Global Climate Change and the Unique Challenges
Posed by the Transportation Sector

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JJ Dooley, CA Geffen and JA Edmonds
Joint Global Change Research Institute
Battelle, Pacific Northwest National Laboratory

Abstract

Addressing the challenges posed by global climate change will eventually require the active participation of all industrial sectors and consumers on the planet. To date, however, most efforts to address climate change have focused on only a few sectors of the economy (e.g., refineries and fossil-fired electric power plants) and a handful of large industrialized nations. While useful as a starting point, these efforts must be expanded to include other sectors of the economy and other nations. The transportation sector presents some unique challenges, with its nearly exclusive dependence on petroleum-based products as a fuel source coupled with internal combustion engines as the prime mover. Reducing carbon emissions from transportation systems is unlikely to be solely accomplished by traditional climate mitigation policies that place a price on carbon. Our research shows that price signals alone are unlikely to fundamentally alter the demand for energy services or to transform the way energy services are provided in the transportation sector. We believe that a technological revolution will be necessary to accomplish the significant reduction of greenhouse gas emissions from the transportation sector.

Introduction and Motivation

The appropriate place to begin any analysis of efforts to address climate change is the 1992 United Nations Framework Convention on Climate Change (UNFCCC). This convention has been ratified by more than 194 nations and was ratified by the U.S. Senate in the fall of 1992.[1] The UNFCCC commits its signatories to undertake actions to achieve the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[2]

The focus on stabilizing *concentrations* of greenhouse gases as opposed to leveling out annual emissions is important for a number of reasons. First of all, it is the rising cumulative concentrations of greenhouse gases in the atmosphere that will determine the extent and magnitude of adverse environmental damage resulting from climate change. The avoidance of these environmental impacts is the primary reason for attempts to

[1] United Nations Framework Convention on Climate Change official website. http://unfccc.int/resource/conv/ratlist.pdf Last updated September 24, 2002.

[2] United Nations Framework Convention on Climate Change, Article II. It is important to note that the Framework Convention on Climate Change is silent on what would be a "safe" atmospheric concentration for greenhouse gases and that these levels remain a subject of debate.

control greenhouse gas emissions. Second, as demonstrated by Wigley, Richels and Edmonds (1996)[3] and more recently Edmonds (2002)[4], stabilizing atmospheric concentrations will require that net emissions of CO_2 eventually go to zero. The implication of this is that eventually (and this could unfold over the course of hundreds of years) the entire *global* economy must approach net zero emissions of CO_2. This paper focuses on the challenges posed by moving the global transportation system and all associated infrastructures from its current state to a future state of net zero emissions.

The Energy Challenge Posed by Climate Change

A fundamental transformation of the way in which we obtain and use energy will be required if we are to achieve the stabilization goal articulated in the UNFCCC. The magnitude of the change that will be required to accomplish this transformation of the global energy system is sometimes not well understood. Efforts over the past decade to negotiate the Kyoto Protocol, which requires signatories to reduce emissions and hold them at a specified level relative to a 1990 baseline for the period 2008-2012, have focused much attention on ways in which energy might be conserved or how countries or regions might increase the market penetration of renewable energy systems. While these are truly beneficial and worthwhile activities, the scope and scale of the climate change problem suggests that these alternatives alone are insufficiently robust to put the global economy on a pathway to zero net emissions. Additional technological alternatives must be found to meet our future energy needs.

Fossil fuels remain abundant and therefore inexpensive (relative to alternative energy sources) and can play a significant role in future energy systems if their associated technologies for extraction, transformation and use continue to advance. Table 1 presents data on the total estimated resource availability of various classes of fossil fuels. Whether these fossil fuels will all be exploited for their energy is a function of the cost of finding and acquiring these resources and bringing them to market and the cost of alternative energy sources. Ongoing research in both the public and private sectors may further increase the potential for the economic and safe use of currently unavailable resources, such as methane hydrates. For the purpose of the present analysis, however, what is important is the magnitude of these potential fossil fuel energy resources.

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[3] Wigley, T.M.L., Richels, R., & Edmonds, J. (1996) Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. Nature, 379, 240-243.

[4] Edmonds, J. 2002. "Atmospheric Stabilization: Technology Needs, Opportunities, and Timing," in U.S. Policy on Climate Change: What Next? J.A. Riggs (ed.), The Aspen Institute, Aspen, CO. pp. 46-71.

Table 1: Carbon Content of Fossil Fuel Energy Resources Potentially Available After 1990 (PgC, petagrams of carbon)[5]

Energy Form	Resource Base	Range of Resource Base Estimates	Additional Occurrences	Resources plus Additional Occurrences
Conventional Oil	170	156-230	200	156-430
Conventional Gas	140	115-240	150	115-390
Unconventional Gas	410	--	340	750
Coal	3,240	--	3,350	3,240-6,590
Tar Sands & Heavy Oils	720	600-800	--	600-800
Oil Shale	40,000	--	--	40,000
Gas Hydrates	--	--	12,240	12,240

Now compare the carbon stored in these various fossil energy reservoirs with calculations from Wigley, Richels and Edmonds (1996) for the cumulative allowable emissions from 1990 to 2100 associated with stabilizing CO_2 concentrations at various levels (Table 2). The carbon present in the world's oil and gas resource base, when amplified by that present in other fossil fuel resources (coal and unconventional sources) is many times larger than the allowable carbon emissions for any of the CO_2 stabilization targets shown in Table 2. Given that advances in science and technology continue to make previously unattainable fossil fuel reserves economically viable, it appears unlikely that the world will run out of fossil fuels and that the challenge posed by climate change will go away or be self-correcting. In the absence of policies to limit cumulative carbon emissions, technology developments, driven purely by market forces, could enable fossil fuels to remain the core of the global energy system throughout the century ahead. Without a way to capture and dispose of the associated carbon from the use of fossil fuels, such a future would also mean an associated growth in carbon emissions.

[5] Table taken from J. A. Edmonds, H. M. Pitcher, and S. H. Kim. THE LONG-TERM SHAPE OF GLOBAL ENERGY SYSTEMS. Pacific Northwest National Laboratory. PNNL-13733. Washington, DC. November 2001.

Table 2: Cumulative Carbon Emissions 1990 to 2100 Under WRE CO_2 Stabilization[6]

Concentration Ceiling	Cumulative Emissions 1990 – 2100 (PgC)
350 ppmv	363
450 ppmv	714
550 ppmv	1,043
650 ppmv	1,239
750 ppmv	1,348

A Global Energy Technology Strategy

In 2001, researchers at Battelle and its collaborating research partners released a groundbreaking study that was supported by a broad coalition of public, private and non-governmental entities. The study, the Global Energy Technology Strategy[7], was released at the Sixth Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change. This research established the incredible power of a diversified portfolio of advanced energy technologies for addressing the challenge of climate change. Technological advances were shown to have a tremendous potential for significantly reducing the costs of stabilizing atmospheric concentrations of greenhouse gases, and expanding energy options globally. Achieving this potential, however, will require investments in emerging technologies, such as carbon capture and disposal, as well as continued improvements in the price and performance of currently commercial technologies. A long-term technology portfolio must also have the flexibility to address regional differences in geography, energy resources, technical capacity, culture, institutions and economic systems to be successful on a global scale.

The study also highlighted the importance of immediate attention to the development of new technologies, given the long timeframes associated with their development and deployment, and the generally slow pace of retirement of existing capital stock. Technology options that might require radically new infrastructures (for instance, a hydrogen based economy) may be expected to take even longer to establish. In any case, both fossil and non-fossil fuels will be important in a future energy system. Energy conservation, nuclear, solar, sustainable commercial biomass, hydroelectricity, wind and other renewable energy forms can provide means to meet our future energy needs without directly emitting carbon. But, so too can fossil fuels, if the associated carbon can be captured and disposed of in reservoirs that permanently isolate CO_2 from the atmosphere. Carbon capture and disposal technology holds great promise as a potential solution, but will require a significant investment in R&D and technology development before it can become a commercial reality. These technologies may well serve an important role in a

[6] Table taken from J. A. Edmonds, H. M. Pitcher, and S. H. Kim. THE LONG-TERM SHAPE OF GLOBAL ENERGY SYSTEMS. Pacific Northwest National Laboratory. PNNL-13733. Washington, DC. November 2001.

[7] JA Edmonds, et.al. Global Energy Technology Strategy. November 2001. Washington, DC. Battelle.

future global energy system; however, they must be linked with new vehicle and engine designs, and associated infrastructures, to serve the specific needs of the transportation sector. The magnitude of the contribution that the transportation sector makes to global greenhouse gas emissions and mechanisms to begin a path toward reduction are described in the next section of this paper.

Transportation Sector Emissions and The Efficacy of Carbon Taxes

Motor vehicles are the major form of transportation in the developed world, delivering over 90% of all passenger miles in Europe, Canada and the US, and almost 60% in Japan. Freight shipments by truck average 60-70% of all ton-miles in Europe and the US and 40% in Japan.[8] The primary source of energy for the transportation sector is fossil fuels – principally petroleum products. In OECD countries, motor vehicles (passenger and freight combined) account for over 80% of all transportation related energy consumption. A recent report from the OECD predicts that the total motor vehicle stock in developed countries will increase from 552 million vehicles in 1998 to approximately 730 million vehicles in 2020, a total growth of 32%.[9] Growth in population and level of affluence is expected to drive significant growth in motor vehicle production and use in emerging economies as well. The demand for freight and passenger transport (primarily by road) in most developing and transition economies is growing 1.5-2 times faster than their gross domestic product.[10] Worldwide, over 1billion motor vehicles are predicted to be on the road by 2025.[11] The projected growth in transportation demands highlights the magnitude of the challenges ahead if we are to effectively address the energy needs of this sector and at the same time eliminate carbon emissions.

The transportation sector currently accounts for approximately one-third of US CO_2 emissions.[12] This large share of US greenhouse gas emissions implies that sooner or later emissions from transportation systems will need to be controlled if we are to make progress on achieving the stabilization goal of the UNFCCC. Projected increases worldwide in motor vehicle use lend additional urgency to addressing this problem. Government regulation has traditionally had a major impact on the development and adoption of new technology for environmental or safety purposes in the automotive industry. Proposed policies under discussion for addressing carbon emissions, however, are primarily focused on using price signals to energy conservation or spur innovation of lower CO_2 emitting technologies. Pricing policies are based on the premise that if the price of gasoline were to significantly increase, for example by incorporating the environmental externality into the price via a carbon tax, then people would significantly change their driving habits. Emissions would essentially be reduced through energy

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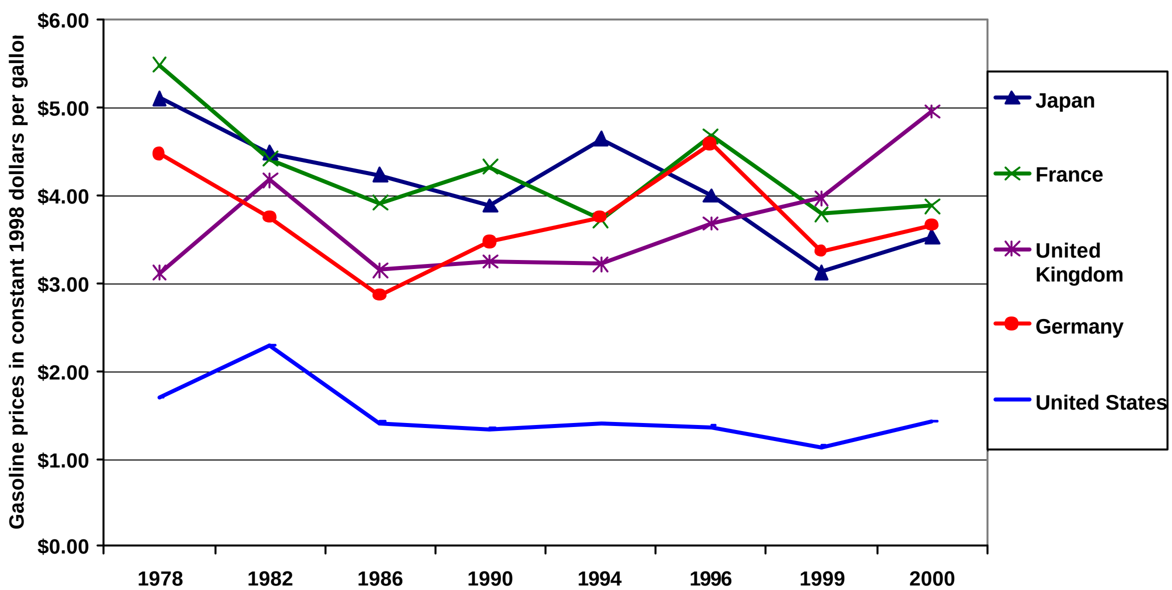
[8] U.S. Department of Transportation, Bureau of Transportation Statistics, G-7 Countries: Transportation Highlights, BTS 99-01, Washington D.C., November 1999.
[9] Organisation for Economic Co-Operation and Development (OECD), OECD Environmental Outlook, OECD 2001.
[10] Lester Brown, et al., State of the World 2001, Worldwatch Institute, W.W. Norton & Company, Inc., New York, p. 106.
[11] United Nations Environment Programme, Global Environmental Outlook, 2000, Earthscan Publications Ltd., London, UK, 2000., p. 13.
[12] U.S. Department of Energy, Energy Information Administration, Emissions of Greenhouse Gases in the United States, 1999, Washington, DC, October 2000.

conservation, use of mass transit, or other energy-saving options. We have conducted a thought experiment as a part of our work in this area to evaluate the effects of such a policy. This example is designed to shed light on the efficacy of carbon taxes[13] in reducing emissions of greenhouse gas emissions in the transportation sector.

Figure 1 reports gasoline prices for selected large OECD nations. As can be seen, Japan, France, the United Kingdom and Germany have all consistently had gasoline prices that are significantly above those found in the United States for the past two decades. In fact the gasoline prices in these other countries have consistently exceeded those found in the United States by anywhere from $1.50 to $3.50 per gallon. When converted to its equivalent in terms of what that price differential would mean if there were a carbon tax, it implies a carbon tax of $600 to $1400 per ton of carbon.

The key point here is that for the past two decades we have been running a type of experiment in terms of the effectiveness of carbon taxes and their ability to decarbonize the transportation sector between these countries and the United States. To be sure, these higher energy prices have encouraged motorists in Europe and Japan to drive more fuel efficient automobiles than the average car in the United States. Yet, this price differential ($600 to $1400 per ton of carbon) has not fundamentally altered the use of internal combustion engines and the free venting of their carbon dioxide to the atmosphere.

Figure 1. Gasoline Prices 1978-2002 for Selected OECD Nations[14]



[13] The use of carbon taxes or some other form of placing a price – and therefore creating a disincentive – on the free venting of CO2 is often seen as a significant aspect of how many nations will reduce their greenhouse gas emissions.

[14] U.S. Department of Energy, Energy Information Administration, International Energy Annual 1999, Washington, DC, February 2001, Table 7.2.

Yet if this same carbon tax equivalent were applied to other sectors of the economy and in particular the electric power sector, the tax would result in profound changes in the way energy is used and the resultant carbon emissions.[15] For example, the US Department of Energy's Energy Information Administration estimates that US compliance with the provisions of the Kyoto Protocol would result in carbon prices of $348 per ton carbon. This carbon price would result in significant reductions in the amount of electricity used in the US (perhaps as much as a 17% reduction) and the share of electricity generated by coal (currently around 50%) would be expected to drop to as little as 12% in 2010. It seems fair to call these profound impacts on the electricity generation sector. Yet we have observed no such effect on the transportation sector, at least across this subset of countries, given this clear price differential.

So if carbon taxes are unlikely to result in a fundamental change in the carbon emissions of the transportation sector, what other options do we have? Our research strongly indicates that the key to decarbonizing the transportation sector will be our ability to develop new technologies that can compete with internal combustion engines in terms of cost and performance of delivered transportation services and associated systems. That means that the cost to own and operate these advanced transportation systems cannot differ markedly from the cost of owning and operating today's vehicles.

Advanced Transportation Technologies: What's the right choice?

The requirement to evolve to a net zero emitting global energy economy has profound implications for the way in which energy will be produced and used over the course of this century and beyond. For the transportation sector, moving to a net zero emissions profile has major implications not only for passenger and freight vehicles, but also for the broader transportation infrastructure. Not only must we develop radical new vehicle and engine technologies that will prevent the emission of CO_2 to the atmosphere, but we must also ensure that the systems that produce and deliver transportation fuels can meet these same requirements. Even with advanced technologies, there are clearly a number of alternatives we might consider for addressing this need. But it is unclear what the best combination of fuel and engine technology might be in the long term – and what transition paths might be most technically feasible and cost-effective. Any of the following transportation fuel and vehicle systems could conceivably evolve into a carbon free transportation system:[16]

- Fossil fuels used to produce hydrogen (H_2) at a large central facility, with carbon captured at the production site and sequestered. The H_2 fuel is then piped through a major network of distribution nodes to local fueling stations, where it is fed into a fuel cell vehicle (much like the gasoline stations of today). As long as the carbon can be effectively captured and sequestered at the production site, emissions from this system primarily include water and heat.

[15] U.S. Department of Energy, Energy Information Administration. Impacts of the Kyoto Protocol on US Energy Markets & Economic Activity. October 1998. Report#:SR/OIAF/98-03. http://www.eia.doe.gov/oiaf/kyoto/kyotorpt.html

[16] These options are described for illustrative purposes. A detailed life cycle analysis of the entire system should be performed to fully evaluate the environmental and cost performance of the integrated system.

- Fossil fuels (natural gas or coal converted to gas) used as a source for distributed or local production of H_2, with carbon capture and disposal occurring at the smaller production sites. The H_2 is stored locally until required for a fuel cell vehicle. Distribution systems are still required.
- A broad spectrum of fossil fuels, including coal, might be used in tandem with carbon capture and disposal to generate electricity that would be transmitted via the national grid to power electric vehicles.
- Commercial biomass may be a potential fuel source, delivered to a refinery where it is converted into biofuels (for instance, biodiesel) and delivered via a network of pipelines to local distribution centers. Conventional vehicles would be fueled by this rather unconventional source.
- Renewable resources such as wind might be employed to create a source of H_2 through electrolysis of water. Production site storage, distribution and delivery networks would need to be established to support this alternative for fueling a fuel cell vehicle powered by H_2.

The examples above suggest a variety of possibilities for a future transportation system that would essentially operate carbon free. Each of the systems above likely has distinct costs, benefits, and drawbacks. For example, advanced technologies such as hydrogen-based fuel cells and carbon capture and disposal offer tremendous potential to reduce carbon emissions from transportation systems worldwide. These technologies, however, are dependent on other advances in system infrastructure and shifts in consumer behavior to achieve their full potential.

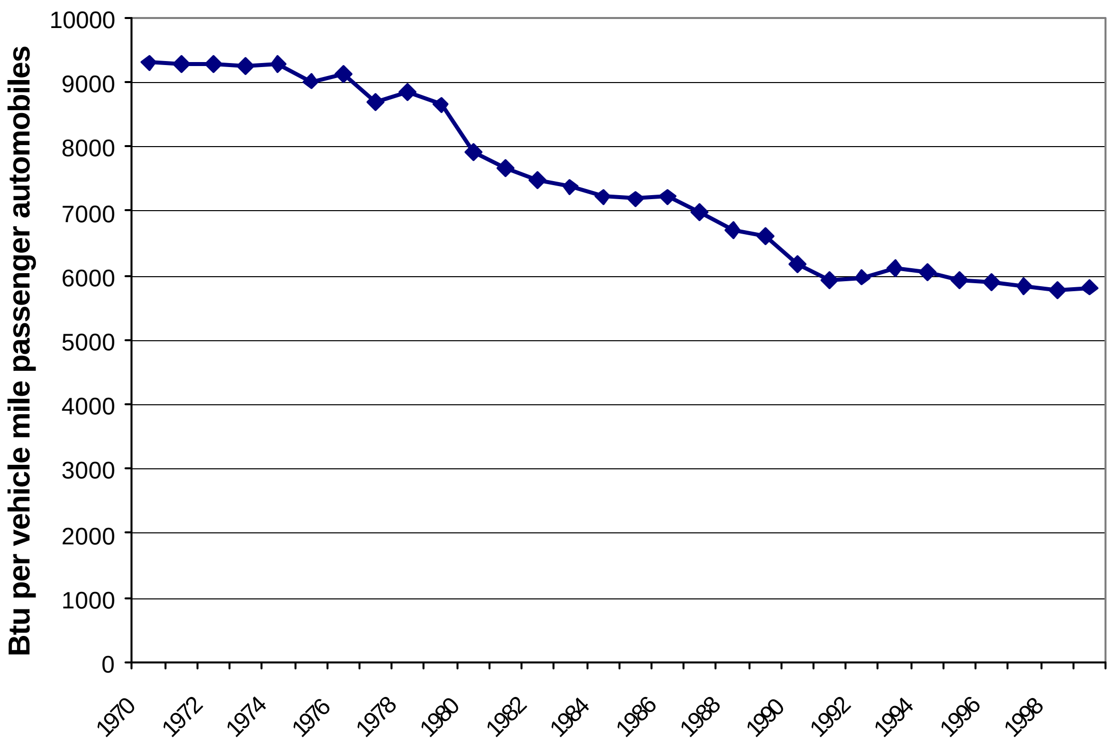
Transition to the Transportation System of the Future

The magnitude of the challenge for transportation systems and the complexity of the range of potential solutions have, until recently, focused attention on other sectors of the economy (such as power generation) for developing potential solutions to climate change. However, the timeframes involved for making substantial changes in the transportation sector demand that we begin now to evaluate the technologies and the supporting infrastructures that will be needed and understand the potential pathways to their development and deployment.

Radical changes to a major technological system will take some time to develop and take hold. Historical data suggests that even with strong governmental and consumer pressure, the timeframes for transition to new technological systems can be significant. We can look to the example of the shifts in vehicle design and efficiency that occurred after the implementation of fuel efficiency standards for automotive fleets in the United States in the late 1970's and early 1980's. Figure 2 reports data on energy use per passenger mile for passenger vehicles in the United States. However, note that it took more than a decade to transform the capital stock in the US passenger vehicle fleet and move to a new and significantly lower energy use pattern.

The transformation of the transportation sector to an entirely new system will take time. Not only must we develop the new vehicle designs, but they must be integrated with new fuel sources, distribution systems and supporting infrastructures. Integrated systems must be evaluated to make decisions on where to most effectively address the carbon emissions from transportation. Production of hydrogen from fossil fuels, for instance, will still generate carbon unless linked with carbon capture and disposal. As we have pointed out, there are various technological alternatives that could be considered. Each of them, however, is still in an embryonic state, and will require significantly more R&D and testing before we can envision a wholesale shift to a future transportation system.

Figure 2. Energy Use Per Passenger Mile
US Passenger Automobiles[17]



Conclusion
Ultimately, the global transportation sector needs to evolve into something resembling at least one of the alternative integrated systems we have discussed in this paper if we are to achieve a carbon free future. The market will eventually determine which of these technology systems will dominate. It is conceivable that the world might be able to support more than one of these zero-emitting transportation systems. However it is clear to us that the key task in the near term is to begin rigorously exploring and evaluating these technologies and their supporting systems so that they will be ready *before* they are needed. The decades required for change in the transportation sector, and the current and growing magnitude of the challenge demand that we place particular importance now on developing the advanced transportation systems we will need in the future.

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[17] U.S. Department of Energy: Transportation Data Book: Edition 21. Table 2.11. October 2002. Oak Ridge National Laboratory. http://www-cta.ornl.gov/cta/data/Index.html