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Climate change dilemma: technology, social change or both? An examination of long-term transport policy choices in the United States

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Abstract

Time is fast running out for formulating a viable global climate policy regime even as it seems obvious that the major initiative will have to come from the United States, which currently appears indisposed to take any meaningful action at all. This paper reviews the prospects for emissions reductions in the US passenger transport sector and the technical, economic, social, and political barriers to developing policies that focus solely on technology or pricing. Using scenarios it shows that, in order to meet stringent emissions targets over the coming half-century, technology and pricing policies may have to be supplemented by strategies to change life-styles and land uses in ways that effectively reduce car dependence. In the medium to long term, bold initiatives that treat vehicle users as citizens capable of shifting their interests and behaviour could form kernels of social change that in turn provide opportunities for removing many of the social and political constraints.

Keywords: Climate policy; Social change; Transport scenarios

1. Introduction

Since defecting from the Kyoto Protocol in 2001, the United States administration seems unwilling as well as politically unable to adopt genuine commitments to reduce greenhouse gas (GHG) emissions. In spite of several promising initiatives at local and state levels[1], it appears obvious that a significant US climate policy agenda will not surface unless major changes start to occur within the domestic American political and cultural landscape. Indeed, the best way to interpret US recalcitrance on climate policy is that it is a product of several overlapping factors that go well beyond the disposition of the present Bush administration: an aggressive anti-mitigation lobby composed mainly of producers and marketers of energy-intensive goods and services (McFarland, 1984); a dominant social paradigm that places faith on material abundance, technology solutions and future prosperity (Dunlap and Liere, 1984); a relatively weak and divided polity whose policies are buffeted by short-term priorities (Skocpol,

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[1]Rather than proceed on a moderate path of climate stabilization as required by the Kyoto Protocol, which the US largely designed and signed but did not ratify, the Bush Administration formally rejected it in 2001. Somewhat more promisingly, in the absence of federal action, several states have stepped forward with programs of their own to reduce GHG emissions. In 2002, California signed the country's first law for reducing car and truck emissions of GHG, while Massachusetts and New Hampshire acted to curb such emissions from power plants. Governors from North-Eastern states have pledged to reduce GHG emissions by about 20% by 2020. Texas has promoted a renewable energy portfolio standard for electricity purchase and several Western and Mid-Western states are investigating carbon

(*footnote continued*)
sequestration. Nonetheless, these measures appear to be already too fragmented, too little and perhaps too late to bring total US emissions anywhere close to the stabilization path that was envisioned for the end of the first commitment period (2008–2012) in Kyoto (Bailie et al., 2001).

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Table 1
Historical and projected sectoral emissions of carbon dioxide in the US (*Source:* Energy Information Administration; projections from AEO, 2003)

	Residential	Commercial	Industrial	Transport		All Sectors
				Passenger	Freight	(MtC)
1980	248	178	484	265	113	1288
1990	257	213	458	311	121	1360
2002	324	275	455	370	137	1561
2025	420	428	586	573	212	2219
1980–2002 growth	1.2%	2.0%	−0.3%	1.5%		0.9%
1990–2002 growth	1.9%	2.2%	0.0%	1.5%		1.2%
2002–2025 projections	1.1%	1.9%	1.1%	1.9%		1.5%

1993); and, perhaps most important, a fragmented electorate that remains largely misinformed about global environmental security, national interests and the economic and social impacts of climate mitigation activities (McCright and Dunlap, 2003). Evidently, a political solution involving an *informed* and *engaged* citizenry is a prerequisite for formulating an aggressive policy framework involving technology research and development, incentives and emissions standards, and mechanisms for implementation. Moreover, a complex and multi-layered set of individual and collective actions indicating commitments from key stakeholder groups needs to occur within a timeframe and at levels commensurate with climate protection goals.

This paper focuses on the passenger transport slice of the problem, which happens to be a significant sector in terms of GHG production (see Table 1). Passenger transport, perhaps more so than any other energy-intensive activity, takes place within a complex matrix of economic, political, social, spatial and technological factors. Extraordinarily deep reductions from transport will be needed over the next half-century or so, and even an ambitious timetable for achieving efficient vehicle technology policy may only be partially successful in meeting these goals. I analyse the panoply of solutions relevant to making major emissions reductions from passenger transport in US and examine the barriers to implementing many technology and pricing options. Based on the finding that attention must also be paid to the drivers of social change that could influence the development of new policies, attitudes, and behaviours, I develop scenarios to show that social change leading to life-style and land-use changes, as well as meaningful technology and pricing policies, will be necessary in order to meet long-term US climate change mitigation goals. Social change, where successful, could redefine prevailing understandings of success, well being and good citizenship, and, in so doing, actually help to overcome some of the political barriers to climate policy.

The paper is organized as follows. Section 2 provides background on the scale of reductions required by 2050 across all sectors. In Section 3, I describe the main drivers of the US transport sector with respect to carbon emissions and current expectations of growth through 2050 without carbon-specific policies. I compare the baseline scenarios against two different technology-based scenarios for transport, both of which come close to, but do not meet, an admittedly steep but important target that I set for 2050. In Section 4, I discuss the extent of the barriers to following the pure technological scenarios portrayed in Section 3 and show that in the absence of serious and early groundwork on these fronts relatively little of significance could be achieved. Section 5 explores land-use and social change research and its implications for alternative scenarios that combine modest life-style and land-use changes with technology. It also describes the types of social and political outreach and technology development that would be necessary to bring about these changes and presents additional scenarios that include the impacts of social change and technology. Section 6 concludes with an assessment of the opportunities and options for a coherent implementation of such activities.

2. Scale of the problem

The Energy Information Administration (EIA) projects that with no new climate policies GHG emissions in the US will rise from about 5.5 tons of carbon equivalent (tC) per capita in 2003 to about 6.6 tons in 2025 (AEO, 2003). Total emissions, in its *Reference* scenario, which also accounts for population increases, are expected to rise by about 40% during this period. In extending the scenario to 2050, total emissions will likely rise more modestly during the latter part of the half-century, given the normal penetration of more energy-efficient devices in buildings, improvements in industrial and vehicle technologies and of renewables and combined heat and power generation for electricity (Bernow et al., 2001). Assuming that the average annual growth in emissions beyond 2025 reduces to half as a result of these factors, and using the middle-series population projections from the US Department of Census, per capita GHG emissions in 2050 would be about 6.7 tC.

Achieving a low to moderate climate impact will require that CO_2 concentrations stabilize at or below 450 ppm by 2100.[2] This in turn will require that global per capita emissions reduce to around 0.6 tC from the current average of around 1.2 tC. Under almost any fair system of allocating emissions rights, the US will therefore need to reduce its emissions over the long term by about 90% relative to current levels.[3] But in the spirit of the "differentiated responsibilities" clause of the UNFCCC, the US and other industrialized countries may have to reduce their emissions towards these levels as early as possible to allow developing countries a brief period where they could *increase* their emissions to accommodate their needs of social and economic development. While international trading may provide some breathing room for the US in the early years, as developing countries begin reducing their own emissions after a short span of growth, the space for credits may actually contract quite substantially (or, equivalently, the cost of tradable carbon could rise dramatically; see, for instance, Leimbach (2003) and Nakicenovic and Riahi (2003)). In other words, the actual emissions of most countries may well start to approach their individual allocations.

A different way of stating the problem is that global annual GHG emissions should drop to roughly one-half of today's levels by about 2050. Since emissions from developing countries would optimally be at the peak of their own expansion during this timeframe, the US would need to reduce its own emissions by about 75% relative to current levels as early as 2050. Fig. 1, based on an equal per capita emissions allocation scheme, provides one scenario of how US allocations would change relative to other Annex I countries and the rest of the world.[4]

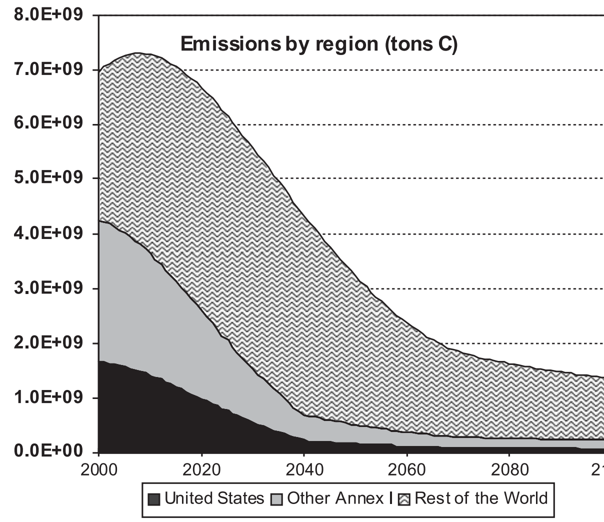

Fig. 1. GHG emissions allocations (in tons of carbon equivalent) by region for 450 ppm convergence. *Source:* Global Commons Institute model (www.gci.org.uk).

In the absence of serious climate change mitigation policies, however, US emissions will probably *rise* by over 50% in the next half century (Bernow et al., 2001). Emissions reductions would very likely have to be shared evenly across the entire US economy. With any serious commitment to realize deep reductions, this would be the preferred option on the basis of fair burden sharing, since the current contribution of each sector (barring agriculture) is roughly the same. Thus, although transportation equipment turns over at least 2–4 times faster than power-plant machinery and buildings, it would perhaps be more politically reasonable to ask for comparable percent reductions across the board than to require extraordinary reductions in any one sector. The goal of steadily reducing emissions in each of transport, buildings, and industry to about one-quarter of current levels is therefore not needlessly strict; indeed, it is likely to be an optimal approach to meet US obligations for achieving climate stabilization.

In the short to medium term, however, the political and institutional barriers to sweeping reform options appear nearly insurmountable, which is why much of

[2]The 450 ppm target is a hedging strategy designed to limit average warming to less than 2°C by the end of the century (WBGU, 2003). The Third Assessment Report of the Intergovernmental Panel on Climate Change did not provide estimate on a single climate sensitivity factor, but indicated a range between 1.7°C and 4.2°C warming for a doubling of pre-industrial CO_2 (IPCC, 2001a,b). Given that climate sensitivity is of great importance, a precautionary approach would be to try to aim for early stabilization of concentrations using a moderate sensitivity factor. Note that the German Advisory Council on Global Change has developed scenarios for CO_2 concentrations at 400 and 450ppm to limit temperature change at 2°C by 2100 (Nakicenovic and Riahi, 2003; WBGU, 2003).

[3]There is increasing interest in how to interpret the twin concepts of "equity" and "common but differentiated responsibilities" in Article 3.1 of the UNFCCC. Broadly, there is agreement that developed countries should reduce their GHG emissions faster than developing countries and that, in the long term, GHG allocations should be based on widely accepted principles of climate justice. Among the various schemes proposed are ones in which all countries are allocated equal per capita emissions rights and those that stress historical accountability (Grübler and Fujii, 1991; Neumayer, 2000; Aslam, 2002).

[4]One could, of course, imagine other paths that end up with the 450 ppm concentrations in which the bulk of the emissions reductions take place after 2050. The difficulties with assuming a later decline in emissions are multiple: the reductions would have to be much steeper; delaying emissions reductions leaves open the risk of unforeseen circumstances in technical and political fronts that would be harder to mitigate, even if one were to assume rather sanguinely that new technologies would evolve over time; relying on late innovations could imply having insufficient time for learning and technology transfer across regions.

the discussion on mitigation options has focused on "no-regrets" technology options, e.g., energy efficiency labelling, voluntary agreements, and so on. In the aftermath of the US rejection of Kyoto, there also appears to be a serious political impasse concerning policy instruments involving carbon-based taxes that could reduce emissions by any significant amount in the coming years. Nevertheless, even if such barriers were successfully overcome, it is difficult to expect that *incremental* technological changes alone would bring about major reductions in emissions relative to today's levels.[5] In a study conducted by five US National Laboratories, for instance, aggressive technology-based scenarios yielded emissions reductions in 2020 that were only 8% below 2000 levels (IWG, 2000). Tellus Institute's analysis has shown reductions in 2020 of about 30% relative to 2000 emissions, but these resulted from policies involving technological change as well as modest life-style changes, especially in the transport sector (Bailie et al., 2001). Scenario analysis out to 2050 revealed that emissions reductions of nearly 50% relative to current levels could be achieved through similar policies (Bernow et al., 2001). The sectoral emissions reductions in these scenarios are almost equal, just as their base case contributions are roughly comparable (except for transport's increasing dominance in later years).

Two new technologies (that were not serious options in the studies mentioned above) are now being considered as providing important means to bring about substantial reductions in GHG emissions, with strong implications for transport. The first is the widespread use of hydrogen as an energy carrier, primarily for use in vehicular fuel cells, but also for some stationary applications, including combined heat and power. The second is the sequestration of carbon dioxide into geological formations, including deep unmineable coal beds and deep saline aquifers. Both these technologies are currently at early stages of development, although they show each considerable promise for reducing GHG.

Hydrogen is a clean energy carrier only at the point of end use; it could contribute to substantial carbon (and other) emissions across the fuel chain, depending on how it is produced. Hydrogen from renewables is "zero-carbon", but is costly to produce using current technologies and likely to be infeasible at very large scales because of the inherent intermittency of most renewables and the high costs of long-term hydrogen storage. The most plausible medium-term hydrogen scenarios would involve a combination of centrally produced piped hydrogen from coal or gas reformation and decentralized hydrogen production from electrolysis or on-site natural gas reformation to produce hydrogen. Upstream carbon would therefore have to be managed primarily through a combination of sequestration and renewables, implying that somewhat less than 100% of the hydrogen would realistically be "zero-carbon," at least in the near to medium-term. On the other hand, in the absence of new policies to contain carbon emissions, fuel cell vehicles will not reduce GHG emissions substantially and may even increase them based on the current US reliance on coal for electricity generation.

Sequestration turns out to be more promising in terms of reducing net carbon emissions, although the relevant technologies are less mature than large-scale hydrogen production, delivery and conversion. There are also safety concerns that need to be addressed because of the possibilities of leakage to the surface and induced seismic activity. Other key issues include estimating the potential storage capacity, storage integrity, and the physical and chemical processes associated with injecting carbon dioxide underground. Yet, costs of under \$30 per ton of carbon sequestered (amounting to an additional \$13 per barrel of oil) have been estimated, which potentially makes it competitive with several other efficiency and renewables-oriented projects being considered (Lackner, 2003).

3. "Pure" technology scenarios in passenger transport

Transport in the US is responsible for roughly one-third of its GHG emissions, or about 8% of global emissions. In 2003, (personal and freight) transport GHG emissions accounted for about 40% of total energy-based US emissions. Passenger transport was responsible for about three-fourths of the total energy consumed in the sector, and private road vehicles (dominated by personal cars and light trucks) contributed to three-fourths again of the energy consumption for passenger transport.[6] While its emissions are growing very quickly, transport is perhaps the most difficult sector to regulate because of the sheer size of the vehicle fleet and its relatively slow turnover, and the complex web of institutional interactions among personal attitudes relating to vehicles and land use, local

[5]For a discussion on the global constraints to meeting climate stabilization targets based on available and foreseeable technologies, see Hoffert et al. (2002) and Caldeira et al. (2003). See also the scenarios discussed below.

[6]The fastest growth rate in fuel consumption will, however, be from commercial air travel; it is expected to nearly double by 2020, and grows to nearly three times the present consumption by 2050 (notwithstanding a significant decline in energy intensity). This will be largely the result of the very steep increase in air travel that may be expected for several decades to come, with passenger miles travelled by air approaching one-fourth of all road travel by 2050. Air travel is especially significant from a climate change perspective, because of recent concerns about the additional global warming potential of contrails (IPCC, 1999).

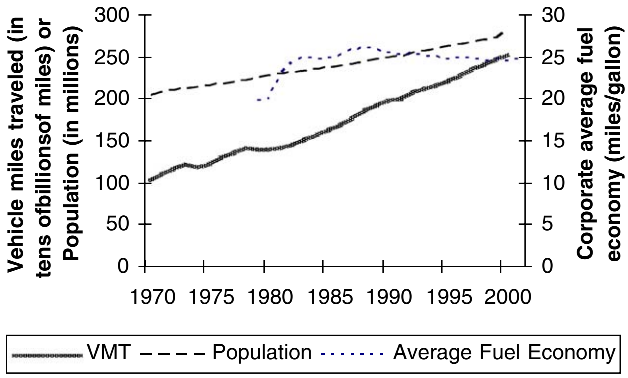

Fig. 2. US trends of population, vehicle miles travelled, and estimated average fuel economy for new cars and light trucks. *Source:* US Census, Davis and Diegel (2003).

politics and the marketing power of the auto-oil industry. These issues are well expressed in transport statistics in the US that are currently unique among industrialized countries, but some of whose trends may soon be replicated elsewhere through the diffusive processes of globalization.

Fig. 2 shows that the annual growth in total vehicle miles travelled (VMT) of automobiles and light trucks since 1970 has exceeded population growth by nearly threefold, which could still be considered a slowing down relative to the two decades before the first oil crisis in 1972–73. Fig. 2 also shows that the average fuel economy of personal passenger vehicles has been declining since about 1989, largely as a result of the growing popularity of light trucks. The combined effect of these two phenomena (i.e., an increase in VMT and decline in average fuel economy) is a 47% increase in GHG emissions from LDVs since 1970. A third phenomenon in the transport sector, and indirectly a driver of GHG emissions by inducing increased travel, is the steady growth in personal vehicle ownership. Motorization was believed to have reached saturation around 1989, when the number of private vehicles per licensed driver reached unity, but it rose (quite incredibly) to a level of about 1.07 household vehicles per driver by 2001 (nhts.ornl.gov).[7]

The US EIA's *Reference* scenario shows that VMT will continue to grow because of income effects in the face of nearly constant driving costs. The fuel economy of new gasoline-powered LDVs will improve very modestly through 2025, but the share of sales of alternatively fuelled vehicles will grow from about 4 to 17% (AEO, 2003). The net impact is that gasoline use by LDVs will increase by about 56% during this period. The *Reference* scenario can be extended beyond 2025 simply by extrapolating trends in fuel share and energy intensity in the last few years of the scenario (2020–2025) out to 2050, which gives the result of a near doubling in LDV gasoline use (from about 16 to 26 quads between 2003 and 2050).

There are two broad approaches to reduce passenger transport emissions: using technologies and new modes to reduce the emissions per passenger-mile travelled; and using land-use planning and otherwise inducing life-style changes to reduce the need for motorized transport per se. In the US, the dominant approach for emissions control has been to rely on technology to reduce emissions from personal transport, which I consider in this section. In Section 5, I explore the role of land-use and behavioural change to cause people to use more efficient modes to reduce emissions per passenger-mile as well as reduce their number and length of trips.

To what extent will pure technology-based strategies for personal vehicles be successful in bringing about deep reductions in emissions? Significantly, it turns out, if most of the assumptions concerning policies, research and development are borne out. There are at least two variants of technology-based policy scenarios to consider: one where hydrogen plays an important but not dominant role and another that assumes a full-fledged "hydrogen economy" by 2050. Fig. 3 shows life-cycle (i.e., including tailpipe and all upstream) carbon emissions from passenger transport (including other modes than LDVs) under three scenarios, a business-as-usual or *Reference* case, a policy reform case involving a portfolio of advanced vehicle technologies (*PR Tech*), and a "pure" hydrogen case (*H2 Tech*). More detailed assumptions behind each of these scenarios (and of others presented subsequently) are available in the Appendix, but it should be mentioned here that less of the hydrogen produced is zero-carbon in the early years (30% by 2025) than later (up to 80% by 2050).

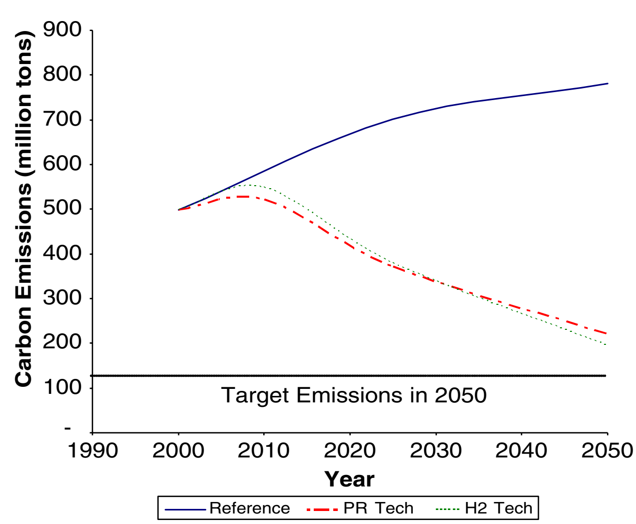

Fig. 3. Life-cycle carbon emissions from passenger transport (reference and two pure technology scenarios).

[7]With rental and other fleet vehicles included, this figure is about 1.2 vehicles per licensed driver (Davis and Diegel, 2003).

In the *H2 Tech* case, carbon emissions from passenger transport can be reduced by 61% below current levels, compared with a 57% *increase* in the *Reference* case. The *PR Tech* case, despite having significant numbers of conventionally fuelled vehicles in the road fleet, manages to achieve a respectable 56% reduction in carbon emissions relative to current levels. Indeed, the *PR Tech* strategy achieves reductions exceeding *H2 Tech* in the early years and, but for the fact that zero-carbon hydrogen production ramps up by 2050, could remain competitive with the *H2 Tech* approach.

4. Barriers associated with tax strategies and other technology-forcing options

The steep reductions in carbon emissions in the alternate passenger transport scenarios, while impressive, do not quite reach the 75% target we had proposed earlier in spite of the assumption of major technological commitments over an extended period. In the *PR Tech* scenario, these imply a steadfast policy environment to improve the fuel economy of the conventional fleet progressively over time, along with a substantial introduction of alternately fuelled vehicles, including hydrogen. The *H2 Tech* scenario involves a strategic commitment of a different sort, calling for the transformation of the entire fuelling infrastructure and fleet towards hydrogen fuel-celled vehicles in the course of about three or four generations of vehicle turnover. While both options are technically feasible, and perhaps even commercially viable,[8] there are a number of technical, economic, social, and political impediments associated with their implementation.

The *PR Tech* scenario, given its diversified portfolio approach, might generally be considered the more viable proposition of the two, but it is also rife with risks. The most obvious is the prevailing political reluctance to set tough policies at the federal level to induce the manufacture and purchase of more efficient vehicles. The two main policy levers for achieving this goal are technology-forcing standards on new vehicles and gasoline taxes. Since 1975, the federal government has been more comfortable with the former approach, when it set Corporate Average Fuel Economy (CAFE) standards for cars with the ultimate goal of doubling fuel economy within a decade. By 1990, the average standard for cars had indeed doubled to 27.5 miles per gallon (mpg) (compared to the average 1975 level of 14 mpg). For light trucks, the Congress then mandated no increase from the 1996 value of 20.7 mpg from 1998 through 2003, which was repealed in 2001.

Meanwhile, though, as shown in Fig. 2, the combined fuel economy of the new LDV fleet began to decline in the 1990s because of the increased penetration of light trucks. Several economists have argued that the CAFE strategy actually encouraged customers to switch purchases to light trucks because they had lower standards, and hence lower costs for the same level of service, but it has turned out that manufacturers have even been having trouble meeting standards for light trucks (Lave and Lave, 1999). The bigger political question relates to the effectiveness of outside political pressure to keep Congress from mandating a tougher fuel economy standard. Recently, for instance, a potent combination of farm and automotive lobbies managed to push through legislation that gave manufacturers fuel economy credits for selling dual fuel or E85 vehicles that could run on ethanol and gasoline, regardless of the fact that most purchasers of these vehicles would run them almost exclusively on gasoline until ethanol became more widely available.

A standard policy argument is that Pigouvian, or appropriate externality, taxes are more efficient than command-and-control style regulation for reducing the undesirable impacts of externalities. Gasoline taxes, it has been argued, would encourage people to car-pool, take public transport, or live closer to work, and would help cut GHG emissions. Studies find that depending on how income is computed (lifetime, annual, or consumption expenditure) and whether or not non-owners of vehicles are included, usage taxes can be either regressive or progressive (Poterba, 1991; Walls and Hanson, 1999; West, 2004). The main barrier in the US, however, is that fuel taxes have been a highly politically sensitive issue for several years (e.g., Plotkin and Greene, 1997). In several European countries, gasoline taxes are more than eight to ten times the levels in the US where, in real terms, state and federal taxes have actually declined steadily since 1962.[9] Part of the reason for the decline is public resistance to taxes, under the false perception that gasoline taxes are more "painful" than taxes on any capital goods, including vehicles. For instance, in one recent survey, when asked to choose hypothetically between a 3% tax on new vehicles and a 25 cent/gallon tax on gasoline to address global warming, 70% chose the former but only 17% preferred the latter, even though the total expenditure in present value terms would have been around the same.[10] Moreover, average gasoline expenditures in the US amount to less than about 2% of median household income, and even a

[8]The overall cost-effectiveness of the two scenarios has not been computed here, but other studies with fuel-economy-based policies similar to *PR Tech* indicate that the fuel savings from energy efficiency will likely more than offset the costs (Bailie et al., 2001).

[9]http://www.chevron.com/about/currentissues/gasoline/apiprice/gasoline_price_trends.shtm.

[10]Opinion Research Corp. for NREL phone survey 2/98, cited in http://www.ott.doe.gov/pdfs/patterson.pdf.

tripling in gasoline prices would actually cause little or no dent in non-gasoline household consumption patterns.

Public attitudes about gasoline taxes obviously constitute a major barrier to using them as a policy tool and better communication about their impacts is clearly an important task to address existing misconceptions. Besides, vehicle purchase decisions tend to be far too complex for gasoline tax policies alone to play a decisive role (Greene 1998). Plotkin and Greene (1997) and Agras and Chapman (1999) have argued that an appropriate technology standard in combination with a tax will perhaps be most effective in reducing emissions. Cross-country analysis also shows that fuel prices and strong government policies relating to vehicle and fuel taxes and various types of standards play a significant role in shift in modal mix away from personal cars towards modes with lower carbon intensities (Greening, 2004).

Nevertheless, there is no getting around the fact that the political history of the past two decades has not been encouraging. A doubling in the fuel economy of new cars in the next 25 years will require an average improvement of about 3% per year, which is a more aggressive and steady rate than we have seen for fuel economy during the past 25 years or so (as opposed to criteria emissions). The paradox is that, while polls indicate support for fuel economy improvements (Greene 1998), the public also seems to display a preference for larger, more powerful vehicles and a distaste for gasoline taxes. Moreover, policymakers' attempts to set stronger fuel economy standards have remained hemmed in by strong lobbies at the federal level and, increasingly, at the state level. In other words, while regulation and gasoline taxes are both theoretically viable policy options, there appears to be no straightforward means to remove the political and institutional roadblocks along the way.

In the case of the *H2 Tech* scenario, by contrast, there are signs that the policy environment is relatively less complicated, at least insofar as the horizon for making difficult choices is shifted from the near to medium term. A national level commitment to move towards a hydrogen future has been fairly robust since about 2002, with billions of dollars of investment in hydrogen infrastructure and vehicle technology research funded by the federal and California governments as well as the automobile majors. A hydrogen "roadmap" has been developed, which proposes a coordinated and focused effort to examine all aspects of storage, production, delivery and applications of hydrogen in a full-fledged hydrogen economy.[11]

[11]http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf.

Hydrogen as a dominant carbon solution does, however, face two major obstacles: a classic "chicken-and-egg" problem relating to which should come first, large-scale hydrogen infrastructure or the introduction of hydrogen-fuelled vehicles at a commercial scale, and the high costs of both infrastructure and vehicles. There are patent risks associated with early government or private financing of infrastructure in the absence of a robust market demand for vehicles. Similarly, apart from a few risk-averse early adopters, it seems hard to imagine that the average vehicle buyer will be induced to invest in a fuel cell vehicle, even with subsidies, so long as the wide availability of hydrogen remains uncertain. Among the possible solutions to this dilemma are the transitional introduction of dual fuel vehicles with internal combustion engines; a fleet strategy, where government and private fleets, which have centralized fuelling facilities, would first absorb hydrogen vehicles; and a corridor approach, where a government-funded fuel infrastructure is "seeded" in and around a few important inter-city transport corridors and allowed to evolve over time as the market takes off. The history of similar programs for vehicles with alternative fuels like methanol and compressed natural gas is not very promising, however, and the fundamental risks are only partly mitigated in each of these strategies. Finally, the expense and risks of producing zero-carbon hydrogen may not be worthwhile in the near term, especially when other conventional options are available (Keith and Farrell, 2003).

If the purely technological solutions face serious obstacles, perhaps it is an indication that we need to stop being coy about including approaches that focus on human behaviour and the institutional context, which obviously play enormously important roles in generating vehicular emissions. More importantly, treating the public as passive consumers of new technology rather than active citizens capable of making intelligent choices about their future will, in the end, undermine democratic culture and forego opportunities for substantial social as well as environmental benefits. In fact, research suggests that the more people are promised technological solutions, the less willing they are to reduce automobile use (Tertoolen et al., 1998). On the other hand, approaches that carry substantial public support will have the added benefit of helping to overcome many of the political and institutional barriers that have hitherto plagued technical solutions.

5. Reducing car dependence through land-use and behavioural changes

Historically, it is the development of automobile culture that one associates with the construction of massive motorways designed for local travel in increasingly expansive metropolitan regions, subsidized parking, and tax policies that charged highway use far lower than its social costs and provided subsidies for low-density living. The US steadily lost an average of 1.5 million acres of farmland each year since 1960 to strip malls, highways, roads, parking lots, resorts, service stations, single family homes, and the like, while the average number of cars in use grew nearly five times and the average VMT per American increased by nearly half. The negative consequences of these changes are well known: sprawl, loss of open public spaces, congestion, inefficient transit performance, loss of mobility and access for the poor, elderly and the disabled, and local and global environmental pollution (Cervero, 1986; Ewing, 1994; NAP, 2002). What we now collectively experience as ''automobility'' is represented by a complex set of institutions (that is, rules, practices, habits, laws) and infrastructure that have evolved over decades and managed to reinforce car dependence and sprawl (Sheller and Urry, 2001; Rajan, 1996).

According to Gorham (2003), car dependence has three main components: the built environment (sprawl, poor accessibility), which can imply a physical and social need for a car for routine and essential activities; emotional and behavioural associations with a car (e.g., status), which is linked to marketing efforts and rises with income; and circumstances tied to specific household activities where lifestyle patterns (e.g., job-related or family needs) require the use of particular types of personal vehicles (e.g., pick-up truck or sports-utility vehicle). Of these, the most attention is paid to the impact of land-use form on car use, but at least some of the evidence suggests that this is not a simple or unequivocal relationship (Crane and Crepeau, 1998; Boarnet and Crane, 2001a,b), indicating that social psychological and other circumstantial factors also play important roles.

Changes in the built environment and behaviour will undoubtedly play a shared role in reducing car dependence, and therefore emissions. Understanding and ultimately changing circumstantial factors appears to be much more difficult than the other two sources of car dependence, which may indicate the need for further research in this area. To the extent that any shifts in behaviour (and associated attitudes) will also reflect some increased political support for emissions control (mediated, in part, by the reductions in travel demand, and therefore life-cycle vehicle costs) as well as changes to the built environment, one might infer that social change, technology and land-use improvements could act synergistically to reduce emissions. In this section, we focus on the role of planning and social psychology to reduce car dependence and develop scenarios that combine modest changes in life-style (induced by changes to the built environment as well as by other forms of social influence) with the technology improvements we have discussed until now.

The major strategies that would reduce the need for driving through changes in the built environment would include integrated land-use and transport planning and life-cycle cost accounting of the environmental impacts of alternative options. The most cost-effective options, from the standpoint of sustainable development, may involve

- the development of dense urban growth corridors that are matched with corridors for mass transport development plans;
- infrastructure improvements to encourage multimodalism within and between urban centres so that people would have easy connections among different modes (e.g., walking, bicycling, and riding trains);
- travel-demand management and demand-reduction strategies such as the subsidization of mass transit use and car/van pooling;
- the enhancement of communications infrastructure to reduce the need for vehicle trips;
- the creation of safe pedestrian walkways and bicycle paths in combination with strict motor vehicle parking regulations in urban core regions, to make walking and bicycling the preferred alternatives to driving.

The relationship between transport and land use is complex and dynamic, but, if effective, developments in transit and land-use planning could generally be expected to have a beneficial effect on GHG emissions over the medium term, by fostering relatively high-density communities with mixed land use where people could walk to the station, with short drives and cycling providing additional alternatives to walking. But, within typical sprawl-oriented communities that make up the North American landscape, even a substantial mode shift from cars to transit alone may not produce any emissions benefits if transit routes are inefficient or if they run with poor load factors (Delucchi, 2000).

To a large degree, prior land-use and transport planning decisions have caused many communities to be locked into travel patterns that are almost entirely dependent on automobiles (Cervero, 1986). Many ''personal travel decisions'' are thus not quite personal, but are strongly, if not irrevocably, influenced by the prevailing urban form. Similarly, many contextual factors, including price, government policies, the quality of schools and other public services, and proximity to jobs and social activities, influence where individuals live. But, in spite of these constraints, most individuals and households *do* have some room to alter their behaviour in ways that may reduce car use through altered mode choice or trip lengths, by better coordination of their daily activities, or by adjusting their housing location. The converse is also true. The evidence from the UK and several Scandinavian countries (where the built environment and government policies provide far greater encouragement than in the US for multi-modal transport) is that personal attitudes and habits play important roles in mediating travel behaviour (Aarts and Dijksterhuis, 2000; Verplanken et al., 1994). Utility-based models of travel behaviour typically focus on the maintenance of fixed travel-time budgets, based on aggregate data showing that total travel time expenditures are inelastic with respect to travel-time costs (e.g., Zahavi et al., 1981); or on utility maximization of discrete choices (Ben-Akiva and Lerman, 1985). However, these approaches do not allow for learning and attitudinal change, and are inadequate to explain the fine-grained structure of travel decisions especially relating to trip-chaining, "excess travel" and other phenomena (Kitamura et al., 1997; Handy et al., 2003).

People's willingness to transform their behaviour towards environment-friendly choices may, as Stern (2000) suggests, hinge on different types of factors, including contextual ones such as availability of alternative modes, personal capabilities or skills and knowledge, and attitudinal ones such as beliefs and values, and habits or routines. These are not necessarily independent, and may indeed reinforce one another. For instance, if the waiting time for a bus is lengthy (*context*), a new transit user, who usually travels by car (*habit*) and has not mastered the bus schedule (*personal capability*), may develop a strong negative *attitude* toward transit, especially if he/she finds no social or environmental value in public transport.

To the extent that attitudes and habits mediate travel behaviour, it is likely that shifting them in favour of transit and non-motorized vehicles will have a positive impact on actual behaviour, as long as they are complemented by a change in the physical and social context to make such behavioural change possible. Altering the existing patterns of car dependence and sprawl therefore depends critically on initiatives to *improve human capacity*, a *shift in the social context* at the local level and changes in individual *attitudes* and *habits*. Steg and Tertoolen (1999) propose several strategies to influence individual preference about mode choice and residential location, classified as structural (involving 'push' or 'pull' measures that provide behavioural incentives away from car use) and cognitive–motivational ones (attempting to change people's understanding). Structural strategies include ones we have seen: financial/economic measures; the provision of physical alternatives/changes (car-pooling, transit, traffic control); technological innovations; legal regulation and enforcement measures; and organizational change (where new choices are provided in a group setting in the hope that new habits and attitudes will take root and flourish).

Cognitive–motivational strategies are of at least two types: information provision and learning. The first entails improving people's knowledge of transport/land-use choices and increasing their environmental awareness with the intention of changing their attitudes. This turns out to be a much more difficult proposition than one might imagine, since there first need to be viable alternatives to solo driving in place and, even with the right incentives, people tend to filter out important information or stick to habits that require fewer cognitive resources for decision-making. At any rate, the huge advertising budgets of the auto industry spent on transmitting the opposite message (e.g., that driving is "fun" and therefore inherently a good thing) make it virtually impossible for even the most sustained communication campaigns to be able to influence large numbers of people effectively to change their behaviour. Furthermore, 'cognitive dissonance,' or an almost reactive inconsistency between attitudes and behaviour, is not an uncommon result of such campaigns (Tertoolen et al., 1998). Finally, and perhaps most importantly, knowledge may be necessary but is certainly insufficient to prompt significant behavioural change. But, in spite of these difficulties, social education will likely have long-term benefits in terms of raising public support for direct policy measures relating to car use.

Social modelling is an important part of learning approaches that deploy social situations to change behaviour. Social modelling seeks to exploit the fact that strong public role models and social comparison processes relating to status and power seeking can have a powerful influence on people's attitudes, preferences and habits. To the extent that such behaviour is visible and of a sufficiently high profile, e.g., when a celebrity emphasizes his or her decision to shift travel choice and residential location, citing the associated impacts on the environment, significant numbers of admirers may feel motivated to emulate these actions. Other social influences involving learning include conformity pressures, authority influences, reciprocal concessions and social learning techniques involving incentives, disincentives and feedback.

The evidence from social psychology seems to be that behavioural change is influenced by several complex factors, but that at a societal level it could take place at a sufficiently large scale given the right circumstances. Indeed, human history is replete with examples of major shifts in societal attitudes and behaviour around perceived collective goods like the environment, national security and multicultural harmony. In the transport sector, such a large-scale shift in attitudes will likely change the focus towards building communities in which walking and public transport once again become prevalent (which is essentially the goal of New Urbanism; see for instance, Calthorpe and Fulton, 2001). Table 2 summarizes some of the broad social

Table 2
Social psychological approaches for reducing car dependence

Approach	Examples
Structural/Situational	
Push factors	
Increased costs	Fuel and vehicle taxes
	Tolls
	Congestion and distance-based pricing
	Priced parking
Decreased availability	Reduced parking spaces
	Reduced single-occupancy vehicle (SOV) lanes
	Car-free zones
	Vehicle use restrictions (e.g., car-free days)
Pull factors	
Financial incentives for reducing car-use	Parking "cash-outs"
	Pay as you drive insurance
	Reduced transit fares
	Location-efficient mortgages
Attractive alternatives	Improved walking and cycling infrastructure
	Telecommuting and flex time
	Well-designed and efficient transit options
	Improved intermodal linkages
	High occupancy vehicle (HOV) priority
	Improved accessibility through mixed land use
	Green space protection
	Car sharing
	Home-delivery services
Cognitive–Motivational	
Cognitive	
Information provision	Advertising campaigns (efficient vehicles, transit, smart growth)
	Footprint calculators
Social influences/learning	
Social modelling	Role model endorsement of smart growth and transit
	Positive images of alternative lifestyles and travel patterns
Conformity pressures	Employee or community programs encouraging bicycling
	Publicity about the proliferation of smart growth communities
Reciprocal concessions	Option of congestion charge or car-free zone
Authority	Expert endorsement for reducing car-use (e.g., obesity linkages)
Norms	Community and cultural norms favouring bicycles and pedestrian access
Other motivational	
Changing life-circumstances	Job changes (e.g., near transit)
	Car no longer affordable

psychological categories and approaches for reducing car dependence, with examples of how they may be implemented.

In a series of coordinated Australian 'Travel Smart' programmes on household based-change, individuals choosing their own method of changing travel behaviour have significantly reduced their car trips and travel (Taylor and Ampt, 2003). Without involving alterations in the external infrastructure, the reductions have resulted from a combination of efficient trip chaining and increased walking, cycling and public transport use. Travel diaries, neighbourhood compacts, and individualized marketing that includes information provision and reinforcement by project sponsors have caused people to think rationally about their travel behaviour. The approach appears to work at a deep level of involvement and is found to have long-term effects. Given the type of self-selection in these studies, the individuals making the commitment are unlikely to undergo a major attitudinal change, but their combined behavioural changes could be expected to influence among other groups through the processes of conformity, authority and modelling.

Metropolitan visioning and long-term planning exercises also provide ample opportunities to make change attractive. In 1991, Portland, Oregon's regional government began work to develop its 2040 Plan, following the principles of new urbanism to transform the metropolitan area into a multi-nucleated urban form, develop a multi-modal transport system and designate mixed use regional and town centres. The outcome has been the development of making Portland an American poster-child of smart growth and transit friendly cities. There is modest evidence in parts of Southern California of behavioural change associated with the development of an ambitious subway system, a commuter rail network and the introduction of Bus Rapid Transit along specific corridors (TCRP, 2003). In spite of serious engineering and financial difficulties, transit-oriented development has taken place around several Metro stations, and ridership in many transit modes has exceeded expectations. For instance, in Long Beach, which is connected to the Blue Line, 10% of residents commute using transit (about two to three times the regional average). That these changes are taking place in a region with perhaps the largest vehicle intensity in the world (supporting over 10 million cars and light trucks in the five-county area) is of course remarkable, although there are clearly both structural and cognitive factors influencing the changes. The most important among the former are the growing congestion on freeways and the increasing availability of options, while the latter includes both positive advertising campaigns about transit and word-of-mouth endorsement. Similarly, the unprompted eulogizing of hybrid-electric vehicles by Hollywood celebrities has caused their popularity to rise (Hakim, 2002).

A deeper and more widespread transformation along these lines would first require an in-depth understanding of the social conditions under which travel decision preferences (particularly, attitude and habit formation) are learned. But far more important than an intellectual appreciation of these processes is an institutional willingness to democratize decision-making practice on transport and land use. The history of automobile regulation in the US has been remarkable in its technocratic emphasis, where a narrow set of experts from industry, government and academia have taken on the massive project of reshaping the American landscape and culture. While setting policies to control automobile pollution, for instance, regulators have always treated the public (comprising primarily of drivers) as if they were simply the bystanders in a complex technical and institutional situation rather than citizens whose own actions were largely responsible for the problem and who could be bootstrapped into taking collective action (Rajan, 1996). The concerns of those adversely affected by such policies were never adequately represented, nor was there any attempt to use the opportunity to build understanding and consensus around travel and land-use that could avoid the need for increasingly complicated technology-based solutions. Similarly, in his analysis of the policy shifts relating to California's ZEV mandate, Brown (2001) argues that the California Air Resources Board (CARB) ignored the tremendous public support for electric vehicles and imputed to them instead the ''unacceptability'' of having vehicles with relatively short ranges.

It seems evident, then, that interventions to try to shift behaviour will have to take two complementary forms. At the level of civil society, social influence and learning could provide important reasons for people to change attitudes and habits about driving and residential location. While a majority of Americans appear currently to prefer suburban, single family homes over townhouses, a significant minority prefers high-density housing and reduced auto orientation (Myers and Gearin, 2001). This raises the possibility that with greater awareness of climate concerns attitudinal shifts are conceivable, if environmentalists and others use social influence and learning approaches creatively. But institutional change also needs to occur within regulatory agencies; for instance, policy-makers should alter their own practices by creating the institutional and jurisdictional basis for a regional, transit-oriented planning authority that accommodates interactions with civil society and sets the tone for innovation through structural strategies as well as cognitive–motivational ones. The latter would entail programmes of communication, education and incentives aimed at influencing the transport behaviour of the public in the direction of sustainability. For instance, it could be emphasized that sustainable transport and land-use strategies need not lead to life-style compromises even for the affluent. Rather, they would likely enhance the quality of life for all, by improving the environment, reducing congestion, reducing the need to use personal vehicles, creating open public spaces, building social ties (Freeman, 2001), and encouraging walking and other forms of physical activity (Ewing et al., 2003).

How much can behavioural change involving land use and mode choice affect GHG emissions? Fig. 4 shows a set of three scenarios (along with the *Reference* case)

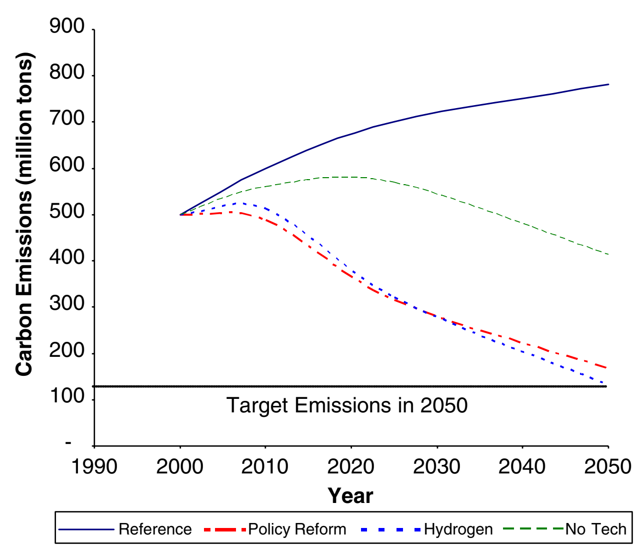

Fig. 4. Life-cycle carbon emissions from passenger transport (reference and three behaviour-based scenarios).

that each requires a certain degree of behavioural change that effectively reduces the use of personal vehicles. The first scenario, *No Tech*, is a case in which several changes are expected to take place in the way people "consume" automobile culture, but where no new technology policies are included. This 'pure behaviour' scenario illustrates the extent to which consumption choices can affect VMT growth, and therefore emissions. Significantly, the *No Tech* emissions in 2050 are 17% below 2000 levels, or at less than half the *Reference* case emissions, even though *the same technology is deployed* in both scenarios.

The two other scenarios involve the same technology improvements described in Section 3, but with the same VMT reductions arising from the *No Tech* case (similar to Bernow et al., 2001). That is to say, they assume modal changes in road, rail and air transport and further VMT reductions from land-use and attitudinal changes, as well as substantial efficiency improvements in all modes. As in the *PR Tech* scenario, the *Policy Reform* scenario also assumes a fuel efficiency initiative for LDVs, a portfolio requirement for sales of electric, hydrogen-fuel cells and (cellulosic) ethanol-powered light-duty vehicles and accelerated introduction of advanced aircraft engine technologies and high-speed rail. The life-cycle carbon emissions from passenger transport are reduced by 67% over half a century as a result of these changes. In the *Hydrogen* scenario, all these policies except for fuel shifts to electric and ethanol are continued, resulting in 100% of the light-duty stock consisting of hydrogen-powered vehicles by 2050. Again, it is equivalent to the *H2 Tech* scenario combined with the *No Tech* modal assumptions. The carbon reductions now reach 74% below 2000 levels, a result that was contingent on the combination of technological and social change happening over nearly a half-century.

6. Conclusions

All the scenarios discussed here for the passenger transport sector are merely illustrative and by no means predictions of how actual emissions will change in the long term. However, they provide important clues about the level of emissions reductions that are achievable under even ambitious programs and policies within the transport sector and provide indicative directions for further research. First, it is quite unlikely that US climate mitigation obligations could be met purely through technological and pricing policies, given the considerable technical, economic, social, and political barriers along the way. Even a hydrogen economy is not a panacea and may actually increase emissions, relative to other approaches involving efficiency and low-carbon fuels, unless determined efforts are made to generate zero-carbon hydrogen. Second, a series of programs that induce advanced technology commercialization as well as social change could potentially increase efficiency in vehicles, modes and land use, the last two implying a reduced reliance on personal vehicles. The emphasis of current climate change R&D should therefore be at least as much on social and cultural factors as on technology.

At the same time, sweeping policies that entail both a dramatic infusion of new technology and vastly altered everyday attitudes towards personal transport and land use cannot be implemented in a vacuum. A large part of the effort needed to bring the US into conformity with climate stabilization goals will require paying attention to processes that influence such a transformation. There is some evidence of small changes in this direction, which are already taking place in the New Urbanism movement, where larger numbers of people across the US are opting to live in compact and walkable cities having mixed-use zoning and multiple choices for transport, rather than in dispersed suburbs that encouraged sprawl throughout the latter half of the 20th century. But these changes can be most importantly mobilized at both local and national levels through some combination of learning and organizational change, particularly through demonstration of the personal, environmental and societal benefits of altered land uses, technologies and life-styles. Broad changes on the policy and political landscape are indeed more likely to occur only if sufficient numbers of individuals and groups within a society reorient their cultural frame to think about their consumption behaviour and technology choices within the context of sustainable futures.

A major shift in outlook and practices of mobility need be neither utopian nor the result of some dark ideological program of persuasion; rather, it is highly probable that increased understanding of the imminent sustainability crisis alone will spawn new forms of collective reasoning to make personal adjustments seem obvious and necessary. Moreover, such change would likely come into view within the social imagination as an expression of new conceptions of success, well being, and the "good life" rather than as a denial in the quantity or quality of goods and services consumed. In short, it is timely to begin considering behavioural concerns as well as technology, largely because doing so may actually help overcome some of the institutional and political barriers that currently seem intractable.

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Appendix Scenario development

The tool used to build the scenarios in this paper is *PoleStar*, which was developed by the Stockholm Environment Institute–Boston (Heaps et al., 1998). *PoleStar* is an adaptable accounting system for mounting economic, resource and environmental information, and for examining alternative development scenarios. It is used to examine alternative socio-economic and environmental futures, based on relationships between the drivers of change and indicators of their impacts. It does this in an open manner owing to the complexities, uncertainties and the role of human agency in these processes. *PoleStar* has been applied and refined at global, continental, national and regional scales. Data structures, time horizons, and spatial boundaries can be customized—and each can be expanded or altered in the course of an analysis. Specific sub-areas of interest can be represented within a larger region studied, and the level of detail across and within sectors or areas can be varied as needed. It can accept information from formal models, existing studies, or other sources. A *PoleStar* application begins with the Current Accounts, a snapshot of the current state of affairs. Scenarios are then developed to explore alternative futures as economic, resource and environmental accounts, based on assumptions and models developed for the application. Finally, environmental and resource pressures are computed and evaluated in comparison to user-defined sustainability criteria.

In this study, the *Reference* case is simply an extension of the EIA Reference case beyond 2025 (based on AEO, 2003), with modest improvements in fuel economy (about 15% by 2050 over 2000 levels) that are driven simply by market forces and ongoing innovation, with no new policies influencing the outcome. Modal shares across vehicle types and classes are expected to evolve beyond 2025, based on trends in the EIA forecast. In contrast with Schafer and Victor (2000), we do not assume that the share of passenger vehicles in the U.S will decline over time as a result of faster modes such as aircraft satisfying the rising demand for mobility within a fixed travel time budget. Their assumption is that total transportation activity per capita is a linear function of per capita GDP and that average travel time per day remains at about 1 h per day. Instead, we propose that a basic demand for self-directed forms of mobility will likely remain significant (Salomon and Mokhtarian, 2002), but that physical constraints, including congestion, may temper the growth in automobile travel moderately.

The *PR Tech* case has the following policies: regulations set to achieve a doubling or so of fuel economy for new gasoline cars and light truck by 2025; modest penetration of ethanol, electric and hydrogen-fuel cell vehicles by 2025, reaching 20%, 20%, and 25%, respectively, of new LDV shares by 2050; improvements amounting to more than a doubling in fuel economy of other modes by 2050, including rail, bus, and air; the introduction of high-speed rail covering more than a fifth of all rail; and a quarter of bus and rail fleets using hydrogen-fuel-cell vehicles by 2050. No policies related to mode shifting or travel demand reduction are included in this pure technology scenario. The *H2 Tech* scenario is identical to *PR Tech*, except that the ultimate goal is to saturate the light-duty fleet with hydrogen-powered vehicles by 2050, rather than adopt a portfolio strategy involving a mix of alternative-fueled vehicles. Thus, in intervening years, say, 2020–2025, when fuel cells account for about 15% of the LDV share, the rest of the vehicles are primarily gasoline and electric vehicles.[12] Hydrogen is not expected to be used in aircraft in this scenario.

It is assumed that by 2025, in both *PR Tech* and *H2 Tech* scenarios, about 60% of hydrogen demand is met by electrolysis (equally mixed between conventional and renewable or zero-carbon electricity) and the rest by (on-site or centralized) natural gas reforming. Electric vehicles generate upstream carbon emissions according to a typical electricity generation mix and biomass-derived fuels (especially from cellulosic biomass) yield some net negative carbon emissions. In 2025, 70% of electricity generated is zero-carbon (either through renewables or sequestration), by 2050 this reaches 100%. In 2050, 80% of the hydrogen is "zero-carbon" because of greater sequestration and the expanded use of renewables; the rest is from on-site natural gas reforming.[13]

In the *No Tech*, *Policy Reform* and *Hydrogen* scenarios, behavioural changes include the following: shares of light trucks do not increase as predicted by EIA, but rather stagnate at 2000 levels (comprising about 33% of the LDV fleet); 10% of passenger-miles traveled (PMT) is shifted to transit from cars and light trucks by 2025, increasing to 25% in 2050; 2% of air travel shifts to rail by 2025, increasing to 5% in 2050; and all modes reduce PMT by 5% by 2025, and a further 20% by 2050. The changes are admittedly aggressive in later years, but reflect a combination of modal shift to more efficient modes (like transit, which have correspondingly higher load factors) and an overall reduction in motorized travel that is consistent with the objectives of smart growth policies.

A summary of key assumptions in the scenarios is provided in Table 3.

[12] Electrics and hybrids are typically considered as being on the critical path to fuel-cell vehicles, which is the reason for their increased penetration in this scenario.

[13] A certain amount of on-site hydrogen production with associated carbon emissions in remote areas will likely continue to take place even in a full "hydrogen economy," given the costs and scale requirements of distributing piped hydrogen from centralized production facilities.

Table 3
Key scenario assumptions

	Reference		No Tech		PR Tech		H2 Tech		Policy reform		Hydrogen	
	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050
Vehicle Pop (millions)												
Cars	146.16	165.61	177.69	169.63	146.16	165.61	146.16	165.61	177.69	169.63	177.69	169.63
SUVs	52.92	59.96	37.20	19.94	52.92	59.96	52.92	59.96	37.20	19.94	37.20	19.94
MiniVans/Pus	73.10	82.83	51.39	59.49	73.10	82.83	73.10	82.83	51.39	59.49	51.39	59.49
Passenger-miles travelled (billions)												
All light-duty vehicles	6611.97	9608.46	4833.51	3193.60	6611.97	9608.46	6611.97	9608.46	4833.51	3193.60	4833.51	3193.60
Transit bus	22.35	24.08	563.90	1018.28	22.35	24.08	22.35	24.08	563.90	1018.28	563.90	1018.28
Intercity bus	34.40	37.06	248.53	427.11	34.40	37.06	34.40	37.06	248.53	427.11	248.53	427.11
School bus	86.81	93.52	187.09	267.69	86.81	93.52	86.81	93.52	187.09	267.69	187.09	267.69
Pass rail	38.04	48.59	304.12	579.18	38.04	48.59	38.04	48.59	304.12	579.18	304.12	579.18
Air	1151.41	1601.43	997.99	1054.92	1151.41	1601.43	1151.41	1601.43	997.99	1054.92	997.99	1054.92
Fuel economy for sample modes/fuels (BTU/mile)												
Gasoline cars	5356.8	5047.8	5356.8	5047.8	2703.4	2016.1	2703.4	2016.1	2703.4	2016.1	2703.4	2016.1
Hydrogen cars	3133.4	2863.6	3133.4	2863.6	2182.3	1579.1	2182.3	1579.1	2182.3	1579.1	2182.3	1579.1
Diesel transit bus	19,725.4	15,399.6	19,725.4	15,399.6	17,153	12,411.5	17,153	12,411.5	17,153	12,411.5	17,153	12,411.5
Jet fuel air	404,990.1	369,292.1	404,990.1	369,292.1	348,842.2	194,784.1	348,842.2	194,784.1	348,842.2	194,784.1	348,842.2	194,784.1

	All scenarios	
	2025	2050
H_2 production		
Fraction of H_2 produced from natural gas that is zero carbon (%)	60	80
Fraction of H_2 produced from electrolysis that is zero carbon (%)	70	100

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