A Wedge Analysis of the U.S. Transportation Sector

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Abstract

The concept of stabilization wedges is introduced and applied to the U.S. transportation sector in order to assess the potential of approaches that could reduce both greenhouse gas emissions (GHGs) and petroleum consumption. Three general approaches are assessed using a wedge analysis, including (1) improvements in vehicle technology, (2) switching to lower-GHG fuels, and (3) utilization of travel demand management (TDM). A broad range of assumptions are considered for each of these approaches, reflecting the wide range of estimates regarding alternative transportation fuels, improvements in vehicle technology, and potential reductions in TDM. A wedge analysis is used to help frame the issues involved and to compare the numerous transportation approaches using a common metric – namely a wedge count.

It is shown that approximately nine U.S. transportation sector wedges, each representing 5,000 MMT CO_2e of cumulative reductions between now and 2050, would be enough to flatten emissions in the sector. Just over four wedges could flatten emissions from the passenger vehicle category. A wedge analysis was performed on a wide range of scenarios involving just passenger vehicles. Fuel switching alone could yield up to 2.3 wedges. Vehicle technologies, when combined with fuels, could account for up to 3 wedges given a 30% market share by 2050. TDM alone could account for up to 1.4 wedges given a 15% reduction in travel growth by 2050. By contrast, a system approach combining the three approaches can result in 4 to 9 wedges.

Executive Summary

Recently, there has been increasing interest in the potential of vehicle technology, fuels, and travel demand management (TDM) to reduce GHG emissions and petroleum consumption in the transportation sector. However, comparative analysis of these three approaches can be particularly challenging due to the different time horizons for each approach, the large number of options available, and the interactions between approaches. Much of the literature has focused on specific studies of individual vehicles, fuels, or TDM options. The study attempts to provide an integrative analysis of system approaches that combine all three – technology, fuels, and TDM.

To help develop a more convenient, common metric for evaluating the numerous approaches available in the transportation sector, this study builds off the "stabilization wedge" concept first developed by Rob Socolow and Stephen Pacala at Princeton University.[1] A wedge analysis method is applied to more clearly frame the problem, by (1) breaking down emissions from the transport sector into more convenient wedges and (2) comparing the impact of the three approaches. Comparisons are also made showing the impacts from applying each approach independently of each other versus a system approach that combines all three. A simple metric, the "wedge count," is used to make comparisons of the numerous approaches.

The authors conclude that:

- The stabilization wedge framework can be effectively scaled for different analysis levels. In this study, one wedge for the U.S. transportation sector (USTS) is defined as an approach that is capable of reducing 5,000 MMT CO_2e of cumulative emissions between now and 2050. These are called USTS wedges.

- Approximately nine USTS wedges would be enough to flatten emissions in the U.S. transportation sector over the analysis period (2007-2050). Out of these nine wedges, roughly half would be enough to flatten emissions from passenger vehicles, two wedges to flatten those from freight trucks, one wedge for aviation emissions, and another one and a half wedges to flatten emissions from marine, rail, and non-transportation mobile sources.

- The wedge approach provides a metric to make evaluations based on *cumulative* emission reductions over longer timeframes, rather than incremental reductions for a specific year. From a climate perspective, it is cumulative emission reductions that are of primary significance.

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[1] Stephen Pacala and Robert Socolow (2004), *Science*, **305,** 968.

- By themselves, individual approaches incorporating vehicle technologies, fuels, or transportation demand management (TDM) approaches could moderately reduce, but not flatten, emissions from now until 2050. Most of the system approaches analyzed, by contrast, could yield more than the 4 to 5 wedges needed to flatten passenger vehicle emissions. The most transformative scenarios analyzed could nearly flatten the entire U.S. transportation sector emissions, despite the passenger vehicle category representing only half of the sector's emissions.

- Near-term vehicle technologies can have as much of an impact in terms of GHG reductions as future, longer-term technologies largely because of timing. To achieve the most wedges however, longer-term technologies are needed. This is largely because longer-term technologies allow for additional emission reductions in the later period when the potential of near-term technologies have already been fully utilized.

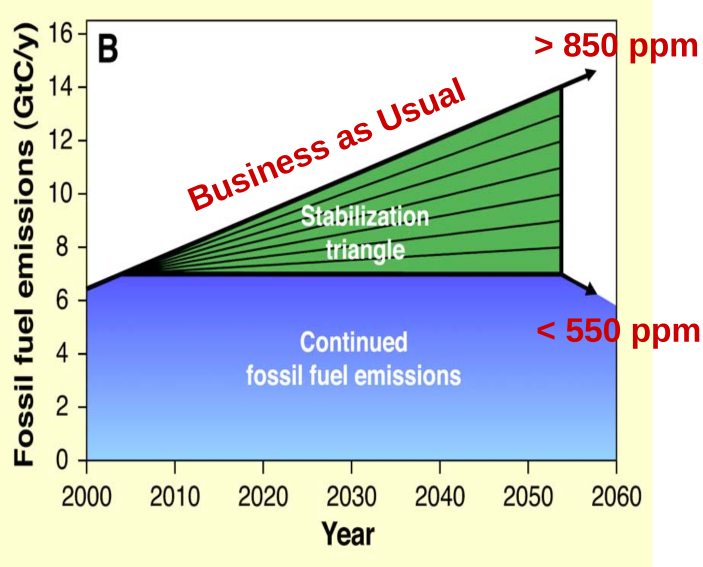
- Nearly all the approaches discussed have significant ancillary benefits associated with the wedges. The approaches that reduce GHG emissions also necessarily reduce petroleum use. For example, achieving five wedges could result in 7 to 8 million barrels of petroleum saved in 2050. Additional examples of ancillary benefits include reduced congestion from TDM approaches and the synergies between the electricity sector and transportation sector when using alternative fuels such as electricity.

- The wide range in the number of wedges shown reflect an attempt to bracket the potential GHG reductions for each scenario using both optimistic and conservative assumptions regarding individual vehicle technologies, fuels, and TDM approaches.

Introduction

In 2004, Pacala and Socolow introduced the idea of a "stabilization wedge" as a heuristic tool to evaluate different greenhouse gas (GHG) emission scenarios.[2] Under this framework, the emissions gap, or difference, between the business-as-usual case and one that stabilizes concentration can be sliced into "stabilization wedges," as shown in Figure 1. A stabilization wedge was defined as a reduction activity that over the next 50 years could cumulatively reduce 25 billion tons of carbon emissions (or about 92,000 million metric tons of CO_2) on a global level. It was estimated that seven of these global-scale wedges – added up – would allow global emissions to be flattened (or kept at today's level) over the next 50 years.[3] Fifteen potential strategies were presented that could potentially reduce GHG emissions by one wedge. Examples of these strategies range from making advancements in power generation, increasing end-user efficiency and conservation, to making improvements in agricultural and forestry practices. The original wedge analysis focused on global emissions and scenarios. In the following study, the wedge analysis approach is scaled down and applied to the U.S. transportation sector.[4]

Figure 1: A global-scale stabilization triangle and the individual wedges (in green). Reproduced from Pacala, Socolow, *Science* (2004), **305**, 968 with labels in red added. A business as usual emissions trajectory could result in atmospheric concentration levels 850 ppm CO_2 or greater. Removing the emissions embodied by the stabilization triangle would be analogous to emission pathways stabilizing below 550 ppm.



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[2] Ibid. One wedge, under Socolow's definition, represents 25 billion metric tons C-equivalent over 50 years (or 91.6 billion metric tons of CO_2e).

[3] The business-as-usual pathway likely would lead to a tripling of carbon concentrations in the atmosphere compared to pre-industrial levels (280 ppm). The flat path, by contrast, would likely lead to stabilization less than twice pre-industrial levels (<560 ppm) as long as emissions were reduced more substantially after fifty years. R. Socolow and S. Pacala (2006), "A Plan to Keep Carbon in Check," *Scientific American*, September 2006, 50-57.

[4] While the focus is on approaches for the U.S. transportation sector, the wedge analysis can be scaled to approaches focused on any level or economic sector.

Stabilization Wedges for the U.S. Transportation Sector

A method is presented to define emission wedges for the U.S. transportation sector (USTS). The USTS alone represents approximately 10% of all energy-related greenhouse gas emissions worldwide and over a third of all transportation emissions worldwide.[5] Over the next 50 years, the GHG emissions from the USTS could be poised to grow another 80% above current levels due to increases in the number of vehicles and their activity.[6] Absent a shift in this trajectory, the USTS is poised to add nearly 200,000 MMT CO_2e to the atmosphere over the next 50 years. This additional flow into the atmosphere could approximately translate to a rise of 12 ppm in global atmospheric concentrations.[7] Note that a path that flattens emissions over the next fifty years at today's levels, followed by additional reductions after 50 years, is analogous to stabilizing concentrations below twice that of pre-industrial levels (i.e. 560 ppm CO_2 versus 280 ppm).[8, 9]

Figure 2 illustrates the triangle necessary to flatten emissions from the U.S. transportation sector from now until 2050 (i.e. a 43 year time span). The cumulative emissions embodied by the upper triangle are approximately 45,000 MMT CO_2e. The figure also shows how the triangle can be sliced into smaller, more manageable wedges. If this triangle is sliced into USTS wedges of 5,000 MMT CO_2e each, then nine USTS wedges would need to be avoided to flatten the sector's emissions.[10] For perspective on the relative size of each USTS wedge, the amount of carbon dioxide in one wedge -- or 5,000 MMT CO_2e -- is roughly equivalent to removing four years worth of U.S. personal vehicle GHG emissions over the next 43 years. We use this USTS wedge of 5,000 MMT CO_2e as a "carbon metric" to compare the potential of numerous approaches to reduce GHG emissions.

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[5] For 2005, we estimate that the direct emissions attributable to the U.S. transportation sector was about 2,000 MMT CO_2e, not including non-transportation mobile source emissions, such as from construction and agricultural equipment. If these emissions, as well as the fuel cycle emissions, are included then the USTS represented nearly 2,750 MMT CO_2e in 2005. Total global GHG emissions in 2004 were 27,044 MMT CO_2e, based on the U.S. DOE (2004), *International Energy Annual*, Energy Information Administration. These USTS emissions were compared against the World Business Council for Sustainable Development (WBCSD)'s Sustainable Mobility reference case for global transportation emissions, adjusting for sources not included in the WBSCD value but included in our estimates. L. Fulton and G. Eads, (2004), *IEA/SMP Model Documentation and Reference Case Projection*, WBCSD.

[6] U.S. DOE (2006), *Annual Energy Outlook*, Energy Information Administration. This estimate assumes that the forecasts to 2030 continue at the same 1.3% annual growth to 2056.

[7] This estimate assumes that 200,000 million metric tons will be added over the next 50 years, with half the quantity being sequestered by oceans and forests. Emissions of 8,000 MMT CO_2e translates to about a 1 ppm (one part per million) increase in atmospheric CO_2e concentrations (not including natural sequestration by ocean and forests).

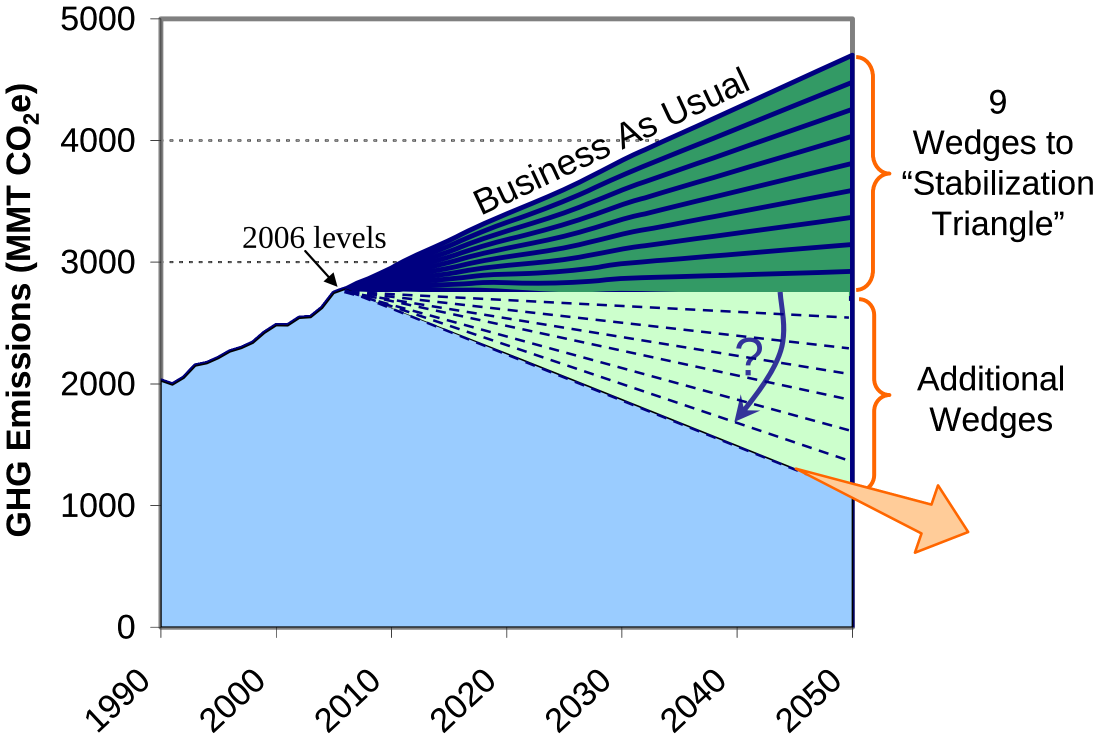
[8] A doubling of pre-industrial levels, 280 ppm CO_2, means 560 ppm. However, many models consider 450, 550, 650, and 750 ppm scenarios, a convention we adopt here. Including all GHGs, the current CO_2-equivalent concentration is approximately 430 ppm. The approximate range of temperature increase associated with a doubling in emissions is estimated to be between 1.5 to 4.5°C, with the upper range increasing in recent years. Lower concentrations (e.g. 450 ppm) are associated with lower probabilities of reaching higher temperatures. HM Treasury (2006), *Stern Review on the Economics of Climate Change,* United Kingdom.

[9] The global GHG emission pathways were presented in T. Wigley, R. Richels, and J. Edmonds (1996), *Nature*, **379**, 240-243 and in the *IPCC Special Report on Emissions Scenarios, (*2000). Nebojsa Nakicenovic and Rob Swart (Eds.), Cambridge University Press, UK. pp 570.

[10] Each of these wedges would be approximately equivalent to reducing 5 MMT CO_2e in the first year and an additional 5 MMT of reductions thereafter, growing to 220 MMT in year 2050.

Since approximately nine USTS wedges would keep the sector's emissions flat and on a pathway analogous to a 550 ppm CO_2 trajectory, obtaining additional wedges would allow USTS emissions to follow a trajectory consistent with lower concentrations.[11] The potential of the USTS to reduce more emissions than represented by this flattening is assessed by considering a number of scenarios involving advanced vehicle technology, low GHG fuels, and TDM approaches for the passenger vehicles category.

Figure 2: The U.S. Transportation Sector's (USTS) GHG emissions with nine USTS wedges that would flatten emissions (upper triangle). Additional wedges are also shown that would lead to levels below simply flattening emissions. The projections include emissions associated with the fuel cycle.



A "wedge count" is shown in Figure 3 for the each of the sources in the U.S. transportation sector, displaying the number of wedges needed to flatten each source. For example, over four (4.3) wedges would be needed to keep passenger vehicle emissions flat.[12]

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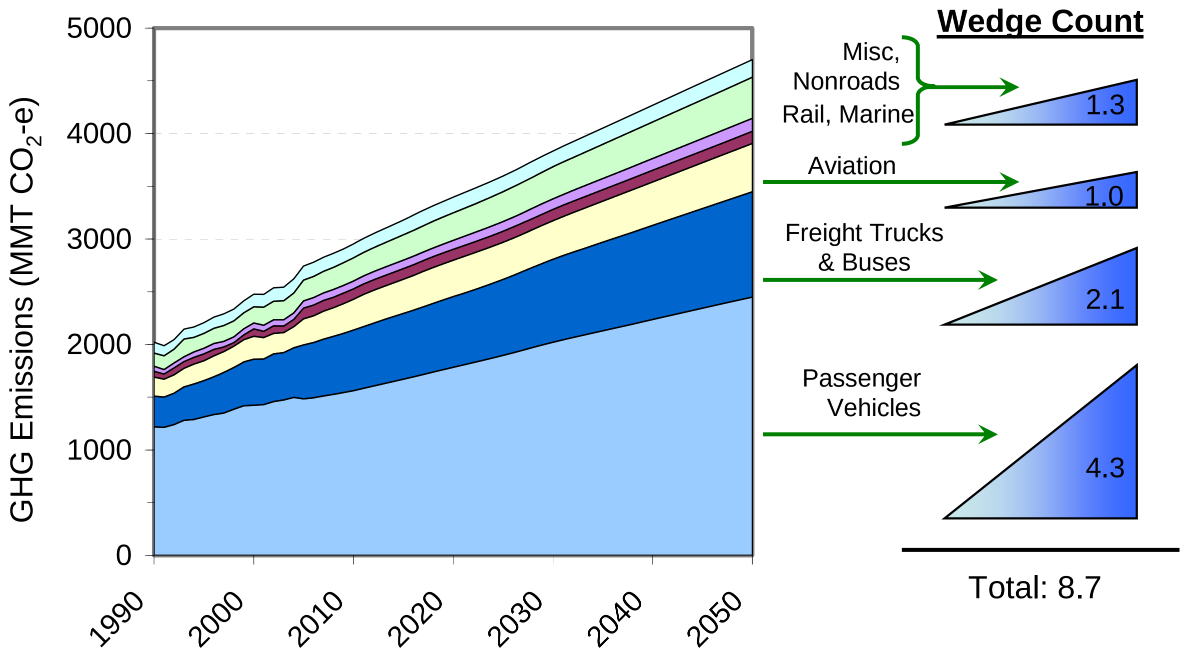
[11] GHG emissions act globally, so from a climate perspective, only the cumulative amount of GHG emissions matter. Thus, to keep overall global emissions constant, developed nations would need to reduce more if developing nations emit more. This is particularly true if it is assumed that developing nations need some room for emissions growth as they modernize. As Pacala and Socolow (2006) state, "To freeze emissions at the current level, if one category of emissions goes up, another must come down...And if today's poor countries are to emit more, today's richer countries must emit less."

[12] The wedge count to just flatten emissions from each transportation source is as follows: 4.3 wedges for passenger vehicles, 2.1 for freight trucks and buses, 1.0 for airplanes, and 1.3 for non-road, locomotive, marine, and pipeline sources of GHGs. Thus, the total number of wedges is 8.7 for the transportation sector.

The growth in emissions from commercial trucks, freight trucks, and buses would compose another two wedges, while aviation would add another wedge. Emissions from rail, marine vessels, and non-transportation mobile sources (e.g. construction equipment, off road vehicles) would compose another 1.3 wedges.

Figure 3: U.S. transportation sector GHGs by emission categories. The wedge count on the right shows the number of 5,000 MMT CO2e wedges needed to flatten emissions from each category. Flattening emissions from passenger vehicles would require the most wedges (4.3) out of the approximately 9 wedges.



Vehicle Technology, Fuel, and TDM Approaches

Generally, three parameters determine the amount of GHG emissions from transportation sources: the choice of fuel, the vehicle activity level, and the energy efficiency of the vehicle.[13] For the passenger vehicle category, emissions (E) can be described as the product of the carbon content of the fuel (C), vehicle activity in vehicle miles traveled (A), and fuel consumption (F) – conveniently described as the EFAC equation:

$$E = Emissions_{(Carbon)} = \underbrace{\left(\frac{Gallons}{Mile}\right)}_{Fuel\ Consumption}\underbrace{\left(\frac{miles\ \ traveled}{Vehicle}\right)}_{Activity}\underbrace{\left(\frac{mass\ C}{gallon}\right)}_{Carbon\ Content} = F \times A \times C$$

Consideration of the EFAC equation suggests that approaches that reduce emissions are ones that would, by definition, need to either lower the amount of fuel consumed, the carbon content of the fuel, or the vehicle's activity (or vehicle miles traveled, VMT). Thus, we evaluate various scenarios involving each of the following approaches:

- Adopting advanced vehicle technology
- Switching to low-GHG fuels
- Utilizing travel demand management (TDM).

A number of what-if scenarios are considered that involve each of the above approaches. Comparisons between each what-if scenario are made based on an assessment of the number of wedges that could be obtained, or a wedge count. An evaluation is also performed of scenarios involving "system approaches" that utilize all three approaches – namely vehicle technology, fuels, and TDM. [14]

Several factors make a wedge comparison particularly useful in assessing these three disparate approaches. First, comparing combinations of approaches involving all three approaches can be particularly challenging due to interactions and feedback mechanisms between vehicle technologies, fuels, and travel demand.[15] The analysis provides an integrated method by which to more clearly compare the numerous vehicle technologies, fuels, and travel demand management (TDM) approaches, both independently of each other and in combination. Second, the wedge approach also provides a metric to make evaluations based on *cumulative*

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[13] This mathematical expression can be considered a variant of the conceptual IPAT equation, debated in the 1970s in works by Paul R. Ehrlich, John Holdren, and Barry Commoner. See Marian R. Chertow (2001), "The IPAT Equation and Its Variants: Changing Views of Technology and Environmental Impact," *Journal of Industrial Ecology*, **4** (4), 13-29.

[14] Note that this concept of a *system approach* is not in reference to the "systems approach" commonly used in the management science and operations research literature.

[15] Note that combined effects cannot be simply added since they follow a multiplicative relationship. For example, a 30% reduction in each of these variables (C, A, and F) would not lead to a 90% overall reduction, but rather E_{new} = 0.7 x 0.7 x 0.7 = 0.34 (or a 66% overall reduction).

emission reductions over a longer timeframe rather than the more commonly used metrics: percent GHG reduction or absolute GHG reductions for a specific analysis year. From a climate perspective, it is *cumulative* emission reductions over longer time frames that are of primary significance. Discussions of reductions have tended to focus almost exclusively on incremental rather than cumulative emission reductions. Issues of timing and staging of the approaches can also be considered using the wedge analysis (e.g. the impact of near-term versus long-term technologies). Finally, the wedge analysis can be scaled to fit any analysis level of interest, including a specific emissions category, economic sector, or national and global levels.

There are many advanced automotive technologies that can lower vehicle GHG emissions and petroleum consumption. These can include (1) ongoing improvements in conventional areas such as aerodynamics, tires, lightweight materials, accessories, gasoline engines, and mechanical transmissions, (2) expanded use of powertrains already commercialized such as electric hybrids and diesels, and (3) the future introduction of even newer powertrains such as ethanol-optimized vehicles, plug-in hybrids, and fuel cells. Likewise, there is a wide variety of transportation fuels that could provide large GHG and oil benefits based on production processes that involve renewable feedstock or carbon capture and sequestration. These alternative fuels (or energy carriers) include such examples as biofuels, electricity, and hydrogen among others.

Transportation or travel demand management (TDM) includes a large suite of options that seek to use transportation system resources more efficiently and effectively. Several diverse examples include increasing the number of regional transit-oriented options, improving land use planning to make cities more accommodating to pedestrians, employing market-based congestion pricing, or even adopting pay-as-you drive automobile insurance.[16]

A system approach involves considering more optimum synergies among two or three of the approaches. As an example, Figure 4 provides an illustrative example of the benefits from using a system approach that combines both advanced vehicle technology and low GHG fuels. While vehicle technology alone can achieve significant petroleum and GHG reductions, a system approach combining both technology and low GHG fuels can achieve significantly greater petroleum and GHG reductions. The amount of displaced petroleum occurs largely in proportion to the amount of alternative fuel used. By contrast, a wide range of GHG reductions is possible when switching to an alternative fuel, with the range depending on the sources or feedstock used process the fuels. For example, a vehicles running on ethanol (e.g. E85) would achieve much higher GHG reductions if the ethanol were derived from cellulosic feedstock versus corn. Similarly, while electric vehicles displace nearly all petroleum usage (there may still be some usage during electricity generation), the GHG reductions largely depend on whether the electricity used is derived from coal or from renewable sources.

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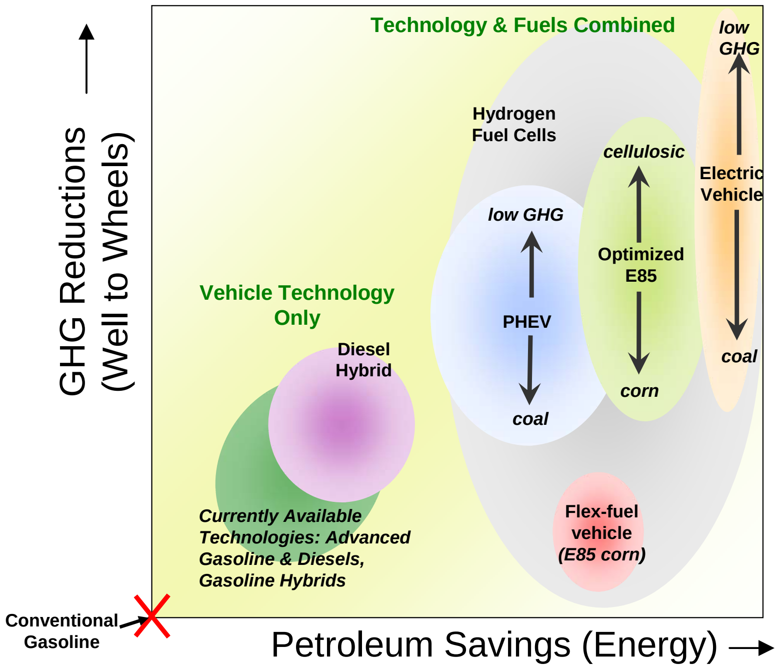
[16] These approaches are also known more generally as transportation demand management.

Figure 4: Illustrative example of GHG reductions and petroleum savings for (1) various technology-only approaches and (2) combinations of vehicle technologies with alternative fuels. The reductions relative to today's conventional gasoline vehicle are shown. Note that the size and position of the bubbles are illustrative and assumptions-driven.



Technology, Fuel, and TDM Approaches for Passenger Vehicles

The potential of technology, fuels, and travel demand approaches to achieve reductions are considered for the passenger vehicle category (or light-duty vehicles). Passenger vehicles contribute approximately half of all USTS emissions. The remainder of emissions comes from such sources as commercial trucks, marine vessels, railroads, airplanes, and other sources like construction equipment.[17] For this wedge analysis, only approaches covering passenger vehicles are considered.[18] If approaches covering other transportation categories are included, even larger reductions would be possible along with greater flexibility in the options used.

Vehicle Technology Approaches:

Technology innovation has been the main driver to reducing emissions in the past, and will remain a key approach for reducing emissions in the future. We compare the impacts from increasing the population of advanced internal combustion engine (ICE) vehicles (gasoline and diesel), hybrid electric vehicles, optimized alternative fuel vehicles, plug-in hybrid electric

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[17] In 2003, the emissions budget of these non passenger vehicle categories (including locomotives, pipelines, lubricants, mobile AC, and refrigerated transport) represented 716 MMT CO_2e emissions. EPA (2006), *Greenhouse Gas Emissions from the U.S. Transportation Sector 1990-2003*.

[18] The Annual Energy Outlook 2006 reference case scenario was used as a basis for the reference scenario used here for GHG emissions (with modifications), along with adjustments for non-transportation mobile source emissions and fuel-cycle emissions.

vehicles, and fuel cell vehicles.[19] Many of these vehicle technologies are described in greater depth in an EPA study on new powertrain technologies.[20]

Table 1 lists the technologies modeled and the fuel efficiency improvements assumed for each particular vehicle technology. The specific fuel economy improvements shown in Table 1 can vary based on the specific assumptions – the values assumed for this study are shown.[21] The “reduction potential” for each technology, in terms of wedges, is evaluated based on the following scenario: greater penetration of the particular technology into the fleet, such that the market share reaches 30% above the baseline share after 15 years.[22] For instance, to evaluate the impact of gasoline hybrid electric vehicles, an increase is modeled to start in 2010, reaching an additional 30% greater market share by 2030, keeping constant through 2050. This equivalent treatment of technologies allows for the “stabilization potential” of each technology – in terms of wedges -- to be compared. Note that this study uses the same “what-if” scenarios to assess the *technology potential*; it does not model the *market potential* of the technology.[23] However, in theory an economic model that has detailed representation of the vehicle and fuel markets could also be used to conduct a wedge analysis based on consumer and manufacturer preferences. An economics based approach would give more insight into the timeframe in which these technologies could be accepted into the market and the benefits and costs associated with each specific wedge.

The ranges of GHG reductions shown in Table 1 account for low and high estimates for fuel-cycle emissions. For technologies using electricity from the grid, such as electric vehicles or plug-in hybrid electric vehicles, the upstream impact of GHG emissions from power plants are considered. The upper range of upstream emissions is bound by assuming the additional electricity demand is met by new pulverized coal sources, while the lower range is bound by assuming low-GHG emission sources that by comparison with coal emit approximately 10% of the emissions.[24] This might represent, for instance, an integrated coal combined cycle (IGCC) plant with additional carbon capture and sequestration or a utility mix that is heavily weighed toward wind sources or nuclear energy. For the hydrogen fuel cell scenario, the high and low values encompass a wide range of assumptions that includes hydrogen generation from solar energy, natural gas, or coal based energy sources.

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[19] Optimized alternative fuel vehicles refer to a category that can either run on flex-fueled or dedicated alternative fueled systems, but with optimization of the combustion process for the alternative fuel.

[20] For a description of these technologies, see EPA (2005), *Interim Report: New Powertrain Technologies and Their Projected Costs, Office of Transportation and Air Quality*, October 2005, EPA420-R-05-12, www.epa.gov/otaq/technology. An updated version will be available in the Spring or Summer of 2007.

[21] Ibid.

[22] A standard S-shaped curve for the market penetration was used.

[23] For all vehicle technologies other than pure electrics and fuel cells, the market penetration begins in 2010 and grows to 30% by 2025 using a standard S-shaped curve. For pure electrics and fuel cells, it was assumed that the technical hurdles were greater such that the what-if scenario starts 5 years later in 2015 and reaches 30% by 2030.

[24] The upstream carbon factors are based on estimates obtained from the Integrated Planning Model which looks out to 2030. The lower bound is given by a supercritical pulverized coal plant while the upper bound is represented by an IGCC plant with carbon capture and sequestration. *Introduction to EPA Modeling Applications Using IPM*, “Chapter 2: Modeling Framework,” EPA's Clean Air Markets Division, 2004.

Figure 5 displays the potential wedges for each technology assuming the 30% market. As an example, a gasoline-hybrid electric vehicle is shown under this what-if scenario. In the inset box, other vehicle technologies and their wedge counts are shown. The wedge count provides a comparative analysis between the technology and fuel combinations based on cumulative emissions. The grey area for each wedge count illustrates the potential wedge range, which is largely dependent on the fuel cycle emissions. For instance, an optimized vehicle running full-time on E85 could achieve 1.3 wedges if the feedstock for ethanol is from corn or up to 2.7 wedges if the feedstock is from cellulosic biomass.[25] As a reference, the maximum wedge count a vehicle technology could achieve (i.e. zero fuel-cycle emissions) would be 3.6 wedges. In general, the largest reductions are achieved by using both low GHG fuels combined with advanced vehicle technologies. However, no single technology will likely fulfill the mobility needs of every driver. Thus we do not consider scenarios involving 100% of any particular technology.

Table 1: Vehicle technology categories and their assumed fuel economy and GHG emissions relative to a baseline, conventional gasoline vehicle.

Vehicle Technology	Vehicle Fuel Economy Improvement[26]	Percent Reduction in GHG Emissions (fuel-cycle)[27]
	vs. Conventional Vehicle	
Advanced Gasoline Engine and Advanced Diesel Engine	35-40%	20-26%
Hybrid Electric Vehicle (Gasoline)	40%	29%
Hybrid Electric Vehicle (Diesel)	70%	35%
Optimized E85[28]	-4%	38 to 80%
Advanced Optimized E85[29]	30%	54 to 85%
Plug-In Hybrid Electric[30]	65%	31 to 62%
Electric	390%	31 to 94%
Fuel Cell[31]	270%	21-92%

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[25] Note that for vehicles that have a flex-fuel option (such as E85 FFVs or plug-in hybrid electric vehicles) the range of reductions also depend on user behavior (not considered here). For all combined technology and fuel approaches, the availability of a fuel infrastructure (outside of conventional petroleum fuels) is also a key variable.

[26] The percent improvement is relative to the business as usual conventional vehicle. The on-the-road, average fuel economy assumed for the base year (2005) for a new conventional vehicle was 20.3 mpg. The business as usual improvement in fuel economy was assumed to be approximately 0.5% per year.

[27] The calculated GHG emissions refer to those associated with the fuel cycle and vehicle use. It does not include the emissions generated from the manufacturing or scrappage of the vehicle. The range given reflects different assumptions regarding the fuel cycle emissions.

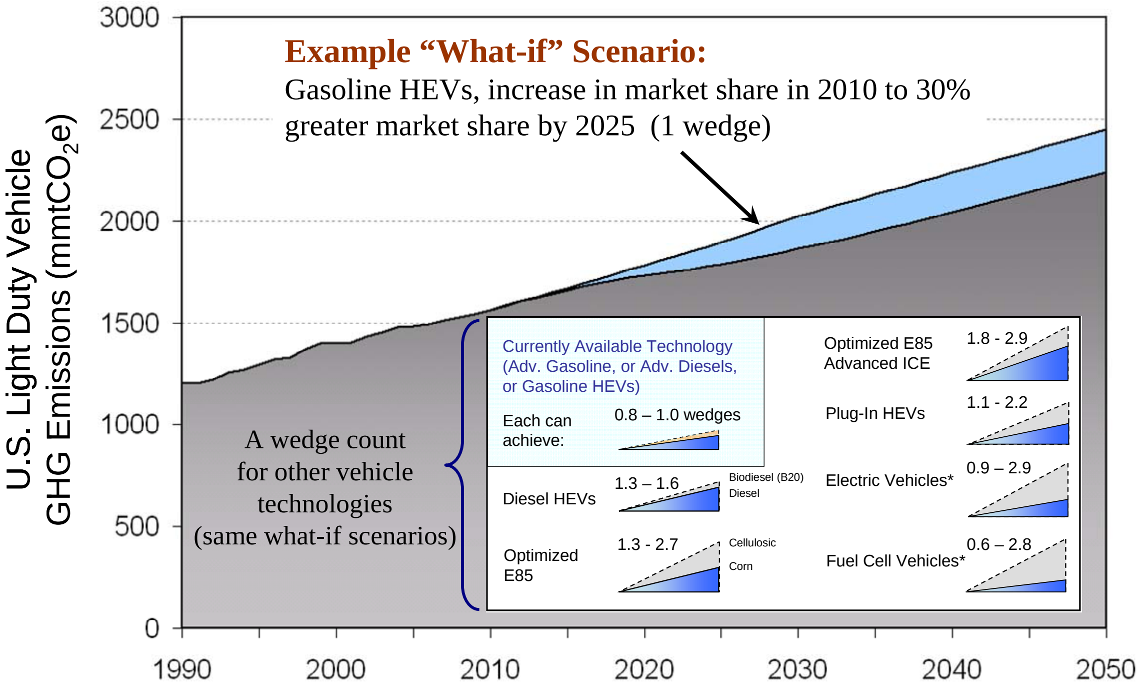
[28] This assumes that the optimized E85 vehicles are optimized to run on E85 and have improved efficiencies beyond current flex-fueled vehicles. The lower value in well-to-wheels emissions represents if the biofuel were 100% corn-derived ethanol while the higher value represents if the biofuel were 100% cellulosic derived.

[29] An advanced optimized E85 vehicle would include the engine optimization for E85 in conjunction with an advanced technology package analogous to an advance gasoline engine vehicle

[30] The PHEV category assumes a plug-in vehicle capable of obtaining 40 miles in an all-electric mode after charging the battery. This range from the battery would allow for approximately half of the VMT driven under an all-electric mode (or blended mode). It is likely that PHEVs will be sold with a 10 mile electric range first and that this range will be increased as battery technology develops. However, we have considered PHEV40s only for simplicity, given the longer term nature of the analysis.

Timing also plays a critical role in the number of wedges that can be achieved. For instance, if optimized E85 vehicles began entering the fleet in 2020 versus 2010, the upper wedge count would drop from 2.7 wedges to 1.9 wedges. In some cases, currently available technology that is deployed early can have as significant an impact as future vehicle technologies that are deployed later, largely due to timing.

Figure 5: The potential emission reductions, in terms of a wedge count, for several vehicle technologies. The wedge count assumes a 30% greater market share for each technology by 2025. *For electric vehicles and fuel cell vehicles, the what-if market share reaches 30% five years later by 2030 due to large technical hurdles remaining.



Low GHG Fuel Approaches:

Reducing the carbon intensity of the fuel supply, or fossil fuel-decarbonization, is one of the most important approaches for reducing both emissions and petroleum consumption. A number of alternative fuels with potentially lower GHG emissions include biomass-derived fuels (e.g. ethanol, biodiesel, butanol, methanol), natural gas, hydrogen, and electricity among

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[31] The GHG reductions were calculated using Argonne National Laboratory's GREET model. The range represents cases where hydrogen gas is generated at a central facility by using coal or using solar generated electricity. The current production method of reforming natural gas at a refueling station reduces GHG emissions by 55%. Also see J. Heywood, M.A. Weiss, A. Shafer, S.A. Bassene, and V.K. Natarajan, (2003), *The Performance of Future ICE and Fuel Cell Powered Vehicles and Their Potential Fleet Impact*, Laboratory for Energy and the Environment, December 2003, Massachusetts Institute of Technology.

others.[32] The lifecycle emissions of these fuels mainly depend on how these fuels are derived and the choice of vehicle technology.

There are a number of shorter and longer term fuel approaches available to reducing GHG emissions. These approaches can range from incorporating biofuels into the petroleum fuel pool as a low level blend, all the way to shifting the transportation sector into a hydrogen economy. Recently, there has been much focus on the potential of plug-in hybrid electric vehicles, which can be powered by both gasoline and by electricity from the grid. Shifting emissions from the vehicle tailpipe to power plants has its advantages in terms of GHGs, but only if the electricity sources are less carbon intensive over the entire lifecycle. Note that most of the low GHG fuels approaches also require some additional vehicle technology to be adopted (e.g. an electric powertrain). Widespread use of some fuels, such as hydrogen or E85, represent different degrees of change to the fuel infrastructure.

In Figure 6, a what-if scenario is shown for ethanol. Although there are a broad range of possible low GHG fuels, ethanol is shown as only one possibility. The scenario demonstrates the impact of 60 billion gallons (bgal) of ethanol substitution for gasoline by 2050, with 15 bgal from corn ethanol and 45 bgal from cellulosic ethanol. [33] Note that these scenarios, which only focus on fuels, do not assume technology improvements beyond the business as usual case.[34] Approximately 1.4 wedges can be obtained in the 60 bgal ethanol case shown. A case involving 90 billion gallons of ethanol is also shown to achieve 2.3 wedges – over half the wedge count needed to flatten passenger vehicle emissions.[35] Figure 6 displays the potential wedges each of these fuel scenarios could obtain. Using a low-GHG fuels approach, it can be observed that 0.7 to 2.5 wedges result. While these reductions are significant, using ethanol alone would not be enough to obtain the more than four wedges necessary to flatten just passenger vehicle emissions.

Current trends in the U.S. toward increased use of biofuels, however, should be considered in the context of longer-term transitions from conventional petroleum supplies toward unconventional sources. As the most accessible, cheapest supplies of conventional petroleum

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[32] Fischer-Tropsch fuel cycle emissions, which include coal to liquids processed through indirect liquefaction, would be higher than conventional gasoline and diesel fuel cycles if carbon capture and sequestration is not used. R.H. Williams, E.D. Larson, and H. Jin (2006) discusses the possibility of biomass and coal co-firing to reduce GHG emissions in "F-T Liquids Production from Coal and Coal + Biomass with CO_2 Capture and Alternative Storage Options: Aquifer CO_2 Storage vs CO_2-Enahnced Oil Recovery," Draft article, presented at the Energy and Environmental Security Initiative, University of Colorado at Boulder, January 19, 2006.

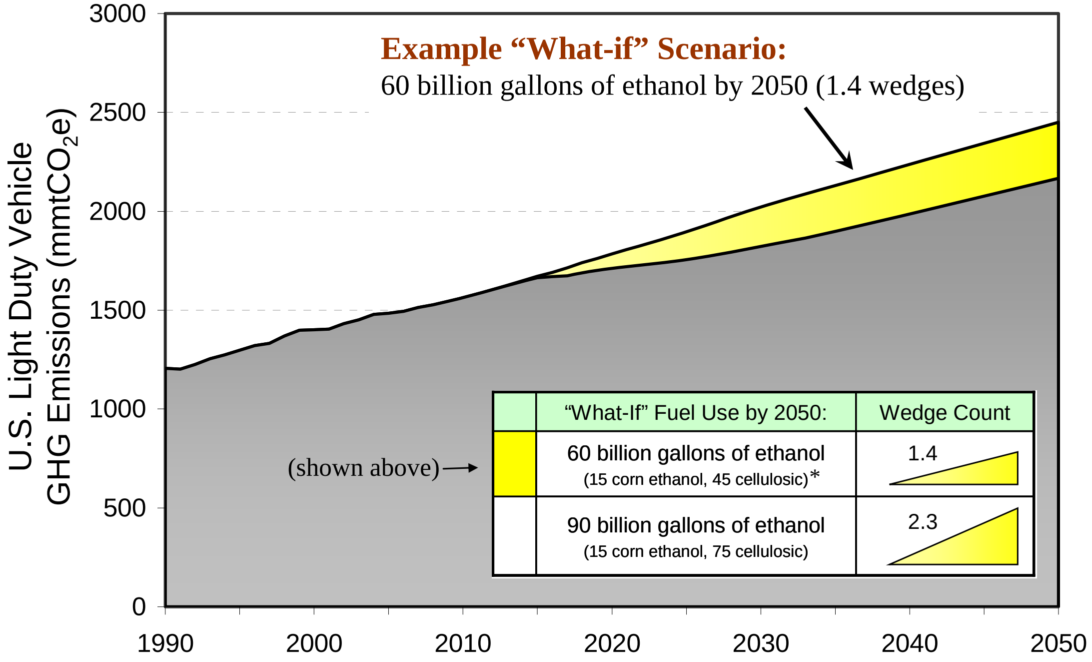
[33] In the scenarios that were evaluated, corn ethanol was assumed to supply all ethanol in the early years and slowly supplemented by cellulosic ethanol over the 2007-2050 timeframe. By 2050, it was assumed that approximately 90% of the ethanol was cellulosic based. Under these assumptions, corn ethanol did not exceed 15 billion gallons in any single year. Most estimates for domestic corn ethanol production and usage vary. See for instance National Corn Growers Association (November 2006), "How much ethanol can come from corn?" and the U.S. DOE (2007), *Annual Energy Outlook*, Energy Information Administration.

[34] For the 60 and 90 billion gallon ethanol cases, a 15% and 30% penetration of non-optimized E85 vehicles was assumed respectively to enter the fleet by 2025. In addition to the E85 use, a 10% ethanol blend in gasoline was also assumed. The assumptions regarding the fleet penetration were the same as used in the vehicle technology section.

[35] An upper estimate of 116 billion gallons of ethanol a year in 2030 was calculated based on USDA/DOE (2005) *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, April 2005. http://www.osti.gov/bridge.

resources are utilized, alternative sources are being developed and utilized as transportation fuels. In addition to renewable sources for fuels, unconventional fuel sources such as extra heavy oil, tar sands, deep water and artic sources, oil shale, gas-to-liquids and coal-to-liquids are being increasingly utilized.[36] Many of these fuels, with higher fuel-cycle emissions of GHGs, could represent a re-carbonization of fuels rather than a de-carbonization of fuels, offsetting the current trend toward lower GHG fuels.[37]

Figure 6: Potential reductions in wedges using a low GHG fuel approach involving ethanol (assuming business as usual vehicle technology improvements).



	"What-If" Fuel Use by 2050:	Wedge Count
🟨	60 billion gallons of ethanol (15 corn ethanol, 45 cellulosic)*	1.4
⬜	90 billion gallons of ethanol (15 corn ethanol, 75 cellulosic)	2.3

* Assumed 10% ethanol blend in gasoline with 15% and 30% penetration of non-optimized E85 to achieve 60 and 90 bgal respectively

Travel Demand Management (TDM) Approaches:

By far the most significant factor to past growth in GHG emissions has been increases in the number of vehicles on the road and in vehicle usage. While the average fuel efficiency has remained virtually unchanged over the past twenty years, the number of passenger vehicles in use has increased by roughly 50% over this time.[38] Each vehicle on the road today is also, on average, being driven more than in the past. Total vehicle travel from passenger vehicles is projected to grow by another 60% between now and 2030, due to the increasing number of

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[36] Greene D.L., Hopson J.L., and Li J. (2006), *Energy Policy*, **34**, 515-531. Information also from Stuart McGill's (2005) presentation, "Exxon-Mobil: Taking on the World's Toughest Energy Challenges" *Goldman Sachs Global Energy Conference 2005*. January 11, 2005.

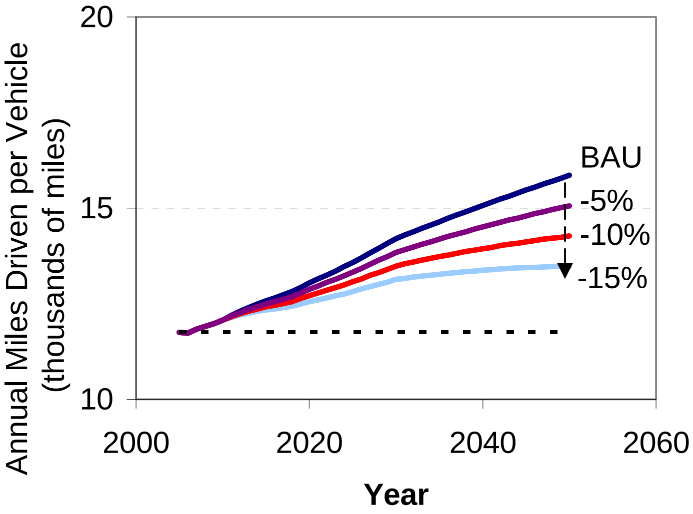
[37] A. Brandt, A. Farrell (2007), "Scraping the bottom of the barrel," forthcoming in *Climatic Change*.

[38] R. Heavenrich (2006), *Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2006*, U.S. EPA, July 2006.

drivers and the mileage driven by each driver.[39] The fuel efficiency of new vehicles, by contrast, is projected to improve by only 12% on average over this time frame. Options that have significant, long-term potential for reducing vehicle activity include such approaches as regional land-use planning, transit-oriented development, shifting travel to more energy-efficient modes, or increasing vehicle occupancy rates.[40] Many of these options also create ancillary benefits from reduced traffic congestion, urban air pollution, and fuel consumption.

As an illustrative example, the impact from reducing total vehicle miles traveled (VMT) incrementally over time is assessed. Although the specific TDM approaches used to achieve this reduction is not modeled here, there have been a number of studies that have evaluated the potential of some of these approaches, albeit on a regional level.[41] Given the long-term nature of many of the approaches (e.g. land use planning), the impact of a gradual reduction in average VMT over a 40 year timeframe is considered (2010-2050). Several, plausible what-if scenarios are shown in Figure 7 whereby total national VMT is reduced by 5%, 10%, and 15% by 2050 versus the 2050 business as usual case. For example, this might occur if average VMT per vehicle grows at a slower rate from now until 2050.

Figure 7: An example is shown where per-vehicle VMT is incrementally reduced from 2010 to 2050, so by 2050 the VMT is 5%, 10%, and 15% below the BAU.



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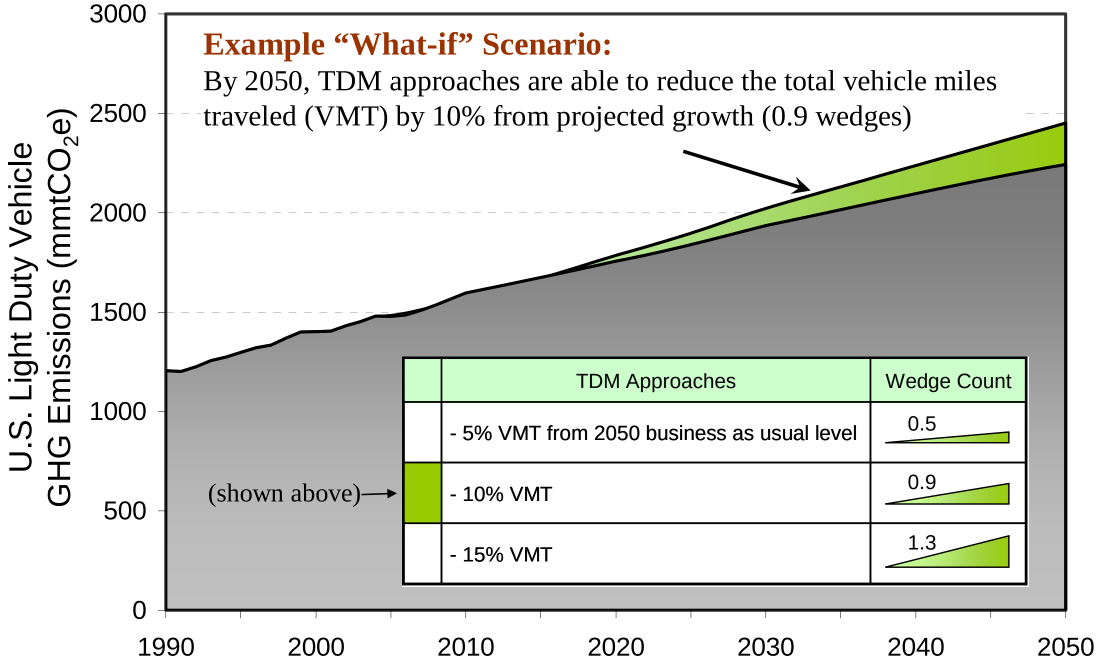
[39] U.S. DOE (2007), *Annual Energy Outlook*. Energy Information Administration. The average miles driven per driver is projected to increase from 13,000 today to nearly 17,000 by 2030.

[40] A shift within a specific mode, such as from SUVs to passenger vehicles, or between two modes (heavy duty truck to locomotive), could also reduce emissions.

[41] See for instance: David L. Greene (1996), *Transportation and Energy*, Eno Transportation Foundation, Washington, D.C.; Center for Clean Air Policy (2007), *CCAP Transportation Emissions Guidebook Part One: Land Use, Transit & Travel Demand Management*; David L. Greene and Andreas Schafer (2003), *Reducing Greenhouse Gas Emissions from U.S. Transportation*, Pew Center on Global Climate Change; EPA (2001), *Our Built and Natural Environments: A Technical Review of the Interactions Between Land Use, Transportation, and Environmental Quality*," January 2001l; ICMA (2006), *Getting to Smart Growth: 100 Policies for Implementation*, International City/County Management Association.

The potential wedge counts from these what-if scenarios are shown in Figure 8. Nearly one wedge is obtained from a 10% reduction in VMT by 2050. The inset in Figure 8 shows the two additional VMT scenarios achieving between 0.5 to 1.3 wedges. Achieving sufficient wedges, as well as a more sustainable transportation system, will likely require that future growth in vehicle travel is offset to some degree.

Figure 8: Reductions of 5%, 10%, and 15% in average vehicle VMT by 2050 versus the business as usual growth.



System Approaches: Combining Vehicle Technologies, Fuels, and TDM

Independently, each approach appears to have the potential to significantly reduce GHG emissions from the transportation sector, but not enough to flatten emissions. When the approaches are combined however, there are even greater opportunities and added flexibility to reduce emissions. If certain technology approaches, such as plug-in hybrid electric vehicles or hydrogen fuel cells, are paired with low GHG sources of electricity, then the GHG and petroleum benefits of the technology dramatically improves. In addition, past experience has shown that absent measures that address growth in transport activity, much of the reductions from technology or fuel approaches can be offset. Blending travel demand management approaches with appropriate technology and fuel approaches would thus yields the largest potential for emissions reductions.

Eight potential system approaches were evaluated for light duty vehicles which combine advanced vehicle technologies, low GHG fuels, and/or TDM. Figure 10a, b, and c show three different, what-if scenarios that achieve 5 wedges from the light duty vehicles. Note that this is more than the 4.3 wedges necessary to flatten passenger vehicle emissions from now to 2050. The three scenarios vary in focus, with the first scenario (a) considering a large deployment of hybrid vehicles, the second (b) focusing on widespread use of optimized E85 vehicles and ethanol, and the last (c) assuming widespread use of electricity and hydrogen as a fuel.

For each scenario shown in Figure 10, the individual approaches are broken down and differentiated by color. The inset tables provide further details of this breakdown. In each of the three scenarios, the sum of the individual approaches adds up to five wedges. A list of additional, illustrative scenarios that can achieve 4, 5, 6, 7, 8, or 9 wedges are presented in the appendix. Considering the potential wedges from other transportation categories would expand the wedge counts.

Several general observations can be made regarding the wedge counts based on these examples and those considered in the appendix. First, a wide range of wedges are possible depending on the type of technologies, fuels, and TDM approaches adopted. Absent any fuel or TDM approaches, up to 3.5 wedges could be achieved if vehicle technologies already observed in the marketplace, such as hybrids and advanced engine ICEs (internal combustion engines), compose the entire market by 2050. To achieve more wedges than this, additional technologies that utilize low-GHG fuels (e.g. biofuels, electricity, hydrogen) or travel demand reduction approaches are necessary.

Second, to obtain 6 or more wedges from the light-duty vehicle category, reliance on all three approaches would likely be needed. For example, an approach that could achieve 7 wedges (example 4 in the appendix) would require a 10% reduction in projected VMT growth by 2050 as well as significant shares of vehicles using either E85 or electricity from low-GHG sources. Third, the upper limit for the light-duty vehicle category appears to be about 9 wedges -- enough wedges to flatten the entire transportation sector's GHG emissions. To reach this maximum wedge count however, aggressive deployment of near-zero emission vehicle technologies and fuels would need to be employed (e.g. cellulosic ethanol, electricity from nuclear or renewable sources).

Expanding the approaches to include other transportation categories would allow for greater flexibility and additional wedges to be obtained.[42] The scenarios shown here and in the appendix are only several examples out of a much larger technical "solution space" which describe all possible combinations. Further development and innovation in vehicle technologies, low GHG fuels, and travel demand management will likely continue to expand this solution space.

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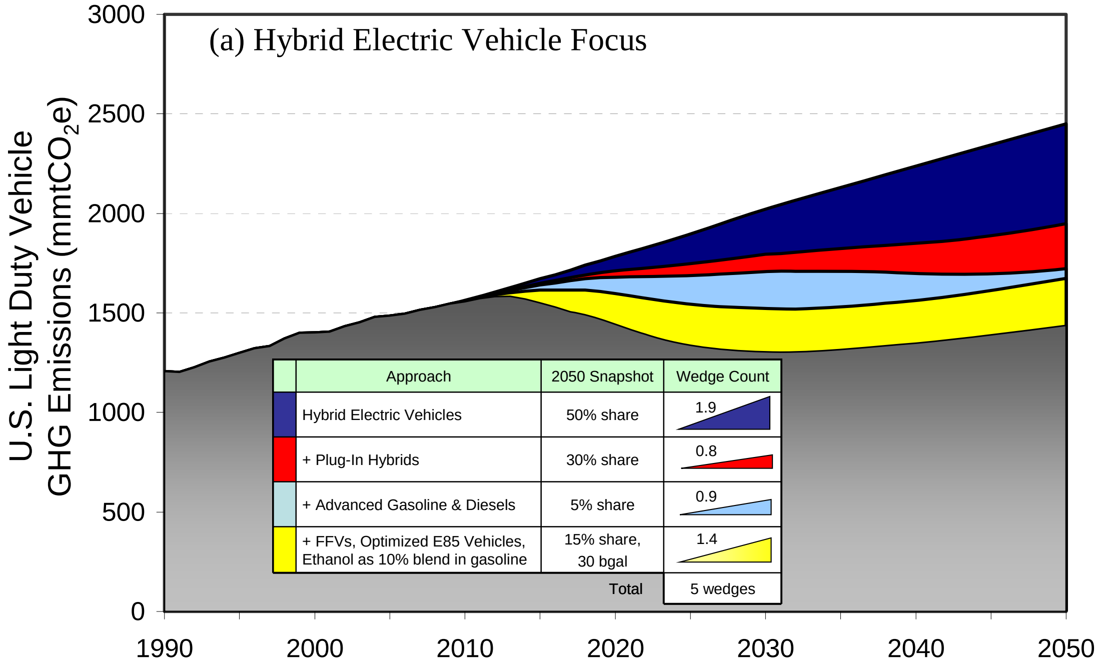
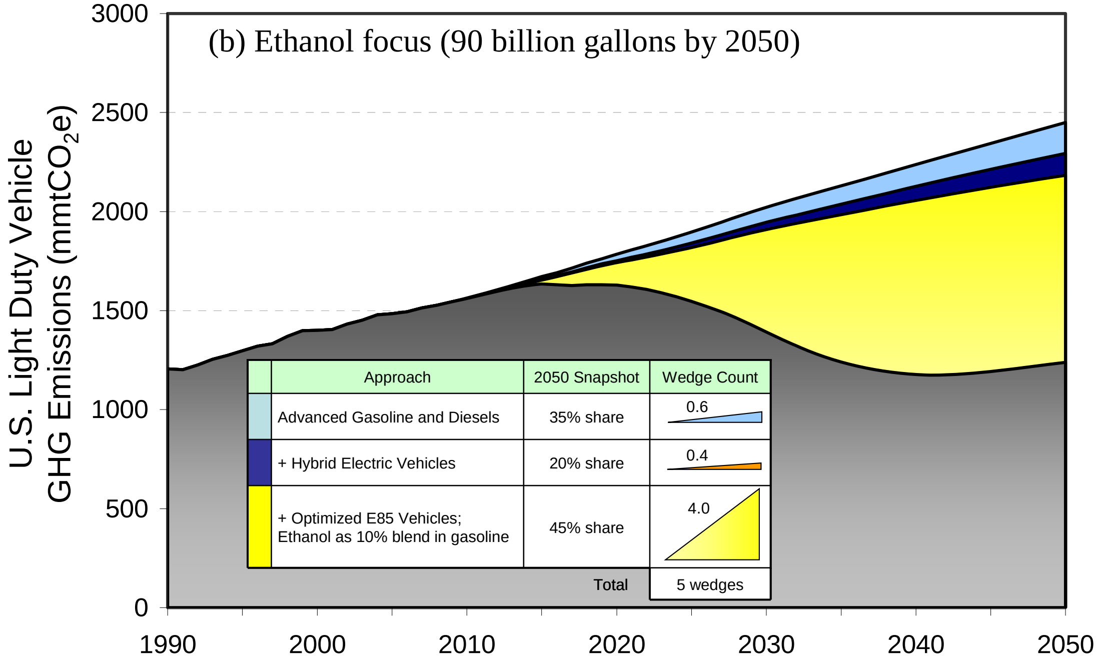
[42] The diversity of transportation categories, ranging from passenger vehicles, heavy-duty freight trucks, to rail, marine, and aviation, suggests that developing scenarios of approaches -- customized for each category – would be more effective in the long-term than focusing on a single, "silver bullet" approach.

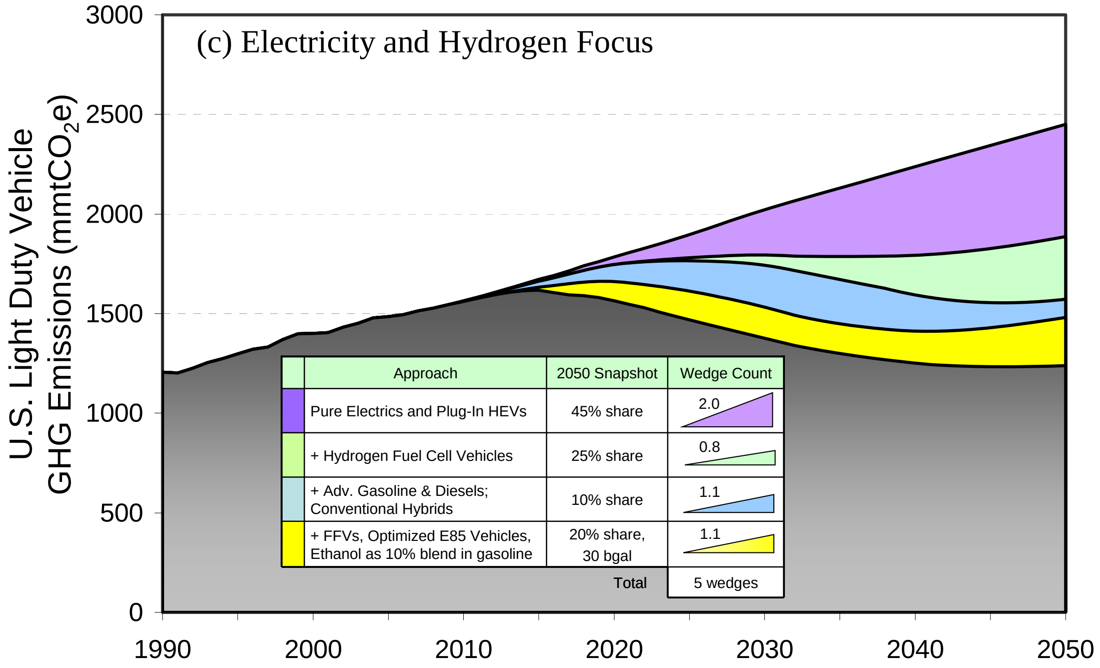
Figure 9: Three examples of system approaches that achieve 5 wedges. Example (a) assumes predominantly hybrid electric vehicles, including plug-in hybrids, by 2050. Example (b) assumes nearly half the vehicles run on E85, equivalent to roughly 90 billion gallons of ethanol by 2050. Example (c) assumes technologies that require electricity (electric vehicles, plug-in hybrids) and hydrogen (fuel cell vehicles) as fuels.



	Approach	2050 Snapshot	Wedge Count
🟦	Hybrid Electric Vehicles	50% share	1.9
🟥	+ Plug-In Hybrids	30% share	0.8
🟦	+ Advanced Gasoline & Diesels	5% share	0.9
🟨	+ FFVs, Optimized E85 Vehicles, Ethanol as 10% blend in gasoline	15% share, 30 bgal	1.4
		Total	5 wedges



	Approach	2050 Snapshot	Wedge Count
🟦	Advanced Gasoline and Diesels	35% share	0.6
🟦	+ Hybrid Electric Vehicles	20% share	0.4
🟨	+ Optimized E85 Vehicles; Ethanol as 10% blend in gasoline	45% share	4.0
		Total	5 wedges



Ancillary Benefits of USTS Wedges

Nearly all the approaches discussed have significant ancillary benefits associated with their respective wedges. One of the largest, ancillary benefits is the reduction in petroleum consumption implied by the scenarios.[43] Since most of the GHG emissions from the U.S. transportation sector are directly due to combustion of carbon-based fossil fuels, the approaches that remove wedges also reduce large amounts of petroleum consumption. For example, the scenarios shown in Figure 10 that reduce by 5 wedges imply a reduction of roughly 7 to 8 million barrels per day (mmbd) in 2050.[44] For comparison, today’s consumption by the entire transportation sector is approximately 14 mmbd.[45] Approaches that reduce GHG emissions in the transportation sector will necessarily reduce petroleum use. However, the converse is not necessarily true. As discussed in the fuel approaches section, simply reducing petroleum dependence through use of unconventional fuels such as tar sands, oil shale, or coal to liquids can negate some of the GHG reductions shown here.

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[43] For a discussion of ancillary benefits (in terms of innovation), see Ashford, Nicholas and George Heaton, Jr. (1983), *Law and Contemporary Problems*, **46** (3), 109-157; Porter, M. and C. van der Linde (1995b), *Journal of Economic Perspectives*, **9** (4), 97-118.

[44] Current gasoline and diesel consumption is roughly 14 mmbd for the entire transportation sector, with light duty vehicles composing more than 60% of the total. By 2050, the light duty vehicle sector is assumed to consume nearly 14 mmbd under the business as usual growth scenario.

[45] U.S. DOE (2007). *Annual Energy Outlook*, Energy Information Administration.

A second ancillary benefit arises from the possible linkages between the utility sector and transportation sector. If the transportation sector is increasingly electrified, low GHG generation utilized in the electricity sector can yield additional dividends in the transportation sector. Third, many of the TDM approaches that reduce travel demand have the additional benefit of reducing congestion. TDM approaches would be particularly valuable in countering any rebound effects associated with improving vehicle fuel efficiency.[46] While not considered here, many of the approaches presented here offer may also offer greater opportunities to reduce criteria emissions. These potential ancillary benefits can also be ascribed to specific wedges.

Conclusion

For the U.S. transportation sector, system approaches that combine advanced vehicle technology, lower GHG fuels, and TDM yield the largest potential and flexibility for lowering both GHG emissions and petroleum use. A number of system approaches exist that can achieve more than the four or five (4 - 5) wedges needed to flatten passenger vehicle emissions. By contrast, individual approaches may reduce emissions moderately but may not result in enough wedges to flatten emissions in the passenger vehicle category.

Since cumulative emissions are the driver for atmospheric CO_2 concentrations, options in the transportation sector are better compared on a cumulative emissions basis rather than an annual reduction basis. A wedge analysis, which compares cumulative emissions, shows that some of the near-term vehicle technology can have as much impact as some of the longer-term technologies, largely because of timing. However, to obtain enough wedges to flatten or reduce below current emission levels, both the long-term options appear necessary in addition to the near-term ones. Both early deployment and long-term development of vehicle, fuel, or TDM approaches appear necessary to obtain sufficient wedges.

Last, if efforts are limited to only passenger vehicles, the task of achieving the nine (9) wedges – the stabilization triangle for the U.S. transportation sector – will be a very challenging one. Incorporating a system approach for commercial trucks, marine vessels, railroads, airplanes, and non-road vehicle sources would yield a larger technical "solution space" that could allow for greater than nine wedges to be achieved.

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[46] The rebound effect was not considered here, as no economic assumptions regarding fuel prices was made for petroleum or any of the alternative fuel. Recent literature suggests that the rebound effect has become smaller, possibly due to rising household incomes relative to fuel expenses. See for example K.A. Small and K.V. Dender (2005), "The effect of improved fuel economy on vehicle miles traveled: estimating the rebound effect using U.S. state date, 1966-2001." *Policy & Economics*, U.C. Energy Institute. Much of the literature also indicates that travel time budgets may be the most important factor for limiting individual vehicle miles traveled.

Appendix:

*Table 1A: Examples of eight different system approaches for passenger vehicles that could achieve up to 4 to 9 wedges. The assumptions used for each what-if example show the vehicle market share, ethanol volumes, and TDM approach assumed in order to achieve the wedges. *Examples 2a, 2b, and 2c are shown in Figure 10 of the text.*

Example System Approaches	Assumptions (2050 snapshot of market share)	Wedge Count (low & high estimates)
1)	80% (adv. gas, adv. diesels, and gas hybrids); 20% (optimized E85) 50 bgal of ethanol (15 corn, 35 cellulosic). No TDM approaches assumed.	**4.0**
2a)*	50% (gasoline and diesel hybrids); 30% (plug-in hybrids); 5% (adv. gas and adv. diesels); 15% (non-optimized E85 and optimized E85) 30 bgal ethanol (15 corn, 15 cellulosic). No TDM approaches assumed.	**4.9 to 5.6**
2b)*	35% (adv. gas and adv. diesels); 20% (gasoline and diesel hybrids); 45% (optimized E85) 90 bgal ethanol (15 corn, 75 cellulosic). No TDM approaches assumed.	**5.0**
2c)*	10% (adv. gas, adv diesels, conventional hybrids); 20% (optimized and adv. optimized E85s); 45% (plug-in hybrids and electric vehicles); 25% (hydrogen fuel cell vehicles) 30 bgal ethanol (15 corn, 15 cellulosic). No TDM approaches assumed.	**4.2 to 6.9**
3)	60% (adv. gas and adv. diesel); 40% (optimized and advanced optimized E85) 80 bgal ethanol (15 corn, 65 cellulosic). -15% reduction in VMT from TDM.	**6.0**
4)	35% (adv. gas, adv. diesel, and gas HEVs); 25% (adv. optimized E85) 40% (plug-in hybrids and electric vehicles) 40 bgal ethanol (15 corn, 25 cellulosic). -10% reduction in VMT from TDM.	**5.2 to 7.0**
5)	10% (gas HEVs); 60% (optimized E85 and adv. optimized E85); 30% (plug-in hybrids and electric vehicles) 80 bgal ethanol (15 corn, 65 cellulosic). -15% reduction in VMT from TDM.	**6.7 to 8.0**
6)	30% (advanced optimized E85); 40% (electric vehicles); 30% (hydrogen fuel cell vehicles) 40 bgal ethanol (15 corn, 25 cellulosic). -15% reduction in VMT from TDM.	**5.2 to 9.0**