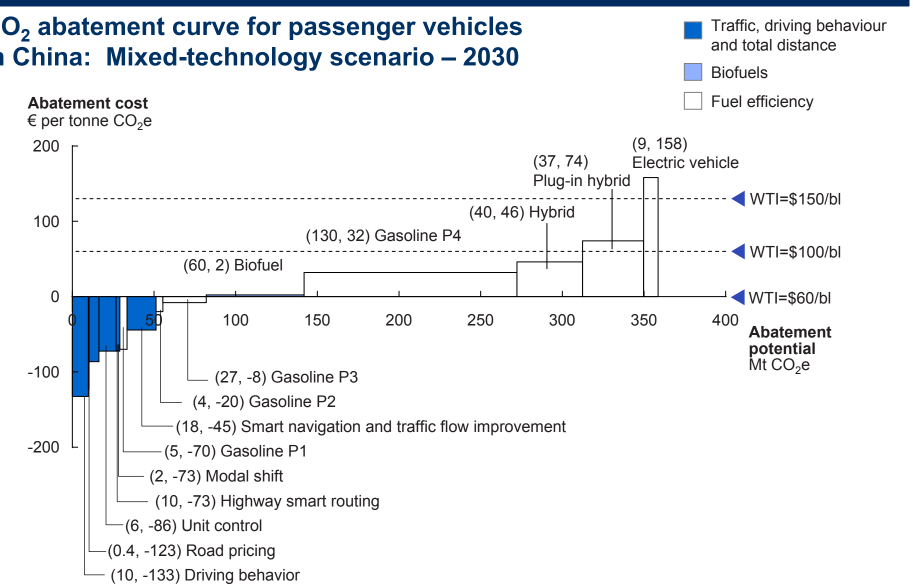
CO_2 abatement curve for passenger vehicles in Europe: Mixed-technology scenario – 2030



Source: McKinsey analysis

Exhibit B-3

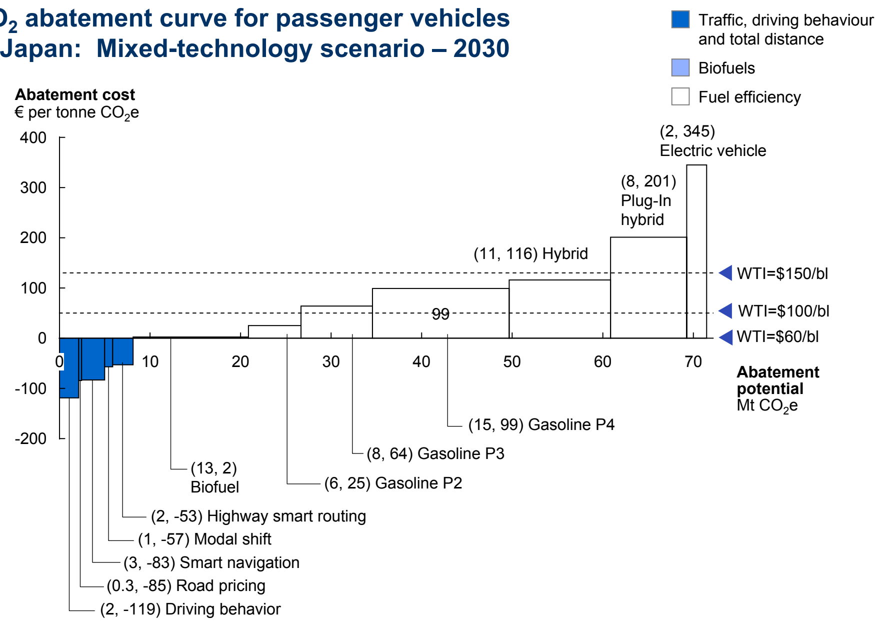
CO_2 abatement curve for passenger vehicles in China: Mixed-technology scenario – 2030



Source: McKinsey analysis

Exhibit B-4

CO_2 abatement curve for passenger vehicles in Japan: Mixed-technology scenario – 2030



Source: McKinsey analysis

McKinsey & Company is a global management consulting firm dedicated to helping the world's leading organizations address major challenges. With consultants deployed in 50 countries around the globe, McKinsey advises on issues of strategy, operations, organization, and technology.

For more information about this report, please contact McKinsey through this address: automotiveco2report@mckinsey.com

March 2009

http://www.mckinsey.com

McKinsey&Company