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Long-term greenhouse gas emission and petroleum reduction goals: Evolutionary pathways for the light-duty vehicle sector

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ABSTRACT

To meet long-term environmental and energy security goals, the United States must reduce petroleum use in the light-duty vehicle fleet by 70% and greenhouse gas emissions by a factor of ten compared to business-as-usual growth projections for the year 2050. A wedge-based approach was used to quantify the scope of the problem in real terms, and to develop options for meeting mid-century targets. Four mitigation mechanisms were considered: (1) improvements in near-term vehicle technologies; (2) emphasis on low-carbon biofuels; (3) de-carbonization of the electric grid; and (4) demand-side travel-reduction initiatives. Projections from previous studies were used to characterize the potential of individual mitigation mechanisms, which were then integrated into a light-duty vehicle fleet model; particular emphasis was given to systemic constraints on scale and rates of change.

Based on these projections, two different greenhouse gas (GHG) mitigation implementation plans were considered ("evolutionary" and "aggressive"). Fleet model projections indicate that both the evolutionary and aggressive approaches can effectively end US dependence on foreign oil, but achieving an 80% GHG reduction requires changes that extend significantly beyond even the aggressive case, which was projected to achieve a 65% reduction.

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1. Introduction

Over the next half century, the United States light-duty vehicle fleet faces two broad-based challenges:

- 1) It must achieve deep reductions in transport-related CO₂ emissions, on a full fuel cycle ("Well-to-Wheel") and vehicle lifecycle ("Cradle-to-Grave") basis.
- 2) It must transition from its near-total reliance on petroleum to a more diverse array of fuels that can be generated from different primary energy feedstocks.

The US transportation sector currently accounts for approximately 33% of total greenhouse gas (GHG) emissions in the United States, and the 2008 EIA Annual Energy Outlook projects this fraction to remain roughly constant through 2030 [1]. Stabilizing atmospheric concentrations of CO₂ at a level that would minimize the long-term impact of climate change requires deep reductions in

GHG emissions. The 110th congress has proposed a number of different pieces of legislation aimed at addressing this issue; the most aggressive of these bills aim for a 60–80% reduction in GHG emissions by 2050 compared to a 1990 baseline. Assuming that the transportation sector must reduce GHG emissions by a fraction equivalent to its share of total societal emissions, the total US light-duty vehicle CO₂ emissions will need to drop by about 80% compared to its 1990 baseline.

In a similar vein, there is a great deal of momentum aimed at lessening our dependence on foreign oil towards an eventual goal of achieving energy independence. For example, President Bush's 2007 State of the Union address called for a 20% reduction in petroleum use by 2017. According to a business-as-usual scenario in which EIA projections to 2030 are extended to the year 2050, total petroleum consumption in the light-duty fleet will grow from the present-day value of 550 billion liters per year to 850 billion liters per year in 2050. This baseline does not take into account legislation enacted in 2007 to increase Corporate Average Fuel Economy (CAFE) standards to a fleet average of 35 miles per gallon by 2020. Over this same time period, U.S. petroleum production is projected to increase slightly, but at a slower rate than demand; this means that imported petroleum will comprise an increasing fraction of the

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Table 1
Pathways to sustainable mobility.

	Description/examples	Barriers/constraints
Demand-side management (DSM)	- Reduce growth in vehicle kilometers traveled - E.g., fuel taxes, road pricing, urban planning	- Requires behavioral change - Politically unpopular
Domestic, low-carbon fuels	- Hydrogen - Electricity - Biofuels	- Development of sustainable feedstocks and production - Implementation at scale
Vehicle technology	- High-efficiency ICE - New propulsion systems (P/HEV) - Reduced road load (e.g., weight reduction)	- Cost, technological, and infrastructure barriers - Market focus on performance

petroleum consumed. Achieving this goal of energy independence over this timeframe requires that we reduce petroleum consumption by 600 billion liters, or about 70% of total petroleum used.

There are a number of different ways to reduce the petroleum consumption and GHG emissions from light-duty vehicles. Broadly speaking, these include reducing the rate of growth in vehicles kilometers traveled, reducing vehicle fuel consumption, or reducing the carbon content of transportation fuels (Table 1). The method for meeting these long-term goals is a subject of intense debate. The recent past has seen a great deal of emphasis on meeting these long-term goals via a single technological fix. In the last decade, this emphasis has shifted between electric vehicles (California ZEV mandate), fuel cell vehicles (FreedomCAR), and biofuels (Renewable fuel standard of EISA 2007). More recently, plug-in hybrid vehicles have gained a great deal of momentum. In general, these longer-term solutions face steep barriers in terms of technological risk, they are difficult to implement at the needed scale, and they are constrained in their near-term impact by system inertia.

Policies that encourage these technologies and behavioral changes have an important role to play. Regulatory measures, such as fuel economy or GHG emission standards require vehicle suppliers to attain specified levels of performance. Fiscal measures, such as fuel taxes, carbon taxes, feebates, import tariffs, Pay-As-You-Drive measures, and scrappage programs use price incentives to encourage reductions in petroleum consumption and GHG emissions [3,4]. Given that a broad range of stakeholders influences petroleum consumption and GHG emissions, and that both

technological and behavioral changes are necessary to achieve reductions, several studies have proposed packages of coordinated policy measures [5–7]. These authors have found that the combined effect of packaging policy measures can be consistent, reinforcing, and can overcome political barriers that may impede a focus on one dominant strategy.

In this paper, we develop a plan for meeting long-term climate change and petroleum reduction targets that similarly focuses on implementing a combination of technologies and behavioral changes that are available in the near-term and at a scale that places less strain on the transportation and energy system as a whole. Such an integrated approach offers a robust, low risk path towards meeting mid-century energy security and GHG reduction targets.

This paper expands on the above studies that have addressed energy security and GHG mitigation from the U.S. light-duty vehicle fleet. It contributes and expands to existing body of literature in two important ways. First, it extends the results of a major study of vehicle and fuel technologies conducted by the Sloan Automotive Laboratory at MIT from the medium-term (i.e., 2035) to a 2050 timeframe [2]. This allows for a longer-term perspective that aligns with mid-century GHG reduction targets. Second, it provides an assessment of four integrated mitigation mechanisms and considers lifecycle energy use and GHG emissions from vehicle and fuel technologies. This provides a comprehensive picture of the opportunities and implications of aggressively pursuing energy security and GHG reduction policy goals.

We have chosen to target a 60–80% reduction in GHG emissions from 1990 levels and the elimination of all petroleum imports (70% reduction in light-duty fleet petroleum) by the year 2050. The reduction targets imply that GHG emissions drop to between 265 and 560 million metric tons of carbon dioxide equivalent (MMtCO₂e), and petroleum use drops to 260 billion liters. In comparison, under a “No Change” scenario, in which new vehicle fuel consumption remains unchanged, by 2050, the U.S. light-duty fleet greenhouse gas emissions are estimated to reach 2900 MMtCO₂e by 2050, and light-duty fleet petroleum use will reach 870 billion liters [8]. Profiles of GHG emissions and petroleum use for the U.S. light-duty vehicle fleet are shown in Figs. 1 and 2, respectively.

Several recent studies conducted out of the MIT’s Sloan Automotive Laboratory [2,9–11] quantified the potential of different vehicle technologies and transportation fuels to reduce the petroleum and greenhouse gas emissions of a typical American sedan

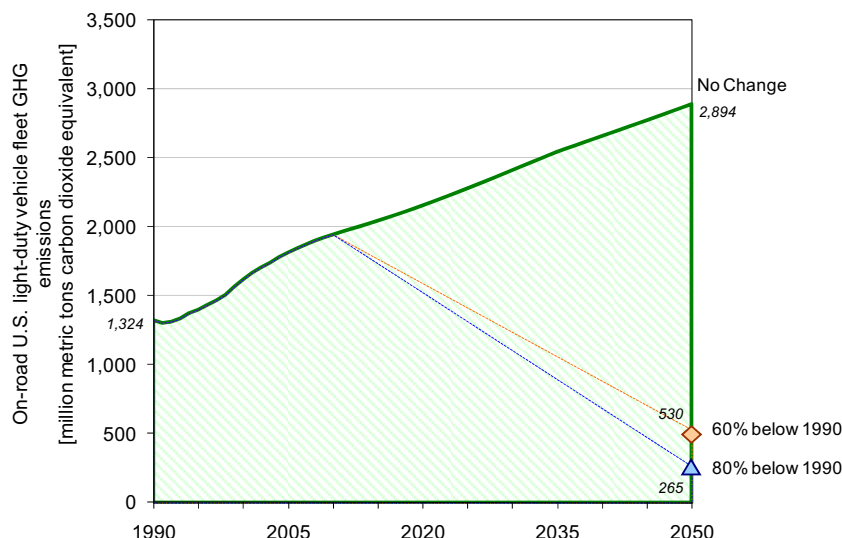


Fig. 1. Greenhouse gas emissions from U.S. light-duty vehicles under a No Change scenario, and targets for 60 and 80% reductions in emissions from 1990 levels by 2050.

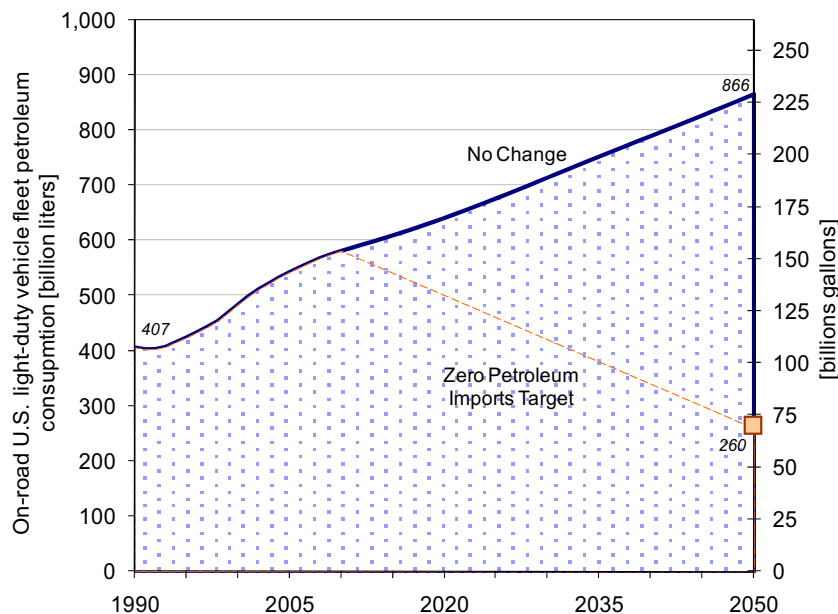


Fig. 2. Petroleum consumption by U.S. light-duty vehicles under a No Change scenario, and the target for zero petroleum imports by 2050 (italicized numbers are in billions of liters).

over the next 25–30 years. These studies offer a comparison of individual vehicle technologies, estimate plausible contributions from biofuels given systemic constraints on scale, and model the fleet impacts of these contributions to the year 2035.

The research presented in this paper extends these results by quantifying the integrated effect of four GHG and petroleum reduction pathways on the full US light-duty vehicle fleet in the year 2050. The mitigation mechanisms that we consider are: (1) improvements in current or close-to-market vehicle technologies under several different market penetration scenarios; (2) increasing emphasis on low-carbon biofuels; (3) aggressive de-carbonization of the electric grid; and (4) demand-side initiatives aimed at reducing the rate of growth of total vehicle travel. For each pathway, we quantify the resultant GHG and petroleum reduction for two different scenarios. The first scenario (“evolutionary case”) is based on reductions that we estimate to be achievable via *evolutionary* changes: these pathways require implementation and improvement of technologies and policies that are within the realm of historical precedent, although we push the limits of these precedents. The second scenario (“aggressive case”) is based on reductions that would require more extensive systemic changes across each of the targeted reduction pathways. While this aggressive case extends the envelope of past experience, we do not consider the targeted levels implausible; rather, they will require fundamental shifts in how society uses, views, and values personal mobility.

The results identify several technologically feasible paths to approaching the long-term goals identified. Moreover, because these pathways focus on lower-risk technologies and modest scaling requirements, they offer a robust solution to the transportation sector’s long-term challenges.

2. Methodology

This analysis combines four fuel use and GHG emission reduction strategies within a model of the U.S. light-duty vehicle fleet to estimate future fuel use and GHG emissions: (i) vehicle technology and fleet penetration assumptions; (ii) the future carbon-intensity of the electric grid; (iii) cellulosic and corn-based biofuel projections; and (iv) private light-duty transportation demand. Detailed aspects of these reduction strategies are outlined in the subsections below.

The fleet model calculates future fuel use and GHG emissions of the U.S. light-duty vehicle fleet based on vehicle sales, retirement, average car and light-truck fuel consumption, and vehicle travel per year. The structure of the model is shown in Fig. 3, and a detailed description can be found in Bandivadekar et al. [2].

2.1. Vehicle technology and fleet penetration assumptions

To estimate the fuel use and greenhouse gas emissions of future vehicle technologies, we used the results of technology projections previously published in Kasseris and Heywood [9] and Kromer and Heywood [10]. We chose to focus our evaluation on vehicle technologies that are either available as mass market vehicles at present, or seem likely to come to the mass market in the next five to ten years. As such, we have included improved gasoline and diesel vehicles, gasoline hybrid electric vehicles (HEVs), and gasoline plug-in hybrid electric vehicles (PHEVs) in our analysis. We chose not to include fuel cell vehicles or fully battery-electric vehicles; while both technologies show promise over the long-term, we opted to focus the emphasis to 2050 on technologies that

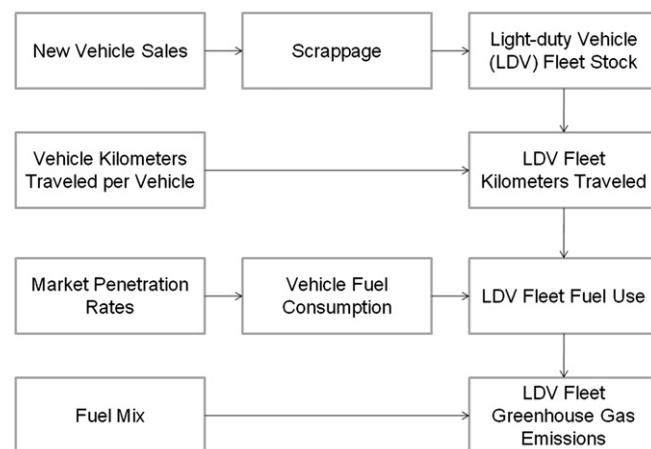


Fig. 3. Structure of the light-duty vehicle model.

Table 2

Relative GHG emissions and petroleum consumption of 2035 vehicles compared to the 2005 baseline.

Vehicle technology	Relative to 2005 NA-SI ^a vehicle	
	GHG emissions	Petroleum consumption
2005 NA-SI	1	1
2035 NA-SI	0.63	0.63
2035 Turbo SI ^b	0.55	0.55
2035 Diesel ^c	0.51	0.54
2035 HEV ^d	0.35	0.35
2035 PHEV-30 ^e	0.34	0.18

^a NA-SI = naturally aspirated spark-ignition engine.

^b Turbo SI = turbo-charged spark-ignition engine.

^c Diesel = diesel (compression-ignition) engine.

^d HEV = hybrid-electric vehicle.

^e PHEV-30 = plug-in hybrid vehicle, 30-mile all electric range.

may be widely adopted in the next ten years [12–14]. The results of these projections for the vehicle platforms of interest are summarized in Table 2; data is presented relative to a 2005 naturally aspirated spark-ignition (NA-SI) vehicle.

These technologies are listed in order of both increasing efficiency and increasing cost. The improved conventional NA-SI and turbo-charged spark-ignition (Turbo SI) technologies are low-cost technologies. Diesels, which require a sturdier engine and advanced emissions after-treatment, incur some cost penalty, but may offer significant fuel savings for heavier vehicles and highway-dominant driving. Hybrid vehicle costs can decrease significantly from their present-day value and may in the future achieve price-parity with emissions-controlled diesels. Finally, plug-in hybrids, which require a large energy storage system, are likely to continue to incur a significant cost penalty in the future, although this penalty will decrease with continued improvement of battery technology.

In addition to improvements in engine and transmission efficiency, the evolutionary case assumes incremental reductions in aerodynamic drag and rolling friction, as well as a 20% reduction in weight achieved through lower-cost material substitution and component downsizing. The more aggressive case assumes a 35% weight reduction in all vehicles. This level of change could be accomplished using more exotic materials at a significantly higher cost; alternatively, it could be achieved via a systemic shift to smaller vehicles in addition to the material substitution and component downsizing that is included in the evolutionary case. Our calculations account for the embodied higher material cycle greenhouse gas emissions of future vehicles due to the additional material substitution and the integration of additional powertrain components [8].

The plug-in hybrid technology projection assumes an electric grid emissions rate consistent with the EIA 2030 US average grid, which assumes minimum de-carbonization. This assumption is varied in subsequent sections to evaluate the effect of a de-carbonized electric grid on the transportation sector. In addition to deploying advanced vehicle technologies, we assume that the market share of light-duty trucks decreases linearly from its 55% share in 2007 to 30% by 2035, at which point it remains constant until 2050.

The fleet impact of these vehicle technologies was simulated using the Sloan Laboratory model of the U.S. light-duty vehicle fleet developed in Bandivadekar et al. [2]. Reductions in the relative fuel consumption of vehicles are assumed to increase linearly until 2035. While opportunities for increasing efficiency of these technologies will not be exhausted by 2035, we postulate that further reductions are unlikely to continue at the same rate as in the previous decades. As a conservative assumption, we assume that relative vehicle fuel consumption remains constant from 2035 to 2050.

We estimated the penetration rate of new vehicle technologies in the US market by analogy with previous experience in the transport

Table 3

Market introduction and early-stage market penetration assumptions.

	Market introduction	5% of sales
HEV	1998	2011
Diesel ^a	2009	2011
PHEV	2012 (est)	2025

^a Models meeting criteria emissions standards in all U.S. states. Diesel vehicles are already 5% of new light-truck market.

sector. The deployment of different engine and transmission technologies in the US LDV market from 1948 to 2006 shows that even very cost-effective technologies such as Variable Valve Timing (VVT) have taken ten to fifteen years to penetrate half of new vehicle sales [15]. Based on a broad survey of technological change in automobile industry, Nakicenovic [16] observed that it took 10–30 years after introduction of a new technology before it was deployed in half of the new vehicles.

Based on market entry dates as shown in Table 3, we first estimated the time it takes for a technology to comprise 5% of new vehicle sales: this is based loosely on the market trajectory of the hybrid vehicle to date, in which hybrids will have grown to about 2% of the market in one decade. If hybrids continue to grow at a 30% annual growth rate (the average for the last several years), they will go from 2% currently to 5% of sales by 2012.

To estimate viable rates of growth above the 5% mark, the market penetration of diesel vehicles in Europe and of lock-up automatic transmissions in the US market are used as points of reference (Fig. 4). The sales growth in automatic transmissions – a less demanding change than transitioning to a new powertrain – achieved average sales growth of 15% per year over a 20 year period (1978–1998) before saturating at about 85% of the market. The penetration of Diesel vehicles in Europe follows a slower trajectory: in this case, sales grew at an average annual rate of about 8% from 1980 to 2006. This is a reflection of the fact that shifting to a new powertrain is a much larger change than changing transmissions. It is also important to recognize that the shift to diesels in Europe is a product of both improved technology (such as common rail injection) and a series of technology forcing policies (such as high fuel prices, preferential taxation of diesel, and taxes on engine displacement). In contrast, the shift towards automatic transmissions has been driven purely by technological advances and market forces.

These historical examples give a sense of the difficulty in maintaining high growth rates once the technology has achieved a threshold level of market penetration. The 15% growth rate of

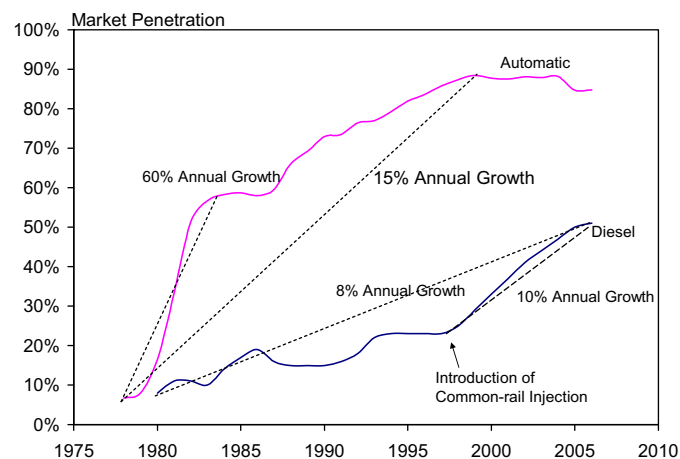


Fig. 4. Market penetration rates of different vehicle technologies. Source: Automatic transmission penetration data from [16]; Diesel penetration data from [17].

Table 4

Annual rate of sales growth required to go from 5% of new vehicle sales in the "starting year" to the "target market penetration" in the year 2040. Lighter boxes are considered more plausible.

5% of Sales in year...	Target market penetration		
	25%	50%	75%
2010	6%	8%	9%
2015	7%	10%	11%
2020	8%	12%	14%
2025	11%	17%	20%
2030	17%	26%	31%
Growth rate			

automatic transmissions is likely unrealistic for a new powertrain technology once it has passed the 5% mark; this might be viewed as an upper-bound. The rapid growth of diesel vehicles in Europe is a reflection of the growth rate for a new powertrain that can be achieved through a combination of competitive technology and strong policy incentives.

Of course, it must be recognized that for radically new vehicle technologies the magnitude of change in terms of vehicle technology, supply chain, and infrastructure is far outside the realm of experience and could potentially restrict technology diffusion rates below that of diesels. On the other hand, a combination of historically high energy prices, increasingly stringent policy, and improved technology could drive diffusion rates towards the higher end of these constraints.

Using these observations, Table 4 estimates the required growth rate in new vehicle sales required to meet different market penetration targets by 2050; the boxes are shaded according to the plausibility of different market penetration scenarios. As shown, for a technology that is already in the market in small numbers – such as the hybrid vehicle – 75% market penetration is plausible: assuming that sales reach 5% between 2010 and 2015, an annual sales rate of 6–11% is needed to achieve market penetrations of 25–75% in the 2050 fleet. In contrast, an aggressive plug-in hybrid penetration scenario is much more difficult: assuming it reaches 5% sales between 2025 and 2030, the plug-in hybrid would require 11% sales growth to achieve a 25% penetration target (plausible, but difficult); higher levels of market penetration are even more challenging.

This analysis of technology penetration rates was used to estimate plausible market penetration levels for different vehicle technologies. These scenarios assume that the market penetration of hybrid vehicles and plug-in hybrids correlate (so that a high penetration of hybrid vehicles implies a high penetration of plug-in hybrids). These are collectively referred to as "advanced technologies". The balance of the in-use fleet is comprised of a combination of improved gasoline, turbo-charged gasoline, and diesel vehicles. The evolutionary case assumes that the advanced technology vehicles comprise 75% of the fleet by 2050; of these, 50% are hybrids and 25% are PHEVs. This level of penetration requires that hybrids achieve 5% market penetration between 2010 and 2015, and that PHEVs enter the market by 2012 and achieve 5% market penetration between 2020 and 2025. The aggressive case assumes the same 75% fleet penetration of advanced technology vehicles, but includes 50% penetration of plug-in hybrids and 25% penetration of conventional HEVs. These assumptions are summarized in Table 5

Table 5

Market penetration scenarios.

Scenario	Fraction adv. tech (%)	Conventional			Adv. tech	
		NA-SI (%)	Turbo (%)	Diesel (%)	HEV (%)	PHEV (%)
Evolutionary	75	13	6	6	25	50
Aggressive	75	13	6	6	50	25

2.2. Electric grid

To illustrate the impact of de-carbonizing the electric grid on fleet-wide GHG emissions, a low-carbon grid scenario was introduced in the fleet model. This scenario assumes a grid mix that includes 50% non-GHG emitting sources; 15% natural gas generation; and 35% coal. In this scenario, the fossil generators operate at higher efficiency than in the base case: the average efficiency of natural gas power plants increases from 43% to 50% (LHV), while that of coal increases from 35% to 40% (LHV). In addition, we assume 2/3rd of the GHG emissions from fossil power plants are captured and stored (Table 6). At present, carbon capture and storage (CCS) is still in its infancy, and deploying it at such a large-scale will no doubt be challenging, but not implausible [18].

Alternatively, a similar level of grid-based reduction may be achieved with less aggressive de-carbonization levels if there is greater use of electricity in transportation. This end may be achieved either by deploying higher electric range vehicles (such as PHEV-60s or all electric vehicles for a portion of the fleet), or if PHEV users tend to use their vehicle primarily for shorter, electricity-dominant trips [10]. The vehicle technology assumptions are based on a plug-in hybrid fleet composed of vehicles with a 30-mile electric range (PHEV-30). It is estimated that a vehicle with this electric range travels half its miles under electric power from an off-board source. Transitioning to a fleet of PHEVs with a 60-mile electric range increases this fraction to 65–70% of vehicle miles.

Because the assumed level of grid de-carbonization is already quite aggressive and additional grid de-carbonization offers only marginal benefits, the same electric grid reductions are used for both the evolutionary and the aggressive scenario.

2.3. Biofuels

Our mid-century biofuel projection is based on extending nearer-term biofuel projections to the year 2050. These projections include contributions from both cellulosic and corn-based feedstocks, and assume improvements to both crop yield and process efficiency. It is likely that the next generation of biofuels will have different feedstocks and composition [19]. While we anticipate shifts in current cropland towards energy feedstocks, the study's projections do not account for the indirect land-use change impacts. Although volumetric mandates have driven the growth of biofuels in the recent years, we expect low-carbon fuel standards (LCFS) to become the primary long-term driver for biofuels usage. Therefore, the contribution of biofuels towards reducing GHG emissions should be considered optimistic, but not implausible.

Current production of ethanol in U.S. is approximately 0.55 million barrels per day by volume, or 0.36 million barrels of oil [1]. Compared with 5.2 million barrels per day of domestic crude oil production or 10.2 million barrels per day of crude oil imports, the contribution from corn ethanol is quite small. The renewable fuels standard mandated by the energy policy act of 2005 will ensure that approximately one million barrels per day of corn ethanol by volume (~57 billion liters per year) is produced in the U.S. in the next decade.

Table 6

Fuel cycle energy and GHG emissions for different electricity generation sources.

	GHG emissions (g CO ₂ /MJ ^a)	Coal (%)	Gas (%)	Oil (%)	Non-GHG emitting (%)
Base Case (2030 EIA Avg Grid)	208	58	15	2	25
Clean Grid ^b	42	35	15	0	50

^a GHG emissions per MJ in the tank (LHV).

^b Under the clean grid scenario, 2/3rd of fossil power plants are equipped with CCS. Plants equipped with CCS are not considered "non-GHG emitting sources".

The Renewable Fuels Association estimates that ethanol producers are currently adding new capacity of more than 22 billion liters per year of ethanol production, thus effectively doubling the total ethanol production capacity in the U.S. to 45 billion liters a year by 2011. The United States Department of Agriculture (USDA) expects corn ethanol production to reach 50 billion liters by 2015 [20], while the National Corn Growers Association estimates that between 48 and 68 billion liters of ethanol could be produced from corn in 2015–2016 without disrupting other agricultural markets [21].

Corn production is expected to continue to increase, though a majority of this increased acreage is not in the expansion of total cropland but in the shifting of other agricultural crops, such as cotton and soybeans to corn production [22]. Additionally corn is expected to be shifted from the export sector to the ethanol industry. In the past, US world corn exports represented 60–70% of the US corn market; with an expanding ethanol industry that share is expected to drop to 50–60% [22].

Currently, no commercial facilities process cellulosic material into ethanol, although several pilot plants to convert ligno-cellulosic material such as corn stover have been announced. In February 2007, the Department of Energy provided \$375 million for construction of six such pilot plants. The corresponding industry cost share is expected to be 1.2 billion dollars [23]. These pilot plants combined are expected to produce 570 million liters (150 million gallons) by 2010.

The Energy Independence and Security Act (EISA) of 2007 requires the blending of 80 billion liters (21 billion gallons) of advanced biofuels with 21 billion liters (5.5 billion gallons) blended from cellulosic biomass starting in the year 2012. The Context Network, an Iowa based consulting service, estimates that production of cellulosic ethanol could grow to 1500 million liters (400 million gallons) by 2015 [24]. Further growth in cellulosic ethanol will depend on success of the first generation of pilot plants, capital costs and sizing of commercial scale processing plants, as well as feedstock availability at scale. At present, the capital cost requirements of building a cellulosic facility are expected to be five times as much as those of a comparable corn ethanol facility [25].

Based on availability of feedstocks and improvements in processing technology, Groode and Heywood [11] estimated that 35–50 billion liters of cellulosic ethanol could be produced from corn stover and switchgrass by year 2025. With an increase in ethanol conversion rates, this could further increase to 60 billion liters. Groode concludes that further increases in cellulosic ethanol will come only from increasing the yield of switchgrass per acre of land. If current switchgrass yields could be doubled, then more than 60 billion liters of cellulosic ethanol could be produced from switchgrass alone, taking the total amount of cellulosic ethanol available close to 100 billion liters.

We assume that at least 70 billion liters each of corn ethanol and cellulosic ethanol will be available to displace gasoline by the middle of the century. In practice, 140 billion liters of biofuels could be obtained from a variety of different feedstocks including ethanol from sugarcane in Brazil, and biodiesel from algae and waste oils. This level of biofuel deployment is assumed for the evolutionary case. For the aggressive case, we adjust our biofuel assumptions such that the entire biofuel supply is from second generation of biofuels sourced from low-GHG intensive feedstocks.

2.4. Demand reduction/ reduce VKT

Greenhouse gas emissions and fuel use from light-duty vehicles may also be reduced by lowering the demand for private vehicle travel. This section outlines a feasible amount of demand-side reduction, and estimates the magnitude of fiscal policies that would be needed in order to encourage consumers to reduce their demand for travel in private light-duty vehicles.

The rate of growth in vehicle travel is expected to slow in the future, as a result of changes in population demographics, and saturation in the number of vehicles per person in the United States. At the same time, it is estimated that population growth—particularly in the Southern and Western U.S.—as well as the expansion of urban areas will keep growth in vehicle travel between 1.6 and 2.4% per year [26,27].

The EIA projects that total light-duty vehicle travel will grow by 57% between 2008 and 2030, from 4.43 to 6.94 trillion km [1]. In comparison, the MIT fleet model estimates that travel will increase at a more gradual rate, rising from 5.06 to 6.74 trillion km between 2008 and 2030, and reach 8.18 trillion km by 2050. This accounts for both increasing numbers of drivers and growth in the average distance traveled per driver each year.

Increases in the cost of light-duty vehicle travel can slow the rate of growth in vehicle travel. For example, the EIA's 2008 Annual Energy Outlook projects a 40% increase in the fuel cost of travel¹ by 2030 under its High Price Case relative to the Reference Case; this is estimated to reduce vehicle travel by 6% [1]. Thus, reductions in vehicle travel on the order of 5–10% seem feasible from changes in the cost of fuel alone, although they require substantial increases in the cost of travel.

Fiscal policies that encourage consumers to drive less include fuel tax increases, Pay-As-You-Drive insurance programs, and road or congestion charging measures. Fuel tax increases directly influence the price of fuel, and can correct for externalities such as the environmental damage from local air pollutants and carbon dioxide emissions, as well as economic losses from dependence upon petroleum-based fuels. Fuel taxes also influence the cost of travel, and can indirectly correct for externalities such as congestion and traffic-related accidents. The main disadvantage of fuel tax increases is that an array of stakeholders are aligned against these tax increases, making them politically difficult to implement.

Pay-As-You-Drive (PAYD) insurance would roll the up-front costs of monthly or annual insurance payments into a price based on the distance driven by an individual. By calculating insurance premiums on a *pay-as-you-drive* basis, rather than an *all-you-can-drive* basis, this system would provide drivers with a continuous price incentive to lower vehicle travel. According to economic literature, substantial social benefits on the order of \$150–225 per insured vehicle are available by linking insurance premiums to annual travel [28–30]. Premiums on the order of 4 cents per km have been suggested; individuals who drive below-average would pay less on insurance premiums than under the system, while those who travel above-average would pay more.

Finally, road charging or congestion charging systems offer a way to directly charge light-duty vehicle travel. Over the long-term, road charging and mileage-based user fees that are able to differentiate rates based on the time of day (i.e., peak versus off-peak hours) and location (i.e., congested city center versus rural roads) may offer an efficient and equitable alternative to fuel taxes as a way of raising revenue for transportation infrastructure [27,31].

To determine the magnitude of a fiscal incentive that would be needed to encourage consumers to reduce their vehicle travel, it is necessary to estimate their sensitivity to changes in the price of vehicle travel. Many studies have measured the elasticity of demand for light-duty vehicle travel relative to changes in the fuel cost of travel. Most have found that a 10% increase in the fuel cost of travel roughly corresponds to a 1–2% reduction in annual vehicle travel, or an elasticity of –0.1 to –0.2 [4]. As an additional point of reference,

¹ The fuel cost of travel is the cost of fuel per unit of distance driven by a vehicle. It is calculated by multiplying the price of fuel (in dollars per liter, or dollars per gallon) by fuel consumption (in liters per kilometer or gallons per mile).

Table 7

Summary of evolutionary GHG & petroleum mitigation pathways.

Pathway	Scenario	
	Evolutionary	Aggressive
Vehicle Technology	<ul style="list-style-type: none"> - 75% fleet penetration of advanced technology, 50% HEV. - Evolutionary improvements to conventional and advanced technologies. - 20% vehicle weight reduction within a given vehicle segment - Shift in sales mix from 55% trucks to 20% trucks. 	<ul style="list-style-type: none"> - 75% fleet penetration of advanced technology, 50% PHEV. - Evolutionary improvements to conventional and advanced technologies. - 35% vehicle weight reduction within a given vehicle segment - Shift in sales mix from 55% trucks to 20% trucks.
Biofuels	<ul style="list-style-type: none"> - 70 billion liters each of cellulosic and starch-based ethanol 	<ul style="list-style-type: none"> - 140 billion liters of low-GHG biofuel
Clean Grid	<ul style="list-style-type: none"> - 80% reduction in GHG emissions from EIA 2030 base case 	<ul style="list-style-type: none"> - 80% reduction in GHG emissions from EIA 2030 base case
Demand Reduction	<ul style="list-style-type: none"> - 10% reduction in transportation demand compared to reference projections for demand growth. 	<ul style="list-style-type: none"> - 30% reduction in transportation demand compared to reference projections for demand growth.

the 6% reduction in vehicle travel under the High Price Case in the 2008 Annual Energy Outlook [1] implies an elasticity of -0.20 .

Recent studies have suggested that drivers may be becoming less sensitive to changes in the cost of travel [32,33]. It is believed that that higher incomes and lower rates of fuel consumption in vehicles may have insulated consumers from having to react to changes in the cost of travel, reducing the overall effect of fuel price and vehicle technology on the demand for vehicle travel and fuel use [34]. Other studies that have looked at older, historical travel demand data have estimated travel elasticities of up to -0.3 with respect to the price of vehicle travel [35–37]. We use this estimate as an upper-bound estimate of the sensitivity of consumers to changes in travel demand to investigate the range of fuel prices that would be necessary to achieve the targeted reductions in VKT.

It is also important to recognize that the demand for vehicle travel is also related to changes in the rate at which vehicles consume fuel. As the fuel economy of new vehicles improves, it becomes possible for consumers to drive further for the same price as before, thus increasing the demand for private vehicle travel. This is known as the *rebound effect*.

Due to the rebound effect, as the fraction of advanced technology reduces the rates of fuel consumption in light-duty vehicles, higher fuel prices are required to achieve the same reduction in vehicle travel. For example, under the evolutionary advanced technology penetration scenarios discussed above and a conservative assumption of drivers' sensitivity to changes in prices, U.S. fuel prices (including local, state, and federal taxes) would have to increase by more than five times the 2005 average by 2050 to reduce vehicle travel by 10% relative to the reference scenario. The large increase in fuel taxes necessary to offset improvements in vehicle fuel consumption suggests that road charging—which charges on the basis of distance traveled, rather than fuel consumed—may become an attractive alternative to fuel taxes over the longer-term as a method of incorporating externalities such as climate change, air pollution, congestion, and accidents into the price of travel [31,38].

Of vital importance alongside these fiscal demand reduction policies are transportation demand management (TDM) strategies. TDM involves strategies or policies that achieve a more efficient use of transportation resources. These measures play an important role in reducing VKT without directly increasing the cost of travel, as well as achieving other policy objectives, such as reducing car accident fatalities, traffic congestion, commuting times, and urban sprawl [39,40]. Examples of TDM measures include: improving public transportation infrastructure, car sharing and car pooling programs, transit-oriented planning practices, developing bicycle lanes, adjusting parking rates, levying congestion fees, and applying smart growth practices in the design of urban communities. [40–42] While short-term opportunities exist to reduce transportation demand, the timeframe for implementation of non-fiscal approaches on the scale necessary to achieve sustained, nation-wide reductions in travel is long-term and the costs are

difficult to quantify, but case studies of projects that have been undertaken in the United States have shown them to be cost-effective at mitigating transportation emissions [42,43].

For the evolutionary case, we targeted a 10% reduction in light-duty vehicle kilometers traveled (VKT) below the 8.18 trillion km projected by the MIT fleet model in 2050 under the “No Change” scenario. This reduction is estimated to be achievable using only fiscal policies that increase the cost of private vehicle travel. This reduction target corresponds to a 45% increase in light-duty vehicle travel by 2050 relative to 2008 levels, compared to a 62% increase under the No Change scenario.

This evolutionary scenario assumes that a 10% increase in the fuel cost of travel results in a 1% reduction in light-duty vehicle travel, or an elasticity of -0.1 . These assumptions are on the conservative end of previous estimates of the response in vehicle travel, and match reasonably well with recent estimates². Assuming a fuel cost of travel for light-duty vehicles of 8 cents per km in 2010³, a 10% reduction would imply a travel cost of roughly 22 cents per km by 2050. For an average individual who travels 24,000 km per year, this would increase annual travel costs by \$3500.

Our aggressive demand reduction case targets a 30% reduction in VKT. For this scenario, we assume a demand elasticity of -0.2 , a level that rests at the higher end of recently published estimates. This higher elasticity would offer a 20% reduction at similar cost to the 10% reduction achieved in the evolutionary case. It is assumed that the remaining 10% reduction is achieved via widespread implementation of some of the non-fiscal approaches (i.e., urban planning policies, mode-shifting, etc.). This assumption is consistent with the reduction that could be achieved through a comprehensive application of best practices in smart growth and improved transportation choices as estimated by Winkleman et al. [42].

Under a more optimistic travel demand elasticity assumption of -0.3 with respect to the price of vehicle travel (meaning that consumers are more sensitive to increases in the price of travel), our evolutionary scenario corresponds to a price of 11 cents per km traveled by 2050. The aggressive scenario would correspond to a price of 17 cents per km traveled.

2.5. Summary of GHG and Petroleum Mitigation Pathways

Table 7 summarizes the targeted GHG and petroleum reduction strategies, and the magnitude of the change that we have targeted. While a rigorous evaluation of the relative difficulty in pursuing the

² For comparison, Small and Van Dender [24; p. 19] found the short-run elasticity of vehicle travel to fuel cost of travel to be -0.0257 (or a 0.26% reduction in travel for a 10% increase in the fuel cost of travel), and a long-term elasticity of -0.1211 (a 1.2% reduction in travel).

³ Assumes a fleet average fuel consumption of 11.8 L/100 km and a fuel price of \$2.50 per gallon, including existing local, state, and federal taxes. The fuel price is consistent with the EIA's projections of motor gasoline prices in 2010.

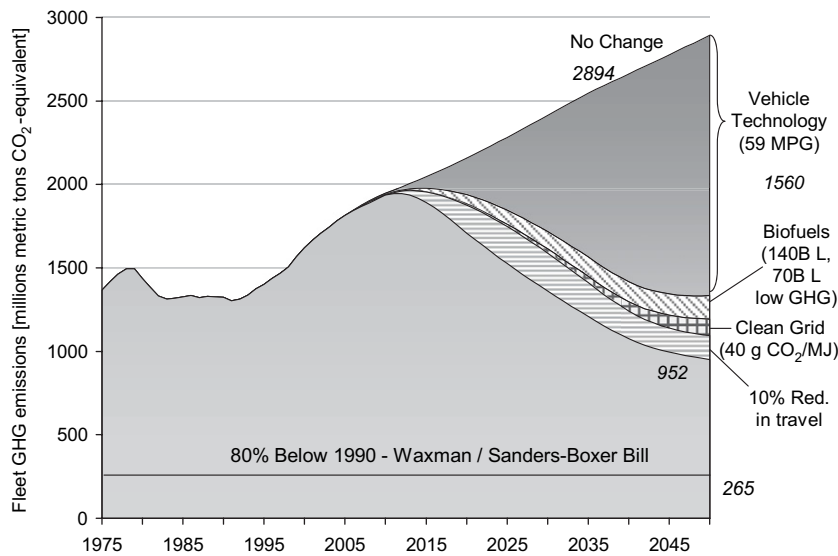


Fig. 5. Avoided CO₂ emissions under evolutionary GHG reduction implementation scenario.

proposed mitigation paths (advanced vehicle technologies, domestic low-carbon fuels, and demand-side reduction) is beyond the scope of this study, the magnitude of the proposed change for each of the pathways was selected to be qualitatively similar to each other.

The vehicle technology scenarios require sustained growth of new technologies and consumer acceptance of increasing emphasis on fuel economy gains; but, they do not require new fueling infrastructure or sustained market penetration rates that are outside the realm of historical experience. These technologies come at increased cost, but they recover these extra costs within 5 years through savings in fuel relative to current fuel consumption levels. Plug-in hybrid technology is estimated to recover the up-front extra cost in 5–7 years by 2035.

The expansion of the biofuels stream requires continued improvements in process and land-use efficiency, as well as continued process cost reductions – but it does not require expansion of crop lands. The de-carbonization of the electric sector is already underway, and there are many options to meet the target identified –

whether it entails a strong focus on nuclear power, fossil generation with carbon capture and storage, distributed renewables, centralized renewables, or some combination of the four. Demand-side reduction initiatives have been structured here as a gradual curtailment of private transportation in response to increased travel costs. While these changes could conceivably be achieved without a bottom-up redesign of our cities, they impose substantial limitations on the transportation choices of consumers in the future, and would likely require large investments in public transportation infrastructure.

3. Results and analysis

Figs. 5 (“Evolutionary”) and 6 (“Aggressive”) show the projected year-by-year fleet GHG emissions to 2050 for our two different mitigation scenarios. The upper line in each figure shows the “No Change” reference case, while each wedge in the figure illustrates the contribution from different mitigation mechanisms. Figs. 7 and 8 compare the avoided CO₂ emissions and petroleum use (respectively) in the year 2050 for the different mitigation scenarios; this

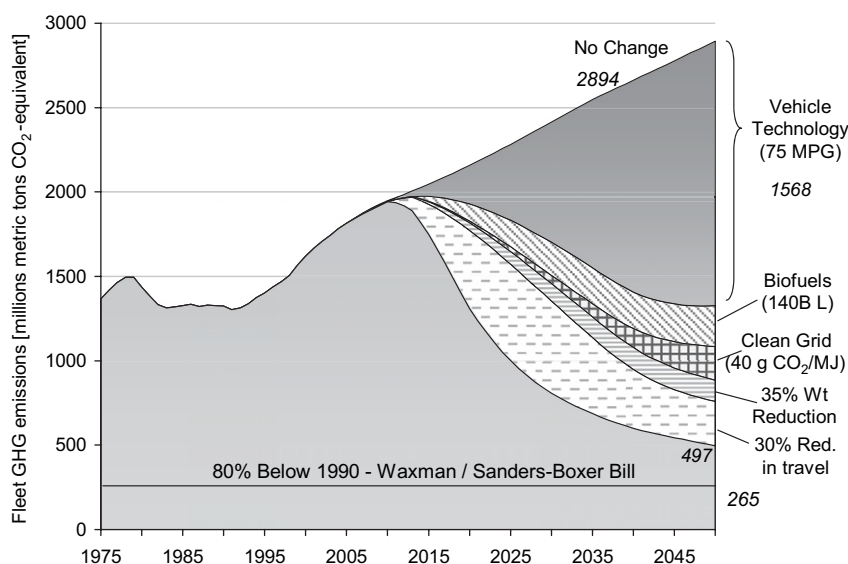


Fig. 6. Avoided CO₂ emissions under aggressive GHG reduction implementation scenario.

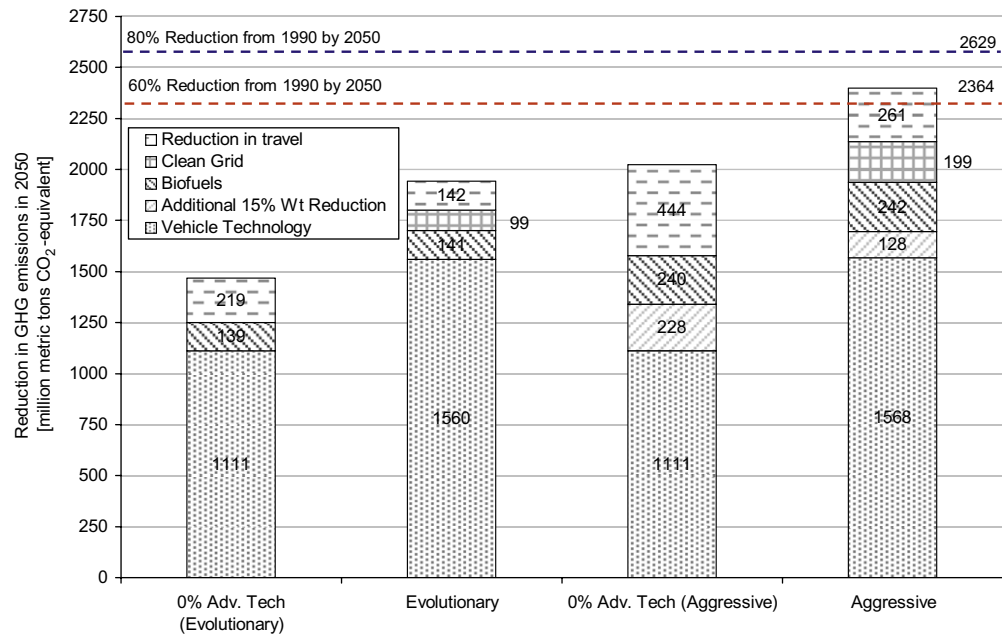


Fig. 7. Avoided CO₂ emissions under GHG/petroleum mitigation plans.

data is summarized in Table 8. The bars, moving from left to right, show progressively more aggressive scenarios. In addition to the evolutionary and aggressive scenarios, we have included an additional scenario for the evolutionary and the aggressive cases with no deployment of advanced technology vehicles.

The bottom segment of each bar (or uppermost wedge in Figs. 5 and 6) shows the avoided emissions or petroleum use of the “vehicle technology” mitigation scenarios described in Table 6. As shown, the vehicle technology path offers the highest leverage of any of the options: depending on the technology penetration scenario, implementing improved vehicle technology accounts for between $\frac{1}{2}$ and $\frac{3}{4}$ of the avoided emissions/petroleum use needed to meet the specified targets. The additional 15% weight reduction that is included in the aggressive case offers only marginal improvement compared to the evolutionary case; this is because the vehicle is already highly efficient (and in the case of the hybrid vehicles, it recovers a fraction of its inertial energy through regenerative braking). As shown, this weight reduction has a far greater effect when deployed in a conventional-vehicle dominated fleet, as is the case for the aggressive 0% Advanced Technology scenario (Fig. 8).

Strikingly, much of the vehicle technology benefit comes from improved conventional technology: for example, the “0% Advanced Technology” scenario reduces CO₂ emissions by approximately 1120 MMtCO₂e and 330 billion liters of petroleum. Penetrating the fleet with 75% advanced technologies, as is assumed for both the aggressive and evolutionary case, offers reductions of 1560 MMtCO₂e and approximately 560 billion liters of petroleum. These improvements from conventional technology reflect the impact of directing technical innovation towards emphasizing fuel efficiency rather than vehicle performance or size [44].

It is also important to note that, without including a de-carbonized electric sector, the impact of new vehicle technology has a comparatively greater impact on meeting the petroleum reduction target than the GHG goal. This is because the PHEV does not offer a significant GHG benefit over the hybrid vehicle in the base case scenario, but does greatly reduce the petroleum use. For example, fleet petroleum use is 15% lower in the aggressive (50% PHEV) scenario compared to the evolutionary (25% PHEV) scenario, but the GHG emissions from the vehicle technology segment are very similar in both cases.

In the evolutionary scenario, improvements to the electric grid have only a small impact in the transportation sector. This is a reflection of both the limited extent to which the plug-in hybrid penetrates the fleet by mid-century (25% in the high-end scenario), and the fact that electricity is assumed to power only 50% of the PHEV-30’s miles traveled [10]. In the aggressive scenario, electric grid reductions comprise a much larger fraction of the total. While the impact of the improved electric grid may be relatively small without widespread deployment of PHEVs, reducing the GHG footprint of the electric sector is generally regarded as a lower-cost path to GHG reductions than focusing on the transport sector. As such, these improvements are likely to occur as part of the electric sector’s mitigation plan. It should also be noted that the impact of de-carbonizing the electric sector would grow further if vehicles were to become more electrified, either through higher range PHEVs or fully electric vehicles.

Introducing a large-scale stream of low-GHG biofuel is a very important contributor to the long-term GHG and petroleum reduction targets. The cellulosic stream offers both GHG and petroleum reduction, while the starch stream offers primarily petroleum

Table 8

Summary of total petroleum and GHG emission reductions under each of the advanced technology scenarios compared to 1990 baseline of 1324 MMtCO₂e and 866 billion liters (15 MBD).

Goal	Reduction target	Actual reduction			
		Scenario			
		0% Adv. tech (evolutionary) (%)	Evolutionary (%)	0% Adv. tech (aggressive) (%)	Aggressive (%)
Zero imports	70% below 2050 baseline	60	80	75	95
Stringent Climate Policy	60–80% below 1990 levels	–10	30	30	65

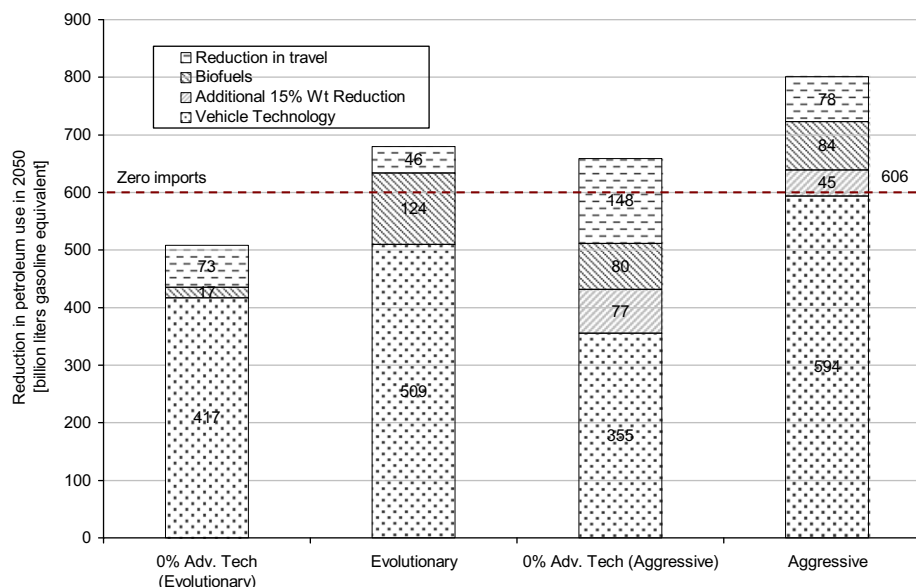


Fig. 8. Petroleum reduction under GHG/petroleum mitigation plans.

reduction benefits. Because the total energy demand of the fleet is decreased by the introduction of higher efficiency vehicles, biofuels are able to meet a significant fraction of this demand (20–30%, depending on the scenario). Reducing the overall energy demand of the fleet using other mitigation pathways helps greatly ease the scale constraint on biofuels.

The demand-side reduction wedge introduces a non-technology-based avoidance opportunity which offers both GHG and petroleum reduction. As discussed above, based on recent consumer responses to the cost of travel, the price incentives necessary to stimulate this level of reduction in private vehicle travel may have to be large. With an increasing share of advanced technologies in the fleet, vehicles are able to drive the same distance with less fuel and the contribution of demand-side reductions declines.

As shown, several of the petroleum reduction scenarios are able to meet the specified target. However, only the aggressive scenario meets the 60% reduction below 1990 levels, and none of the scenarios meet the 80% reduction target.

4. Conclusion

The results of this study illustrate the magnitude of the challenge facing stakeholders within the transportation sector. While the combination of pathways suggested by the aggressive scenario reduces the light-duty fleet's GHG emissions by 84% compared to the 2050 baseline, and 65% relative to 1990 levels, these pathways require broad-based systemic changes in the amount that we drive, the level of performance that we expect from our vehicles, and how we produce our fuel. Achieving the vehicle technology target requires that: (1.) vehicle performance does not improve from current levels; (2.) vehicle weight is reduced by one-third compared to that of today's vehicles; (3.) PHEVs enter the market in the next five years, grow to 5% of the market by 2020, and sustain market penetration rates that push the envelope of our realm of experience for the following two decades. In a similar vein, achieving the biofuel target requires the successful development of a low-GHG, economic biofuel feedstock or feedstocks that are suitable for growth across diverse geographic areas. Developers will also need to continue to improve the yield of the feedstock over a period of decades. The demand reduction targets require increasing the marginal price of

vehicle travel, as well as a shift towards more concentrated living and working areas. These changes must be executed in parallel with aggressive de-carbonization of the electric grid.

Actually meeting an 80% mid-century GHG reduction target in transportation sector requires changes that extend significantly beyond these initial steps. It is likely that successfully meeting such a target would entail still deeper cuts in transportation demand, and perhaps a fundamental change in what we expect from our vehicles in terms of size, performance, and utility, and the fuels that drive them. The difficulty in actually meeting the transportation sector's GHG reduction targets further suggests that other sectors which have more cost-effective mitigation options may need to meet a greater share of the burden.

More broadly, these results stress the importance of focusing on pathways that reduce GHG emissions and petroleum consumption in the transportation sector. We estimate that achieving GHG emission reductions of even 30% below 1990 levels in the year 2050 will end oil imports in the U.S. Reducing GHG emissions by 60–80% of 1990 levels while meeting the transportation sector's energy needs, however, will require a much more concerted effort. Focusing on a combination of advanced vehicle technologies, low-carbon alternative fuels, and behavioral change from consumers offers a robust approach for meeting long-term targets while minimizing environmental and economic costs. Working towards these goals will ensure energy independence while making serious progress to avert the long-term impacts from global climate change.

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