Transportation Research Part D 14 (2009) 222–229

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Notes and comments

Greenhouse gas mitigation supply curve for the United States for transport versus other sectors

Nicholas Lutsey *, Daniel Sperling

Institute of Transportation Studies, University of California, Davis, One Shields Ave., Davis, CA 95616, USA

ARTICLE INFO

Keywords:
Climate change
Cost-effectiveness
Energy policy
Vehicle efficiency

ABSTRACT

To compare transportation greenhouse gas mitigation options with other sectors, we construct greenhouse gas mitigation supply curves of near-term technologies for all the major sectors of the US economy. Our findings indicate that motor vehicles and fuels are attractive candidates for reducing GHGs in the near and medium term. Transport technologies and fuels represent about half of the GHG mitigation options that have net-positive benefits – so-called “no regrets” strategies – and about 20% of the most cost-effective options to reduce GHGs to 10% below 1990 levels by 2030.

1. Introduction

Transportation accounts for about 25% of energy-related greenhouse gas (GHG) emissions in the world, but about a third of emissions in the US and other industrialized countries (International Energy Agency, 2008; US Energy Information Administration, 2008), although in some areas, including California, transportation’s carbon footprint can reach 40% of emissions (California Air Resources Board, 2008).

The mitigation of transportation-specific GHG emissions must overcome many, institutional, and infrastructural challenges, including low fuel price elasticity by owners of passenger vehicles; strong demand for personal travel, air travel, and goods transport; and the difficulty of jointly introducing new low-carbon fuels and fuel-efficient propulsion technologies. In addition, petroleum use is becoming more carbon-intense as easily-accessed and higher quality reserves are depleted. Further, technological change can be slowed by the sluggish turnover of vehicles, long product cycles in the automotive industry, large sunk costs in oil infrastructure, and fluctuating and generally low consumer demand for increased vehicle efficiency. Yet calls for transportation sector GHG mitigation are intensifying. US federal energy legislation in 2007 mandated increases in fuel economy standards and an expansion of biofuels for transportation. California and other states have begun to enact vehicle standards, alternative fuel requirements, and travel growth reduction plans under the authority of climate change and clean air laws (see, e.g., Lutsey and Sperling, 2008).

2. Background

Transportation is often considered one of the most difficult sectors for reducing GHG emissions. The high estimated mitigation costs in transportation are due largely to the fuel price inelasticity of consumers in purchasing more efficient vehicles and reducing vehicle use (Small and Van Dender, 2007), the absence of commercially viable substitutes for petroleum, and increasing dependence on personal vehicles for travel. Vehicle purchasers generally are found to implicitly undervalue the

* Corresponding author.
E-mail address: nplutsey@ucdavis.edu (N. Lutsey).

1361-9209/$ - see front matter
doi:10.1016/j.trd.2008.12.002

future energy savings of vehicle efficiency (Greene, 1998; Greene et al., 2008) and often are unaware of, categorically exclude, or erroneously estimate the value of vehicle efficiency in their purchasing practices (Turrentine and Kurani, 2007).

To the extent mitigation costs are relatively high in transportation, it will be difficult to incorporate the sector into prospective carbon markets. In the political arena, it is widely accepted that the politically acceptable limit of carbon charges is about \$10–\$100 per tonne of carbon dioxide equivalent (CO_2e). Trading on the European Union's Emission Trading Scheme in mid-2008 had stabilized at about \$40 per tonne, and analyses of potential US federal climate legislation estimated carbon trading prices would be \$40–\$90 per tonne through 2030 (US Environmental Protection Agency, 2008; Paltsev et al, 2007). Carbon charges of \$40–\$100 per tonne CO_2e equate to \$0.35–\$0.90 per gallon of transportation fuel. Low price demand elasticities, fluctuating oil prices, the undervaluing of energy savings, and the absence of low-carbon fuel alternatives suggest that these levels of carbon prices, whether arrived at via a cap-and-trade program, carbon tax, or other mechanism, would not have much effect on GHG emissions in the transportation sector (Sperling and Gordon, 2009). As Kopp (2007) points out, the particular characteristics of the transport sector result in the conclusion that either the transport sector needs separate policies from economy-wide mechanisms or it is more economically efficient to reduce GHG emissions initially from other sectors, for example, electricity generation. This logic all contributes to the conventional wisdom that transportation sector GHG reductions come at a high cost.

This reasoning is misleading. First, the difficulties in the transportation sector are largely the result of market failures, whereby vehicle users do not bear or act on the full cost of their travel activity and its impacts. These barriers are largely surmountable. The use of incentives and forcing mechanisms can accelerate the development and commercialization of low-carbon fuels and aggressive new standards for vehicle fuel economy and tailpipe GHG emissions can accelerate innovation on the vehicle side and compel consumers to internalize the fuel and GHG implications of their vehicle purchases. These policy actions are already being taken, and are likely to be strengthened. Second, including fuel savings in the analyses offers a truer picture of how transportation technologies compare with options in other sectors. Finally, transportation GHG reduction has particularly large and prominent non-market benefits, including oil security and urban liveability.

Here we examine how and to what extent transportation can contribute to cost-effective GHG reductions in the US economy. We evaluate the cost-per-tonne GHG emission reduction of technological options across economic sectors using comparable assumptions. Our analysis focuses on the two largest components of transportation sector emissions – passenger automobiles and commercial freight trucks – that together make up about 80% of transportation GHG emissions in the US Transportation and non-transportation sectors' mitigation technologies are compared by costs and emission-reduction potential.

3. Transportation mitigation options

We apply a marginal GHG abatement cost curve, or "supply curve," framework to conduct a bottom-up technology-based comparison of strategies to reduce GHG emissions. This analysis encompasses all the major economic sectors (transportation, residential and commercial buildings, industry, agriculture, and electricity) and major technologies used in those sectors. The horizon year is 2030, and the study area is the US We investigated hundreds of near-term technologies across the different sectors. The technologies investigated are either commercially available or in a demonstration phase of development.

Each sector's baseline characteristics for future years are assumed to follow reference trends from the US Energy Information Administration's (2007; 2008) *Annual Energy Outlook*, and the US Environmental Protection Agency (2007a). We investigate alternatives for GHG mitigation for each sector using prior research on each sector and evaluate net cost-effectiveness of GHG mitigation technologies with respect to their incremental cost, energy savings, and GHG emission impact compared to reference technologies. A real discount rate of 7% is used to be consistent with federal public policy-making guidelines (Office of Management and Budget, 1992).[1]

Here, we discuss the results of the analysis, focusing on transportation-specific findings from the wider study. The universe of transport GHG emission mitigation strategies can be grouped into three areas – vehicles, fuels, and travel demand. Table 1 summarizes the transportation GHG mitigation technologies evaluated for cost-effectiveness and provides brief descriptions of the mitigation measures, targeted technologies, and data sources. Both the initial costs of the GHG technologies and the lifetime energy savings are included in the cost-per-tonne metric. All the evaluated strategies are technology-based options for vehicles and fuels, and all assume no utility compromise by vehicle users (e.g., in terms of vehicle size, range, and use).

Travel demand GHG reduction strategies are not included in the analysis. These strategies include: information and communication technologies to provide new and more efficient mobility services (and mobility substitution); incentives and pricing schemes for less-GHG-intense travel; and denser land use patterns that more efficiently sort businesses, residences, and services so as to reduce vehicle travel. Vehicle use-related GHG reductions of 20–40% seem possible over long-term urban planning periods (Ewing et al., 2008). Exclusion of these strategies is because of the difficulty in consistently quantifying their impacts in terms of the chosen cost-effectiveness metric. We simply note that reduced vehicle use offers a promising portfolio of transportation mitigation strategies and would allow for even more reductions from the transportation sector.

[1] For more details of the methodology and of the cost-effectiveness calculations for each technology in each economic sector, see Lutsey (2008).

Table 1
Targeted transportation technologies and GHG reduction potential.

Category	Measure	Emission reduction in 2025[a]	Description of technologies	Cost effectiveness[b] ($2008/tonne CO_2e)	Principal references
Light duty vehicles	Incremental efficiency	20% reduction in rated new vehicle tailpipe CO_2 (g/mi)	Valve (timing and lift), transmission (5-spd auto, AMT), gasoline direct injection (GDI), integrated starter-generator (ISG)	−75 (*−102 to −47*)	Austin et al. (1999), DeCicco et al. (2001), EEA (2001), NECCAF (2004), NRC (2002), NHTSA (2008), Plotkin et al. (2002), Weiss et al. (2000)
	"In-use" vehicle efficiency	10% improvement in "on-road" fuel consumption	Tires (low rolling resistance and inflation education), low friction oil, efficient accessories, efficient A/C	−45 (*−60 to −31*)	ECMT and IEA (2005), CEC and CARB, 2003
	Advanced hybrid gas-electric vehicles	38% reduction in new vehicle tailpipe CO_2 (50% of vehicles)	Full HEV (regenerative braking, battery-electric storage, propulsion from motor(s) and ICE engine)	42 (*−48 to 93*)	An et al. (2001), EPRI (2002), Lipman and Delucchi (2003), NECCAF (2004), Plotkin et al. (2001), Santini et al. (2001)
Commercial trucks	Class 2b efficiency	25% CO_2 g/mi reduction	Variable valve timing and/or lift, improved transmission, gasoline direct injection, integrated starter-generator	−108 (*−135 to −88*)	Austin et al. (1999), DeCicco et al. (2001), EEA (2001), NECCAF (2004), NRC (2002), NHTSA (2008), Plotkin et al. (2002), Weiss et al. (2000)
	Class 3-6 efficiency	40% CO_2 g/mi reduction	Engine efficiency (gasoline direct injection, diesel turbocharging), lower rolling resistance, integrated starter-generator, aerodynamics	−54 (*−95 to −20*)	Vyas et al. (2002), An et al. (2000), Lovins et al. (2004);
	Class 7-8 efficiency	34% CO_2 g/mi reduction	Reduced rolling resistance, engine efficiency, tractor-trailer aerodynamics, lightweight materials, advanced transmission	−87 (*−104 to −63*)	Vyas et al. (2002), Muster (2000), Lovins et al. (2004), Schaefer and Jacoby (2006)
Alternative refrigerant	Alternative refrigerant	Replacement of air-conditioning refrigerant HFC-134a with R-744a (CO_2)	Increased use of CO2 as refrigerant, slight modifications in A/C system (compressors, gaskets, etc.)	67 (*52 to 112*)	CARB (2004), IPCC (2001)
Biofuels	Ethanol fuel substitution	Increase mix of cellulosic ethanol to 13% by volume of gasoline	Agricultural production of cellulosic fuels from both waste and dedicated energy crops	31 (*−21 to 94*)	Wang (2005), US EPA (2005), Farrell and Sperling (2007), Taix (2007), Parker et al. (2008),
	Biodiesel fuel substitution	Increase mix of biodiesel to 5% by volume of diesel	Use of various agricultural, food, and waste industry feedstocks to make biomass-based diesel fuel	51 (*−26 to 128*)	Sheehan et al. (1998), Hill et al. (2007), Farrell and Sperling (2007), Unnasch et al, 2007, US EPA (2007b)
Aviation	Aircraft efficiency	35% reduction in energy intensity	Engine efficiency, aerodynamics, composite materials for weight reduction	−9 (−20 to 17)	Lee (2000), NRC (1992), IPCC (1999), ETSU (1994), CAEP (1995), DCAD, 1997

Notes: To facilitate presentation of all sources, initials of organizations are used in citations.
[a] These technologies are phased in over to 2010–2025 time period.
[b] Includes initial technology costs plus discounted energy costs over lifetime of technology; fuel prices for analysis are based on US Energy Information Administration, 2008; see Lutsey (2008) for full method description.

3.1. Vehicle technology

Available and emerging vehicle efficiency improvements can be categorized into incremental vehicle technologies, advanced technologies, and "on-road" operational practices (Table 1). These distinctions are used in part because policies and regulatory test procedures generally follow them.

Incremental improvements include more efficient combustion (variable valve systems, gasoline direct injection, cylinder deactivation), more efficient transmissions (5- and 6-speed automatic, automated manual, continuously variable), and overall vehicle advances (aerodynamics, light-weighting). GHG emissions rates can be reduced by about 20% with these technologies in new vehicles, as indicated in Table 1. Most studies show that the fuel savings from these incremental improvements more than outweigh the increased vehicle cost, often by a large amount, and even more so if gasoline prices exceed $3 per gallon. Similar incremental technologies also yield substantial GHG reductions and net positive benefits for commercial freight trucks.

Much greater GHG reductions are possible with electric-drive propulsion technologies. These technologies include the increasingly popular hybrid gasoline-electric vehicles, "plug-in" hybrids which use both electricity and petroleum fuels, battery electric vehicles, and hydrogen-powered fuel cell vehicles. Such technologies can cut energy consumption in half and reduce lifecycle GHG emissions, using low-carbon electricity and hydrogen, by 80% or more. However, these advanced technologies generally involve larger initial costs for fuel storage, high development costs, and uncertain learned-out manufacturing costs. Because vehicle turnover is slow and it takes time to deploy a new energy distribution system, it will take time to realize the potential reductions. In the 2030 GHG mitigation scenario for deployment of near-term technologies, hybrid gasoline-electric vehicles are deployed widely, but those powered by electricity and hydrogen are not (a large share of new vehicles may be powered by electricity and/or hydrogen in 2025, but for the entire fleet it would likely be a small share).

The vehicle GHG and fuel economy improvements built into the 2025 scenario are not overly aggressive. For context, the full application of incremental and hybrid gasoline-electric vehicle efficiency measures would result in fuel consumption and GHG reductions similar to those resulting from the fuel economy standards in the US Energy Independence and Security Act of 2007. For this analysis, we examine the prospect of an incremental phase-in of an incremental 20% per-mile fuel consumption improvement, and a phase in of hybrid technology reaching 50% of light duty vehicle sales by 2025. The fuel economy resulting for a new light duty vehicle test-cycle light duty fleet is an average of 38 miles per gallon by 2020, an average fuel economy level somewhat greater than the national standards adopted in 2007, which targets a combined 35 mpg for new cars and light trucks by 2020, but less than the adopted California GHG regulation that equates roughly to 40 mpg.

The third category, "on-road" efficiency improvements, involves a combination of consumer education, vehicle maintenance practices, and "off-cycle" vehicle technologies. Improvements to on-road vehicle efficiency can reduce GHG emissions by up to 20%. Improved maintenance of tires, wheels, oil, and air filters ensure vehicles operate as efficiently as they were designed to do. Technologies in new vehicles that aid driver awareness of fuel use include dashboard instruments that present instantaneous fuel consumption, efficient engine rpm ranges, shift indicator lights, and tire inflation pressure. Another vehicle technology, though not efficiency-related, includes replacing the conventional air conditioning refrigerant, hydrofluorocarbon HFC-134a, with an alternative refrigerant with lower global warming potential gases such as CO_2, refrigerant 744.

3.2. Low carbon fuels

Increased use of low-carbon fuels – or, more accurately, fuels with lower lifecycle GHGs – can greatly reduce overall transportation GHG emissions. Most alternative transportation fuels face a combination of infrastructural and economic barriers. The easiest action is to blend small proportions of biofuels into gasoline and diesel fuel.

The greenhouse gas benefits biofuels from different sources varies greatly. Benefits from sugar cane conversion are substantial, compared to gasoline, but much less for corn. Here we use estimates of 10 to 20% benefits for corn (Wang, 2005; Farrell et al, 2006; Hill et al, 2006) for corn-based ethanol that is slated to enter the transportation fuel stream. Gasoline-substitute biofuels, made from waste materials (agricultural and forestry residues and municipal solid waste) or cellulosic energy crops could have life-cycle GHG benefits of 70–95% (Wang, 2005; TAIX 2007; Farrell and Sperling, 2007). A similar array of biofuel feedstocks can be used to produce biodiesel, which can be mixed into conventional diesel fuel. Studies of the GHG benefits of biomass-based diesel fuels range from 40–80% (Sheehan, 1998; Hill et al., 2006; US Environmental Protection Agency, 2007b, Farrell and Sperling, 2007). All of these referenced studies do not include very recent but uncertain calculations of indirect land use effects (Delucchi, 2004; Searchinger et al, 2008; Fargione et al, 2008). The GHG benefits may prove much smaller or non-existent for farmed fuels as more is learned about these indirect land use effects. But there would be no change in estimates of GHG emissions for fuels made from waste materials and by-product residues from existing processes.

Biofuels in the form of ethanol are already widely blended in the US in proportions up to 10% of gasoline in conventional vehicles, and to a much lesser extent in blends of 85%. Minimal vehicle modification and cost are needed to accommodate high blends of ethanol. In Brazil, most new cars are designed to run on any blend of gasoline and ethanol. Future biofuels may be more similar to gasoline and diesel, in which case almost any blend proportion would be acceptable to vehicles and the fuel distribution system, with no modification.

The biofuels commercialization scenario considered here roughly tracks the requirements of the US *Energy Independence and Security Act of 2007*. We posit an increase to 32 billion gallons of biofuels, mostly ethanol, by 2022, with the vast majority of new additions after 2015 coming from cellulosic feedstocks (US Environmental Protection Agency, 2005; Parker et al, 2008). Assuming GHG benefits of 16% from corn-based ethanol, 85% from cellulosic and waste ethanol feedstocks, and 61% for biodiesel, transportation fuels' carbon intensity is reduced by 11% in 2020 and 16% in 2030 in the scenario.

There are also other transport fuel options systems involving wholly different fuels and fuel distribution systems that can greatly impact GHG emissions. There are fossil fuels with marginally lower-GHG emissions, such as compressed natural gas and liquefied petroleum gases, as well as those next-generation fuels from oil shale, coal, and tar sands that would have much higher GHG emissions unless the carbon from such fuels is captured and stored. Large potential GHG benefits can be achieved by powering vehicles with energy carriers like hydrogen with fuel cells and electricity with "plug-in" hybrids and battery electrics. Electric-drive vehicles, powered by low-carbon versions of these fuels made with biomass, wind, and nuclear energy, or with fossil energy coupled with carbon capture and storage could yield greater GHG reductions than vehicle efficiency improvements alone. For this more near-term cost-effectiveness analysis, none of these more advanced options are included because of their uncertain costs and their low likelihood of making up a substantial portion of the vehicle fleet over our time frame.

4. Supply curve of GHG mitigation options for transportation and other sectors

As indicated above, this paper addresses GHG mitigation across all major economic sectors. The non-transportation actions include electric power sector actions (e.g., coal to natural gas shift, carbon capture and sequestration, and increased nuclear power and renewable electricity), more energy-efficient buildings (including improvements in appliances, lighting, and air conditioning), industrial actions (e.g. in the cement and chemical steel sectors), and agricultural emission-reduction technologies (Lutsey, 2008). The portfolio of technologies includes technologies that could deliver major near-term GHG emission reductions within the US economy by 2025. Cost and performance data are derived from the literature. All identified technologies are available at least in small quantities or being demonstrated in pilot projects. Over a 100 GHG mitigation technologies are included in the analysis, with data from several hundred sources. GHG mitigation strategies involving behavioral change are excluded because of the difficulty in establishing directly comparable cost estimations.

The GHG mitigation technology strategies – in the transportation and other sectors – are ranked using a "supply curve" framework. The sources for reference data and the economic assumptions for each sector are the same as those mentioned above for the transportation sector. The technologies' net cost-effectiveness values are calculated, and the options are ordered (from least to most cost) and they are combined to construct a marginal GHG abatement curve. The curve, shown in Fig. 1, demonstrates the cumulative amount of emission reduction at or below a given GHG reduction cost-effectiveness, or cost-per-tonne CO_2-equivalent emission reduction. The figure shows a supply curve of GHG mitigation actions for all sectors of the US economy, with transportation-specific measures highlighted. 2030 was chosen for the x-axis of the curve because it was the time at which most of the technologies were fully deployed and their GHG impacts would mostly be realized.

All new technologies, fuels, and technology practices were phased in from 2010 to 2025 and then frozen at that level (see Table 1 for details on transportation). Deployment of the equipment (including vehicles and appliances) was assumed to follow logistical S-shaped curves from 2010 through 2025 with no accelerated change in the retirement of older equipment. More infrastructure-intensive GHG reduction technologies e.g. involving aircraft, alternative fuel plants, power plants have slower penetration rates, due to their natural retirement of older equipment.

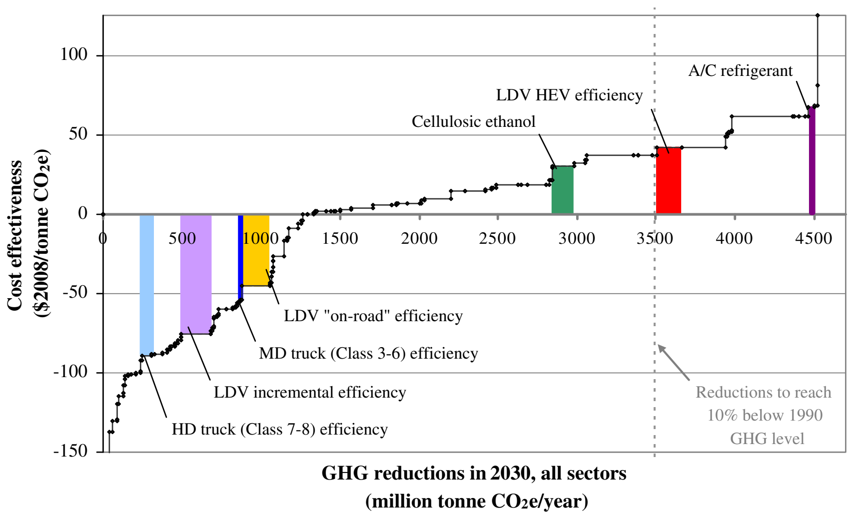

Fig. 1. Marginal cost effectiveness curve of GHG reduction technologies, with transportation technologies highlighted.

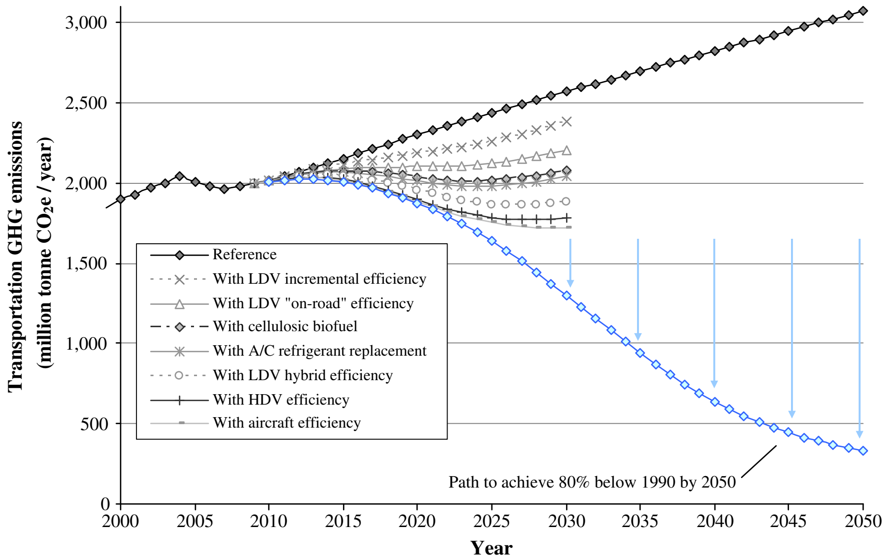

Fig. 2. Transportation sector GHG emissions after technology GHG mitigation options.

The costs in Fig. 1 include the additional technology purchase costs as well as reduced energy operating costs. As shown in the figure, many of the transportation GHG mitigation options are comparatively attractive. Transportation technologies represent approximately half of the "no regrets" GHG mitigation options with net-positive-benefits (i.e., those less than \$0/tonne CO_2e). Of all of the least-cost GHG mitigation options from all sectors that would be needed to reach the benchmark of 10% below the 1990 GHG level by 2030, about 18% of the GHG emission reduction would come from the transportation sector. This net-cost-accounting analysis is similar to that used in the mitigation study by McKinsey & Company (Creyts et al, 2007) that used similar methods and reference data. The results most closely resemble the GHG abatement curve of the McKinsey "high-range" case, which indicates 8% greater GHG reduction potential in 2030 at CO_2e prices below \$50/tonne than this analysis.

5. Role of near-term technologies and fuels in attaining climate goals

If all the transportation technology and fuel changes included in Fig. 1 were deployed, as shown in Fig. 2, they would bring GHG emissions of the transportation sector below 2000 levels by about 2030. If larger reductions are desired to stabilize the climate, another round of more aggressive changes are needed. If one posits that GHG reductions in transportation should be roughly comparable in percentage to other sectors, then far more efficient vehicles and lower carbon fuels would need to be introduced on a massive scale to attain climate stabilization goals of 50–80% fewer GHG emissions. There would also likely have to be significant reductions from projected vehicle use. Car, truck, and aviation use is expected to grow 1.7–2% per year in the US (US Energy Information Administration, 2008), which if realized would offset improvements in vehicle and fuel technologies and make it more difficult and expensive to achieve large overall reductions. Significant reductions in vehicle use would ease the difficulty and cost of achieving large GHG reductions. In summary, achievement of 2050 climate change stabilization goals will almost surely require both substantial reductions in per capita travel and a new round of more efficient and low-carbon vehicles and fuels.

6. Conclusion

This analysis shows that many transportation strategies are cost-effective when compared directly with options in other economic sectors under consistent assumptions. Many transportation efficiency measures generate cost savings over the life of the energy-efficiency equipment investment, when future energy savings are calculated using normal discount factors. We find that such measures within the transportation sector represent half of all of the "no-regrets" options that are available in all the economic sectors. Looking at available near-term technologies from all sectors, GHG emissions in the US could be reduced 10% below 1990 levels by 2030 at cost-effectiveness levels below \$40 per tonne CO_2e. Transportation technologies for vehicles and fuels represent about 20% of these early, highly cost-effective GHG mitigation options.

This finding of the relative attractiveness of transportation options is robust; it assumes oil prices of \$60-per-barrel and excludes co-benefits, such as improved energy security due to decreased petroleum usage. If travel demand reduction measures were included, another increment of reductions would be achieved. These findings are counter to the conventional wisdom that often ignore energy cost benefits and emphasize near-term resistance to the broad suite of technology and behavioral options in the transportation sector.

Although near-term vehicle and fuel technologies are attractive and compelling, they are inadequate to achieve long-term climate goals, such as an 80% reduction in climate emissions by 2050. Achieving deeper long-term emission cuts within the transportation sector will almost surely require a substantial reduction in travel demand, extensive decarbonization of transport fuels, and nearly universal deployment of near-zero GHG emission vehicle technologies, such as plug-in hybrid vehicles, electric vehicles, and hydrogen fuel cell vehicles. Initiatives to reduce vehicle usage, decarbonize fuels, and deploy advanced vehicle technologies will require sustained efforts over decades by industry, government, and consumers.

Acknowledgements

The authors are grateful for funding from the University of California, Davis Sustainable Transportation Center, established through a University Transportation Centers Program grant of the US Department of Transportation and the California Department of Transportation. The authors appreciate the critical feedback from Joan Ogden, Tim Lipman, and anonymous peer reviewers.

References

An, F., Stodolsky, F., Vyas, A., Cuenca, R., Eberhardt, J.J., 2000. Scenario analysis of hybrid Class 3-7 heavy vehicles. Society of Automotive Engineers. 2000-01-0989.

An, F., DeCicco, J., Ross, M., 2001, Assessing the Fuel Economy Potential of Light Duty Vehicles, SAE paper 2001-01FTT-31, Society of Automotive Engineers, Warrendale.

Austin, T.C., Dulla, R.G., Carlson, T.R., 1999. Alternative and Future Technologies for Reducing Greenhouse Gas Emissions form Road Vehicles. Prepared for Committee on Road Vehicle Technology and Fuels, Natural Resources Canada, Sierra Research, Inc., Sacramento.

California Air Resources Board (CARB), 2004. Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Gas Emissions from Motor Vehicles, <http://www.arb.ca.gov/regact/grnhsgas/isor.pdf>. Accessed in January 2008, October 22, 2005. August 6.

California Air Resources Board (CARB), 2008. Climate Change Draft Scoping Plan: A Framework for Change, CARB Sacramento.

California Energy Commission (CEC) and California Air Resources Board (CARB), 2003. Reducing California's Petroleum Dependence. Appendix C, Attachment B, <http://www.energy.ca.gov/fuels/petroleum_dependence/documents/Report>. Publication # 600-03-005SD, May.

Committee on Aviation Environmental Protection (CAEP), 1995. Report of the Emissions Inventory Sub Group. International Civil Aviation Organization (as cited in Lee, 2000).

Creyts, J., Derkach, A., Nyquist, S., Ostrowski, K., Stephenson, J., 2007. Reducing US Greenhouse Gas Emissions: How Much at What Cost? Executive Report. McKinsey & Company. December.

DeCicco, J., An, F., Ross, M., 2001. Technical Options for Improving the Fuel Economy of US Cars and Light Trucks by 2010–2015. American Council for an Energy-Efficient Economy, Washington, DC. April.

Delucchi, M.A., 2004. Conceptual and Methodological Issues in Lifecycle Analyses of Transportation Fuels. Institute of Transportation Studies, University of California, Davis. UCE-ITS-RR-04-4.

Dutch Civil Aviation Department (DCAD), 1997. Aviation Emissions and Evaluation of Reduction Options (as cited in Lee, 2000).

Energy and Environmental Analysis, Inc. (EEA). 2001. Technology and Cost of Future Fuel Economy Improvements for Light-Duty Vehicles. Draft Final Report, Prepared for the National Academies National Research Council, Washington DC.

Energy Technology Support Unit (ETSU), 1994. An Appraisal of UK Energy Research, Development, Demonstration and Dissemination, FTSU, London.

European Conference of Ministers of Transport and International Energy Agency (ECMT and IEA), 2005. Making Cars More Fuel Efficient: Technology for Real Improvements on the Road, Organisation for Economic Co-operation and Development, Paris.

Ewing, R., Bartholomew, K., Winkelman, S., Walters, J., Chen, D., 2008. Growing Cooler: The Evidence on Urban Development and Climate Change. Urban Land Institute, Berlin.

Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land clearing and the biofuel carbon debt. Science 319, 1235–1238.

Farrell, A.E., Plevin, R.L., Turner, B.T., Jones, A.D., O'Hare, M., Kammen, D.M., 2007. Ethanol can contribute to energy and environmental goals. Science 311 (5760), 506–508.

Farrell, A., Sperling, D., 2007. A Low Carbon Fuel Standard for California: Part 1: Technical Analysis. Institute of Transportation Studies, University of California, Davis. UCD-ITS-RR-07-07.

Electric Power Research Institute (EPRI), 2002. Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles. EPRI 10006892, Palo Alto.

Greene, D.L., 1998. Why CAFE worked. Energy Policy 26, 595–614.

Greene, D.L., German, J., Delucchi, M.A., 2008. Fuel economy: The case for market failure. In: Cannon, J., Sperling, D. (Eds.), Reducing Climate Impacts in the Transportation Sector. Springer, Amsterdam.

Hill, J., Nelson, E., Tilman, D., Polasky, S., Tiffany, D., 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proc. Natl. Acad. Sci. 103, 11206–11210.

Kopp, R.J., Policies to reduce CO_2 emissions from the light-duty vehicle fleet. In: Kopp, R.J., Pizer W.A. (Eds.), Assessing US Climate Policy Options. Resources for the Future, November.

Intergovernmental Panel on Climate Change (IPCC), 1999. IPCC Special Report on Aviation and the Global Atmosphere, IPCC, Montreal.

Intergovernmental Panel on Climate Change (IPCC), 2001. Climate Change 2001: Working Group III: Mitigation 3.8.6 Technological and Economic Potential. <http://www.grida.no/climate/ipcc_tar/wg3/>.

International Energy Agency (IEA), 2008. Energy Technology Perspectives: Scenarios and Strategies to 2050. IEA, Paris.

Lee, J.J., 2000. Historical and Future Trends in Aircraft Performance, Cost, and Emissions. Master's thesis, Massachusetts Institute of Technology.

Lipman, T.E., Delucchi, M.A., 2003. Hybrid-Electric Vehicle Design Retail and Lifecycle Cost Analysis. Institute of Transportation Studies, Davis. UCD-ITS-RR-03-8.

Lovins, A.B., Datta, E.K., Bustnes, O.-E., Koomey, J.G., Glasgow, N.J., 2004. Winning the Oil Endgame: Innovation for Profits Jobs and Security. Rocky Mountain Institute, Snowmass.

Lutsey, N., 2008. Prioritizing Climate Change Mitigation Alternatives: Comparing Transportation Technologies to Options in Other Sectors. Ph.D. Dissertation, UCD-ITS-RR-08-15. Institute of Transportation Studies, University of California, Davis.

Lutsey, N., Sperling, D., 2008. America's bottom-up climate change mitigation policy. Energy Policy 36, 673–685.

Muster, T., 2000. Fuel Savings Potential and Costs Considerations for US Class 8 Heavy Duty Trucks through Resistance Reductions and Improved Propulsion Technologies until 2020. Massachusetts Institute of Technology. EL 00-001.

National Research Council (NRC), 2002. Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards. National Academy Press, Washington, DC.

National Highway Traffic Safety Administration (NHTSA), 2008. Preliminary Regulatory Impact Analysis: Corporate Average Fuel Economy for MY 2011-2015 Passenger Cars and Light Trucks. US Department of Transportation, Washington, DC.

National Research Council (NRC), 1992. Aeronautical Technologies for the Twenty-First Century.

Northeast States Center for a Clean Air Future (NECCAF), 2004. Reducing Greenhouse Gas Emissions from Light-Duty Motor Vehicles. NECCAF, Boston.

Paltsev, S., Reilly, J., Jacoby, H., Gurgel, A., Metcalf, G., Sokolov, A., Holak, J., 2007. Assessment of US Cap-and-Trade Proposals. Massachusetts Institute of Technology. Report 146.

Parker, N., Tittmann, P., Hart, Q., Lay, J., Cunningham, J., Jenkins, B., Nelson, R., Skog, K., Milbrandt, A., Gray, E., Schmidt, A., 2008. Strategic Development of Bioenergy in the Western States: Development of Supply Scenarios Linked to Policy Recommendations Task 3: Spatial Analysis and Supply Curve Development. University of California, Davis.

Plotkin, S., Duleep, K.G., Greene, D., 2002. Examining the Potential for Voluntary Fuel Economy Standards in the United States and Canada. Argonne National Laboratory, Argonne. ANL/ESD/02-5.

Plotkin, S., Santini, D., Vyas, A., Anderson, J.L., Wang, M., He, J., Bharathan, D., 2001, Hybrid Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results, Argonne National Laboratory Report ANL/ESD/02-2, Argonne.

Santini, Danilo, J., Vyas, A.D., Anderson, J.L., An, F., 2001. Estimating Trade-Offs Along the Path to the PNGV 3X Goal. 80th Annual Meeting of the Transportation Research Board, Washington, DC.

Schaefer, A., Jacoby, H.D., 2006. Vehicle technology under CO2 constraint: a general equilibrium analysis. Energy Policy 34, 975–985.

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., Shapouri, H., 1998. Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus: Final Report, NREL/SR-580-24089, Washington, DC.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.-H., 2008. Use of US cropland for biofuels increases greenhouse gases through emissions from land use change. Science 319, 1238–1240.

Small, K., Van Dender, K., 2007. Fuel efficiency and motor vehicle travel: the declining rebound effect. Energy J. 28, 25–51.

Sperling, D., Gordon, D., 2009. Two Billion Cars: Driving Toward Sustainability. Oxford University Press, Oxford.

TAIX, L.L.C., 2007. Full Fuel Cycle Assessment Well to Wheels Energy Inputs Emissions and Water Impacts. Sacramento.

Turrentine, T.S., Kurani, K.S., 2007. Car buyers and fuel economy? Energy Policy 35, 1213–1223.

US Environmental Protection Agency (US EPA), 2005. Greenhouse Gas Mitigation Potential for US Forestry and Agriculture. EPA 430-R-05-006, Washington, DC.

US Environmental Protection Agency (US EPA), 2007. Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2005. EPA-430-R-07-002, Washington, DC.

US Environmental Protection Agency (US EPA), 2007b. Greenhouse Gas Impacts of Expanded Renewable and Alternative Fuels Use. EPA-420-F-07-035, Washington, DC.

US Environmental Protection Agency (US EPA), 2008. EPA Analysis of the Lieberman-Warner Climate Security Act of 2008. USEPA, Washington, DC.

US Energy Information Administration (US EIA), 2007. Annual Energy Outlook 2007. US Department of Energy Report DOE/EIA-0383(2007), Washington, DC.

US Energy Information Administration (US EIA), 2008. Annual Energy Outlook 2008 (Early Release). US Department of Energy Report DOE/EIA-0383(2008), Accessed in January 2008.

Vyas, A., Saricks, C., Stodolsky, F., 2002. The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks. Argonne National Laboratory US Department of Energy, Washington, DC. ANL/ESD/02-4.

Wang, M., 2005. Updated Energy and a Greenhouse Gas Emission Results of Fuel Ethanol. In: 15th International Symposium on Alcohol Fuels, San Diego.

Weiss, Malcolm, A., John, B., Heywood, Elisabeth M. Drake, Andreas Schafer, and Felix F. AuYeung. 2000. On the Road in 2020: A Life-Cycle Analysis of New Automobile Technologies. Energy Laboratory Report # MIT EL 00-003, Massachusetts Institute of Technology.