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Foreword

Hillsman and Southworth indicate that, whereas technical options to reduce emission rates exist, the fragmentation of responsibility for key transportation activities among diverse groups of decision makers requires coordination of decision making. Policies to shift to alternative fuels affect decisions by fuel suppliers and infrastructure developers. The authors suggest that additional research is needed to determine the most effective demand management strategies.

Irwin and Johnson present a preliminary assessment of the implications of long-term climatic changes due to the greenhouse effect for future conditions in Canada and the likely effects of such developments on Canadian transportation. The authors assume that emissions of greenhouse gases will be controlled so that their concentrations in the atmosphere stabilize by 2050 and that longer-term responses will reach equilibrium during the following decades.

Saricks explores noninterventionist options for reducing emissions of carbonaceous pollutants from mobile sources. The author discusses expectations from emission control systems designed to reduce the output of regulated pollutants and then explores opportunities appearing to have good potential for success for incremental control of emissions. The author concludes that evolutionary developments in most transportation activities will play an effective role in mitigating the contribution of domestic mobile sources to "greenhouse warming."

Nesbitt et al. postulate that electric vehicles could result in large reductions in urban air pollution. Consumer acceptability, however, is limited because of the short range of the vehicles. One possibility for overcoming this disadvantage is to supplement battery energy with electricity supplied through the roadway. The authors state that the technology could prove economically competitive with petroleum-fueled motor vehicles but that continuing research and development is needed to narrow cost uncertainties.

Mintz and Zerega discuss the U.S. Department of Energy's administration of oil overcharge funds and illustrate the kinds of projects that state and local officials should consider in successfully developing a conservation program.

Factors That May Influence Responses of the U.S. Transportation Sector to Policies for Reducing Greenhouse Gas Emissions

EDWARD L. HILLSMAN AND FRANK SOUTHWORTH

Transportation vehicle operations in the United States contribute 32 percent of the nation's emissions of carbon dioxide and 7 percent of the world's emissions from energy use. Technical options to reduce emission rates exist, but policies to reduce emissions must recognize the fragmentation of responsibility for key transportation activities among diverse groups of decision makers and the need to coordinate their decision making. Policies to increase vehicle fuel efficiency affect decisions by vehicle suppliers, transportation service suppliers, and those who demand transportation services. Policies to shift to alternative transportation fuels affect decisions by these decision makers, by fuel suppliers, and possibly by infrastructure developers as well. Projected long-term increases in the demand for transportation services will offset emission reductions from these policies unless service can be delivered by modes with lower emissions or demand growth can be managed, as in other sectors of the economy. Additional research is needed to determine the most effective demand management strategies.

Recent international meetings and U.S. legislative proposals have recommended reducing annual emissions of carbon dioxide (CO_2) and perhaps other greenhouse gases by 20 to 50 percent over the next 10 to 50 years to forestall or reduce atmospheric warming and other changes in global climate. The institutional structure of decision making in the transportation sector, the nature of the sector's technologies, and the processes of technological change present opportunities for and constraints on reducing greenhouse gas emissions. They require careful consideration when designing policy options to implement an emissions reduction strategy. Some of the more important opportunities and constraints, their causes, and the implications they may have for policies that might reduce greenhouse gas emissions are identified.

TRANSPORTATION'S CONTRIBUTION TO GREENHOUSE GAS PRODUCTION

Vehicle operations in the U.S. transportation sector consume 28 percent of the nation's energy, 97 percent as petroleum fuels (*1*). It is estimated that this contributes 32 percent of the nation's emissions of CO_2 from energy use and 7 percent of the world's emissions of CO_2 from energy use (*2*). Highway transportation modes consume 73 percent of the energy used in vehicle operations (*1*) and will be the focus of any effort to reduce greenhouse gas emissions significantly.

In addition to vehicle operations, transportation contributes to CO_2 emissions through

- The energy used to refine petroleum into fuels,
- The energy used to make and maintain transportation vehicles,
- The energy used to build transportation infrastructure,
- The energy used to make the materials from which vehicles and infrastructure are made, and
- The chemical processes of producing cement for infrastructure.

Transportation also contributes other gases that contribute to global warming: mobile air-conditioning equipment used in transportation is a significant emitter of chlorofluorocarbons (CFCs), and the natural gas pipeline system releases some methane (CH_4). Finally, motor vehicle operations release significant amounts of nitrogen oxides (NO_x), which may be precursors to nitrous oxide (N_2O), another greenhouse gas, and carbon monoxide (CO), which may retard removal of CH_4 from the atmosphere. CFCs, CH_4, and N_2O contribute more per molecule to warming than does CO_2, and together at present atmospheric concentrations these other greenhouse gases may contribute roughly as much to warming as CO_2 does now (*3*).

Efforts to reduce the transportation sector's emissions will require such potentially radical changes as fuel switching, rapid movement of new and cleaner vehicle technologies from prototype to production and marketing, and substantial modifications in the demand for transportation services. The speed at which such changes will occur depends largely on the speed with which the innovation process leads to technological breakthroughs in fuel and engine designs, the methods adopted for bringing such advanced technology to the marketplace, and the response of the marketplace (i.e., businesses and households) to both private-sector and public-policy initiatives to change the way we travel. Much has been written on the technical aspects of new fuels and engine designs (*4–6*). Relatively little analysis has been devoted to how the sector's processes for making decisions affect its ability to adapt to change and the choices it makes about the supply of, demand for, and use of these new technologies.

The transportation sector changes incrementally. Since World War II, the structure of the U.S. economy has changed slowly but dramatically through growth and major shifts from the Northeast to the South and West. The transportation sector has responded with new infrastructure, vehicle technologies,

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services, and demands. Change on this scale, at this pace, can apparently be accommodated. Considering the long lead times required for investments in relatively inflexible transportation infrastructure and plant and operating equipment and at the same time the major revisions in government regulation of transportation service supply, the transportation sector has demonstrated a remarkable capacity for institutional change during the past three decades. This flexibility will probably be tested to its limits if a concerted effort to bring about environmentally sound transportation systems becomes necessary because of global warming.

STRUCTURE OF DECISION MAKING IN THE TRANSPORTATION SECTOR

Although it is conventional to divide the transportation sector into modes, analysis of the sector's decision making is more meaningful if it is divided according to decisions made with respect to five major activities:

- Infrastructure supply,
- Vehicle supply,
- Fuel supply,
- Transportation services supply, and
- Demand for and consumption of services.

With a few exceptions (notably railroads and pipelines, which supply both services and their own infrastructure, and households or businesses that supply transportation services to meet their own demand), businesses that engage in one of these activities do not engage to any significant extent in the others. All the activities involve decisions about large, long-lived capital investments that require long lead times. Once made, these investments constrain subsequent decisions in the sector. The number, size, and influence of individual decision makers vary with the different activities.

Infrastructure Supply

Infrastructure developers are relatively few in number, and governments are the primary decision makers for several modes. Federal and state governments have primary responsibility for developing and building highways, and the federal government has this responsibility for inland navigation. Federal, state, and local governments develop port and airport facilities, but local governments are significant only in developing general aviation airports, which contribute relatively small quantities of greenhouse gases. Local governments are significant decision makers in providing streets and in determining associated spatial patterns of demand for services. Private-sector development of infrastructure is limited to (*a*) railroads, of which, following the mergers of the 1980s, fewer than 20 of the largest account for most of the track; (*b*) oil and gas pipeline companies, which number roughly 136 and 1,700, respectively; and (*c*) a dozen or so major airlines, whose investments in terminal facilities at hub airports affect airport capacity.

Each of these organizations typically contracts with much larger numbers of other businesses that build the infrastructure, but in general it is necessary to influence only the relatively small number of actors mentioned to effect change in the provision of infrastructure. Lead times to plan and build new infrastructure can range from a few years to a decade or more, depending on the mode and local circumstances.

Vehicle Supply

The same is true for vehicle suppliers. Worldwide, there are no more than 30 significant automobile suppliers (*7*). The U.S. market for automobiles and light trucks is supplied by the "big three" domestic automobile makers, a half dozen Japanese manufacturers operating or building plants in the United States, and imports from another dozen or so major manufacturers worldwide. Only seven major heavy-truck manufacturers and only two major diesel-electric railroad locomotive builders currently produce in the United States. A handful of companies dominate the world's production of commercial aircraft and engines.

Once again, these large companies contract with a much larger number of small enterprises to supply vehicle components. Significant change can be brought about by policies aimed at the major companies. However, lead times for new products are 3 to 5 years in most modes if a commercial prototype exists and longer if such a prototype must be developed. Production of successful designs may run for 6 years or longer and, once added to the fleet, a vehicle may operate for 7 to 20 years, depending on the mode. Therefore, major changes in the stock of vehicles can take 10 to 15 years or more to implement.

Fuel Supply

Petroleum supplies 97.4 percent of transportation fuel, and 74 percent is refined by the 16 largest oil companies. A much larger number of companies are involved in transporting, distributing, and selling the fuel to the final consumer. Again, investments tend to be long-lived, and lead times for fuel supply and transportation facilities tend to be long; those for fuel retailing can be much shorter.

Service Supply

Stephenson (*8*) categorized the nation's commercial transportation service suppliers in 1987. There were 856 Class I truckers (with $5 million or more in annual revenue), 1,266 Class II truckers, 35,500 smaller Class III truckers, and between 100,000 and 150,000 owner-operator trucking firms. There were 14 major airlines (with $1 billion or more in annual revenues), 80 smaller national and regional carriers of various sizes, and 169 commuter and cargo airlines. There were 18 Class I railroads (with $50 million or more in annual revenues) and 481 smaller Class II and local railroads, including many short-line operators. Waterborne transport consisted of a mixture of businesses, none of which dominated the mode. To these must be added bus and taxi companies and the vehicle fleets of governments, businesses, and households that supply their own transportation services. The transportation service supply activity thus contains a larger and more diverse group of decision makers than the activities described previously, especially in highway transportation.

During the past decade deregulation of transportation service supply industries has led suppliers to give greater attention to reducing the costs of providing services and, in some cases, to improving the match between service provision and service demand. Increased price competition coupled with the rather stagnant transportation market of the early 1980s led to declining revenues and a reduction in investment in more efficient equipment or in other, longer-range cost-cutting measures. The age of vehicle fleets in all major transportation modes has been increasing as a result.

The airline and trucking companies, in particular, appear to be on the verge of major investments to replace aging vehicles at a time when they are also seeking to expand their services. Airlines are seeking to reduce vehicle purchase and financial costs rather than fuel costs (*9*) and are concerned that reducing the latter would increase the former; the same appears to be true for trucking companies. Energy costs are roughly 10 to 20 percent of the total costs of supplying commercial transportation services; in comparison, labor typically accounts for 40 to 70 percent of total costs. Present concerns with vehicle purchase costs may reduce the rate of fleet turnover, as may the present backlog of orders at major aircraft suppliers. The recent trend of airline companies to lease rather than purchase vehicles requires additional study to determine its effects on fleet fuel efficiency.

Service Consumption

All individuals, households, firms, and public organizations consume transportation services. Travel as an activity continues to increase rapidly. Highway vehicle miles traveled (VMT) are projected to increase at an annual rate of 2 percent for the foreseeable future (*10,11*), doubling by 2020. Growth rates for highway freight, air freight, and commercial air transportation are also projected to remain high. As will be discussed, projected growth in demand is a major constraint on the ability to reduce emissions of greenhouse gases from present levels.

Much consumption of transportation is a consequence of demand for other activities that require transportation (commuting, movement of goods); some consumption results from a demand for the experience of travel itself in leisure or social activities or as a demand for variety and mobility. On the average, U.S. households spend about 21 percent of their income on transportation services, which is more than they spend on food and clothing (*11*). Although this percentage has been reasonably constant during the past 35 years, its makeup has changed. For example, between 1969 and 1983, commuting declined from 33.6 to 30.1 percent of household VMT, and other related business activities declined from 7.9 to 4.2 percent. During the same period, discretionary VMT, notably in shopping and personal business trips, increased from 19.3 to 30.4 percent of household travel (*11*).

Even the demand for and consumption of transportation involves long-term commitments of large amounts of capital, primarily in buildings, factories, and housing. Businesses and households may relocate, but they leave behind fixed investments that constrain development of infrastructure and aggregate demand for transportation services.

Implications of the Transportation Decision-Making Structure

This decision-making structure has several implications for any effort to introduce major changes into the sector. First, the fragmentation of decision making into these five functions means that many changes, especially fundamental ones, will require measures to coordinate decisions across functional groups. The long lifetimes and large sizes of investments in the sector's various activities increase the need for coordination, because the risk that changes in one activity may not be consistent with investments in the others discourages fundamental changes. Second, the variation in size and market dominance among businesses that perform these different functions means that different approaches will be required to influence decision making. Policy instruments geared to the few rarely apply with equal success to the many. It is easier to ensure that a small number of large businesses comply with regulations than it is to ensure that a large number of small businesses or individuals do so. On the other hand, providing new information or a tax credit may influence the decision making of households, but large businesses already may have all the information they need for their own decisions, and a tax credit large enough to influence their decisions may be too large to gain political support. Thus, efforts to change decisions in the transportation sector require that policy instruments be matched to the characteristics and needs of the decision makers.

Significant reductions in the sector's potential emissions will require a carefully tailored package of instruments aimed at different decision makers. If such reductions are to be realized in the next 15 to 20 years, the long lead times and lifetimes of investments in the sector require that such a package be assembled and implemented quickly.

STRATEGIES FOR REDUCING EMISSIONS

Five broad strategies could reduce greenhouse gas emissions from the transportation sector:

- Improve methods of infrastructure construction,
- Improve methods of vehicle manufacture,
- Improve vehicle fuel efficiency,
- Switch to nonpetroleum fuels with significantly reduced greenhouse gas emissions, and
- Modify demand for transportation either by encouraging the use of transportation modes with lower emissions levels or by reducing the rate of growth in demand for transportation services.

The first two strategies are oriented toward manufacturing and are not considered further. The last three seek to reduce emissions from transportation vehicle operations and are the focus of the remainder of this paper. The relationships between technological and decision-making processes within the sector and the options chosen to influence these processes will determine the success of the strategies.

Relationships Among the Strategies

These three strategies are themselves interrelated. Table 1 and Figure 1 present estimates of CO_2-equivalent emissions

TABLE 1 EMISSIONS OF CARBON DIOXIDE–EQUIVALENT GASES FROM ALTERNATIVE HIGHWAY VEHICULAR FUELS (*12*)

		Scenario 1		Scenario 2		Scenario 3	
		CO_2-equivalent emissions[1] from present fleet and VMT, or from a 29 mpg fleet in 2020 after 2% growth/year in VMT		CO_2-equivalent emissions[2] from 29 mpg fleet with present VMT, or from 58 mpg fleet in 2020 after 2% growth/year in VMT		CO_2-equivalent emissions[2] from 58 mpg fleet in 2020 after 1% growth/year in VMT	
Fuel	**Feedstock**	GT/year	% change relative to present petroleum fleet	GT/year	% change relative to present petroleum fleet	GT/year	% change relative to present petroleum fleet
Electricity	Solar	0	-100	0	-100	0	-100
Hydrogen	Solar	negligible	~-100	negligible	~-100	negligible	~-100
Natural Gas (CNG, LNG)	Biomass	0	~-100	0	~-100	0	~-100
Methanol	Biomass	0	~-100	0	~-100	0	~-100
Compressed Natural Gas	Natural Gas	1.081	-19	.541	-60	.383	-71
Electricity	Natural Gas	*	-18	*	-59	*	-71
Liquified Natural Gas	Natural Gas	1.135	-15	.568	-57	.402	-70
Methanol	Natural Gas	1.293	-3	.647	-51	.458	-66
Electricity	Present Power Mix[3]	*	-1	*	-51	*	-65
Gasoline	Crude Oil	1.336	-	.668	-50	.473	-65
Electricity	New Coal Plants	*	+26	*	-37	*	-55
Methanol (high-efficiency plant)	Coal	2.026	+52	1.013	-24	.718	-46
Methanol	Coal	2.639	+98	1.320	-2	.935	-30
Hydride	Coal	2.677	+100	1.335	-0	.948	-29
Liquid Hydrogen	Coal	3.240	+143	1.620	+21	1.148	-14

[1] See (12) for further details. Some emissions were omitted from the calculations.

[2] Calculated by authors from the estimates made by (12); some of their assumptions may not hold up under these additional calculations.

[3] The current plant mix generates electricity from coal, petroleum, natural gas, and from sources that do not emit greenhouse gases.

*Estimates of aggregate carbon emissions from electric vehicles depend upon level of penetration assumed in the fleet; such vehicles cannot be used in some applications. Calculations of percent change for electric vehicles are on a per vehicle basis which assumes that electric vehicles would be 3 times more efficient than the internal combustion vehicles they replace. This may be unrealistic in the 29 and 58 mpg scenarios.

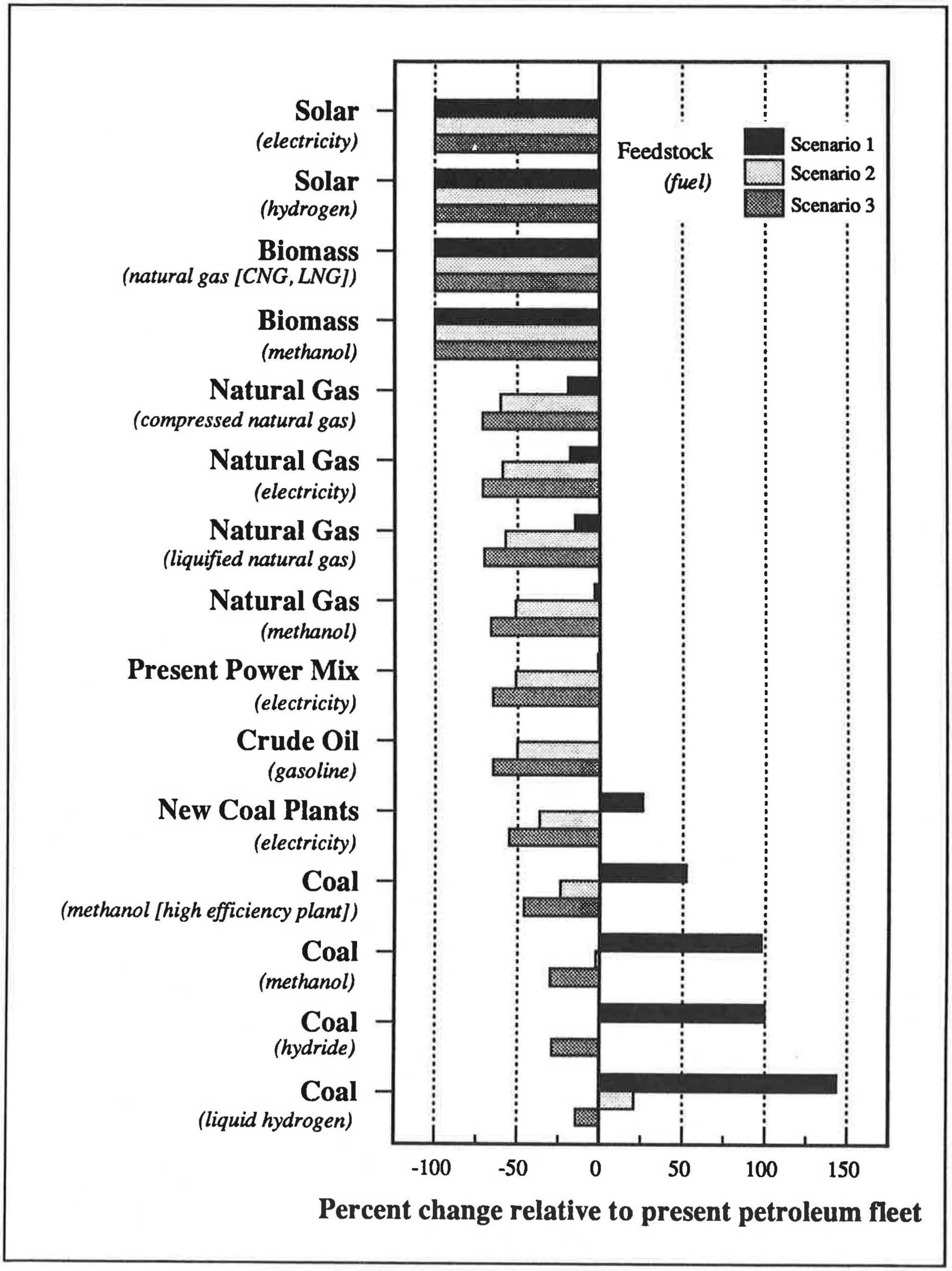

FIGURE 1 Percentage change in emissions of carbon dioxide–equivalent gases from alternative highway vehicular fuels.

(calculated on the basis of the warming effect of CO_2 and other gases) for some alternative automobile fuels and their supply systems in three fuel-efficiency–demand scenarios; the information relies heavily on work by DeLuchi et al. (*12*). The 2 percent annual growth rate in VMT assumed in the scenarios is within the range of growth projected by the Federal Highway Administration (*11*) and yields a near-doubling of VMT by 2020. Thus, a policy to double vehicle miles per gallon (mpg) for the petroleum-fueled fleet during the next 30 years would reduce *growth* in greenhouse gas emissions but would not reduce *emissions* from present levels.

Fuels from solar or renewable biomass feedstock would eliminate emissions in all three scenarios, assuming that biomass used to supply fuels was regrown. In the first scenario (present demand and mpg or doubled demand and mpg by 2020), replacing petroleum fuels with natural gas or with electricity from the present power plant stock would yield modest reductions in emissions—less than the 20 percent target that some have proposed. Although Table 1 does not present the effects of switching fuels when demand increases and fuel efficiency does not, it is clear that under such a scenario growth would more than offset the emission reductions that switching to natural gas would achieve. All coal-based fuels would increase emissions in the first scenario.

In the second scenario (present demand with doubled mpg or doubled demand with quadrupled mpg), all the fuels derived from natural gas would reduce emissions by at least 50 percent, and methanol from coal would reduce emissions by 24 percent from present levels. In the third scenario (halved demand growth rate with quadrupled mpg), VMT would increase nearly 35 percent by 2020. Increased fuel efficiency would allow all the coal-based alternative fuels to reduce emissions from present levels, but still by less than 50 percent, and still by less than what improved fuel efficiency would permit natural gas- or petroleum-based fuels to achieve.

Growth rates projected by the Federal Highway Administration for heavy-truck VMT are even higher than the 2 percent/year used in Table 1 and Figure 1, as are growth rates for commercial air traffic projected through 2000 (*13*). Thus, although the emission totals and reductions for these modes would differ from those for automobiles, a general problem remains of reducing emissions while demand increases.

Strategies to improve fuel efficiency, switch fuels, and reduce VMT are related in another fundamental way. Two obstacles to the use of alternative fuels are the large quantity of fuel that must be supplied to the vehicle fleet relative to the availability of some fuel feedstocks (biomass and some sources of natural gas) and the lower energy density and reduced vehicle operating range for a volume of alternative fuel. Improving vehicle fuel efficiency reduces the quantity of fuel needed to supply a vehicle fleet, as does reducing growth in demand for travel. In addition, improvements in drivetrain efficiency, vehicle weight, and aerodynamics are largely independent of fuel and engine technology and would allow a given volume of fuel to provide a greater operating range. Thus, doubling fuel efficiency and switching to methanol, a fuel with half the energy density of gasoline, would leave the range of the vehicle unchanged from present expectations and experience and might improve the attractiveness of methanol-fueled vehicles to potential purchasers.

Because of these interrelationships, a policy to reduce greenhouse gas emissions from present levels should view the strategies as complements rather than as substitutes for each other. For convenience, however, the three strategies will be discussed separately.

Improving Fuel Efficiency

Several trends may reduce CO_2 emissions slightly in the short term (less than 10 years) even without a change in policy. First, the average new vehicle being marketed is more fuel efficient than the average vehicle now in service for automobiles (30 percent), heavy trucks (15 to 20 percent), railroad locomotives (15 percent), and commercial aircraft (*1,8,14,15*). The process of vehicle replacement thus will cause some reduction in fuel consumption and emissions. Second, average new-car fuel efficiency has been improving slightly even in the absence of stricter efficiency standards, and the technology to improve fuel efficiency continues to develop for several reasons (*4*) unrelated to fuel efficiency (for example, to reduce passenger compartment noise, maintenance requirements, or manufacturing costs). The effectiveness of these trends in reducing CO_2 emissions is limited by the long time periods needed to replace entire vehicle fleets—on the order of 20 years for cars, longer for commercial aircraft—and by anticipated increases in the demand for transportation. In addition, preferences of vehicle purchasers for vehicle characteristics other than improved fuel efficiency will reduce the improvement in fleet fuel efficiency below what existing technology could achieve.

A technology base exists for increasing the rate of improvement in fuel efficiency for automobiles, which consume 44 percent of the energy used in vehicle operations, and probably for other modes as well. The U.S. Department of Energy has estimated that proven technology could substantially improve new-car fuel efficiency to 35 to 40 mpg and be cost-effective at gasoline prices of $1.50 to $2.00 per gallon (*14*). Bleviss (*4*) reports prototypes developed by European automobile makers that would average more than 60 mpg in city driving and 70 mpg in highway driving, in some cases with vehicle price, passenger space, and comfort comparable with cars now on the market. Although many of these prototypes use diesel engines that may be unable to meet restrictions on other pollutants, the prototypes also use technologies that would improve fuel efficiency regardless of engine type. It is likely that additional technologies to improve fuel efficiency exist but are not now cost-effective. Although some disagreement exists about the cost of achieving different levels of fuel efficiency, there appears to be agreement that the technology is available to improve fuel efficiency. Two factors limit its rapid introduction.

First, although "quick fixes" can be introduced into automobile product lines in 3 to 5 years, good solutions usually require more than one product generation (*7*). Quick fixes frequently sacrifice cost or performance of the vehicle in order to achieve the objective of the fix (improved fuel efficiency in this case), whereas good solutions require less sacrifice and sometimes yield improvements in cost or other performance characteristics as well as in the targeted objective (*4*). The normal process of technological change in vehicle design and manufacture is incremental, in large part because of the complexity of the vehicle and the manufacturing systems that produce it (*7*). Exceeding this pace increases technical risk for the manufacturer and the subsequent risk that vehicle purchasers will be dissatisfied and will purchase from a competitor.

Second, even if technological change entailed no technical risk in the product, the fragmented decision making in the sector would place a manufacturer or component supplier at financial risk. Decisions taken today to improve vehicle fuel efficiency might fail to match consumer demand for fuel efficiency once the new product reaches the market in 3 to 5 years. This could place the manufacturer at a disadvantage relative to other manufacturers who choose not to improve the fuel efficiency of their products. Thus, decisions of one manufacturer to produce vehicles need to be coordinated with those of other manufacturers and with the decisions of service suppliers who purchase vehicles.

One way to effect this coordination is through average fuel economy standards such as those imposed in the 1970s to improve automobile fuel efficiency. The corporate average fuel economy standards assured each vehicle manufacturer that its competitors would provide comparable levels of fuel efficiency even if future demand for fuel efficiency decreased (as in fact has occurred). This reduced a major source of uncertainty for the manufacturers (*4,5,7,15*). In addition, by requiring continual, gradual improvements in fuel efficiency to levels announced in advance, the standards reduced the technical risk of having to make major changes in vehicle design all at once in order to comply with the standards. A recent analysis by Greene (*16*) indicates that since the automotive fuel efficiency standards were imposed in 1975, they appear to have been at least twice as important as market trends in fuel prices in affecting automobile makers' planning for future products.

One suggested alternative to standards for coordinating decision making is to use higher fuel prices or fuel taxes to encourage the purchase of more fuel efficient vehicles and thus to encourage manufacturers to supply these vehicles. However, von Hippel (*17*) concludes that when automobiles reach a fuel efficiency of approximately 30 mpg, or slightly above the current new-car average fuel efficiency in the United States, the life-cycle cost of improving fuel efficiency offsets reductions in the life-cycle fuel cost from lower fuel consumption. As a result, purchasers become indifferent to further improvements in fuel efficiency, even for large increases in the price of fuel. In addition, households behave in the aggregate as though they use discount rates well above market rates to value future savings from lower fuel consumption. Von Hippel's analysis suggests that the point of indifference to higher fuel efficiency already has been reached in the domestic automobile market, and that higher fuel prices or taxes will have little direct effect on the fuel efficiency of new cars being purchased. The principal value of higher fuel taxes would be (*a*) as a signal to manufacturers and purchasers that the government considers fuel efficiency to be important and (*b*) as a source of revenue that could be used to fund other measures to reduce emissions of greenhouse gases from transportation.

Although highway vehicles with greater fuel efficiency could be marketed in 3 to 5 years, most of the vehicles they replace would continue in service with other owners instead of being removed from service. Half of the automobiles sold in a given year still will be in use 10 years later, and trucks remain in use for even longer periods (*1*). Thus, an additional decade would pass before the new vehicles begin to reduce fuel consumption significantly, and close to another decade would pass before the fleet turns over completely. Given the large market and long useful lifetimes for used vehicles, efforts to accelerate fleet turnover are likely to be very expensive. Therefore, if policy makers conclude that significant improvements in fuel economy are needed to reduce emissions in 15 to 20 years, policy instruments must be enacted quickly to meet such a schedule.

The recent emergence of global markets for vehicle manufacturers is a further and increasingly important factor in the sector's ability to change. It complicates the choice of options for implementing policy. In the case of automobiles, the United States is such an important portion of the global market and economies of scale are sufficiently important to competitiveness that setting standards for the performance of vehicles sold here can influence the performance of vehicles marketed elsewhere (*4*). On the other hand, requiring domestic commercial airframe and engine manufacturers to improve vehicle performance could place them at a disadvantage relative to foreign manufacturers, especially in foreign markets. In such a case international as well as national agreements on vehicle performance may be needed before implementing domestic policies.

Finally, the behavior of transportation service providers in operating and maintaining vehicles needs to be coordinated with vehicle designs that improve fuel efficiency. Unlike changes in vehicle technology, changes in operating and maintenance practices can be implemented in a few years and bring about immediate reductions in greenhouse gas emissions. For example, increasing automobile speed to 65 mi/hr from 55 mi/hr can reduce fuel efficiency from 5 to 30 percent, depending on the vehicle (*1*), and idling the engine of a heavy truck to keep fuel warm during prolonged cold-weather stops uses much more fuel than a fuel heater (*18*). Short-duration training programs for automobile drivers have been shown to reduce fuel consumption by 10 percent in the short term (*19*). However, additional research is needed to determine the most effective means of providing this information and, because little is known about how long changes in operator behavior persist after short-duration training, additional research is needed to determine how best to deliver information for long-term retention and use.

Similarly, poorly maintained vehicles consume more fuel than those in tune. Augmenting state and local automobile inspection programs so that they test fuel efficiency as well as other emission control and safety equipment could reduce fuel consumption. Trucking and airline companies are beginning to anticipate a shortage of skilled labor to maintain vehicles and are placing greater emphasis on the expected maintainability of what they buy (*20*). If inspection and maintenance programs for automobile fuel efficiency become widespread and stringent, these programs might cause automobile makers to design vehicles that require less cost and effort to maintain and perhaps also reduce the long-term cost of the inspection program.

An additional obstacle may arise if the federal government requires programs to encourage changes in operator behavior but leaves implementation to local or state governments, as has occurred in the past. Implementation of inspection and training programs at local or state levels promotes flexibility and tailoring of the programs to local circumstances. However, effective programs (especially requirements for inspection and maintenance) may not have the political and financial resources needed to realize their potential.

Switching to Cleaner Fuels

If greenhouse gas emissions are measured at the vehicle exhaust, then electricity, hydrogen, natural gas, methanol, and ethanol all yield fewer emissions than petroleum fuels (*21*). However, the production and supply systems for each of these cleaner alternatives require energy and can emit greenhouse gases. The net effect of switching from petroleum to other fuels depends on the combined production and consumption system. Any policy to reduce greenhouse gas emissions by switching from petroleum to other fuels should consider the feedstock, the processes to be used to convert it to fuel, the form of the fuel, and the level of demand anticipated (see Table 1 and Figure 1).

Vehicle technologies that use alternative fuels have been demonstrated commercially (*5,22*), although electricity cannot power all modes and the performance of presently available electric highway vehicles remains extremely limited compared with that of petroleum vehicles. Recommendation of a choice of alternative fuels is beyond the scope of this paper except to note that electricity from nonfossil sources or nonemitting solar or biomass fuel feedstocks are probably the only long-term solutions to prevent atmospheric concentrations of greenhouse gases from increasing. However, a policy to switch to an alternative will need to coordinate decision making across the five activities of the transportation sector.

As discussed at length by Sperling (*5*), the introduction of vehicles that use alternative fuels requires assurance to the vehicle suppliers and to the service suppliers who purchase vehicles that the alternative fuel will be available for the expected lifetimes of the vehicles, competitively priced, and reasonably convenient. Potential suppliers of alternative fuels, on the other hand, require assurance that there will be vehicles and demand for the fuel before they will invest in supplying it. Production of methane and electricity requires less coordination than production of alcohol fuels because they already have large end-use markets outside transportation and could absorb small, gradual increases in demand from transportation. However, electric vehicles that require an electrified right-of-way would require coordination with infrastructure suppliers to assure vehicle manufacturers and purchasers that the vehicles could be used. Without these assurances, the long lead time between a decision to invest in alternatives and a return on the investment makes switching fuels extremely risky.

A technical solution to some coordination problems is dual-fueled vehicles that can use either petroleum or an alternative fuel (*5*). Such vehicles have been demonstrated for methanol and compressed natural gas, but they usually incur penalties in cost, fuel efficiency, and performance relative to single-fueled vehicles. For example, dual-fueling might not incur any fuel efficiency penalty when petroleum fuels are used, but the vehicle would not be optimally efficient with the alternate fuel.

The need to coordinate decision makers would be greatest for highway modes for several reasons. First, this portion of the transportation sector contains the largest number of decision makers, primarily among service suppliers. Second, within a few broad categories (light trucks, heavy trucks, and cars), highway vehicles are functionally homogeneous. When combined with a slow turnover of the vehicle fleet and a relatively stagnant vehicle market, this homogeneity makes it difficult for alternatives to penetrate the market. Within each category, most vehicles are designed to be and are used as general-purpose vehicles under a wide range of conditions; the vehicles are not specialized for a specific trip purpose, driving range, geographic area, or time slot. The flexibility, mobility, and quality of service of these vehicles deteriorate rapidly if fuel supplies are uncertain or restricted in quantity or geographic range, as was evident during the oil supply interruptions of the 1970s. Finally, the relatively stagnant growth of the U.S. automobile market compounds the problems of market homogeneity, because an alternative must take market share from existing product lines instead of from growth in the market.

The exceptions to this generalization are commercial service suppliers who own their own fleets and operate within an urban area or between a small number of urban areas; they include airlines and railroads as well as some service suppliers who use highway vehicles. If these service suppliers have assurance that the fuel will be available, they can provide their own refueling facilities and schedule the operation of their vehicles to ensure that these facilities will be adequate. However, these suppliers account for only a small proportion of highway vehicles, which consume the most fuel.

Brazil, Canada, and New Zealand all have adopted policies to switch portions of their highway vehicle fleets from petroleum to alternative fuels (*5,22*). On the basis of this international experience, effecting a switch to alternative fuels requires a concerted, strong, well-funded package of government actions directed at a variety of concerns and various decision makers. Measures are needed to ensure the production of the alternative fuel; these are highly dependent on the alternative chosen (*5*). Measures are also needed to ensure

- The retail price competitiveness of the alternative fuel,
- The availability of the alternative at enough locations and in enough quantity to make refueling convenient,
- The conversion of existing vehicles and the production of new vehicles to use the alternative in sufficient quantity to provide a stable market for suppliers of the alternative, and
- The availability of personnel who are competent to convert existing vehicles and to maintain vehicles that have been converted or designed to use the alternative.

Modifying Demand

Demand for transportation services affects greenhouse gas emissions both in its size and in the choice of transportation modes used to provide the service.

Most of what is understood about individual transportation demand involves mode choice rather than the decision or need to travel. Most research on mode choice has emphasized the choices commuters make between the automobile and travel by rail transit, bus, carpooling, or vanpooling, in which high-occupancy vehicles (HOVs) deliver a service that is perceived to differ qualitatively from individual car use. Research on commuter mode choice and policies to influence it have been motivated by desires to reduce energy consumption, reduce traffic congestion, improve urban air quality, and plan investments in infrastructure. Each of these objectives should prompt continued interest in mode switching, even in the absence of concern over global climate change.

Options for influencing mode choice include

- Controls on parking and highway use (including provision of HOV lanes),
- Fiscal incentives and subsidies that increase the cost of solo commuting relative to HOV modes or that reduce costs for developers and business tenants who promote HOV use by their companies and employees; and
- Informational incentives such as advertising and moral suasion directed at businesses and individuals to promote or use HOV modes.

With the exception of a small (but growing) number of dedicated HOV bus-rideshare lanes, these options have had limited success in shifting commuting demand from private automobiles to HOV modes (*23*). People value highly the privacy and convenience of the automobile. However, the lack of success of many schemes may also be due in part to the local nature of the effort. As in the case of vehicle inspection programs, local implementation of mode-switching programs enables plans to draw on detailed local understanding of opportunities and constraints on various mode-switching options. However, even with support from the private sector, local governments often find it difficult to change people's preferred travel behavior. Federal funds to support local mode-switching efforts would reduce the vulnerability of these efforts to loss of local funding and might promote more effective local plans. In addition, these past efforts have been small in comparison with the federal expenditures, funded from user taxes, that support the provision of infrastructure for the modes from which switching is desired.

Approximately one in five commuters in 1983 was a ridesharer (in a carpool or vanpool), which reduced the nation's transportation energy use by an estimated 4 percent (*23*). Only about 6 percent of commuters used public transportation (*11*). Even doubling the proportion of commuters who share rides would yield only a small reduction in the rate of greenhouse gas emissions, because commuting accounts only for 30 percent of annual highway VMT.

On the other hand, there is great potential to reduce future demand for transportation energy by reducing the growth rate in demand for transportation services, as the estimates in Table 1 indicate. Unfortunately, too little is understood about the determinants of demand for transportation service to permit the design of policies to reduce the projected growth rate in VMT by a significant percentage. National forecasts of demand still depend largely on projecting present trends into the future instead of on an understanding of how changes in the locations and behavior of individuals and businesses affect the number and lengths of trips demanded. Most transportation planning takes projected demand as something given and then attempts to satisfy it instead of taking a more integrated approach that asks whether it might be more cost-effective to reduce future VMT growth.

In this regard, although transportation planning has a rich literature, its approach to demand today is similar to the way electric power systems planning approached demand before the mid-1970s; since then, the electric utility industry has begun to recognize the potential to reduce service costs by modifying projected demand instead of accepting it (*24*). Analogous efforts in the transportation field can be found in the promotion of flexible work time and staggered work hours, opportunities to substitute telecommunications for physical movement, and land-use planning or other measures to reduce the number or length of vehicle trips for commuting and shopping.

Pursuing the comparison between sectors, efforts to manage electricity demand growth have occurred in a decision-making structure that is much less fragmented than that in the transportation sector. For example, the activities of supplying infrastructure, energy (fuel), and service are largely integrated within the electric utility, and many policies to manage demand can be directed at the utility through the public utility commission that already regulates it. In addition, the utility has a direct relationship with each customer, through metering and billing for service, which it can use to provide information and repackage its service to influence consumer demand for electricity. Research will be required to identify both alternative institutional arrangements that will better manage demand for transportation services and policy instruments to encourage these arrangements to develop. Deregulation and the increasing importance of vehicle leasing in several modes illustrate that the decision-making structure of the transportation sector can change.

A more fundamental obstacle to managing transportation demand is uncertainty about determinants of demand. For example, major uncertainties exist about how people and institutions will respond to changes in technologies and services that might permit (but not require) a reduction in physical movement, to the effective increase in leisure time that might result if the amount of time required for commuting to work were reduced substantially, and to the seemingly inevitable increase in urban traffic congestion during the next two decades. Plausible scenarios can be constructed that predict increased, steady, or reduced demand for travel in response to each of these conditions.

Similarly, major uncertainties exist about the effect of fuel prices on future demand. The oil price increases of the 1970s demonstrated that a significant, rapid increase in retail fuel prices can reduce demand in the short term (*25*). However, higher prices did not persist into the medium and long term to permit study of their effectiveness in these periods. In addition, improvements in vehicle fuel efficiency reduced the cost of driving despite high fuel prices. Finally, part of the decline in VMT observed following the fuel price increases may have been caused by the economic recessions induced by the higher fuel prices, not by direct consumer responses to the higher prices.

Demand for freight transportation involves similar issues of mode choice amid broad economic trends whose implications for future demand are uncertain. Railroads, heavy trucks, and inland waterways long have competed for certain types of business, but trends in the economy may change future mode choices. For example, manufacturers in many industries are switching from production strategies that rely on large inventories to strategies that maintain smaller inventories delivered more frequently in smaller lots (*26,27*). This shift toward "just-in-time" delivery favors modes with great flexibility and high fuel consumption (and emissions), such as truck and air, relative to rail and barge modes. Although railroads are successfully contesting some markets for high-value shipments, in general the potential to reduce greenhouse gas emissions by shifting freight to energy-efficient modes appears small given the continuing changes in manufacturing strategy. The long term implications of these changes in production strategy for transportation demand are unclear. In the short term, they are likely to increase demand for transportation. In the medium and long terms, relocation of some parts and materials suppliers to be near the final assembly plant will reduce demand, but it is uncertain how large the reduced demand will be relative to present demand.

In short, much more research is needed to understand the determinants of demand before policies can be formulated to reduce expected rates of VMT growth. Some large-scale experimentation or monitoring of household behavior before and after the introduction of flexible work schedules or telecommunications should be part of this effort, to determine the extent to which people use reductions in some forms of travel to increase other travel activities. The effects of land use patterns on transportation should be examined in addition to the historic emphasis on the effects of transportation access on land use. The microscale of land use planning needs more careful attention; for example, suburban office parks have the potential to reduce trip length, but their internal structure may discourage use of public transportation for commuting to them. The study of suburban "activity centers" (*28*) would complement this effort, as would the further development of combined public- and private-sector projects to encourage experimentation with such mutually designed controls on land development as traffic control warrants.

CONCLUSIONS

Aggressive intervention will be needed to reduce emissions of greenhouse gases from the operations of transportation vehicles. Much of this intervention can be directed at relatively small numbers of key decision makers, especially vehicle manufacturers and fuel suppliers, as well as at transportation service companies involved with air and rail. Such intervention, in the form of standards for vehicle fuel efficiency, requirements for the use or production of alternative fuels, and standards for vehicle operation and maintenance, could reduce substantially the expected growth rates in transportation energy consumption and the associated emissions. To achieve the maximum possible reduction from these interventions, they should be complemented by measures to encourage fuel-efficient decision making by the much larger number of people who purchase and operate highway vehicles. Unless this package of measures is complemented further, however, either by policies to reduce anticipated growth in demand or by significant improvements in the cost and performance of alternative vehicle-and-fuel systems that cause no net release of greenhouse gases, in the long term emissions will increase from present levels. These alternatives require additional research in the short term if they are to yield results that can be used to reduce greenhouse gas emission by the 20 to 50 percent levels that some have suggested may be desirable during the next 10 to 50 years.

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Implications of Long-Term Climatic Changes for Transportation in Canada

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A preliminary, strategic assessment of the implications of long-term climatic changes due to the greenhouse effect for future conditions in Canada and the likely impacts of such developments on Canadian transportation are presented. It is assumed that emissions of greenhouse gases will be controlled through international cooperation so that their concentrations in the atmosphere stabilize by about 2050 at conditions equal to the "2 × CO_2" scenario (equivalent to twice the preindustrial concentration of carbon dioxide) and that longer-term responses (e.g., melting of ocean ice cover and northward movement of permafrost, the tree line, and agriculture) will reach equilibrium during the following decades. The most significant changes affecting Canadian transportation would probably be increased marine and air services followed by a northward extension of road and rail networks and a new equilibrium between marine and land transportation that would reflect the longer shipping season in the St. Lawrence Seaway and year-round operation of the Port of Churchill on Hudson Bay. Major expenditures would be required to protect coastal transportation facilities from floods and possibly to maintain navigation in the face of lower water levels on the Great Lakes. In general, however, if global temperatures stabilize as assumed, the implications for Canadian transportation of the postulated scenario will probably be, on balance, positive for Canadian transportation. There would, however, be significant costs in adapting to the new circumstances, and a number of implications for policy and research and development are outlined.

A continuing warming trend due to increasing atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and other greenhouse gases (GHGs) that transmit incoming solar radiation but capture the outgoing infrared (heat) radiation from the earth would have significant impacts on average global temperatures and precipitation patterns. Simulations of future conditions under the "2 × CO_2 scenario," in which the concentration of CO_2 would be twice as high as the preindustrial level (it has already increased 25 to 30 percent above that level), indicate that average global temperatures would be 1.5°C to 4.5°C higher than at present. Increased absorption of solar radiation due to reduced ice and snow coverages would cause greater winter temperature increases (3°C to 12°C) in high latitudes. Though less reliable than the temperature estimates, climate model estimates of precipitation patterns suggest that there may be a relative reduction in precipitation in mid-latitudes (i.e., southern Canada) and an increase in the mid-north (i.e., between 55 and 65 degrees north latitude).

There is also considerable uncertainty regarding the rate of temperature increase. Whereas industrial, space heating and cooling, transportation, and other activities of modern society emit GHGs at increasing rates, other factors, such as atmospheric chemical reactions and the rate of absorption of CO_2 by the ocean, may act to retard or accelerate the rate of increase of these gases in the atmosphere. Recent estimates suggest that an increase in the mean global temperature of 3°C could be experienced within 30 years (by 2020) or possibly not until 200 to 300 years from now; the "most probable" estimate falls somewhere in the latter half of the 21st century, about 60 to 100 years from now. Past trends in average global temperatures and future projections (illustrating the wide range of uncertainty in the latter) are given in Figure 1.

In the absence of concerted and effective action to limit the rate of GHG emissions, there is every likelihood that global warming trends will continue as GHG concentrations increase beyond the level of the 2 × CO_2 scenario. Though "equilibrium" conditions reflecting that scenario are the basis for this paper and its broad conclusions regarding Canadian society and transportation, the longer-term consequences of continued global warming would be ominous for the viability of Canadian society.

PHYSICAL AND BIOSPHERE CHANGES IN CANADA UNDER THE 2 × CO_2 SCENARIO

A number of important changes affecting Canada in terms of permafrost, snow and ice cover, water levels, growing seasons, and vegetation regimes would be expected to accompany such climate changes:

- The southern limit of permafrost areas would move northward 200 to 600 km. This expectation is based on an estimated migration of 100 to 150 km per 1°C warming. Methane emissions from rotting muskeg in these areas might increase.
- The mean ocean level would increase in the Atlantic, Arctic, and Pacific oceans by about 1 m (with a range in the estimated increase of 20 to 140 cm by 2050). In addition, average sea surface temperatures would increase by 2°C to 3°C; Hudson Bay, the Gulf of St. Lawrence, and the Great Lakes–St. Lawrence basin would be generally free of ice; numbers and sizes of icebergs would not change predictably; the Labrador Current would become stronger and have a correspondingly increased influence on the eastern seaboard; and surface salinity on the shelf areas of Canadian coastal waters would decrease.
- In the absence of level control measures that could be taken and would probably be at least partially effective, water levels in the Great Lakes would be reduced by about 30 cm in Lake Superior; 70 cm in Lakes Michigan, Huron, St. Clair, and Erie; and 70 cm or more in Lake Ontario.

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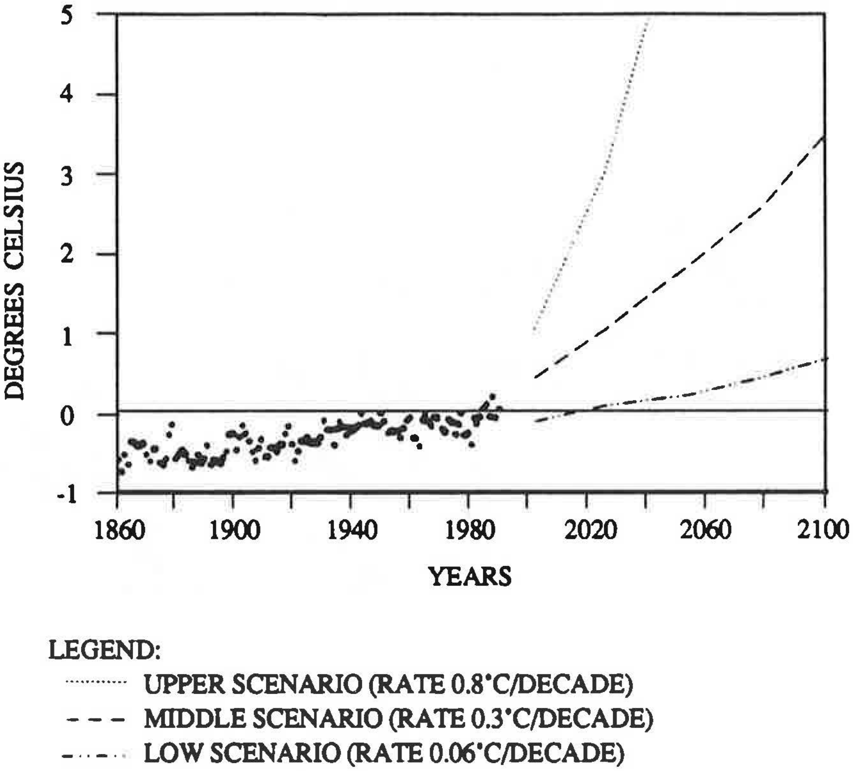

FIGURE 1 Trends in average global temperature, 1860–2100 (*1*).

- Air quality would be reduced because of increased intrusions of polluted air masses northward from industrial basins in the United States, increases in regional pollution episodes, and increases in acidic deposition (acid rain).
- Water quality would be reduced because of reductions in stream flows and basin levels. Aquatic plant growth would increase because of increases in water temperature. Some wetlands bordering lakes and oceans would dry out, and other wetlands would migrate toward lower-level coastal areas.
- Mean winter snowfall would be reduced by 20 to 80 percent in areas south of 60 degrees latitude; the greatest change would occur north of the lower Great Lakes. The snow-covered season would shorten by 2 to 10 weeks in mid-latitudes. "No snow areas" in southern Ontario would significantly increase. Sub-Arctic (e.g., in the latitude of Yellowknife, Churchill, and Ungava) snowfall would increase by 10 to 20 percent, but the snow-covered season would be reduced by 30 to 40 days owing to earlier spring and later fall seasons.
- As shown in Figure 2, the boreal (coniferous) forest would migrate northward (possibly by 200 to 600 km). The deciduous forest and other major ecosystems would move northward correspondingly and replace coniferous growth. The overall size of boreal forest coverage would probably be reduced, but the reduction would be offset at least partially by increased rates of tree growth.
- Growing seasons would lengthen. Increases would range from up to 40 days in the northern prairies to as much as 61 days in southern Ontario. Droughts might become more frequent and severe and particularly affect the southern prairies and southern Ontario regions. Grain production in the Palliser triangle of southern Saskatchewan might become marginal, and slight drops in agricultural produce might occur in other parts of the southern prairies and in southern Ontario. The increased precipitation and growing season in areas farther north, however, might produce substantial increases in agricultural yields in northern Ontario (e.g., the clay belt area around Sudbury), northern Quebec, Labrador, the prairie provinces, and British Columbia. The primary limitations would be soil availability and quality in many of these northern areas. Adaptation of farming methods and crop types (e.g., a change from spring to winter wheat in the southern prairies and to corn in portions of Ontario and Manitoba) might produce increases in these areas as well, although increases in drought frequency could introduce greater uncertainty regarding farm viability.
- Increases in vegetation productivity (up to 50 percent) and drought resistance due to direct biological impacts of 2 × CO_2 concentrations have not been taken into account in the preceding impact assessment. These may more than offset the tendencies to reduced agricultural and forest production. Net increases may result instead.
- Average winter temperatures would trend substantially upward throughout Canada, especially in the sub-Arctic and Arctic areas. Summer temperature increases throughout Canada would be smaller but still significant. The frequency and length of summer heat waves would increase; for example, the climate in southern Ontario would more closely approximate that of southern Ohio at present.

Some of these responses to climatic change, in particular the migration of permafrost areas and forest types, would lag many decades behind the date at which 2 × CO_2 atmospheric conditions might occur owing to factors such as thermal inertia

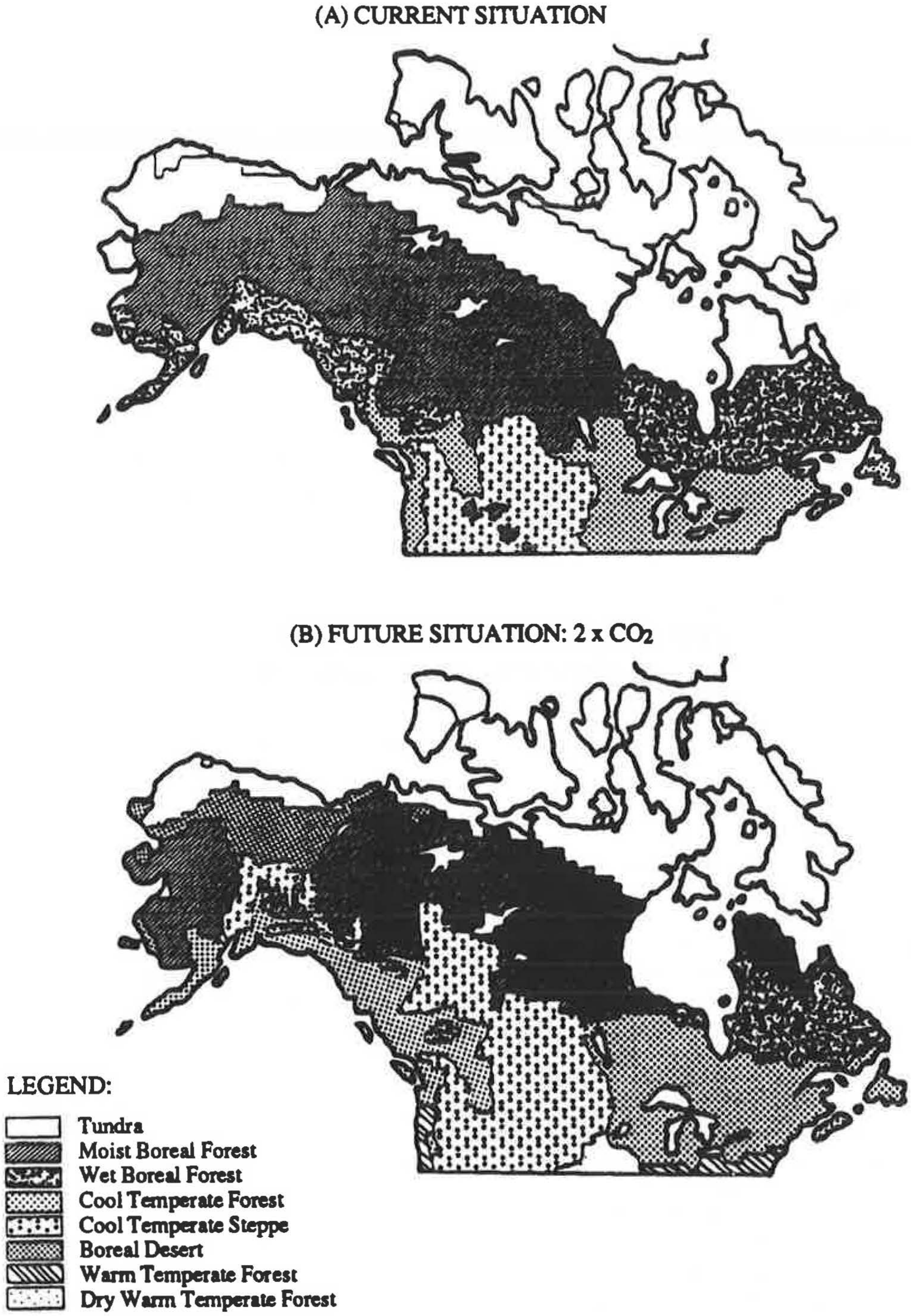

FIGURE 2 Projected changes in major ecosystem distributions under 2 × CO_2 scenario (*2*).

and biological response times. The 2 × CO_2 scenario discussed is based on the assumption that policies to limit GHG emissions result in a leveling off of CO_2 and other GHGs at double their preindustrial concentrations and that sufficient time thereafter passes to allow physical and biological responses, such as the migration of permafrost areas and forest types and the melting of some ice cap areas, to reach equilibrium with the new climate conditions.

IMPACTS ON HUMAN ACTIVITIES

The above physical and biosphere changes would be expected to have a number of impacts on societal activities in Canada. The impacts would include the following:

- Areas suitable for agriculture and forestry activities may spread northward by 200 to 600 km or 120 to 400 mi, which could substantially increase the north-south dimension of settled, agricultural areas in parts of Canada, subject to the suitability of soil types and coverage for such activities. Shorter, warmer winters and a northward migration of sea ice would also contribute to year-round mining, shipping, and related activities in sub-Arctic and Arctic areas and expansion of settlements in many northern areas of the country.

- Resettlement from low-lying coastal areas subject to increased flooding due to rising ocean levels may occur, and accompanying public works may protect such areas and related transportation facilities.
- Hydroelectric power generation could be reduced in southern areas (e.g., by about 10 percent in southern Ontario) owing to reduced flow levels but could be increased substantially in northern areas (e.g., by about 30 percent in the James Bay–Quebec power generation project with similar increases in Labrador, the northern prairie provinces, and British Columbia).
- Energy consumption for heating purposes may be reduced (by about 40 percent in most parts of Canada), and energy consumption for summer air-conditioning may be increased (by 5 to 10 percent, mainly in southern Canada).
- Agricultural output in southern Canada may be reduced, remain the same, or increase. Agricultural production may significantly increase farther north (existing areas of agriculture may experience a 10 percent increase, and new areas may come under cultivation).
- Forest production and logging may be reduced or increased, with increases more likely on balance. A shorter logging season in some areas may result from shorter winters.
- Commercial downhill skiing operations in southern Ontario and Quebec will probably disappear. Skiing seasons in northern Ontario and Quebec and in Rocky Mountain areas will probably be shorter.
- Summer tourism may increase owing to longer summers and incentives to travel farther north into cooler areas.

IMPLICATIONS FOR TRANSPORTATION IN CANADA

Transportation Supply and Cost

Table 1 summarizes the possible impacts of climate changes on supply and cost aspects of Canadian transportation—that is, on the ease with which transportation ways and terminals can be established and vehicles and other equipment operated and the overall capital and operating cost of providing transportation that results.

As indicated, there could be substantial impacts on all modes of transportation. Some of the more significant would affect ocean shipping, particularly in Arctic areas. Some of these impacts would be beneficial (e.g., deeper drafts in harbors and channels and longer shipping seasons, potentially year-round, in the Great Lakes–St. Lawrence system, Hudson Bay, and the Labrador coast area). Some would probably lead to increased costs (e.g., flooding of harbor facilities, greater need for navigation aids owing to increased precipitation and storm frequencies, and probable increases in requirements for search and rescue activities). Shipping on the Great Lakes might experience increased costs owing to reduced drafts in harbors and channels, which would require vessels to carry reduced payloads and make more trips. It seems likely, however, that this could be mitigated by structures and systems to control lake levels at close to current levels under possible conditions of reduced river flows and greater evaporation losses.

Automotive transportation (the road mode) is the dominant mode for passenger transportation, carrying 70 to 90 percent of this traffic in most parts of the country. It is also extremely important for freight transportation, particularly in southern Canada, where it carries more than half of the freight by value of commodities and about half of the tonnage. A beneficial effect of the climate trends described earlier would be substantially reduced winter maintenance activities and expenses (e.g., snow removal), particularly in southern Canada, where the shorter winter season would possibly be combined with less snowfall. In the mid-north, the benefits of a shorter winter season might be offset by greater winter maintenance activities during the season to remove increased snowfall. Impacts that would increase costs for the road mode include the need for realignments and measures to avoid flooding of coastal roads owing to increased sea levels, a shorter season during which winter roads can be used in northern areas, and a general reduction in the efficiency of heat engines caused by warmer temperatures. In urban areas, this latter effect would probably be offset by a reduction in winter warm-up times for automotive engines, which would contribute to the overall efficiency of energy use for the relatively short trips in urban areas.

Canada's railways play an extremely important role in the movement of freight, particularly bulk commodities, in both east-west and north-south directions. Coupled with marine transportation on the Great Lakes and at ocean ports, they play a central role in carrying major export commodities such as grain, forest products, and mineral products, as well as various types of manufactured goods, such as automobiles and automobile parts. Beneficial climate effects on the railways could include decreases in winter maintenance costs and, with the northward retreat of permafrost areas, an enhanced ability to stabilize the roadbed of northern lines (e.g., the line to Churchill, Manitoba). Effects leading to increased net costs could include losses of winter bulk traffic owing to year-round navigation on the Great Lakes–St. Lawrence system, realignment or protection to avoid flooding of coastal lines, and lower efficiency of heat engines owing to higher average temperatures.

The air mode would experience similar impacts of warmer temperatures, both on engine efficiency and on the lift of aircraft in warmer, less dense air, which marginally reduces allowable payloads. Although float planes would benefit from a longer season (owing to reductions in the duration of winter ice on northern lakes), the length of the season in which winter air strips could be used would be correspondingly shorter. Increases in precipitation in the mid-north could lead to more downtime or increased costs for improved navigation aids, or both.

Transportation Demand

Potential impacts of climatic change on the demand aspects of Canadian transportation are summarized in Table 2. As

TABLE 1 POTENTIAL IMPACTS OF CLIMATIC CHANGE ON SUPPLY ASPECTS OF CANADIAN TRANSPORTATION

MODE/AREA	CLIMATIC CHANGE	TRANSPORTATION IMPACTS
Marine-Ocean	Rise in ocean level	- deeper draft in harbours and channels - possible flooding of harbour facilities during storms, high tides, etc.
	More precipitation/winds	- greater need for navigation aids
	Reduction in ice formation	- winter navigation in St. Lawrence may not require ice-strengthened vessels; more winter traffic
Marine-Arctic	Reduction in ice cover	- longer shipping seasons in Labrador, Hudson Bay, etc; more use of Port of Churchill for grain, arctic resupply, etc. - more shipping in high arctic; possible greater need for icebreaking (although lower class?), search and rescue, navigation aids, etc.
Marine-Great Lakes	Lower lake levels	- reduction in available draft and efficiency of lake fleet leading to higher shipping costs - possibly could be mitigated by structures to control lake levels
	Less ice cover	- makes 11 month or year round navigation much more feasible
Marine-Mackenzie	Less ice cover, higher water levels	- longer season, increased draft and payloads
Roads-South	Generally higher temperatures	- less efficiency of heat engines (offset by less requirement for “warming up”)
	Higher winter temperatures and greater precipitation	- less winter maintenance (e.g. snow removal) in southern areas - possibly more winter maintenance further north - better drainage required

	Increase in ocean levels	- flooding of some coastal roads, with resulting need for realignments, improvements and/or protection measures
Roads-North	Higher winter temperatures	- less use of winter roads; more demand for air cargo movements - shorter seasons for winter maintenance but greater snow removal effort (increased snow fall) during the snow season
Railways	Generally higher temperatures	- lower efficiency of heat engines - possible decrease of winter maintenance although offset by greater precipitation - year-round navigation on Great Lakes will even out seasonal demand for eastbound grain transportation and remove/reduce winter peak "at and east" movements
	Reduction in permafrost	- change in new roadbed requirements for certain lines, e.g. Churchill; could be lower or higher cost
	Increase in ocean levels	- floodings at some coastal lines leading to need for realignment, improvements and/or protection measures on coastal routes
Air	Generally higher temperatures	- lower "lift" of aircraft - lower efficiency of heat engines - less use of winter airstrips - longer season for float planes
	More precipitation/winds	- more down time and/or need for navigation aids

TABLE 2 POTENTIAL IMPACTS OF CLIMATIC CHANGE ON DEMAND ASPECTS OF CANADIAN TRANSPORTATION

INDUSTRY/AREA	CLIMATIC CHANGE AND EFFECT	TRANSPORTATION IMPACTS
Agriculture-B.C. and Prairies	Increase in temperature may result in slightly increased (or decreased) agricultural volume and probably increased variety of products	- possibly greater volume but more specialized transportation requirements - possibly more exports from prairies and B.C. - possible year-round use of Churchill and Thunder Bay as grain export ports
	Change in precipitation patterns will change relative productivity of agricultural areas with northward extension of agricultural areas where soils allow and with possible higher frequency of drought conditions in southern areas	- changes in gathering system for agricultural products will be required - possible increase in annual demand fluctuations and resulting need for transportation flexibility and cost reduction
Agriculture-South Central and Eastern Canada	Increase in temperature may reduce or increase volume of products from existing agricultural areas; northward extension of agricultural areas where soils allow will add new production; possible increase in frequency of drought conditions with likely greater variety of products	- possibly more exports from Ontario, Quebec, Atlantic Provinces - likely year-round use of Great Lakes/St. Lawrence seaway transportation system for exports and other traffic - possible increase of trucking and intermodal services for flexibility and efficiency in serving changing demands, both E-W and N-S
Agriculture-Mid-North	Increase in temperature and precipitation will likely increase volume and variety of products	- greater development of clay belt, northern prairies and Peace River areas will require transportation improvements in the north

Forest Industries	Changes in temperature and rainfall will alter growing patterns	- possibly more production in north and less in south, with changes in transportation demand
Fossil Fuels	Increase in winter temperatures will reduce demand for space heating Increase in summer temperatures will increase demand for air conditioning	- lower demand for transportation of oil and gas and of coal for electricity generation - somewhat greater demand for heavy oil and coal for electricity generation in summer months
Arctic Resource Extraction	More activity	- greater demand for transportation: air. sea and land
Settlement Patterns	More dispersion of population and employment into mid-north and arctic areas	- dispersion of transportation demand with more demand in mid-north and arctic areas
Leisure Industry	More summer recreation, less skiing in south and more in north	- changes in passenger transportation demand
Global Concern About Greenhouse Effects	Possible restrictions on emissions of CO_2, CO, No_2, and other GHG's	- changes required in vehicle and heating technology (e.g. hydrogen-fuelled engines and on-board storage; electric vehicles with improved batteries or fuel cells for urban use, drawing on nuclear-generated electric energy from central plants for recharging)

noted earlier, the most significant general impact of this type would probably be from a northward spreading of agricultural, forestry, and mining activities, which would result in increased population and intensified settlement patterns in Canada's mid-north and Arctic areas. In some respects, the shape of Canada's major settled area could be changed from a ribbon (a few hundred kilometers wide from north to south and 5000 km long) to more of a rectangle. The settled area could approximate 1000 km or more in the north-south direction. The marine, road, rail, and air modes would have to expand their facilities and service coverage accordingly. This would entail substantial capital and operating costs, but on balance it would represent an economic opportunity because revenues from the increased northern traffic should more than offset the increased costs.

As indicated in Table 2, an increase (or decrease) in prairie grain production coupled with a northward expansion of production (where allowed by soil types and coverage) could lead to greater (or lower) export volumes. There would probably be an eastward trend in export movements if Thunder Bay or Churchill, or both, were able to operate 12 months per year owing to reduced ice coverage. The prairie gathering system for agricultural products would have to be extended northward. This would probably be combined with consolidation of country elevators into inland terminals, greater use of trucking on an expanded road system to the inland gathering points, unit and solid trains for rail movement to the ports, and possibly a northward expansion of rail lines.

Changes in the level of agricultural output from south, central, and eastern Canada would be less certain. Increases or decreases could be experienced in various areas, and crop types might be changed to adapt to the new conditions. There could be more exports from Ontario, Quebec, and the Atlantic provinces because year-round navigation on the Great Lakes–St. Lawrence Seaway system and a possible increase in trucking and intermodal services would provide greater flexibility and efficiency in serving changing demand for both east-west and north-south movements of agricultural products.

There would probably be enhanced agricultural development in northern areas, such as the Peace River district in northwestern Alberta and the clay belt area in northeastern Ontario, which would contribute to the requirements and changes. This is true also because of the probable northward extension of forestry activities (by as much as 200 to 600 km as noted earlier). Coniferous trees and other northern species would be logged in areas not previously forested as the tree line moves north. Hardwood and deciduous production would increase as the southern limits of the boreal forest move north and coniferous growth is largely replaced by deciduous forest in those areas.

As mentioned earlier, there would be a substantial lag (on the order of 50 to 100 years following establishment of the new climate regime) in the response of forests to the changed conditions owing to the time required for tree growth and regeneration.

Fossil fuels, such as coal, oil, and natural gas, require transportation from their areas of production, particularly in western Canada, to other parts of the country. Reductions of energy demand for space heating (by as much as 30 to 50 percent per household) would lead to reduced demand for the movement of coal by rail, although this would not be a major impact owing to the substantially greater importance of natural gas and oil as fuels for space heating in Canada. Reduced demand for movements of the latter fuels by pipeline would also be likely. The reduction in winter demand for space-heating energy would also be slightly offset by an increase in summer energy demand for air-conditioning (on the order of 10 percent according to some estimates), which would probably lead to some increase in fossil fuel consumption for electricity production during the summer season.

As noted at the end of Table 2, global concerns about greenhouse effects may lead to national and international energy policies aimed at reducing the consumption of fossil fuels, which produce CO_2, CH_4, N_2O, and other greenhouse gases. Steps in this direction would also have the effect of reducing transportation demands for fossil fuels.

Finally, passenger transportation may be affected, particularly by changes in the patterns and extent of leisure travel. There would probably be more summer travel to cottage and camping areas in cooler northern areas and to take advantage of the longer summer season. Reduced skiing opportunities in southern areas could also lead to increased winter travel to skiing areas farther north.

In general, it appears likely that there will be an increased in the geographic extent and possibly the volume of demand for both freight and passenger transportation resulting from these effects and particularly from the northward extension of agricultural, forestry, mining, and other activities.

Transportation Implications

Table 3 gives a broad assessment of the impacts of the above conditions on Canadian transportation. The first two columns in the table describe the mode/area and transportation impacts and are a slightly condensed version of the types of supply and demand impacts illustrated in Tables 1 and 2. The other six columns in the table summarize, in broad terms, other ways of describing the impacts. These may be summarized as follows:

- The geographic extent of a northward expansion of settlement and related activities in Canada could be major and would affect all four modes (marine, roads, rail, and air), leading to substantial northward extensions of facilities and services.
- Additional capital costs to maintain and restore transportation facilities affected by flooding and other climate impacts would, in general, be modest or moderate. A possible exception could be major public works to prevent decreases in water levels in the Great Lakes due to possible substantial decreases in river flows and increases in evaporation rates.
- There would be major capital costs to expand transportation systems and services into northern areas, particularly for the road and rail modes. Significant or major capital costs would also be likely for expansions to the ocean marine mode (depending on whether Canada decides to expand its own merchant marine fleet), for increased coastal trade, and for increased coast guard and defense activity in the context of substantially increased northern marine, air, and other forms of transportation.

TABLE 3 ASSESSMENT OF IMPLICATIONS FOR CANADIAN TRANSPORTATION

MODE/AREA	TRANSPORTATION IMPACTS	GEOGRAPHIC EXTENT	ADDITIONAL CAPITAL COST		CHANGE IN UNIT OPERATING COST	SCALE OF SOCIO-ECONOMIC IMPLICATIONS	NATURE OF IMPACT
			To Maintain/ Restore System	To Meet Expanded Area and/or Demand			
Marine-Ocean and Marine Arctic	Increased Export Trade	Major	N/A	Minor-Significant	Minor Decrease	Significant	Net Benefit
	Increased Coastal Trade	Major	N/A	Significant	Moderate Decrease	Significant	Net Benefit
	Ice-Free Labrador/Hudson Bay	Major	N/A	Moderate	Significant Decrease	Moderate	Net Benefit
	Harbour/Dock (Re)Construction	Limited	Moderate	Moderate	Neutral	Modest	Net Cost
	Increased Coast Guard Activity	Major	N/A	Significant	Significant Increase	Moderate	Net Cost
	Increased Defence Activity	Major	N/A	Significant-Major	Significant Increase	Moderate	Net Cost
Marine - Great Lakes	Increased Export/Import/Coastal Trade	Significant	N/A	Moderate	Neutral	Modest	Net Benefit
	11 or 12 Month Operations	Significant	N/A	Modest	Minor Decrease	Moderate	Net Benefit
	Expanded Water Level Control System	Significant	Major	N/A	Moderate Increase	Moderate	Net Cost
Roads - South	Decreased Winter Maintenance (Snow Removal)	Major	N/A	N/A	Moderate Decrease	Modest	Net Benefit
	Realignment/Protection from Coastal Flooding	Moderate	Significant	N/A	N/A	Modest	Net Cost
Roads - North	Expanded System to Serve Northern Areas	Major	N/A	Major	Modest Increase	Major	Net Benefit
	Realignment/Protection from Coastal Flooding	Modest	Moderate	N/A	N/A	Minor	Net Cost
	Shorter but Heavier Snow Removal Season	Major	N/A	N/A	Modest Increase	Modest	Neutral
	Shorter Season for Winter Roads	Significant	Modest	N/A		Modest	Net Cost
Railways	Expanded System to Serve Northern Areas	Major	N/A	Major	Modest Increase	Major	Net Benefit
	Realignment/Protection from Coastal Flooding	Modest	Moderate	N/A	N/A	Modest	Net Cost
	Reduced Winter Traffic Due to Ice-Free Great Lakes	Significant	N/A	N/A	Neutral	Modest	Neutral
	Improved Operations on Northern Lines	Moderate	Moderate	N/A	Moderate Decrease	Modest	Net Benefit
	Net Decrease in Winter Maintenance	Major	N/A	N/A	Modest Decrease	Modest	Net Benefit
Air	Expanded System to Serve Northern Areas	Major	N/A	Significant	Modest Increase	Major	Net Benefit
	Expanded Navigation Aids (or Down Time)	Major	Moderate	Moderate	Modest Increase	Modest	Net Cost
	Lower Lift and Engine Efficiency	Major	N/A	N/A	Modest Increase	Minor	Net Cost
	Shorter Season for Winter Airstrips	Significant	Modest	N/A	Moderate Increase	Modest	Net Cost
	Increased Coast Guard and S & R Activity	Major	N/A	Significant	Significant Increase	Moderate	Net Cost
	Increased Defence Activity	Major	N/A	Significant-Major	Significant Increase	Moderate	Net Cost

Legend:

Five Point Impact Scale in Declining Order: Major; Significant; Moderate; Modest; Minor
Net Benefit = Transportation revenues may increase relative to costs, possibly in the context of an overall increased transportation role
Neutral = Costs and Benefits offset each other
Net Cost = Transportation costs may increase relative to revenues
N/A = Not applicable

- Increased coast guard, search and rescue, and defense activity would also contribute to significant increases in unit operating costs. These would be partially offset by significant decreases in unit operating costs owing to extended ice-free navigation in northern waters. Other minor, modest, and moderate increases and decreases are also identified.
- The northern expansion of road, rail, air, and marine transportation services would have major socioeconomic impacts. Other changes, including a shorter winter season and its various implications, would have more moderate socioeconomic impacts.
- As indicated in the last column of Table 3, the preliminary assessment suggests that, on balance, there might be net benefits to Canadian transportation under the estimated 2 × CO_2 scenario conditions. Although a substantial number of entries in the table are expected to lead to an increase in net costs, these items tend to be less important in geographic extent, increased capital and operating costs, and scale of socioeconomic implications. A number of the more important impacts (in particular, those related to the northward extension of transportation systems) are seen as leading to a net benefit, increased revenues more than making up for increased costs.

Environmental protection in Canada's north could be an important issue and would have to be addressed. Also, as stated earlier, continuing warming beyond the scenario described here would eventually be fatal to human beings and the entire biosphere. The preliminary findings of this paper should not, therefore, be taken as an endorsement of "no action" to reduce GHG emissions. On the contrary, early and sustained action will be required if the warming trend is to be halted, and it may already be too late to achieve equilibrium at the 2 × CO_2 level instead of a higher level.

SYNTHESIS AND CONCLUSIONS

Likelihood, Timing, and Importance of Canadian Transportation Implications

On the basis of the assumption that international policies to limit GHGs stabilize climate conditions by about 2050 as described for the 2 × CO_2 scenario, Table 4 presents a summary of the likelihood, timing, and relative importance of the various types of Canadian transportation implications described earlier. A five-point scale is used, the terms in declining order of importance or likelihood being high, medium-high, medium, medium-low, and low.

The approximate timing ranges shown in the table reflect the assumption that the rate of temperature increase will be somewhat greater than the most probable trend discussed earlier (that is, that an average global temperature increase of about 3°C to 4°C will be experienced by 2050).

TABLE 4 LIKELIHOOD, TIMING, AND IMPORTANCE OF CANADIAN TRANSPORTATION IMPLICATIONS

MODE/AREA	TRANSPORTATION IMPACTS	LIKELIHOOD	TIMING	IMPORTANCE
Marine-Ocean and Marine Arctic	Increased Export/Coastal Trade	Medium	2040-2150	High
	Increased Winter/Summer Navigation	Medium-High	2030-2070	High
	Harbour/Dock (Re)Construction	High	2030-2050	Medium
	Increased Coast Guard/Defence Activity	Medium-High	2030-2070	High
Marine - Great Lakes	Increased Export/Import/Coastal Trade	Medium	2030-2070	High
	11 or 12 Month Operations	High	2020-2050	High
	Expanded Water Level Control System	Medium	2030-2050	Medium-High
Roads - South	Decreased Winter Maintenance	High	2020-2050	Medium-Low
	Realignment/Protection from Coastal Flooding	High	2030-2070	Medium-High
Roads - North	Expanded System to Serve Northern Areas	Medium	2040-2150	High
	Realignment/Protection from Coastal Flooding	High	2030-2070	Low
	Shorter but Heavier Snow Removal Season	Medium-High	2030-2050	Medium
	Shorter Season for Winter Roads	High	2030-2050	Medium-Low
Railways	Expanded System to Serve Northern Areas	Medium	2050-2150	High
	Realignment/Protection from Coastal Flooding	High	2030-2070	Medium-High
	Reduced Winter Traffic due to Ice-Free Great Lakes	High	2020-2050	Low
	Improved Operations on Northern Lines	High	2030-2100	Medium
	Net Decrease in Winter Maintenance	High	2020-2050	Medium
Air	Expanded System to Serve Northern Areas	Medium	2030-2150	High
	Expanded Navigation Aids (or Down Time)	Medium	2030-2070	Medium-High
	Lower Lift and Engine Efficiency	High	2030-2050	Low
	Shorter Season for Winter Airstrips	High	2030-2050	Low
	Increased Coast Guard and S & R Activity	Medium-High	2030-2070	High
	Increased Defence Activity	Medium-High	2030-2070	High

On the basis of Table 4 and in line with the broad assessment in Table 3, it is suggested that the transportation impacts of high importance are related closely to expanded transportation facilities and services to serve northern areas of the country and associated changes in export and coastal trade, year-round marine transportation, and requirements for coast guard, search and rescue, and defense activity.

The likelihood of a substantial northward expansion of Canadian agriculture, forestry, and settlement is considered to be lower than the likelihood of increased ocean levels and winter navigation. Northward expansion depends to some extent on precipitation forecasts, which are considered to be very uncertain. Furthermore, changes in precipitation will take substantially longer to occur because of the lag effects in the northward movement of permafrost, the establishment of forest cover in these areas, and resulting agriculture and settlement activities. This is reflected in the wide timing ranges shown in Table 4; for example, northern expansion of the transportation system is estimated to be most significant in the period 2040 to 2150, increased winter and summer navigation in northern seas is seen as likely during the period 2030 to 2070, and 11- or 12-month navigation on the Great Lakes–St. Lawrence system could occur somewhat earlier (e.g., 2020 to 2050).

Policy Issues

A number of relevant policy issues stemming from these preliminary and tentative findings include the following:

- Control of greenhouse gas emissions;
- Sovereignty and defense;
- Northern environmental protection;
- Transportation system planning and investments;
- Transportation system operation, regulation, and adaptation;
- Transportation cost minimization; and
- Continuing surveillance, research, and forecasting.

Brief comments on each policy issue will be made.

Control of Greenhouse Gas Emissions

It has been estimated that 60 to 80 percent of the measured 25 to 30 percent increase in CO_2 concentrations from preindustrial levels has been due to the burning of fossil fuels for space-heating, industrial, transportation, and other purposes. Recent data for Canada indicate that approximately 25 percent of the fossil fuel energy consumed is used for transportation purposes. This includes gasoline consumption by automobiles, trucks, and buses; diesel and bunker fuel oil consumption by trucks, locomotives, marine engines, oil pipeline pumping stations, buses, and automobiles; coal burned in electric generating stations to produce electricity for electric-vehicle operation (e.g., subways, streetcars, trolley coaches, and elevators); and natural gas and propane (used to a small extent for automotive transportation, with larger consumption of natural gas to fuel pumping stations on natural gas pipelines).

Transportation uses of fossil fuels, therefore, are probably contributing 15 to 20 percent of the emission rate of CO_2 and probably higher percentages of nitrous oxides. These percentages are probably somewhat higher than the average for all countries because of Canada's extended geography and relatively high production and transportation of bulk commodities. Even so, transportation is a significant contributor to the greenhouse effect.

Canada and other countries will undoubtedly be considering changes in their energy policies to reduce the emission of GHGs. These changes, in turn, could lead to mandated restrictions on the use of fossil fuels in transportation. Restrictions could take the form of public education for greater conservation (through fewer trips, use of smaller cars, etc.), increased taxes on such fuels, or even rationing to restrict their use. Measures of this type would, in turn, lead to increased research and development activities to develop practical means of propulsion that reduce or eliminate the production of CO_2 and other GHGs.

One such approach would be intensified development of batteries and fuel cells for electric vehicles. In order to be effective, however, the additional electricity required would have to be produced by nuclear power or some other means that does not require the burning of fossil fuels. Increased use of nuclear power, at least with existing forms of fission reactors, would have other environmental implications (e.g., the safe storage of fission products), which are beyond the scope of this paper. Another possibility, which would also require considerable research and development for practical transportation applications, would be the development of engines and on-board storage systems for the use of hydrogen as a transportation fuel. Hydrogen has the distinct advantage of creating only water vapor (H_2O) from its combustion, so its use as a fuel would probably contribute less to the greenhouse effect than would use of fossil fuels.

Sovereignty and Defense

Increased ice-free navigation in northern waters and a northward movement of settlement and other human activities in Canada and other Arctic countries would make more evident the need to assert Canadian sovereignty and provide effective coast guard and defense in the country's northern and Arctic areas. Policy issues related to transportation include the modal balance and technology used for these purposes; for example, it may be that reductions in Arctic ice could affect the required mix of vessels in Canada's navy. Consideration might therefore be given to using the funding that would have been devoted to that purpose for other types of transportation and surveillance equipment in the context of the settlement, transportation, and economic activity scenario for northern Canada by 2050 that is described earlier in this paper.

Northern Environmental Protection

As permafrost areas recede to the north, the fragility of the northern environment may be reduced. The environmental impacts of a northward movement of settlement, agriculture, forestry, mining, and related transportation activities into these areas may be more acceptable than at present. This will remain an important policy area, however, and will require careful study and consultation before major actions are taken along these lines.

Transportation System Planning and Investments

Many components of transportation infrastructure have an estimated life of 50 years or more. Given the possible timing of the above impacts, summarized in Table 4, it is therefore important that transportation system planning take these trends and possibilities into account. Major transportation investments and disinvestments should be made with the same long-term trends in mind. Policy makers would be well advised to ensure that alternatives have been considered that, though equally cost-effective during the next 2 or 3 decades, may be more so in the longer range because of a greater ability to meet changing requirements, such as those outlined in Tables 1, 2, and 3. For example, abandonment of the Port of Churchill as a grain export port and of the rail line that serves it might prove to be a costly decision if the port were to become attractive in 30 or 40 years owing to northward extensions of grain production and ice-free year-round navigation in Hudson Bay and Hudson Strait.

Transportation System Operation, Regulation, and Adaptation

Similar considerations apply regarding the shorter-term decisions affecting transportation system operation, regulation, and the possible adaptation of the system to meet such conditions. Certain transportation regulations or subsidies may no longer be applicable under the new conditions (e.g., the "at and east" rail subsidy would be obviated by year-round navigation on the Great Lakes–St. Lawrence system). As another example, it may be desirable to change certain operational requirements or regulations affecting the introduction of new technologies that could limit the GHG emissions of one or more transportation modes.

Transportation Cost Minimization

This is closely related to the preceding two points in terms of both capital and operating costs. Investment and operating decisions should be made after consideration of possible changes that would affect the transportation system if the expected climate trends take place. For example, the proposed bridge linking Prince Edward Island and New Brunswick should be designed so that an increase in the mean sea level (which could be on the order of 1 m but might be substantially more) would not compromise the integrity or safety of the bridge or that of marine traffic passing under the bridge. A modest increase in the initial investment at the time of design and construction could reduce or delay the need for extremely costly repairs or modifications at a later date.

Continuing Surveillance, Research, and Forecasting

Given the uncertainties of the climate trends and related transportation implications discussed in this paper, it is clear that Canada and other countries must continue to watch the situation closely, conduct relevant research, and continue to study and make forecasts in these important areas. Such activities will provide an early warning system that will be essential as a basis for addressing the other policy issues outlined.

Suggested Actions

A number of areas are discussed briefly in terms of suggested actions.

Monitoring of Climate-Related Variables

Clearly, Environment Canada is involved in monitoring and studying climate trends and related socioeconomic implications. The time frame for such impacts is long compared with the lifetime of elected governments and many aspects of physical and economic planning, but the potential importance of these trends is great. It is suggested that consideration be given to increased government support for monitoring of climate-related variables, including not only temperature, precipitation, wind velocities, and so forth, but also concentrations of GHGs and related trends and impacts. The difficulty of separating the "signal" of long-term climate trends from the "noise" of shorter-term fluctuations is such that the quality and coverage of information must be of the highest order.

Climate-Transportation Research Studies

In addition to the climate-modeling and related studies being carried out by Environment Canada and other researchers, it would be desirable to expand the range of studies and research related to Canada's transportation system in the context of a continuing warming trend. The following areas could be studied:

- Propulsion systems that do not burn fossil fuels (e.g., electric vehicles using nuclear electric generation, improved batteries and fuel cells, and hydrogen engines and on-board storage systems);
- Improved designs of ice-strengthened vessels and ice breakers for use in areas with light ice conditions;
- Improved designs of snow-removal equipment for heavier snowfalls in sub-Arctic areas;
- The best methods to extend the road and rail systems into the mid-north, including the most cost-effective roles of the road, rail, air, and marine modes; possible earlier use of marine and air extensions; and subsequent extension of road and rail systems;
- Protection of road, rail, air, and marine facilities from rising sea levels;
- Improved stabilization measures for roads, rail lines, and airport runways in areas of discontinuous permafrost; and
- Control of structures and systems to maintain Great Lakes water levels in the face of reduced flow levels.

Given their relative flexibility, it is likely that the marine and air modes will continue to play a dominant role in Canada's northern transportation, at least in the early years of the expected warming trend. If the trend continues, however, the land modes will also be extended northward. Rail extensions would probably be mainly oriented in a north-south direction, and highways and local roads would form a grid network such as now exists to the greatest extent in Saskatchewan and Alberta.

Environmental Protection Studies

Substantial efforts have already been made in this area regarding northern development impacts, but most have been related to specific mining or transportation projects. It would be desirable to broaden these studies to consider possible migration of permafrost areas, forest coverage, and agricultural areas; the impacts of soil suitability and coverage; and related factors. Study and policy consideration will also be required regarding the challenging issues of northward expansion in the context of native land claims and aboriginal rights.

National and International Cooperation

It is essential that Canada continue to be at the forefront of monitoring, research, and international discussions related to these trends and possible policy responses. Canada is well positioned to support and play a leadership role in such activities. As a northern country that could be profoundly affected by an unprecedented and continuing warming trend, it behooves Canada to play an active role in this important policy area.

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Review of Technological and Policy Options for Mitigating Greenhouse Gas Emissions from Mobile Sources

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Noninterventionist options for reducing emissions of carbonaceous pollutants from mobile sources are presented and explored. Expectations from emission control systems designed chiefly to reduce the output of regulated pollutants are discussed first. Opportunities for incremental control of emissions of carbon bound in gaseous form that appear to have good potential for success but do not require new federal tax or incentive measures specifically directed at the greenhouse problem are then explored. The presentation of control technologies considers, in turn, passenger vehicles and light-duty trucks, medium- and heavy-duty vehicles, and nonhighway vehicular modes. Discussion of incremental control opportunities focuses first on hardware and modification of existing fuels for reduced emissions and improved fuel efficiency, then on advanced vehicular technologies and fuels, new refrigerants, and in-use emissions testing and travel reduction strategies. Finally, opportunities for continuation of the current net downward trend in fuel consumption by most nonhighway transportation activities are described. It is concluded that evolutionary developments in most transportation activities—developments driven by the search for greater fuel efficiency, reduction of regulated pollutants, or even simple cost saving—will play an effective role in mitigating the contribution of domestic mobile sources to "greenhouse warming."

A long-standing problem with the reduction of regulated pollutants in vehicular exhaust by means of downstream devices and combustion control techniques is that the engine-out carbon is not captured by these devices, but changes only with respect to the molecular form in which it is bound [carbon monoxide (CO) and unburned hydrocarbons (VOC) to carbon dioxide (CO_2)]. However, tens of millions of dollars has been devoted by vehicle manufacturers and related suppliers to research and development in emission control technology in response to governmental regulations since the 1960s. This investment must not be dismissed simply because it did not recognize the existence of a problem with CO_2 emissions. These controls, aimed as they were at tropospheric air pollutants of both yesterday and today, constitute the starting point, the "given" base from which any strategy to reduce emissions of greenhouse gases from major transportation sources must depart. As such, they are worthy of attention for their present contribution, or lack thereof, to the latter objective. A goal of this paper is to show that many developments, both related to and essentially independent of exhaust controls, are leading toward important potential reductions in the mobile source generation of greenhouse gases.

GOALS AND LIMITATIONS OF PRESENT EMISSION CONTROL SYSTEMS

Passenger Vehicles and Light-Duty Trucks

The decision by manufacturers to incorporate a particular emission control technology in specific model lines is dictated by considerations of cost (market effect) and durability (warranty obligations). In general, the larger the engine displacement, the greater the necessity for both combustion-oriented adjustment of operating parameters and downstream, exhaust-oriented addition of control hardware (including data sensor–feedback devices) to reach required emission limits. Scale of manufacture and other economies often dictate that emission-control equipment and procedures be uniform across passenger vehicle model lines. This is also increasingly true of the lighter end of the light-duty truck market, which is now subject to emission limits similar to those for automobiles.

The most prominent emission control techniques for light-duty passenger vehicles and trucks, and whether they provide any benefit with respect to CO_2 mitigation, are discussed individually below.

Combustion Controls

Fuel Mixture The mass ratio between air and fuel during combustion is an important determinant of the distribution of raw gaseous combustion products [CO, CO_2, nitrogen oxides (NO_x), and unburned hydrocarbons] in the exhaust. Under ideal conditions of temperature and pressure, an air-fuel ratio by weight of about 14.3 to 1 yields maximum flame speed and thus maximum power. This ratio is known as "stoichiometry." However, because conditions within the cylinder of a spark ignition or compression ignition engine are far from ideal, most light-duty engines have air-fuel mixing ratios calibrated slightly lean of stoichiometry at a mixture (in the range 14.9–15 to 1) dictated by optimum performance condition requirements of the three-way catalyst system to achieve simultaneous control of CO, hydrocarbons, and NO_x.

Enriched fuel mixtures have air-fuel ratios less than 14.3 to 1. They can provide greater power increase (torque rise) per unit of time but are more susceptible to higher combustion temperatures, which can increase NO_x, and less complete combustion per stroke, which can increase CO and unburned VOC in the exhaust. Of course, they also generate more carbon per unit of distance.

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Fuel metering into the combustion chamber has become very precise in recent years because of the advent of multiport fuel injection and closed loop fuel control, which provides continuous feedback on the air-fuel mixture from sensors located in both the engine and the exhaust stream. This, in turn, has permitted gains in fuel economy—that is, less fuel is burned per unit of distance traveled. As long as they are not offset by increased power demand, these gains represent the principal contribution of air-fuel mixture control to CO_2 mitigation.

Temperature Regulation Another important determinant of raw engine emissions is combustion temperature. The production of NO_x is stimulated by the presence of excess oxygen at critical high-temperature stages of the combustion process. However, decreased combustion temperature can exacerbate formation of exhaust particulate matter. A critical issue now facing manufacturers of diesel engines is how to achieve the stringent exhaust particulate standards mandated under the Clean Air Act while remaining in compliance with NO_x standards. Any solution sacrificing the fuel efficiency that would otherwise be achievable will have a negative effect on total carbonaceous emissions.

Timing and Wall Quench The timing of spark plug firing, which triggers the explosive combustion in the cylinder of a spark ignition (gasoline) engine, is yet another key parameter in the determination of exhaust pollutants. If this timing is advanced—that is, the spark fires before the rising piston reaches its maximum penetration of the cylinder during the fuel-air compression stroke—the burn is likely to be hotter and more NO_x could be produced. On the other hand, retarding the timing reduces the force of the power stroke and cools combustion but could lead to more CO and unburned hydrocarbons. A phenomenon called wall quench, in which the shock of the explosive burn of the last part of the fuel-air mixture tends to extinguish small amounts of the burning fuel against the cylinder wall, can be important under any spark timing calibration because the unburned product, which is removed during the exhaust stroke, contains both VOC and CO. Perhaps more significant, wall quench represents a failure of the combustion process to utilize productively all of the energy available to the power stroke, which results in increased fuel consumption per unit of distance.

One recent investigation (*1*, p. E43) has sought to mitigate or even eliminate the extinguishing effect of the combustion shock wave by replacing single-spark (direct current) ignition with a semicontinuous arc-combustion (alternating current) system that provides a burn throughout the power stroke and thus consumes the available fuel almost completely. Perfection of such a system could enhance fuel economy and provide an alternative to catalysts (see below) in some vehicles, but any claims to refinement in an existing prototype are premature.

Downstream (Exhaust) Controls

Catalysis A three-way catalytic converter, in conjunction with exhaust-gas recirculation (EGR), has been the principal device for controlling CO, NO_x, and unburned VOC in automobile exhaust since 1981 and will continue to serve in that role for a majority of models in this vehicular class well into the future. This technology also became necessary for controlling exhaust pollutants in light-duty trucks in 1988 (earlier in California). The configuration is installed in virtually all gasoline-fueled light (less than 14,000 lb gross vehicle weight) vehicles, even those with multiport fuel injection, which are capable of more precise control of fuel flow but are still likely to require closed-loop control of air-fuel ratios, catalyst aftertreatment, and EGR to achieve the necessary reductions.

The predominant method of exhaust control on passenger vehicles beginning in 1975 (1979 for light trucks) was the oxidizing catalytic converter, which chemically transformed exhaust CO and unburned hydrocarbons to CO_2 and water. The three-way (oxidation/reduction) catalyst was introduced in 1981 (a year earlier in California), when it was no longer possible in most automobiles to achieve the requisite amount of mitigation of NO_x using only EGR. Since 1984, two configurations of the three-way catalyst have dominated the marketplace: single-bed and dual-bed (*2*).

A single-bed system has a three-way catalyst only, whereas a dual-bed system couples this with an oxidation catalyst. Recent predictions are that by 1990, 60 percent of light-duty, gasoline-fueled vehicles will be equipped with the single-bed system (*2*). Of the two systems, the dual-bed is believed to control CO emissions more effectively at the expense of less efficient elimination of nitrogen oxides (although the standard is still met). This is due to conversion by the second bed of free nitrogen or benign nitrogen-bearing compounds (produced by the first bed) back to nitric oxide (*3*). No system currently in planning would capture or recycle the carbonaceous component of the exhaust.

Air Pumping Pumping of supplemental oxidation air to the exhaust manifold or, after 1980, directly into the dual-bed catalyst, a technique complementing EGR for NO_x control, has been applied to increase control efficiency of the oxidation catalyst for CO and hydrocarbons, especially with larger-displacement engines. As first-generation dual-bed catalysts are phased out, air pumps, which add a parasitic load that in turn lowers fuel economy (thus increasing CO_2), are likely to be eliminated from control systems.

Medium- and Heavy-Duty Vehicles

Vehicles in this class in general share the characteristic that their gross vehicle weight exceeds 8,500 lb. In California the threshold is 6,000 lb. Therefore, vehicles that are classified as "LDT2" by the Environmental Protection Agency (EPA) for regulatory purposes in the 49-state control region are classified as "mediums" in California.

Gasoline-Fueled Trucks and Buses

Through 1989, engine calibration has been the principal method of compliance with the applicable emission standards by gasoline-fueled medium and heavy vehicles. Since model year

1987, vehicles of 14,000 lb or less gross vehicle weight in this class have been equipped with oxidation catalysts to assure compliance with more stringent VOC and CO standards. Heavier gasoline-fueled trucks and buses were specifically exempted from the new standards on the basis of evidence that catalysts of sufficient performance and durability could not be designed for their large-displacement engines and in the belief that gasoline-fueled vehicles in this class would constitute an ever-diminishing share of the fleet (chiefly because of the superior capability, on the average, of diesel engines to perform most of the required missions over the long term and in a fuel-efficient manner). Because of persistently low gasoline prices, the phaseout of heavy-duty gasoline-fueled vehicles is likely to be slower than expected at the time of the rule making. This could mean more fuel consumed in transportation than would have been the case under the originally expected rate of replacement by diesel units.

As with their lighter counterparts, gasoline-fueled heavy-vehicle engines may be adjusted to burn fuel mixtures of varying richness at a variety of temperatures to achieve desired pollutant exhaust rates, thereby effecting trade-offs in performance and fuel economy that may or may not be acceptable. To meet the 1990 (1988 in California) NO_x standard of 6.0 grams/brake-horsepower-hour (g/bhp-hr), exhaust-gas recirculation will be increased and coupled with retardation of ignition timing. Measurable negative effects on performance and fuel economy are expected (*4*). The stricter 5.0 g/bhp-hr standard for 1991 and beyond can be achieved for most vehicles in this class by application of additional EGR and recalibration, both of which will tend to increase fuel consumption per unit of distance and probably CO_2. As of 1985 about 15 percent of the heavy-duty gasoline fleet nationwide was in compliance with the 5.0-g standard, but EPA estimated that about 30 percent of the new-vehicle fleet, and especially those vehicles at the heavier end, would likely require additional hardware modifications, with an unknown effect on fuel economy and performance (*4*).

Diesel-Fueled Trucks and Buses

Analysis of control technology for medium- and heavy-duty diesel-powered vehicles (HDDVs) is inherently difficult because each manufacturer's engines are designed somewhat differently and have varying technical capabilities. Differences among weight-based subclasses compound this difficulty. However, HDDV technology is rapidly advancing to increase vehicle productivity. Enhanced aftercooling, variable injection timing, electronic engine control, increased injection pressure, and higher-efficiency, faster-response turbochargers have been introduced in many model lines to improve fuel economy; reduced emissions, especially of CO_2, can be a side benefit. In fact, most of these techniques directly affect output of NO_x and particulate matter, which is a function of how the techniques are employed. Therefore, simultaneous optimization of fuel economy and regulated emissions will be a difficult but perhaps not unmanageable task (*5*).

New vehicle technologies identified by HDDV engine manufacturers to meet the 1990 NO_x and particulate matter standards of 6.0 and 0.6 g/bhp-hr, respectively, include the following:

1. Addition of turbocharging where not currently used,
2. Turbocharger modifications to enhance efficiency and transient response,
3. Supplementary aftercooling for turbocharged engines,
4. Enhanced aftercooling,
5. Injection timing retardation,
6. Addition of variable injection timing,
7. Increase in fuel injection pressure,
8. Modified fuel injectors, and
9. Modifications of combustion chamber geometry and air swirl rate.

These strategies were cited by manufacturers in their submissions to the EPA docket on the proposed rule making for the final truck emission standards (*4*). Manufacturers also indicated that continued penetration of electronic engine control technology into the truck fleet was likely, and that this technology, though focused mainly on minimizing fuel economy penalties of exhaust and safety regulations, could also reduce total emissions per vehicle.

Applicable new technologies for compliance with the 5.0 g/bhp-hr NO_x emission standard for HDDVs that will become effective with the 1991 model year include charge cooling and air-to-air aftercooling coupled with electronic engine control. Conflict with the mechanisms used to achieve the stringent federal exhaust particulate matter standard beginning in that year (0.25 g/bhp-hr for trucks, 0.1 g/bhp-hr for buses) could lead to substantial fuel economy penalties.

The sections that follow discuss in more detail some of the cited techniques.

Combustion Calibration Techniques 5 through 9 listed above modify combustion-related parameters in the diesel engine. As in spark ignition engines, cooling combustion temperatures or delaying (retarding) the point at which fuel is introduced into the cylinder during the power stroke (Technique 5), or both, can reduce NO_x but can also reduce the fuel efficiency that would otherwise be achievable. Variable injection timing (Technique 6) may be accomplished through electronic engine control and would allow continuing adjustment of the time between each injection of fuel into the cylinders as a means of controlling combustion temperature without the net performance loss that could result from mere retardation. Fuel injector or injection modifications (Techniques 7 and 8) can also be directed at controlling flame temperature after the compression stroke: the aim, intensity, and atomization of the fuel jet as the air in the cylinder is compressed largely determines the intensity, propagation, and thoroughness of combustion. If the configuration of the combustion area itself is modified, and especially if the rate at which combustion air is swirled into the area is increased (Technique 9), lower combustion temperatures with little or no net loss in combustion efficiency or delivered power might be achieved.

Turbocharging was originally installed in diesel engines as a power booster, but it was found that its extra air charge (often from the exhaust stream) into the combustion chamber also improved fuel conversion efficiency without raising cylinder temperature, thus helping to control both particulate exhaust and NO_x. Techniques 1 and 2 recognize the importance of efficient turbocharging.

Charge Cooling, Intercooling, and Aftercooling These are all related techniques again focused on controlling combustion temperature. They may have the added benefit of increasing engine life by reducing instances of overheating and lengthening maintenance cycles (*6*). Charge cooling controls the temperature of the intake air charge without necessarily adding a power boost; intercooling recycles combustion air through a heat exchanger before reintroducing it to the chamber. Aftercooling (Techniques 3 and 4) performs much the same function as EGR in a spark ignition engine, recycling cooled exhaust gases—including CO_2 with its high specific heat and thus significant combustion cooling potential—to the combustion chamber. Of the three methods, the last may be the most effective for NO_x control.

Fuel Switching—Methanol Problems with power delivery and efficiency at high loads have raised considerable skepticism that methanol can serve as an acceptable replacement for diesel fuel in over-the-road heavy-haul truck service. However, the experience in applying this fuel alternative to urban buses (which must meet a stringent exhaust particle standard of 0.1 g/bhp-hr in 1991, 3 years before new heavy trucks are required to do so) in demonstration fleets around the country has been somewhat encouraging. Despite undesirably high rates of fuel flow at idle, diesel buses converted for operation on M100 (essentially neat methanol) have met the stringent particulate standard and, especially with two-stroke engines, can comply with current and future gaseous emission standards (*7–9*). Methanol produced from natural gas feedstock can reduce net generation of CO_2 in the production and combustion of propulsion fuels (*10*).

Diesel engineers reporting to the Society of Automotive Engineers at its February 1986 congress in Detroit speculated that fuel economy losses attributable to compliance with the 1991 and 1994 heavy-duty diesel engine standards for NO_x and particulate matter could reach 5 to 15 percent compared with fuel economy possible without the incremental control (*11*). These fuel economy loss estimates are far more dramatic than those presented by EPA (*4*) for the 5.0 g/bhp-hr nitrogen oxides emission standard considered in isolation.

Horsepower Derating with Continued Improvement in Fuel Efficiency An option for manufacturers to circumvent much of the incremental cost of add-on emission controls and still achieve major reduction in pollutant output is to refine technologies already available to get more delivered work from a given tractive effort (for example, by making productive use of "waste" heat through turbocompounding). This will permit engines of lower power rating and higher net fuel efficiency to perform missions previously reserved for the highest-displacement engines. Less fuel burned translates to lower total exhaust emissions; lower power requirements (reduction in brake horsepower hours) generally, but not always, translate to fewer grams per unit of tractive effort. A recent increase in the sales share of lighter heavy (i.e., Class 4) trucks for use in predominantly short-haul, pickup-and-delivery duty involving larger loads indicates that segments of the heavy-truck market are already moving toward lower power utilization.

Of special note with respect to diesel engines is the recent high degree of success enjoyed by import truck manufacturers creating new market niches with light-heavy (Classes 4–6) diesel trucks intended to move heavy semitrailer loads for relatively short distances in intraurban hauls. It is expected that lower-horsepower diesel units will in the future exert even more pressure to supplant gasoline-powered units in this middle weight range, once a virtually exclusive domain of the spark ignition engine.

Fuel Efficiency Improvements Since 1980 in Nonhighway Activities

The eightfold increase (in current dollars) in fuel price that air, rail, and waterborne carriers of revenue freight and passengers experienced between the early 1970s and 1980s had a delayed but profound effect on the efforts of these carriers to reduce fuel consumption through fleet modernization and greater operational efficiency. For example, the average energy consumption rate per passenger kilometer for certificated (commercial) air passenger carriers declined 46 percent from 1970 through 1984, rail freight energy intensity per ton-kilometer hauled fell by 33 percent from 1972 through 1986, and domestic waterborne commerce experienced a 50 percent savings in energy use per ton-kilometer from 1973 through 1983 (*12,13*).

Dramatic improvements like these have brought about substantial reductions in total fuel consumption for most modes despite a generally upward trend in traffic. From a level of 15.4 billion L of diesel fuel burned in 1979, U.S. railroads had cut consumption to 11.5 billion L by 1986 (*13*). Some of the specific improvements that brought about this reduction are described by Saricks et al. (*14*). Domestic waterborne commerce cut its fuel consumption by 19 percent between 1979 and 1984, and fuel burned for transmission of energy supplies in pipelines fell 13 percent in just 3 years (*13*), although some of the latter reduction may be attributable to an increase in load factor. By contrast, although revenue air passenger kilometers more than doubled from 1975 to 1985, fuel consumption of domestic and international certificated route air carriers increased only 32 percent.

Fuel consumption in nonhighway transportation (on an energy-equivalency basis) fell by 12 percent between 1980 and 1985 (*13*). This reduction in total fuel use may be converted directly, and probably conservatively, to a reduction in total CO_2. Further reductions due to efficiency improvements still under way are likely to be achieved, and there remains ample margin for even more reductions if future increases in petroleum prices prompt them.

Summary of Effects of Existing and Planned Systems

No vehicular technology to save fuel per unit of distance of operation can reduce the production of CO_2 by heat engine combustion for transportation as long as the growth rate in motorized vehicular activity outpaces the percentage improvement in efficiency represented by the technology. Moreover, because the technology required for mitigating pollution in the air was not designed for optimizing fuel efficiency and may in fact work against such optimization, the problem is compounded. Changes in travel activity and behavior that may help lessen the former concern are treated in a subsequent section. With respect to the latter concern, Table 1 summarizes the contribution to fuel-efficient operation (or lack thereof) represented by the principal vehicular air pollutant emission control technologies now in use or expected by 1995. Not surprisingly, changes in diesel systems represent the most extreme cases of emission control effects on vehicle fuel efficiency.

OPPORTUNITIES FOR FURTHER EMISSIONS REDUCTIONS

Control options beyond those already in use are examined in this section. Some of these controls are already scheduled for implementation in response to requirements not directly targeted at the operation of motor vehicles. The options fall under the categories of (*a*) hardware and fuels modification for reduced emissions and improved fuel efficiency, (*b*) advanced vehicular technologies and fuels, (*c*) new refrigerants, and (*d*) in-use emissions testing and travel reduction strategies. Each of these options attempts to ensure that current and potential standards are being met by vehicles on the road, that air quality at the local and regional scale is protected, or that stratospheric ozone depletion is mitigated; all have been demonstrated at the pilot level. Improvements in the technologies and related reductions in costs may be realized with future research and development.

Hardware and Fuels Modification

Although automobiles remain the most numerous mobile sources of carbonaceous pollution, other vehicular types emit

TABLE 1 EFFECT OF POLLUTION CONTROL TECHNIQUES ON CO_2 ABATEMENT

VEHICLE/ TECHNOLOGY	EFFECT POSITIVE	EFFECT NEUTRAL	EFFECT NEGATIVE
Light-Duty Autos/ Trucks			
Enleanment	●		
Temperature Regulation		●	
Spark Timing	●		●
Catalysis		●	
Air Pumping			●
Heavy-Duty Gasoline Trucks			
Combustion Calibration			●
Combustion Cooling		●	
New Fuels	●		
Engine De-rating	●		
Exhaust Sensor	●		
Heavy-Duty Diesel Trucks			
Combustion Calibration		●	
Combustion Cooling		●	
New Fuels	●		
Engine De-rating	●		
Exhaust Sensor	●		
Trap Oxidizer			●

greater amounts of CO_2 per unit of activity. Hardware and fuels modifications that could reduce CO_2 production from both automobiles and other motorized (including nonhighway) sources are reviewed.

Efficiency Enhancers

Bleviss (*15*) has documented a variety of near-term technology options for improving the fuel efficiency of conventional vehicles. Among the most promising with respect to reducing net fuel consumption are variable geometry valves, turbine rotors, and engine displacement; more electronic control of operating parameters; ultralean-burn engines; stratified-charge engines; ceramic engine components; continuously variable transmission; advanced materials for body parts and tires; and ultrahigh efficiency accessories. Whereas adoption of these techniques by manufacturers for use in future vehicles is highly speculative, their combined effect could improve fuel efficiency for cars and light trucks to almost 70 miles per gallon (mpg), with some sacrifice in perceived safety and performance. However, at least one analysis (*16*) has concluded that improvements that would raise average fuel economy above about 37 mpg by the year 2000 would not be cost-effective.

Advanced Catalysts

There appears to be little doubt that incremental improvement in catalyst fabrication quality control (i.e., reduced tolerances) and advances in materials science have resulted in higher functional efficiency for original equipment (OEM) catalysts during their useful life and will continue to do so in the future. One facet of continuing research is focused on (*a*) increasing catalyst crush strength and attrition resistance (to minimize loss of catalyst pellets) by modifying the impregnation of the substrate bed and (*b*) eliminating the need for some of the rhodium and platinum by applying those metals more efficiently by means of a new washcoating procedure (*17*). Ultimately, improvements in catalyst efficiency and durability will translate to reduced total fuel consumption and less CO_2.

Water and Enriched Air Injection for Diesel Engines

Injection of highly atomized water molecules into the diesel combustion chamber to form, in situ, a diesel-water emulsion is a technique currently in development. It would be able not only to reduce the cylinder combustion temperature (with beneficial NO_x effects) but also to increase the oxygen in the combustion mixture, resulting in more complete fuel consumption and thus higher fuel efficiency. However, prototype water-injection systems have been beset by problems including fouling, corrosion, and imprecise metering.

A related technique is to introduce oxygen-enriched (i.e., greater than 21 percent by volume) combustion air for more complete fuel utilization. Supplemental oxygen bottles are used for enrichment in engine test bed applications; it is expected that the ultimate source of oxygen-enriched air for duty on an operating vehicle will be gaseous diffusion or chemical dissociation technology (R. R. Sekar, Argonne National Laboratory, unpublished data). An important aim of these developments is to approach the potential peak operating efficiency of the diesel cycle much more closely.

Increased Compression Ratios for Oxygenated Fuels

Neat and near-neat (85 percent) alcohol fuels provide optimum power delivery at engine compression ratios well above those used in conventionally fueled engines. For example, the compression ratio of a gasoline-powered spark ignition engine should not exceed about 9.5 to 1 (combustion air–ambient air) to ensure proper firing and performance, but the same engine adjusted for neat methanol could operate reliably at a ratio in excess of 11 to 1. A higher compression ratio means more power delivery per stroke and thus greater response with less total fuel consumption. It is this effect of alcohol fuels that results in their ability to deliver more distance per joule of heating value output than does gasoline in the same vehicle (adjusted engine) and consequently to emit lower total exhaust pollutants per unit of distance. This principle also operates, at a more modest level, with any blend of gasoline and oxygenated hydrocarbon or cosolvent ("oxygenated fuels").

Advanced Vehicular Technologies and Fuels

As the end of the century approaches, new prospects for personal and freight transportation are appearing, spurred by advances in microelectronics, high-temperature-resistant materials such as ceramics, multifuel engine technologies, and concern for the impact of transportation on the environment. Manufacturers have reduced the curb weight of many U.S. passenger cars by up to 50 percent since the late 1970s without sacrificing interior or cargo space. Advances in high-strength, low-weight alloys and cheap, durable ceramics that can replace metallic engine parts give promise that this trend will continue.

Diesel trucks are expected to increase penetration of the medium and light end of the truck market. However, conflicts between the use of conventional diesel fuel and the 1991 and 1994 standards for emissions of NO_x and particulate matter may make it attractive for some of the heaviest of these vehicles, especially buses, to operate chiefly on nonpetroleum fuels such as methanol.

The principal technologies and alternative fuels under development that are significant to transportation are discussed in the following sections.

Catalytic Ignition

British researchers are developing a vehicular engine that incorporates a combustion system based on internal catalytic ignition. The engine design has an extra piston and a segregation chamber (not dissimilar to that in the design of some existing stratified-charge engines) that holds fuel until the instant of combustion. Air is drawn into the segregation chamber; then an electronically controlled injector sprays the fuel-air mixture into the combustion chamber, where it is ignited by a platinum catalyst. Ignition continues over the entire surface of the combustion chamber until all fuel is consumed.

Application of the catalyst means that combustion temperature can be lowered and a wide variety of air-fuel ratios (and even a variety of fuels) can be tolerated. Compared with standard droplet ignition, atomized fuel enhances power density and engine speed capability in diesel applications. Preliminary results (*18*) indicate that this engine concept has the potential to cut engine-out CO_2 emissions per mile by about 50 percent and reduce toxic emissions to zero when operating on unleaded fuel.

Multifuel Engines

Some types of propulsion engines require only the energy input of heat to function. That is, if supplemental spark detonation or compression is unnecessary, the specifications for the fuel to be combusted can be much less restrictive. Thus, low-carbon fuels such as alcohol or natural gas can readily and interchangeably be used by these engines.

One class of engine meeting the multifuel-capability criterion is the external combustion engine. Such an engine operates on the principle of heat excitation instead of explosive or compressive ignition to provide motive power. The principal example for potential automotive application is the Stirling engine.

The Stirling engine transfers heat generated by burning fuel in a chamber to a confined gas, such as H_2 or helium, which in turn activates pistons that move a rotary crankshaft. The concept was first demonstrated in 1816. Despite a long-term commitment to development of this engine for automotive use by the U.S. Department of Energy, only prototype vehicles exist today, and research and development have diminished in recent years. Owing to both the multifuel capability of this engine and its efficient combustion process, significantly reduced carbonaceous emissions with good fuel economy have been achieved in the prototypes. Despite noteworthy advances in the technology of piston head seals and improvements achieved by replacing hydrogen with helium as the working fluid, containment of fluid within the cylinder remains a problem for application of Stirling engines in the high-pressure, high-revolution environment of an automobile engine.

The Brayton gas turbine engine is another class of engine that meets the multifuel criterion. It adapts jet aircraft technology to an automotive application. Continuous combustion drives a rotating turbine that provides momentum to the vehicular power train. Prototypes have been tested in long-haul trucking, urban and intercity buses, and full-size automobiles with varying degrees of success (generally, the larger the vehicle, the more successful the application). However, no manufacturer has yet committed itself to producing gas turbine highway vehicles in commercial quantity. This multifuel engine is very fuel-efficient at high operating load, but a problem persists with high NO_x emissions and excessive fuel flow at idle. This problem, coupled with high cost and lower fuel economy, continues to render the state-of-the-art gas turbine uncompetitive with conventional automotive engines.

Electric and Hybrid Vehicles

Electric vehicular propulsion dates from the earliest years of the automobile. Electrics lost the competition with vehicles powered by Otto and diesel cycle engines around 1920 because of their inferior performance in acceleration, speed, and range, poor battery life, and the need for frequent recharging. Modern battery and power train technology have greatly improved on two of these shortcomings (performance and life), so electric-powered vehicles could now fit well into market niches in which maximum daily travel distance does not exceed about 200 km, the vehicle would never be needed for long trips, and daily (probably overnight) recharging is acceptable. Battery packs remain costly, however, and would probably have to be replaced every 30,000 to 40,000 mi given current technology (battery pack leasing arrangements are a possible solution to the high replacement cost). The primary environmental advantage of electrics over petroleum-powered vehicles, of course, is that electric power plants, not the vehicles themselves, are the source of attributable emissions. If the source of the electric power is nonfossil, net reduction in carbonaceous air emissions per unit of distance approaches 100 percent, even including vehicle production. The vehicles also run very quietly.

The weight of the battery pack makes all-electric vehicles heavy. Hybrid vehicles are essentially electrics equipped with auxiliary light-duty gasoline engines that provide both operating range extension and "limp home" capability. Because of the need for a separate drivetrain for the heat engine, prototype versions of hybrid vehicles have been even heavier than their all-electric counterparts. Gasoline fuel economy on the hybrid version is, therefore, very low. The key assumption regarding future commercial viability of hybrids is that the gasoline engine would only have to be used sparingly, if at all. Of course, any use of the gasoline engine will generate CO_2.

The unit cost of state-of-the-art, two- to four-passenger vehicles powered by lead-acid batteries at various demonstration sites around the country has averaged $15,000. However, recent initiatives in California may lead to higher production rates and consequently lower costs per copy for manufacturers presently engaged in pursuing electric vehicle technology, such as General Motors Corporation with its "Impulse" prototype. The California Clean Air Act of 1988 requires implementation by January 1, 1992, of measures that result in major reductions in vehicular air pollution in the state: a 55 percent reduction in emissions of organic gases and a 15 percent reduction in NO_x, with "maximum feasible" reductions in particulates, CO_2, and air toxics. To that end, Section 40920 of the act calls for each air pollution control district to include in its air quality attainment plan "measures to achieve the use of a significant number of low-emission motor vehicles by operators of motor vehicle fleets." At least in the South Coast (Los Angeles area) air basin, such low-emission and ultralow emission vehicles are very likely to include electrics. Some manufacturers are now working closely with the Southern California Edison Corporation and other South Coast organizations to provide, initially, several hundred high-performance electric vans for service in various fleets (*19*). These vehicles will eventually incorporate advanced battery types, including nickel-iron and sodium-sulfur systems, for even better range and performance.

Lower-Alcohol-Fueled Vehicles

The prospects for lower alcohols—especially methanol—as alternative vehicular fuels have grown steadily since it was recognized that the fuel gives off less particulate matter in burning than gasoline or diesel, emits fewer reactive hydrocarbons, and can be produced with enough efficiency from natural gas feedstock (a fuel difficult for a cartel to control) to be price-competitive with gasoline if the latter climbs to a pump price of $1.35 or so (in 1989 dollars). Like gasoline, it is a liquid at dispensing temperature, so it should be more acceptable to the driving public than a nonliquid alternative to petroleum. In theory, because methanol burns at a low flame temperature, its NO_x-forming propensity is lower than that of gasoline; consequently, engine combustion can be calibrated for very low CO_2 with no net increase in NO_x. The corollary to this—that methanol-fueled vehicles should produce significantly lower NO_x at gasoline-comparable output of CO with little or no deterioration in performance—has not been consistently borne out by either certification or in-use testing (which admittedly has been performed on nonoptimized vehicles) (*20*). If methanol is eventually produced from coal, an option often discussed as a means to achieve domestic energy independence in transportation, the resulting increase in the atmospheric loading of CO_2 for the total production and operation cycle could be twice that of the petroleum cycle for equal kilowatts supplied (*10*). Moreover, during the cold (start-up) phase of operation, methanol-fueled vehicles generate much greater quantities of formaldehyde (HCHO, a known carcinogen and highly reactive ozone progenitor) than do their gasoline-fueled counterparts (*21*). (This problem might be solved by preheating the catalyst.)

Some states are moving forward with programs that require the use of alcohol fuels or oxygenated blends (gasoline-oxygenate mixtures that can be 5 to 10 percent alcohol or a similar oxygenating compound, such as ethers, by weight). California, Colorado, New Mexico, and Arizona are in the vanguard. Because of its commitment to low-emission vehicles, California is demonstrating methanol and methanol-blend fuels in automobiles and light trucks. In addition, along with New York City; Jacksonville, Florida; Phoenix; and Seattle, California is demonstrating these fuels in urban buses specially modified to burn them. Despite concerns about "startability" and the performance of alcohol fuels in colder climates, blends of 85 percent methanol–15 percent gasoline and/or cosolvent have not exhibited such problems in federally sponsored testing under conditions of moderate to extreme cold (*22*).

As experience with 85 to 100 percent methanol fuels grows, many of the environmental goals originally envisioned for these fuels could be realized in direct combustion. On the other hand, the greatest promise for methanol, as for any alcohol, in the role of an air pollution-mitigating transportation fuel may ultimately be (*a*) in chemical dissociation technology, in which the fuel is catalytically broken down to molecular hydrogen and CO that are actually burned, producing water and CO_2 as the combustion residuals, or (*b*) as the material oxidized in vehicles powered by fuel cells, which generate almost no air pollution. Because of the higher efficiency of fuel cell propulsion compared with internal combustion engine power, a methanol-based fuel cell should produce roughly half the carbonaceous emissions of methanol burned in a combustion engine per unit of distance. A similar comparison between the relative efficiency of direct methanol combustion and postdissociation combustion of hydrogen from methanol is not available. Although fuel cell technology is still too costly to make near-term application in transportation feasible, projects are under way to accelerate the introduction of this important concept into transportation fleets, and therefore the technology is discussed more fully in a subsequent section.

Vehicles Fueled by Compressed Natural Gas (CNG)

Vehicles powered by natural gas (propane, liquefied petroleum gas) have been prominent from time to time in nations such as Italy, New Zealand, and Canada that have ample reserves of gas but a significant degree of dependence on imported petroleum. Virtually all of these vehicles have been converted to operation on gaseous fuel from stock production automobiles and light trucks, mainly by replacing seals, elastomers, and other materials subject to fatigue and embrittlement in a gaseous environment. Many are capable of running on either petroleum (gasoline or diesel) or gaseous fuel, so-called dual-fuel vehicles. In most applications, the gas is stored as CNG. It is compressed at pressures up to 3,000 lb/in^2 in cylinders bolted to the underside of the chassis and fed as needed directly to the intake manifold or the injectors.

Canada has a long-standing commitment to the use of natural gas and liquid petroleum gas (a combination of propane, butane, and other petroleum-derived gases depressurized to a liquid state) as petroleum fuels, and many gas-powered cars, light trucks, and buses now travel Canadian roads. A few light-truck and van fleets in southern California are currently fueled by natural gas, and more may be converted in response to the requirements of the 1988 Clean Air Act, but such accomplishments may not be repeatable in areas of the nation that restrict the movement of vehicles bearing compressed gases (*23*).

Though CNG, because of its low carbon mole fraction, could unquestionably assist in reducing transportation-generated carbon-bonding gases, there is still no conclusive evidence that transition to gas propulsion will significantly lower atmospheric loading of NO_x and reactive hydrocarbons. Test results for exhaust emissions of NO_x indicate a range of 85 percent reduction to 40 percent increase relative to counterpart gasoline automobiles. In general the results are a function of the amount of spark timing adjustment. Total exhaust hydrocarbons have tested from 44 percent below to 700 percent above gasoline counterparts (*24*). Whereas it is assumed that most of this is relatively inert methane, CNG also contains reactive fractions, such as ethane, butane, and pentane, that appear in its exhaust. Furthermore, expansion of a refueling infrastructure for CNG-powered vehicles, a necessity if this fuel is to make any notable penetration of the operating fleet, poses not only a potential safety problem because of proliferation of compressor units and stations, but also implies a manyfold increase in the number of potential release points of methane (a known greenhouse gas) to the atmosphere.

Flexible-Fuel "Transition" Vehicles

Hybrid vehicles and dual-fuel vehicles are two classes of so-called flexible-fuel vehicles configured to use petroleum and at least one nonpetroleum fuel for propulsion. Several hundred automobiles that can use either gasoline or methanol have also been produced, many of which are in operation in California. There is concern that, during a period of transition to nonpetroleum fuels, limited supplies of the nonpetroleum alternatives could severely inhibit the potential market for dedicated-fuel (exclusive) alternatives to petroleum power. Consequently, vehicles for which this short- to medium-term supply issue is irrelevant are likely to be much more successful in the marketplace. A continuing study sponsored by the U.S. Department of Energy is evaluating future prospects for flexible-fuel vehicles using methanol, natural gas, and electricity (*25*).

Although the indigenous environmental benefits of these vehicles relative to the all-gasoline units they replace are questionable at best, their most important characteristic is that they *can* hasten a transition to fuels cleaner than gasoline.

Fuel Cell Propulsion Systems

Fuel cells are being considered as a potential long-term replacement for internal combustion engines in buses, vans, and, ultimately, passenger cars (*26*). Fuel cell technology is used to provide auxiliary power for lunar landing craft and other space vehicles. It is based on oxidation-reduction reactions in a system closed to external inputs except for the oxidant (generally air). Today's primary challenge is to reduce the capital cost of fuel cell systems to enable their economic adaptation to automotive use. A drawback is the unavailability of "on-demand" high-load output direct from such systems. If the fuel cells are coupled with storage batteries to accommodate variation in load demand (the batteries to be kept continuously recharged by the fuel cells), however, vehicles should have little difficulty maintaining speed and power under normal driving conditions.

Methanol (CH_3OH) is one of several fuels being considered for fuel cell application, especially applications for which reactions at lower temperatures are desirable. For example, a phosphoric acid–based system now being demonstrated on a New York City transit bus vaporizes methanol and water, reforming them at about 200°C to hydrogen, CO_2, water vapor, and a small amount of CO. This mixture is then fed to a phosphoric acid anode, which triggers the energy-releasing reaction. Part of the reaction heat is used for fuel vaporization, and the rest is released through a radiator (*27*). Because virtually all of the methanol fuel is recaptured for reuse and cell operating temperature is low compared with internal combustion engines, VOC and NO_x are all but completely eliminated and, as discussed earlier, CO_2 is approximately halved.

The population of fuel cell–powered vehicles could increase steadily (if not rapidly) in test fleets for the remainder of the century; the possibilities for full commercialization, and the vehicles to which fuel cell systems are best suited, should be known within 10 to 15 years.

Hydrogen Fuel Systems

Hydrogen is an energy carrier rather than an energy source. The difference is critical: in the chemical activity that provides propulsion energy, no waste products are formed as the hydrogen simply combines with oxygen to form water vapor, releasing heat and some NO_x (but no fuel residuum) in the conversion. Thus, hydrogen is the ideal "ultralow-emission" fuel. The key issue confronting its potential application to mobile sources concerns the means for on-board storage. Alcohol was cited earlier as a possible source of hydrogen from dissociation chemistry; this dissociation could take place in the vehicle. Although the process releases extra carbon bound as CO and CO_2, the amount is far less than that generated by direct combustion of petroleum.

If hydrogen fuel is electrolytically produced in large quantities at central facilities, some of which could be nonpolluting solar-powered generating plants, transportation to distribution points and refueling could still be troublesome because of hydrogen's high explosive potential. In the vehicle, the storage medium would probably be either a dry hydride (which can adsorb large quantities of hydrogen gas for later release, but which generally has low efficiency-to-weight ratios), or a Dewar (vacuum) flask for storing the fuel as a liquid. If petroleum-competitive operating range is desired, vessels for storing liquid hydrogen will inefficiently occupy a great deal of space in the vehicle. In addition, fuel could boil off over time.

A marked advantage of any system that could make mass-produced hydrogen usable for transportation is that, if electricity for production is generated from nonfossil energy sources and the fuel produced is distributed through existing gas pipelines, the net reduction in carbonaceous pollution for the entire fuel production–vehicle operation cycle is 100 percent relative to baseline petroleum (*10*). Nevertheless, barring an important breakthrough in dissociation technology, hydrogen-powered cars and trucks are unlikely to be in service to any noticeable degree before the end of the first decade of the 21st century.

Summary of New Fuels and Net Atmospheric Carbon Production

Figure 1 depicts the relationship in net carbon loading for the entire fuel production, delivery, dispensing, and combustion cycle among the principal candidate transportation fuels for the year 2000 and beyond relative to baseline petroleum (*10*). The specific percentage values are open to interpretation, but the relative positions of the fuels in this hierarchy are accurate. Hydrogen and electricity (from nonfossil sources) are clearly the "cleanest" greenhouse fuel paths, whereas coal-to-methanol or coal-to-synfuel conversion is potentially the least desirable. Largely because it bypasses the conversion link in the

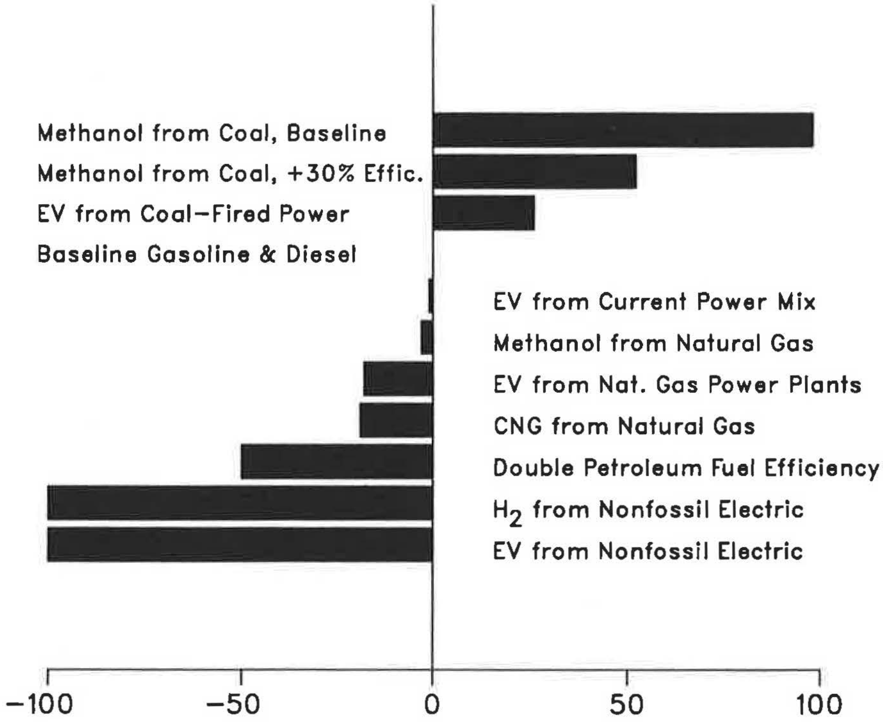

FIGURE 1 Percent change in CO_2 loading relative to petroleum cycle.

fuel cycle, CNG appears to be marginally more attractive than methanol from natural gas feedstock. The data indicate that embarking on an "energy-secure" course toward a transportation system more dependent on domestically produced coal, which would be used either as an electricity generation fuel for electric vehicles or as a liquid fuel feedstock, would be inimical to the goal of reducing transportation's greenhouse gas production.

New Refrigerants

The implication of chlorofluorocarbon (CFC) compounds ($CFCl_3$, CF_2Cl_2) poses a major challenge to the motor vehicle industry and its suppliers. CFCs are extensively used in industrial foam-blown fabrication processes and are almost exclusively the refrigerant used in vehicular air-conditioning systems. They are among the more pernicious greenhouse gases, having a temperature increase potential, on a molecular basis, up to 35,000 times that of CO_2 (*28*) and are destroyers of ozone molecules in the stratosphere. The Motor Vehicle Manufacturers Association of the United States, Inc., has estimated that the CFC refrigerant released to the atmosphere during recharging and because of loss to a vehicle's air-conditioning system during its lifetime is approximately equal in greenhouse warming potential to 100,000 mi of driving.

To comply with international accords, producers in the near future must identify benign compounds that will satisfactorily perform the needed fabrication and cooling functions. They must then replace CFCs with these compounds. Promising replacement refrigerants for vehicular air-conditioning that have so far been identified (and which, for the most part, retain molecular fluorine and carbon without the chlorine) would require larger compressor units than those now in use, which would increase accessory load and thus decrease fuel efficiency. However, the potential CO_2 offset of complete removal of refrigerants should dwarf the attributable increase in CO_2 per mile due to less efficient air-conditioning.

Should manufacturers be successful in developing a benign refrigerant for automotive application that can be implemented in all new vehicles equipped with air-conditioning, it might be constructive to assign a "greenhouse credit" equal to what they might earn by significantly increasing average vehicular fuel efficiency. Although actions to increase efficiency should always be encouraged, substitution of CFC reduction for CO_2 reduction should ease the significant financial burden that domestic manufacturers will encounter if they must simultaneously produce less efficient vehicle air-conditioning systems and far more fuel-efficient vehicles.

In-Use Emissions Testing and Travel Reduction Strategies

Considerable emissions reduction benefit has been and remains to be realized from programs and strategies designed to ensure that current and future exhaust standards are met and that local and regional air quality is maintained. An ancillary benefit is often a net reduction in greenhouse gas emissions.

The most significant of these programs and strategies, most of which will be in widespread application during the next 10 years, are discussed in the sections below.

Inspection, Maintenance, and Antitampering Programs

Inspection and maintenance programs for emissions control are not new. The earliest programs established pursuant to the Clean Air Act date from the mid-1970s. Vehicles in more than 60 metropolitan areas in some 30 states are or at some time have been subject to an in-use emissions check as a partial requirement for vehicular registration (on renewal or transfer of title). Additional states that have received authorization from their legislatures will implement such programs in the near future. In most programs, penalties for noncompliance with inspection requirements generally involve suspension of the driver's license, but penalties may be monetary as well. All programs provide that the expense incurred to bring a vehicle into compliance will not exceed a certain amount, or the repair requirement is waived.

All existing programs are aimed primarily at control of CO and exhaust hydrocarbons. A few programs include soot checks for heavy-duty vehicles. Although some states have a nominal CO_2 limit for the emissions test, exceedance of this limit does not constitute test failure if the vehicle is in compliance for regulated pollutants. However, discovery of a functional problem that generates excess emissions and involves a vehicle's combustion parameters or calibration can lead to repairs that increase fuel efficiency for that vehicle and thus reduce its carbonaceous emissions.

A motor-vehicle tampering survey of 7,388 light-duty vehicles manufactured since 1974 was conducted by EPA in 1987 (*29*). It revealed that at least 19 percent (and possibly up to 31 percent) of the vehicles had emissions control equipment that had been illegally modified. An earlier study (*30*) had estimated that tampering affects at least 26 percent, and possibly about half, of all vehicles manufactured since catalytic converters have been required. The incidence of tampering in light trucks has been especially high, and tampering rates show a large region-to-region variance. However, where inspection and maintenance programs were established, the average rate of tampering fell to 17 percent; where antitampering and antimisfueling inspections were included with the inspection and maintenance requirements, observed tampering rates fell to as low as 11 percent.

Antitampering programs involve periodic vehicle inspections to check the integrity of specific emissions control components. Rendering components of an emissions control system (for example, the O_2 sensor) inoperative through tampering or misfueling can result in incorrect data feedback, which leads to miscalibrated engine combustion and, ultimately, excessive fuel consumption. A typical antitampering program can be combined with an existing state-directed inspection and maintenance program (at relatively low cost because of the consolidation of administrative expenses) or with required periodic safety inspections at state or private state-sanctioned facilities. Such a program might include inspection of the catalytic converter, filler neck restrictor, air pump system, pollution control valve, evaporative control system, and EGR system. A simple test for misfueling that may be included involves taking a swipe sample from the interior surface of a vehicle's tailpipe using lead-sensitive paper to check for the presence of particles that would have been deposited by leaded gasoline exhaust.

California Regulation XV and Related Initiatives

Confronted by mounting air quality problems and a projected doubling of work trips by 2010, the South Coast Air Basin in California has taken what may be a revolutionary step in mitigating mobile-source air pollution: systematic, mandatory suppression of total work trip travel. Under so-called Regulation XV, major employers (those with 100 or more employees)—including groups of employers in commercial and industrial parks—must develop a plan for reducing travel to work in peak hours (through ridesharing, vanpooling, and other group travel concepts) that covers all employees and submit the plan to the South Coast Air Quality Management District for approval. This regulation, encompassing the entire South Coast basin, has been in effect since mid-1988. A similar regulation implemented in the city of Pleasanton, California, in 1984 was credited with reducing peak-hour traffic by 33.7 percent within 1 year after adoption of the ordinance—far in excess of the 15 percent 1-year target and well along to a 4-year goal of reducing peak hour trips by 45 percent (*31*).

Measures like Regulation XV are generically termed "trip reduction ordinances." Interest in adopting such ordinances has now spread beyond California to other chronic air pollution nonattainment areas, such as Phoenix in Maricopa County, Arizona, and Denver, Colorado.

Linking Land Development and Reduction in Distance Traveled

In recent history it has been axiomatic that job creation and decentralized residential land development have worked hand in hand to generate not only major increases in total vehicular trips but also in the distances of such trips—the vehicle miles traveled (VMT). To reverse this effect, measures are being introduced to ensure that ongoing and future residential, commercial, and employment center developments are more closely linked. One such mechanism imposes a "transportation impact tax" on developers. The tax can be waived or mitigated if the developer couples housing unit construction with provision of new office space. Indirect source reviews and permitting, now a feature of many metropolitan planning structures, can deny a developer the right to construct any new facility that may generate sufficient traffic to cause excursions of ambient air quality standards. An effect of such indirect source control is assurance that ridesharing and vanpooling schemes or monetary incentives for transit use will be integral to the development. Failure to implement traffic reduction strategies as part of the development can result in daily fines or revocation of occupancy permits.

The "vertical commutes" (by elevator) of residents of certain central city high-rise structures that accommodate employment on the lower floors and residential units on the upper floors can be emulated in the decentralized high-rise buildings that are increasingly prominent in suburban commercial and office subcenters, on the assumption such structures are designed for or can be converted to dual use. Specific tax- or fee-based incentives to developers and management companies to assure such coordinated use are now under review, predominantly in California.

Telecommuting and Related Developments

Substituting communications for travel (telecommuting), a phenomenon of the computer age, constantly increases in its potential scope. Obviation of some work trips through home-based computer linkages with central operations has opened the way for reductions in the necessity for other personal travel. Shopping, banking, and entertainment trips could be replaced by television, telephone, and direct computer network access.

As diurnal travel becomes increasingly a discretionary activity, the opportunity for making trips that were previously deferred because of the requirement for daily workplace attendance (for example, vacation travel or visits to friends) might lead to an increase in VMT that would offset reductions due to telecommunications. Therefore, the verdict on the ultimate effectiveness of telecommunications as a mitigator of total carbonaceous emissions must be reserved, but it is reasonable to expect that discretionary travel in an area with significant telecommuting opportunities will be more likely to occur in noncongested periods, thus reducing net emissions output per vehicle mile.

Computerized Highways (Enhanced VMT Productivity)

Traffic control strategies designed to reduce the incidence of both excessive speed and excessive congestion, while reducing or at least controlling the growth of total travel miles, can reduce fuel consumption as well as emissions. Such strategies have included paired one-way arterials, railway and road grade separations, upgraded and coordinated traffic signal systems, downtown bypass routes, parking management, and segregation of freight (delivery) traffic from private car traffic.

Traffic signal coordination does not function reliably without computerized control; speed management on urban freeways by means of continuously updated advisory signing would not be effective without computer feedback. The next step in computerized traffic management may well be the automated highway. Sensors in the pavement or along the right-of-way provide data to computers, which in turn notify drivers by a change in signage or the vehicle directly through an on-board transponder that a change in speed, lane, or route is warranted. As vehicles become more electronically sophisticated, trip navigation systems (already available in some models) may be supplemented by radar, sonar, or lidar detectors that continuously gauge clearances around the vehicle and automatically adjust speed to congestion levels. With such systems, safe headways and lane widths could be reduced significantly. Freeway capacity would be increased dramatically without new construction. Greater regularity could be achieved in traffic speed, in contrast to the fuel-inefficient and highly polluting "wave" effect of congestion on driving speed in uncontrolled conditions.

Computerized road capacity enhancement and speed regulation ("smart highways") are now under consideration for testing at key choke points, such as the San Francisco–Oakland Bay Bridge. It is in such locations that VMT productivity improvements are most desperately needed to reduce already intolerable travel times and, as an associated benefit, mitigate the high volume of vehicular pollution associated with congested traffic flow.

OPPORTUNITIES FOR FURTHER ENERGY SAVINGS IN NONHIGHWAY TRANSPORTATION ACTIVITY

Higher productivity in nonhighway transportation (more freight and passengers moved per unit of fuel consumed) implies a reduction in energy demand for a given amount of service performed. Developments in nonhighway modes point to reductions in fuel demand per unit transported beyond those already achieved through the remainder of the century. Such reductions enhance the possibility of more net carbonaceous emissions reduction if activity growth does not offset them.

Railroads

Spurred by highway competition and a greater ability to bring about operational streamlining in the wake of deregulation, railroads are likely to remain active in the following areas:

1. Sale or abandonment of unprofitable branch lines,
2. Motive power consolidation and productivity enhancement,
3. Intermodalism and transmodalism, and
4. Potential electrification of high-density corridors.

Elimination or spin-off of branch lines permits larger carriers to cut back their total fleet horsepower, reduces engine idling, and allows the smaller, shipper-oriented operators that continue branchline service to revise work rules to cut running cost. For example, locomotives may be operated only when needed for car pickup and distribution and not necessarily on a daily basis. As the major carriers devote more and more of their remaining horsepower to main-line (and, to a diminishing extent, classification yard) use, innovations such as the integral train, which optimizes location of power units within a unitized train consist to achieve maximum traction for a given energy input, will become economically more feasible and attractive. Similarly, as these carriers extend their services to truck and barge operations to offer individually tailored door-to-door transportation for shipper clients (transmodalism), maximally fuel-efficient strategies for the entire haul can be devised. Such strategies may include electrification of the most densely used main lines, which could replace fossil-generated with nuclear- or renewables-generated propulsion.

Aircraft

Airframe maintenance may be the most important single measure for maximizing fuel efficiency in aircraft operations. Though there are no direct indications that this maintenance has lagged during the past several years because fuel prices have remained persistently low, it does appear that lower operating costs generally have retarded the rate of turnover that has been expected in the commercial air fleet as a result of the fuel crisis that occurred at the turn of the present decade

(*32*). The next 10 years should witness an acceleration of current turnover rates as much of the fleet approaches the end of its economic life.

Commercial carriers are rediscovering that, for some operations, propeller-assisted aircraft provide fuel efficiency superior to that of standard turbojets. Thus, the 1990s could see a reemergence of turboprop service on some (probably shorter-distance) routes, especially if jet fuel prices surge again. Continued improvements in the efficiency of ground activities should further reduce fuel consumption between flights. Finally, the cost of acquisition and maintenance of general aviation (personal and corporate) aircraft could spur a trend toward "pooling" (much as the railroads now do with motive power) or time-sharing among users. This would tend to attenuate the growth both in new aircraft registration and total operating hours in general aviation because of higher passenger-mile productivity per unit.

Waterborne Vessels

Domestic airshed emissions from waterborne vessels are attributable primarily to inland waterway operations and steamship and diesel motorship hotelling during port layovers. Reductions in fuel burned to perform these activities will result in reduced total carbonaceous emissions. Considerable improvement in steam productivity is being achieved. Many maritime operators have substituted electric-powered for steam-driven feed pumps to provide for the generally low-load steam requirements in port, and other owners are likely to follow. Port calls that at an earlier time would have been necessary have been obviated by using smaller vessels for consignment pickup and delivery to larger carriers at sea. Hull maintenance and ship trim and block coefficients have been modified for greater fuel efficiency, and there is more running at low speed. The Japanese, in particular, have successfully experimented with wind assistance to propel large diesel-powered vessels. The technology of propeller design for improved thrust, which is applicable to both inland and coastal waterway operations, continues to advance. The potential for application of waste heat recovery systems (*33*) to permit performance of equal work with downrated horsepower requirements—important to diesel operation on inland waterways—will grow during the 1990s.

Streamlining of lock and dam operations and maintenance of channel depths, often difficult in drought conditions, would also assist in reducing the quantity of fuel required for the average barge tow. Efforts in this direction will be constrained by the resources and directives provided to the U.S. Army Corps of Engineers, which is responsible for the maintenance of the U.S. domestic waterway system.

CONCLUSION

Table 2 categorizes the opportunities discussed with respect to (*a*) reasons for their adoption and (*b*) relative contribution to mitigation of greenhouse gases from transportation (on a

TABLE 2 RATIONALE OF LIKELY FUTURE TRANSPORTATION TECHNOLOGIES AND POLICIES AND THEIR POTENTIAL EFFECTIVENESS IN MITIGATING GREENHOUSE GASES

TECHNOLOGY OR POLICY	WHY IT WOULD BE ADOPTED	EFFECTIVENESS (1=Low 5=High)
Efficiency Enhancers	Increase in fuel prices and/or improved performance and driveability	5
Advanced Catalysts	*Longer durability and better control needed in rough service*	2
Water/Air Injection	NO_x control and better fuel utilization	3
Compression Ratio >9.5	*Maximize response and performance available from higher-octane fuels*	4
Catalytic Ignition	Optimize burn in cylinder for Otto cycle engines	4
Multifuel Engines	*Energy security or environmental (e.g., "ultra-low-emission") imperatives*	3
Electrics/ Hybrids	Clean air requirements (national and regional); energy security policies	5
Alcohol Fuels	*Energy security/environmental controls*	3
CNG	Same as alcohols	4
"Flex-fuel" Vehicles	*Ease transition to nonpetroleum transportation fuels as part of energy strategy*	1

(*continued on next page*)

TABLE 2 (*continued*)

TECHNOLOGY OR POLICY	WHY IT WOULD BE ADOPTED	EFFECTIVENESS (1=Low 5=High)
Fuel Cell Propulsion	Pollution abatement and renewable energy use in future transportation	4
Hydrogen Fuel	*Same as fuel cells*	5
New Refrigerants (i.e., no CFCs)	Required by international protocols due to stratospheric ozone depletion	5
Inspection/ Maintenance w/ Anti-tampering	*Tighter State Implementation Plan requirements under reauthorized (1990) Clean Air Act*	3
Trip Reduction Ordinances	State, regional, or local environmental compliance requirements	3
Land Development Control	*Same as trip reduction ordinances, or to counteract "sprawl"*	2
Telecommuting	Increase productivity/reduce costs	4
Computerized Highways	*Maximize productivity and utilization of existing transportation infrastructure*	2
Rail Carrier Strategies	Cut costs; increase shipper satisfaction; maximize fuel and labor productivity	4
Aviation Fleet Turnover	*Cut costs; increase load factors; improve fuel and labor productivity*	3
Marine Fuel Productivity	Cut fuel costs (especially for low-speed, low value-to-weight hauls)	2

1 to 5 scale, least to most significant) assuming that they are generally adopted. However, this paper has by no means exhausted the range of options available for moving away from a transportation system responsible for more than 2 percent of man-made carbonaceous effluent. Solar and renewable energy resources have been investigated for vehicular applications as well as for replacement of stationary combustion of fossil fuels. The promise for widespread dissemination of those applications is tangible, though the applications will probably be deferred until the coming century. Yet Table 2 indicates that it is not necessary to look so far beyond what is already coming into play. This is due in part to the perception of economic imperatives and in part to the rekindling of a global environmental awareness and concern. If a majority of the near-term options presented in this paper are generally adopted and the preservation of existing CO_2 "sinks" such as tropical rain forests is successful, transportation will make a major contribution to a restoration of balance in the global CO_2 cycle.

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Initial Assessment of Roadway-Powered Electric Vehicles

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Wide-scale use of electric vehicles (EVs) could result in large reductions in urban air pollution. However, consumer acceptability of battery-powered EVs is limited because of the short range of the vehicles. One possibility for eliminating the range disadvantage of EVs without sacrificing their potential for improving air quality is to supplement battery energy with electricity supplied through the roadway. The costs, environmental impacts, and electric utility impacts of roadway-powered electric vehicles (RPEVs) are assessed. It is concluded that RPEV air quality benefits are substantial and that the technology could prove economically competitive with petroleum-fueled motor vehicles. Continuing research and development is needed to narrow cost uncertainties.

Methanol and natural gas are widely regarded as the leading candidates for near-term petroleum replacement in transportation. However, an increasing number of studies suggest that the environmental and energy security benefits of methanol and natural gas may be relatively modest (*1–8*). Electric vehicles (EVs) provide greater opportunities for energy security and the potential for much larger reductions in emissions. In addition, an electric motor can provide high torque at startup and is technically simple, easy to maintain, durable, efficient, reliable, quiet, clean, and long lasting. EVs themselves are pollution free (power plant emissions are analyzed later), and electricity can be produced from a number of readily available domestic feedstocks.

However, the EV is not without problems. The main impediment to wide-scale consumer acceptance of current-technology EVs in the United States is their limited range. Using durable batteries in existing compact vehicles, the best battery-powered automobiles are capable of traveling only about 75 mi before having to stop to recharge (vehicle air conditioners and heaters reduce range 10 to 15 percent) (*9,10*). A full battery recharge from a typical household electric outlet takes at least 8 hr. Historically, EV battery development has progressed incrementally, and there is no sign of an imminent technological breakthrough.

One prospect for deploying EVs and overcoming the range problem is to replace stored electrical energy on board the vehicle with distributed energy from an electrified roadway. In this scenario a roadway-powered electric vehicle (RPEV) draws energy directly from the electricity grid while it operates over an energized roadway. The vehicle relies on battery reserves when operated off the electrified roadway network and possibly during peak periods of electricity generation. RPEV batteries can be charged while the vehicle travels over the electrified roadway or while immobile. An RPEV transportation system can solve the battery-powered EV range problem while providing air quality and energy benefits.

RPEV TECHNOLOGY

At the center of the RPEV system is the inductive coupling system (ICS), which provides the means for transferring electric power from the roadway to the vehicle. The ICS is often compared to a transformer—an extremely efficient electrical device that employs the principle of mutual inductance to convert variations of current from a primary circuit to a secondary current. Indeed, the ICS functions as an air-core transformer. The roadway contains the primary winding and a pickup inductor on the vehicle contains the secondary winding. However, unlike a regular transformer, the two inductors have different electrical and physical designs. The main difference is the length of the coils—the roadway inductor is many times longer than the pickup inductor.

The cables (or bus bars) embedded in the road are excited with AC electricity by an external power source through power conditioners located along the roadway. When the pickup cables (or bus bars) located underneath the vehicle are over the roadway element, there is inductive coupling and electrical energy is transferred to the vehicle. The magnitude of the gap between the roadway and the vehicle pickup inductor will depend on the system design; however, the largest gap spacing will probably be no more than 3 cm to maximize efficiency (ideally the gap height will be adjustable from within the vehicle to accommodate for various road conditions) (*11,12*).

Figure 1 (*13*) shows the ICS design being used in an RPEV project sponsored by the Program on Advanced Technology for the Highway (PATH). Iron cores made of grain-oriented silicon iron laminations are placed around the aluminum roadway cables and pickup cables to provide magnetic flux paths and increase coupling efficiency. Aside from the physical aspects of the hardware that determine the flux density in the cores and the effective current density in the inductors, inductance efficiency is primarily a function of the pole width of the cores (i.e., the mutual surface area) and the size of the air gap between the roadway and the pickup inductors. Because the transfer of energy is inductive rather than conductive, there is no contact, and thus components wear slowly. Furthermore, there are few potential electrical hazards because all the electrical elements are well insulated and buried in the roadway.

Although the RPEV system enables an electric vehicle to be operated entirely on distributed energy supplied by the grid rather than through energy stored on board, an RPEV is a hybrid vehicle because it maintains a battery for travel

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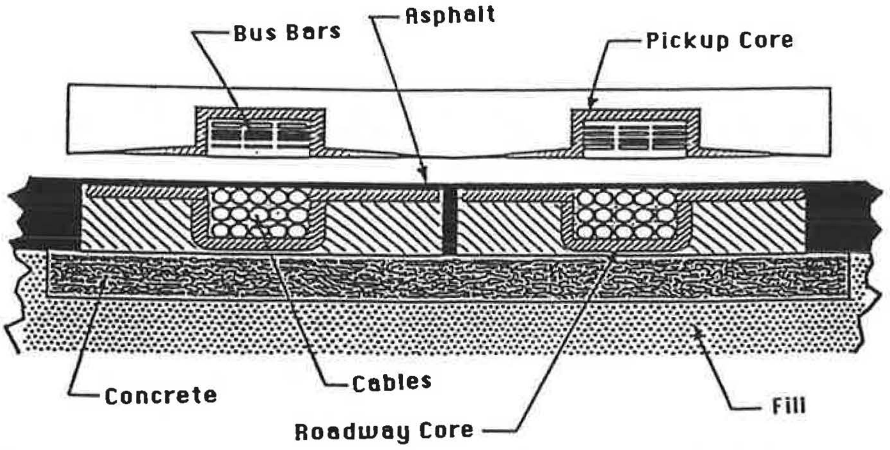

FIGURE 1 Cross section of roadway and pickup inductors (*13*).

off the electrified roadway network. However, unlike a battery-only electric vehicle, an RPEV does not have to be "plugged in" to be recharged; it can be recharged through the inductive coupling system. In addition to providing propulsion power to the vehicle, energy transferred through inductive coupling can also be diverted to the battery for storage. Battery charging through the RPEV system can be accomplished dynamically or statically.

Dynamic battery charging takes place when energy provided by the roadway is greater than what is necessary to propel the vehicle. The excess energy can then be used to charge the batteries while the vehicle is en route. Static inductive battery charging is possible if the vehicle is parked directly over an inductive coupling device. In this case all energy transferred to the RPEV would be used to charge the batteries (RPEV batteries can also be recharged by using a typical household electric outlet). Static inductive battery charging is currently used for large automatically guided vehicles at Disney World and in automated manufacturing plants in the United States, Canada, and Europe. Inductors could be installed in public parking spaces to maximize static recharging opportunities.

Roadway power used by the RPEV is supplied through a distribution network that delivers electricity generated at the power plant to a utility substation. The electricity is routed from the substation to power conditioners located along the roadway at specified intervals. The electricity is then routed in parallel to segments of adjacent roadway; electrification of a roadway lane does not exclude use by other vehicle types. Figure 2 (*14*) shows the electrified roadway energy distribution network. The distance between power conditioners will probably be determined by the maximum allowable voltage in the roadway element, which is a function of the system design and the number of vehicles drawing power from the roadway. The power conditioner spacing will probably be less than 2 km for roadways with fairly high traffic volumes.

This network provides a "fail-safe" design in which the effects of a malfunction are confined to a relatively short distance (i.e., in the case of a power conditioner failure, only 2 km of roadway would lose energy). Unless the RPEV battery is completely discharged (an unlikely circumstance), no problem should be encountered in reaching the next section of electrified roadway or the driver's residence in the event of a power outage.

HISTORY OF THE RPEV CONCEPT

The RPEV concept is not new; in fact, patents for electric vehicle operation by means of inductive coupling date back to the 1890s. Abundant, inexpensive petroleum supplies, however, suppressed the development of such a system for decades.

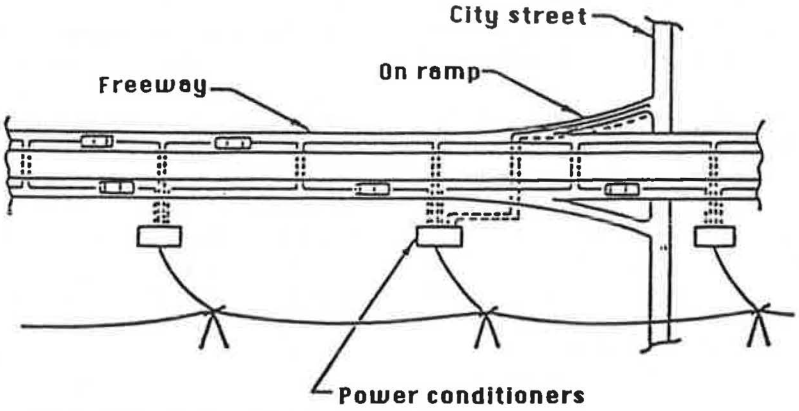

FIGURE 2 Electric roadway schematic (*14*).

In the early 1970s John Bolger designed an ICS that regulated voltage control from the roadway to the vehicle battery—an inherent problem in previous designs. The new design, along with the energy crisis, renewed interest in the RPEV concept. From 1976 to 1982 the U.S. Electric and Hybrid Vehicle Program, with funding from the U.S. Department of Energy, the U.S. Department of Transportation, and the state of California, spent about $1 million on a feasibility study, designing and testing a prototype power coupling and designing and fabricating a test-bed RPEV (*15–17*). The culmination of this program in 1981 was the construction of a modest test vehicle and a 160-ft section of powered roadway at the Lawrence Livermore National Laboratory.

One of the most significant ongoing developments of the RPEV system concept is the Santa Barbara–PATH Bus Project, which began in 1977. The downtown area of Santa Barbara, California, was developed as a sensitive pedestrian-oriented environment. To maintain the congenial atmosphere of the downtown area yet serve the travel needs of shoppers and tourists, city officials elected to implement a mass transit system that would be free of emissions, have a low noise level, and be aesthetically pleasing. This desire for an efficient and environmentally benign mass transit system matched well the attractions of RPEV technology.

In 1979, with the endorsement of the city of Santa Barbara, the Santa Barbara Metropolitan Transit District (SBMTD) was granted a contract by the California Department of Transportation (Caltrans) for the development and demonstration of the RPEV system. The same year a multiphase program was implemented, which consisted of a feasibility study, detailed planning, preliminary engineering, and prototype development and testing of an RPEV bus. The final product was to be a small fleet of RPEV buses continuously operating 10 hr/day over a 5½-mi route (including two electrified miles) in downtown Santa Barbara.

However, because the development of the technology proceeded too slowly for the needs of Santa Barbara, the technology development portion of the project was transferred to PATH at the University of California. A 400-ft test track (with two 20-ft static charging areas) was built in Richmond, California, in late 1989 for the testing and demonstration of the existing RPEV bus.

Efforts are already under way to further improve RPEV technology. In August 1989 a new project, the Playa Vista Electrification Project, was initiated with the objective of advancing RPEV technology. This $2 million project funded by two utility companies—Southern California Edison and the Los Angeles Department of Water and Power—is focusing on reducing fabrication and installation costs of RPEV roadway elements and on the development of automobile-size RPEVs that operate at highway speeds. The project, located in southern California, will involve testing two RPEV vans and a bus on 1,000 ft of electrified roadway. Completion of the facility and initial testing is scheduled for October 1990.

The Playa Vista project is the first stage of a much larger RPEV project that is currently being supervised by an engineering consulting firm in California. The proposed project, with funding provided by a consortium of industrial firms and government agencies, is expected to cost $30 million to $40 million and take 4 years to complete. The objectives of this research and development effort are to build an electrified arterial system to demonstrate RPEVs on a large scale and to prepare the technology for commercialization.

SYSTEM DESIGN

The design of an RPEV system consists of many complex trade-offs between efficiency and cost and is strongly influenced by institutional constraints and financing strategies. At this relatively early stage in the technology development process, attention is focused on relationships between cost, performance, and efficiency. Much research is still needed. For instance, reducing the air gap increases the energy efficiency and thus decreases the operating cost of an RPEV but would require the added cost of maintaining a debris-free, smooth-surface electric roadway. Increasing the core pole width also increases coupling efficiency but incurs an additional cost and weight penalty. Other technical trade-offs include better design of the inductor cores (e.g., using better material, different geometric configurations, or better fabrication processes) and increasing the current in the roadway—again, these improvements are accompanied by a cost increase. A more detailed description of system design trade-offs can be found in Shladover (*11*).

The larger strategic issues are the extent of roadway electrification, financing considerations, and implementation strategies. The first of these issues, the extent of roadway electrification, depends on whether roadway power is intended to supplement vehicle battery power or vice versa. If, for instance, roadway power is designed to supplement battery-powered EVs, then the vehicles will carry large battery packs and only strategically selected limited stretches of roadway will be electrified. The primary financing considerations are who will bear the cost of the necessary infrastructure—the government or users of the system—and through what financing mechanisms. Finally, implementation strategies must be established: what role, if any, should incentives and government mandates play? What role will electric utilities, highway providers, and air quality regulators play? The most workable system design may be one that is amenable to retrofitting battery-powered EVs and RPEV equipment.

In sum, many decisions must be made before the technology problems can be resolved. It would be desirable to clarify the objectives of the RPEV system so that design criteria can be established that give developers of the technology clear goals. Clarification of RPEV objectives is best left to the regions implementing the technology.

LIFE-CYCLE COST OF RPEVs

Ideally, one would calculate the life-cycle cost of a mature, mass-produced RPEV technology and compare it with the cost of owning and operating a conventional internal combustion engine vehicle (ICEV). However, comparing an RPEV with an ICEV is difficult because the latter is a product of more than 100 years of technological evolution, whereas RPEV technology is still in the design stage. Only a special-application RPEV prototype bus has been built for testing and demonstration purposes. Preliminary cost estimates, calculated projections, and engineering principles must be relied on to estimate the life-cycle cost of RPEVs. Although there is a good deal of uncertainty in the estimates, it is important to perform a preliminary cost analysis to determine whether RPEVs can compete with other transportation alternatives. A disaggregate cost model has been developed for this purpose. The key parameters used for the initial evaluation are explained below.

RPEV costs are calculated with respect to a baseline subcompact gasoline vehicle for which all relevant costs are shown in Table 1. Where appropriate and unless otherwise noted, cost items for the RPEV are expressed relative to the baseline ICEV cost components. All costs are given in constant 1989 U.S. dollars. The cost analysis compares RPEVs and ICEVs on equal terms—it is assumed (*a*) that both vehicles are mass produced, have the same interior capacity, and depreciate at the same rate; (*b*) that repair shops and vehicle operators are as familiar with RPEVs as ICEVs; and (*c*) that parts for RPEVs are as readily available as parts for ICEVs.

It was assumed that the RPEV uses an AC power train and regenerative braking and is equipped with a maintenance-free sodium/sulfur (Na/S) battery and on-board charger. Regenerative braking is expected to increase vehicle efficiency by approximately 5 to 15 percent under normal driving conditions (*18–21*). Na/S batteries are advanced high-temperature batteries currently being tested in many prototype EVs; battery assumptions were based on near-term performance goals. On-board transformerless battery chargers integrated with the controller electronics are beginning to replace large expensive stationary battery chargers. These on-board chargers are inexpensive and do not add significant weight to the vehicle. The integrated on-board charger in the electric Chrysler TE-Van is estimated to increase the cost of the vehicle by less than $50 (K. Winters, unpublished data, November 26, 1989); a mass-produced off-board charter would increase the cost by approximately $1,100 (*22*).

Baseline Gasoline Vehicle Assumptions

Baseline vehicle assumptions were intended to apply to a new gasoline vehicle in 2000; RPEVs will probably not be commercially available before then. A wide range of $0.90 to $2.00 per gallon in estimated fuel costs was used because of the high uncertainty associated with future gasoline prices. Fuel economy for gasoline vehicles in 2000 was projected at about 35 mi/gal (*23–25*). It was assumed that life expectancy, salvage value, and the real cost of a new gasoline vehicle will not change significantly over the next 10 years.

Average annual vehicle mileage has been fairly constant for 40 years at 10,000 mi, and there is no reason to expect this to change. On the other hand, the real annual interest rate for automobile loans fluctuates considerably, and therefore a wide range of 5 to 9 percent was used for this input variable. Insurance, maintenance, tires, accessories, and parking and toll costs were based on information from FHWA (*26*).

Vehicle registration fees and sales tax were based on the national average (*27*), and inspection and maintenance costs for pollution control devices were projected on the basis of states that have already implemented such programs. Finally, the national average combined state and federal gasoline tax is approximately $0.20 per gallon (*28*). A range of $0.20 to $0.30 was used to account for likely increases (many states have proposed gasoline tax increases).

The total life-cycle cost of operating the baseline gasoline vehicle, defined by the assumptions given in Table 1, is about $0.30 to $0.37 per mile.

TABLE 1 GASOLINE BASELINE REFERENCE CASE

High	Low	Reference Case Input Data
2.00	0.90	Retail price of gasoline, $/gallon, taxes excluded
35.00	35.00	Overall lifetime vehicle fuel economy, miles/gallon
11,000	11,000	The initial price of the car including tax, $
120,000	120,000	Miles driven over life or until resale
0.00	0.03	Vehicle salvage/resale value, fraction of initial cost
10,000	10,000	Miles driven per year
2,600	2,600	The loaded driving weight of the vehicle, lbs
0.090	0.050	The real annual interest rate for auto loans (equal payments over vehicle life) or foregone consumer savings (full payment at purchase)
71.50	71.50	Insurance payments, first n years with collision insurance, $/month
8.00	5.00	n, years collision insurance is carried
44.36	44.36	Insurance payments, subsequent years without collision insurance, $/month
484.50	484.50	Maintenance costs, $/year, including taxes
10.60	10.60	Parking and tolls, $/month
320.00	320.00	Four replacement tires, $/set, including taxes
50,000	50,000	Life of tires, miles
18.50	18.50	Accessories, $/year
30.00	25.00	Oil, $/year, including taxes
25.00	25.00	Registration fee, $/year
25.00	25.00	Inspection and maintenance fee, $/year
0.30	0.20	Gasoline tax, Federal + State, $/gallon
1.05	1.05	Sales tax on incremental vehicle cost, (1 + %tax)

Notes: Gasoline tax from USDOC (1989); registration fee and sales tax from Intellichoice (1988); insurance information, maintenance, tires, accessories, and parking and tolls from FHWA (1985); real annual interest rates for high-yield consumer savings and auto loans calculated from U. S. Department of Commerce (1989).

Initial RPEV Cost

The initial RPEV cost was disaggregated into four components—vehicle, pickup inductor, on-board controller (OBC), and battery. The costs of these items were amortized over their respective lives (using the discount rate specified in Table 1) and summed to obtain the life-cycle cost of purchasing an RPEV. The cost assumptions are summarized in Table 2.

Vehicle

The initial vehicle cost of an RPEV, excluding battery, pickup inductor, and OBC, was entered relative to the cost of an ICEV. Ford and General Electric, developers of advanced EV test vehicles, suggest that an advanced EV (excluding battery) will cost no more than a comparable ICEV at a "reasonable" production volume (*29*). Pentastar, a Chrysler corporation and developer of the state-of-the-art TE-Van, also suggests that a mass-produced EV without the battery will cost no more than an ICEV (K. Winters, unpublished data, May 19, 1989), and the General Research Corporation concluded the same based on a cost model it developed (*30*). Other EV analysts, including one who contends that EV vans can be manufactured for the same cost as ICEV vans at a production volume as low as 10,000 units/year, concur with these projections (*31–33*; G. Cole, unpublished data, 1989). It is estimated that a production volume of 250,000 vehicles is sufficient for recovering retooling costs necessary for producing a new type of vehicle (*34*). Although the above cost projections are for an EV, they would essentially apply to an RPEV without the pickup inductor, OBC, or battery. It was assumed that an RPEV, without this power supply equipment, will cost the same as an ICEV.

Pickup Inductor

The fabrication cost will probably determine the total cost of the vehicle pickup inductor. On the basis of the cost of the pickup inductor being used on the PATH bus and estimates from Inductran, Inc.—an engineering firm that specializes in inductive coupling technology—the cost of a pickup inductor with suspension system on a subcompact vehicle is estimated to be $1,500 to $4,000 (J. Bolger, unpublished data, 1989; PATH, public demonstrations, 1989).

TABLE 2 RPEV COST ASSUMPTIONS

High	Low	RPEV Input Data
7.00	5.00	Cost of electricity at the outlet or power conditioner, cents/kWhr
10.00	8.00	Cost of peak-hour electricity at the power conditioner, cents/kWhr
0.85	0.90	Efficiency of battery charging
0.70	0.85	Efficiency of RPEV system from power conditioner input to vehicle battery or powertrain
0.70	0.75	Efficiency of battery
5.80	6.40	Ratio of efficiency of RPEV powertrain w/ regenerative braking to ICEV powertrain efficiency
40	40	Desired urban vehicle range on battery only, miles (at DoD below)
0.80	0.80	DoD at desired driving range
Na/S	Na/S	Battery type
0.00	0.03	Battery salvage value, % of initial cost
400.00	250.00	Weight of pick-up inductor & suspension system, lb.
75.00	40.00	Weight of onboard controller unit, lb.
10.00	6.00	Cost of pick-up inductor incl. suspension system, $/lb
650.00	350.00	Cost of onboard controller unit, $
120.00	85.00	OEM battery cost, $/kwh nominal deliverable capacity
1.50	1.40	Ratio of retail to OEM battery cost
0.00	0.03	Pick-up inductor salvage value, % of initial cost
0.00	0.03	OBC salvage value, % of initial cost
80.00	120.00	Battery energy density, max. delivered wh/kg
700	1000	Battery cycles per life, at DoD stated above
0.00	0.00	Cost of RPEV (incl. tax & onboard charger, excl. pick-up inductor, OBC, & battery) minus cost of ICEV, $
10.00	7.00	Number of years collision insurance is carried on RPEV
0.50	0.50	% total annual miles from roadway power
0.50	0.50	% of electric roadway miles during peak hour rates
1.25	1.50	RPEV life/ICEV life
1.05	0.95	RPEV test wt. (excl. battery, OBC, & pick-up inductor) as % of ICEV weight
0.80	0.60	Percent decrease in fuel efficiency per 1 percent increase in vehicle weight
0.85	0.50	Maintenance costs, fraction of gasoline vehicle
2.00	1.00	Cost of building electric roadway lane, $million/mile
10.00	25.00	# of RPEVs using electrified lane each day per lane mile (x 1000)
20.00	25.00	Life of electric roadway, years
1780.00	1465.00	Electric roadway maintenance cost greater than conventional maintenance, $/year/lane mile

OBC

The second largest cost item for an RPEV, excluding the battery, is the OBC. The OBC includes the on-board control computer (OBCC) and the rectifier unit. On the basis of the best available engineering estimates and the PATH bus experience, it is believed that an OBC for an RPEV automobile will cost between $350 and $650 (J. Bolger, unpublished data, 1989; S. E. Shladover, unpublished data, 1989).

Battery

Battery cost is a function of battery size, efficiency, longevity, energy density, specific power, depth of discharge, and salvage value. To accurately size the battery, assumptions must be made about the overall design of the RPEV system and the vehicle range requirement.

Without speculation as to where and how much electric roadway power will be available, it was assumed that the RPEV owner will desire a battery reserve of at least 40 mi for off-system travel at 80 percent depth of discharge (DoD). Battery cost parameters for a future optimized Na/S battery were specified on the basis of available data (*21;35–40*; M. Price, unpublished data, 1990). Na/S batteries are assumed to have a low salvage value because of the low cost of the materials used (*40,41*). Finally, a 40 to 50 percent markup from the original equipment manufacturer's battery cost to retail was assumed (*32,42*).

RPEV Life

An electric motor lasts much longer than a gasoline internal combustion engine. This is important because engine life often determines the life of an ICEV. One fleet of EV vans used in Britain reportedly lasted three times longer than diesel counterparts that were subjected to the same operating conditions (*31*). Data from actual use suggest that an EV will last anywhere from 25 to more than 100 percent longer than a comparable ICEV (*31,32,43*). However, it is improbable that RPEVs will double the life span of an ICEV because of the deterioration of other components, such as brakes, steering, body, and vehicle interior. It was assumed that an RPEV will last 25 to 50 percent longer than a comparable ICEV and initial costs were amortized accordingly. Vehicle life is an important variable in life-cycle cost calculations.

Operating Costs

RPEV Maintenance

AC induction motors are not subjected to the extremes of heat, pressure, and synchronized movement that wear down an ICE. There are no explosions or associated stresses, and there are fewer moving parts. Therefore, it was assumed that the electric motor will require significantly less maintenance work and repairs. In fact, many studies, on the basis of data collected from existing EV fleets, indicate that the maintenance cost of an EV is a fraction of that of a comparable ICEV (*31,43–46*). The range in the literature suggests that an EV may cost 34 to 75 percent as much as an ICEV to maintain and repair. An RPEV will probably have a smaller maintenance cost advantage than an EV because the RPEV is equipped with a pickup inductor and OBC, which require some additional maintenance. However, iron pickup inductors should be extremely durable and the electronics of an OBC should be relatively inexpensive and easy to replace. RPEV maintenance and repair costs were assumed to be 50 to 85 percent of those of an ICEV.

Fuel Cost

The fuel cost of an RPEV is a function of the vehicle fuel economy, electricity cost, fuel tax, usage, the extent of use on the powered roadway, and the extent of use during peak electricity-generating periods.

The efficiency of an RPEV relative to that of a comparable ICEV is the product of the battery charger efficiency, battery efficiency, ICS efficiency, power train efficiency, and vehicle weight. Charger efficiency is estimated at 85 to 90 percent, and the battery efficiency is estimated at 70 to 75 percent (*21;35–38;47*; B. Swaroop, unpublished data, 1989; J. McCoy, unpublished data, 1989). Efficiency of the RPEV system from power conditioner input to the vehicle power train was estimated at 70 to 85 percent (*11*; J. Bolger, unpublished data, 1989). Finally, an efficiency weight factor of 0.6 to 0.8 was used, which means that for every 1 percent increase in RPEV weight relative to an ICEV, fuel efficiency decreases 0.6 to 0.8 percent (*48*).

A comparison of energy efficiencies (from fuel origin to the vehicle wheels) between an ICEV and an RPEV is depicted in Figure 3. As can be seen, the RPEV is 19 to 26 percent more efficient when operated from roadway power (from the power conditioner) than when operated from battery power (from the outlet). Figure 3 also indicates that the relative power train efficiency of an RPEV is approximately 5.6 to 6.6 times that of a comparable ICEV (*20,37*).

On the basis of projections of electricity cost in 2000 by the U.S. Energy Information Administration (EIA) and the California Energy Commission (*49,50*), the cost of electricity was estimated to be 5 to 7 cents/kW-hr for off-peak battery charging and roadway operation and 8 to 10 cents/kW-hr for peak-hour roadway operation (it was assumed the price incentives will restrict home battery charging to off-peak hours). RPEVs can be equipped with meters that record the amount and time (peak or off-peak) of roadway-powered travel for billing purposes.

The gasoline fuel tax is earmarked for roadway maintenance and construction. It was assumed that RPEV users bear the full cost of electrifying existing roadways and the incremental roadway maintenance cost incurred because of electrification in addition to the equivalent ICEV gasoline tax. Because it would be difficult to distinguish between residential electricity used for battery charging and that used for other purposes, an annual RPEV user fee (perhaps based on annual RPEV mileage) would probably be assessed instead of a fuel tax. RPEV system installation and additional electric roadway maintenance costs were internalized in the analysis.

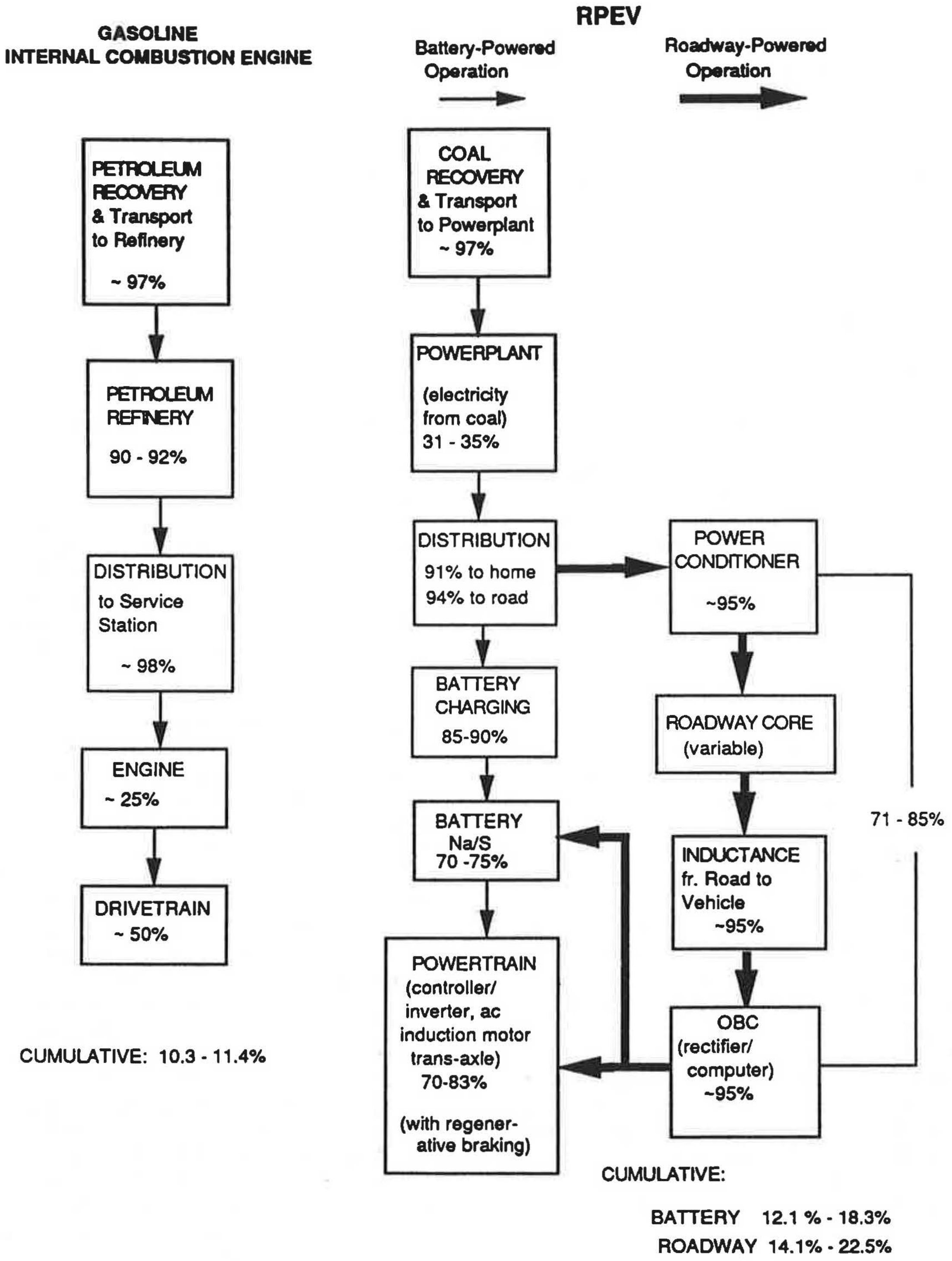

FIGURE 3 Energy flow diagrams.

Finally, it was assumed that the typical RPEV will accumulate 50 percent of its annual mileage by using energy from the road and that 50 percent of that energy will be during peak electricity periods. Changing the proportion of roadway power to battery power usage or the peak-period travel percentage does not have a profound effect on the total life-cycle cost results.

Other Operating Costs

The cost program estimated tire replacement cost, which is a function of vehicle weight, road conditions, and driving patterns. It was assumed that the only difference in the rate of tire wear between an ICEV and an RPEV is due to vehicle weight. Therefore, tire life for the RPEV is decreased in proportion to the total extra weight of an RPEV relative to a comparable ICEV.

Insurance costs are a function of many factors that may or may not be systematically different for RPEVs compared with ICEVs. The only difference that can be estimated with any degree of certainty is that component based on vehicle value. RPEVs, with their battery pack, OBC, and pickup inductor will initially cost more than a comparable ICEV. Consequently, insurance was increased in proportion to the additional cost of an RPEV relative to an ICEV.

Electric Roadway Cost

Installation Cost

Preliminary estimates for electric roadway installation are $1 million to $2 million/lane-mi for mass-produced components installed in existing roadways (*15*; Bechtel Civil, Inc., unpublished data, 1989; S. E. Shladover, unpublished data, 1989; J. Bolger, unpublished data, 1989). This estimate includes the cost of all the equipment and materials necessary to deliver electricity from the utility substation to an RPEV traveling on the electrified roadway and the labor required to install the system.

Electric Roadway Maintenance

Electric roadways will probably require additional maintenance. At least part of this will involve keeping the electric roadway free of debris, cracks, and potholes that could obstruct the inductive coupling of the vehicle and roadway element. Power conditioners will also require routine maintenance. If the electrified roadway is not as durable as expected, maintenance could be extensive because most of the system hardware is embedded in the road. On the other hand, roadway electrification could benefit many cities if it is designed to melt snow and ice, thus eliminating the need for snow removal operations (a feasible option according to one RPEV expert) (J. Bolger, unpublished data, 1989).

Maintenance assumptions were based on data from major highways in urban California (Caltrans, unpublished data, 1989). For the low-cost case, a 50 percent increase was assumed in litter control plus a 25 percent increase in general routine roadway maintenance (sealing cracks, patching potholes, minor overlays, etc.). The high cost estimate increased general maintenance and litter control by 50 percent.

Electric Roadway Life

Because an electric roadway has yet to be built, there are no data on life expectancy under normal operating conditions. The entire roadway system, with the exception of the power conditioner, will be buried and therefore protected from the climate and externally inflicted damage. The power conditioner will be in a self-contained housing and, therefore, also protected. However, the elements embedded in the road could experience heavy loads and continuous loading and unloading cycles (especially if heavy-duty trucks are allowed to travel in the electrified lane). Such physical stress on electric roadway components could have adverse effects.

It was assumed that electric-roadway hardware will last at least as long as the typical urban highway (20 years) and, under the best circumstances, will last 25 years. It was assumed that there is no salvage value at the end of its useful life (even if the hardware is intact and functional after 20 to 25 years, new designs will probably render existing equipment obsolete).

Electric Roadway Utilization

It was assumed that the users of an electrified roadway bear the full cost of electric roadway installation and related maintenance. The cost to each RPEV user depends on how many other RPEVs use the system regardless of the extent of utilization by each individual. To determine the RPEV life-cycle cost, high- and low-utilization scenarios were assumed. If electrified lanes experience high-volume traffic flows typical of the busiest urban Interstates in California, they will carry approximately 25,000 RPEVs each day (electrified lanes can be used by other vehicle types, but if RPEVs become prominent, exclusive RPEV lanes will probably be implemented) (*51*). For the high cost estimate, it was assumed that the electrified lane carries 10,000 RPEVs per day.

COST ANALYSIS RESULTS

On the basis of the input variables discussed above and given in Tables 1 and 2, the life-cycle cost of owning and operating an RPEV was calculated to be between $0.27 and $0.49 per mile, as indicated in Table 3. This brackets the baseline gasoline vehicle cost of $0.30 to $0.37 per mile, which is also indicated in Table 3. As can be seen, RPEVs may compete with ICEVs on the basis of economics alone if relatively optimistic assumptions prevail. Depending on the utilization of the electrified lane, the model indicates that roadway hardware and installation costs combined could account for as much as 12 percent or as little as 3 percent of the total per-mile life-cycle cost (if users bear the full cost of the facility).

The combined vehicle and total battery cost, amortized over the life of an RPEV, is almost equal to the cost of an ICEV. However, at the time of purchase the RPEV costs $2,950 to $6,884 more than the ICEV. The greater initial cost of an RPEV is amortized over the RPEV's longer life. This is important because consumers seldom perform a full life-cycle cost analysis when purchasing a vehicle and thus tend to use a higher implicit discount rate.

Battery technology may have implications far greater than what is reflected in the economic analysis. Although the battery in our RPEV cost analysis constitutes approximately 6 to 9 percent of the total life-cycle cost, advances in battery technology could lower these costs or extend driving range, or both. One of the main advantages of an RPEV is that it overcomes the range limitations of an EV; if batteries improve substantially or rapid recharge becomes feasible, the EV range problem may lose significance and RPEVs would become less compelling an option. On the basis of life-cycle cost, a battery-powered EV defined by the applicable assumptions in Table

TABLE 3 LIFE-CYCLE COST COMPARISON, CENTS PER MILE

High	Low	GASOLINE VEHICLE
5.71	2.57	Gasoline
14.76	11.93	Vehicle
7.84	6.91	Insurance
4.85	4.85	Maintenance
0.30	0.25	Oil
0.46	0.49	Replacement tires
1.27	1.27	Parking and tolls
0.25	0.25	Registration
0.25	0.25	Inspection and maintenance
0.86	0.57	Gasoline tax
0.19	0.19	Accessories
36.74	**29.53**	**Total Private Cost**

High	Low	ROADWAY-POWERED ELECTRIC VEHICLE
2.31	1.21	Total electricity cost for given operating mode
18.93	10.69	Initial vehicle cost
4.52	1.49	Batteries
9.48	7.35	Insurance
4.12	2.42	Maintenance
0.62	0.53	Replacement tires
1.27	1.27	Parking and tolls
0.34	0.28	Registration
0.86	0.57	Fuel tax
0.19	0.19	Accessories
0.049	0.016	Cost for additional electric roadway maintenance
6.00	0.78	Cost for electric roadway installation
48.69	**26.80**	**Total Private Cost**

2 could have a battery much larger than that of the RPEV in the cost analysis. However, vehicle range would still be limited not only by battery size but also by battery recharging time and the amount of vehicle capacity available for battery storage.

SENSITIVITY ANALYSIS

Each cost input parameter is subject to uncertainty, which is taken into account by using a range of possible values. The cumulative effect of uncertainty is reflected in the wide range of the resultant total cost projection. Because it is impossible to accurately determine the probability of each cost within this range, a sensitivity analysis was performed to determine the relative importance of the uncertainty associated with each variable used in the cost calculations. The effect of each variable on the total per-mile life-cycle cost is revealed by switching the low-cost and high-cost estimates for each variable, one at a time.

It was found that the uncertainty associated with any single variable did not have a profound effect on the total cost. The most significant variables were those that concerned RPEV batteries, vehicle maintenance and longevity, and roadway cost and utilization. However, changing three or more variables simultaneously did significantly change the total RPEV cost. For example, switching the high- and low-cost projections for roadway cost, roadway utilization, and RPEV maintenance increased the lower bound of the life-cycle cost 19 percent and decreased the upper bound by 15 percent.

Several other considerations are worth mentioning. A lower interest rate or a higher initial ICEV cost makes the RPEV more competitive by making the RPEV's greater purchase cost less significant. In addition, anything that reduces the required battery size of an RPEV (e.g., increasing the efficiency of the baseline vehicle) will favor the RPEV compared with an ICEV. Finally, the ICEV life-cycle cost is more susceptible to fuel price fluctuations than that of the RPEV because ICEV fuel cost constitutes a greater percentage of the total life-cycle cost.

RPEV EMISSIONS ANALYSIS

Even if RPEVs are more expensive than comparable ICEVs, they still may be preferable from society's point of view because of their environmental benefits. In 1988 more than 100 U.S. cities exceeded the health-based national ambient air quality standard for ozone (*52*). In 1988 highway vehicles accounted for 31 percent of the national total emissions of nitrogen oxides (NO_x), 26 percent of all reactive volatile organic compounds (VOCs), and 56 percent of carbon monoxide (CO) (*53*). As will be seen, RPEVs essentially eliminate transportation-generated CO and VOCs (a primary ozone precursor) and have the potential to substantially reduce NO_x.

To determine the emission impacts of RPEVs it is necessary to determine average fleet emission rates of the ICEVs they replace and the emission rates of power plants for the same pollutants during RPEV electricity generation. The power plant emissions can then be allocated to the RPEV fleet for comparison. If this procedure is followed, an RPEV-ICEV emissions comparison is possible for any level of RPEV penetration. In the analysis RPEV and ICEV emissions were compared under two different scenarios. The first scenario represented the emissions impact from RPEV implementation under current conditions, whereas the second examined implications under circumstances of more stringent ICEV and power plant emission controls.

First, a calculation was made of what the emission rate of an RPEV defined by the cost model inputs would have been given total vehicle energy demand and power plant emission rates in 1988. This was compared with the actual average emission rate for gasoline automobiles during the same year. Emissions from petroleum recovery, refining, and transportation were not counted, but their exclusion did not significantly affect the total vehicle emission rate.

The second scenario compared gasoline automobiles that meet current 50,000-mi automobile emission control standards with RPEVs operating on electricity from a utility mix in which 50 percent of the power plants meet the federally regulated "new source performance standards" (NSPS) (*54*). Calculations were based on EIA's projected power plant fuel feedstock mix for 2000 (*49*). Power plants have about a 40-year life, whereas the national vehicle fleet turns over about every 10 years. Therefore, it was assumed that by the time the entire vehicle fleet meets current emission standards (about 10 years from now), 50 percent of all power plants subject to emission control standards will meet the new source emission standards implemented in 1978 (almost all electricity production in the United States is from power plants subject to the standards).

Particulate emissions from 1988 gasoline automobiles were based on data from the California Air Resources Board (CARB) emissions model—EMFAC7D—to distinguish between particulate emissions from tire wear and those from exhaust. Tire wear accounts for approximately 95 percent of gasoline particulate emissions. The analysis increased RPEV tire wear particulate emissions in accordance with the percent weight increase of an RPEV relative to an ICEV.

Sulfur oxide (SO_x) emissions from a gasoline vehicle, unlike other catalyzed emissions, are a function of the amount of fuel used. SO_x emissions were estimated on the basis of the fact that essentially all sulfur in gasoline is converted to SO_2 on combustion. SO_x emissions for a 1988 gasoline automobile were calculated in the above manner and then scaled up linearly for a 35-mpg ICEV for the 2000 scenario.

Because there are no gasoline vehicle standards for particulates and SO_x emissions and no power plant standards for VOC and CO emissions, it was assumed that these emission rates will remain at current levels (SO_x emissions were adjusted for fuel economy improvements as described above). Furthermore, current SO_x power plant emissions (essentially all SO_x emissions from power plants is SO_2) are less than the standard, so it was assumed that power plants will continue to emit at current levels.

Finally, two levels of RPEV efficiency were used in the analysis. Both high and low fuel economies are based on the RPEV defined by the assumptions given in Tables 1 and 2. The low-efficiency RPEV averages 2.8 mi/kW-hr overall, and the high-efficiency RPEV averages 4.4 mi/kW-hr. These efficiencies include all distribution and system losses and are based on a driving regime that draws 50 percent of all vehicle power from the roadway. The relative emission changes resulting from RPEV use are indicated in Table 4. Results are presented for automobiles only; the results for light-duty vans and trucks are similar.

TABLE 4 PERCENT CHANGE IN EMISSIONS PER MILE DUE TO REPLACING GASOLINE PASSENGER CARS WITH RPEVs

	RPEV Efficiency[1]	VOC	CO	NOx	SOx	Part.
1988 SCENARIO[2]	HIGH	-99.8	-99.8	-68.3	108	23.5
Actual vehicle and powerplant emission rates.	LOW	-99.7	-99.7	-50.6	222	53.3
YEAR 2000 SCENARIO[3]	HIGH	-99.9[4]	-99.2[5]	-65.7	---[6]	16.8[7]
All vehicles meet current emission standards and 50% of all electricity used for RPEVs is from powerplants that meet NSP emission standards.	LOW	-98.2	-98.8	-45.1	---	44.4

1. High RPEV efficiency is 4.4 miles/kwh (from utility station): low RPEV efficiency is 2.8 miles/kwh.
2. Actual gasoline vehicle emission rates based on total gasoline automobile emissions divided by total automobile gasoline consumption divided by calculated average fuel efficiency for gasoline automobiles. Assumes emission rate for gasoline automobiles is independent of fuel economy except for SOx emissions. Excludes emissions from petroleum extraction, refinery, and transport. RPEV emission rates based on powerplant emission rates divided by total powerplant electricity output divided by RPEV fuel economy from the powerplant.
3. Assumes half of all RPEV electricity is from powerplants that meet NSP emission standards (or remain at current levels whichever is less) and that all gasoline vehicles comply with current federal emission standards. Converts HC standard to equivalent VOC standard for comparison purposes by multiplying former by CARB conversion factor of 0.85. Powerplant emissions based on EIA's projected powerplant fuel mix for the year 2000.
4. No NSP standard -- assumes powerplant emission rate remains at 1988 level.
5. No NSP standard -- assumes powerplant emission rate remains at 1988 level.
6. 1988 emission rate lower than NSP standard -- assumes powerplant emission rate remains at 1988 level. No vehicle standard -- assumes vehicles emit at 1988 rate. Result is same as 1988 scenario.
7. No vehicle standard -- assumes vehicles emit at 1988 rate.

EMISSIONS SUMMARY

The emissions analysis indicates that VOC and CO emissions from automobiles will be virtually eliminated with RPEVs. NO_x emissions will also be substantially reduced. SO_x and particulate emissions from transportation are likely to increase with the implementation of RPEVs. However, automobiles are responsible for less than 3 percent of all SO_x emissions and about 16 percent of all particulate emissions in the United States (*53*). NO_x, SO_x, and particulate emissions are all sensitive to the amount of coal used to produce electricity for RPEVs. Reducing the amount of coal-fueled electricity generation will go a long way towards controlling these three emissions.

The percent changes in Table 4 probably understate the air quality benefits that RPEVs will bring about. First, reductions in VOC and NO_x will translate into reductions of anthropogenic ozone, the main constituent of smog. Ozone is formed through a chemical reaction between VOCs and NO_x in the presence of sunlight. Because of the complexity of its formation, a slight decrease in VOCs or NO_x does not guarantee a decrease in ozone formation. However, with VOC and NO_x decreases of the magnitude suggested here, a large decrease is likely.

Second, a number of other air quality and emission benefits are likely to accompany the introduction of RPEVs. It is easier to control and monitor emissions from a few stationary sources than from millions of vehicles. Emission control devices on vehicles are vulnerable to more rapid deterioration (because of more taxing conditions and design criteria), tampering, intentional or unintentional misfueling, and so forth. It is difficult to conduct vehicle emission inspections as frequently as power plant inspections, and surprise inspections of vehicles are more cumbersome and expensive. In addition, the burden and inconvenience of emission control upkeep now borne by millions of individuals would be transferred to a relatively few power plants.

Another consideration is the time of day and location of emission releases. If the battery proves the primary source of power for RPEVs, most recharging and thus electricity generation will take place at night because of pricing incentives. Because sunlight is essential to ozone formation, nighttime charging will result in less ozone; in addition, fewer people will be subject to exposure during the night. More important, RPEVs can transfer emissions from the streets of urban areas where millions of people are subject to exposure to the top of smokestacks, which tend to be located in more remote and sparsely populated areas.

RPEV GREENHOUSE GAS EMISSIONS

It is estimated that transportation accounts for 30 percent of the global warming effect (*55*). In the United States, transportation accounts for approximately 27 percent of all fossil-fuel-generated carbon dioxide (CO_2)—the primary greenhouse gas (*4*). RPEVs offer potential for reducing emissions of greenhouse gases from the transportation sector. The actual benefits will depend primarily on the fuel used for electricity production, the efficiency of electricity production and distribution, and vehicle efficiency.

For this analysis a detailed model that calculates the difference between greenhouse gas emissions from an RPEV and an ICEV was used (*4*). The model calculates CO_2 emissions and CO_2-equivalent VOC, CH_4, N_2O, and CO emissions from ICEV and RPEV use on a per-mile basis. It considers all emissions from petroleum recovery (or feedstock recovery in the case of RPEVs) to end use. CO_2-equivalent emissions are based on the potential global warming effect of VOC, CH_4, N_2O, and CO. The results indicate that the impact of RPEVs on global warming depends strongly on the fuel mix used for generating electricity.

The results in Table 5 indicate the percent changes if all the electricity produced for RPEVs were to come from the indicated feedstock. For example, if the electricity for an RPEV were generated by using the 1988 power plant fuel mix, the vehicle would emit approximately 24 to 51 percent less of the specified greenhouse gases than a comparable ICEV. The high and low vehicle fuel economies are the same used in the emissions analysis—4.4 miles/kW-hr and 2.8 miles/kW-hr, respectively. With the exception of a coal-dominated power plant scenario used with low-efficiency RPEVs, RPEV use will reduce greenhouse gas emissions from transportation. The net reduction of transportation-generated greenhouse gases could be substantial if RPEVs supplant gasoline vehicles on a large scale and environmentally benign fuels are used to generate RPEV electricity.

ELECTRICITY DEMAND IMPLICATIONS—CASE STUDY

Wide-scale electrification of roadways will require increases in electricity production and electricity-generating capacity. Increased demand for electricity can have a positive or negative effect on electricity cost. If the increase occurs during off-peak hours, existing capacity will be more effectively utilized. In most areas, electricity demand peaks during afternoon hours, whereas traffic peaks in the early morning and late afternoon. If RPEVs do not rely heavily on storage batteries during peak electricity-generating periods, wide-scale use of RPEVs could require a significant increase in electricity-generating capacity. To increase generating capacity new facilities must be built. If the number of new facilities needed is large, average electricity costs could increase significantly because new sources of electricity are increasingly expensive (i.e., the marginal cost of production is greater than the average cost). The relationship between peak travel times and peak electricity-generating periods is the most important factor in determining RPEV electricity demand implications.

RPEV impacts on utilities were estimated under the most extreme scenario—the electrification of all highway lanes in California. It was assumed that all vehicles using California highways operate from electricity supplied through the electrified roadway. Traffic volumes and travel patterns were based on actual conditions in Los Angeles during 1985; non-RPEV electricity demand was based on production during 1985 from Southern California Edison, the largest utility in southern California (*56*).

The results indicate that in the unlikely event that *all* of California's highway traffic drew its entire energy supply from the electricity grid instead of from batteries, current production would increase approximately 62 percent and capacity by about 65 percent over 1985 output levels. This analysis is for illustrative purposes only. Complete RPEV penetration

TABLE 5 GREENHOUSE GAS EMISSIONS OF RPEVs RELATIVE TO ICEVs (AUTOMOBILES ONLY)

FEEDSTOCK	% CHANGE FROM ICEV CASE (CO_2-equivalent emissions)[1]	
	Low RPEV Efficiency[2]	High RPEV Efficiency
RPEV fuel from nonfossil electricity (excluding nuclear)	-100	-100
RPEV fuel from nuclear powerplants[3]	-95	-97
RPEV fuel from natural gas powerplants	-32	-56
RPEV fuel from 1988 feedstock mix	-24	-51
RPEV fuel from oil powerplants	-4	-38
RPEV fuel from coal powerplants	+11	-28

[1] CO_2- equivalent emissions include CO_2, VOC, CH_4, CO, and N_2O.
Assumes a national average powerplant efficiency of 33%.
Assumes 50% of all RPEV travel uses real-time electricity provided by the roadway.

[2] Low = RPEV efficiency of 2.8 miles/kwh (from the utility station): High = RPEV efficiency of 4.4. miles/kwh.

[3] Uses current electricity consumption of DOE gaseous diffusion plants; most of this electricity is from coal powerplants.

and highway electrification without on-board battery storage is highly unlikely; actual RPEV electricity demand during peak generating periods will undoubtedly be much lower. In fact, the best RPEV strategy may be to electrify only a modest share of urban Interstate systems because these highways represent just 0.3 percent of the entire U.S. roadway network but carry 12.7 percent of all traffic on the basis of vehicle miles traveled (*57*). In many urban areas the share of traffic on limited-access expressways is much higher—50 percent in Los Angeles (*58*).

POTENTIAL RPEV MARKETS

Applications

Although there have been no RPEV marketability studies, battery-powered EV market penetration studies on the basis of economic criteria and daily travel patterns indicate that electric vehicles could capture a significant share of the private and fleet vehicle markets. Perhaps the most revealing of these studies is one based on longitudinal travel data that examined individual travel patterns over an extended period (*59*).

The study indicated that an EV with a 55-mi range would suffice for 25 percent of the population surveyed on all but 37 days of the year and a vehicle with a 117-mi range would suffice for the same number of people for all but 1 week out of the year. Inability to use a vehicle for 37 days may prove unacceptable to many car owners; however, 7 days is less likely to be a major inconvenience or cost burden. This is even more likely if the 7 days are consecutive which, as the study points out, is usually the case (the 7-day period often represents vacation travel time). A multivehicle household could rely on a second vehicle to meet travel demand for those 7 days and a single-vehicle household could rent a vehicle with a longer range to meet an occasional long-distance travel need.

In addition, the study indicates that only 10 percent of the 2,286 people surveyed nationwide had daily travel patterns that exceeded 55 mi. These survey findings suggest that, although a range of about 55 mi is sufficient to meet the average daily travel demands of most people, a range of at least twice that distance would be needed to make the vehicle versatile enough to compete with longer-range vehicles. Therefore, a typical owner of a battery-powered EV would purchase and carry approximately twice as much battery as is needed on a daily basis. Battery size can be substantially decreased (and life-cycle cost reduced) if RPEV technology is strategically implemented.

Likewise, individuals who cannot recharge a battery overnight (e.g., those who do not have access to off-street parking or an electrical outlet) are excluded from battery-powered EV use. However, these prospective EV owners could recharge an RPEV battery through dynamic recharging or through inductor-equipped parking spaces. This could be an important consideration because approximately 43 percent of all urban dwellers rent apartments and are, therefore, unlikely to have access to an outlet for battery charging (*28*).

Given the above considerations, the largest market for RPEVs is probably as a commuter vehicle or as an around-town vehicle in a multivehicle household. At least one vehicle in every household will probably be capable of an ultralong trip, although this intermittent need could perhaps be met by a rented vehicle. Even as a "commute" vehicle, however, the RPEV would neither necessarily be a secondary vehicle nor accumulate less mileage annually than the long-distance vehicle.

In addition to privately owned commute vehicles, certain job-specific vehicles also provide a good application for RPEVs. Small-to-medium delivery vehicles, certain fleet vehicles (such as utility fleets), taxis, and buses are all prime candidates for RPEV use. Two extensive surveys of fleet managers—the North American Van Market Survey (*60*) and the EPRI/Detroit Edison survey (*61*)—found that electric vans with a 60-mi range could replace almost 200,000 vans in the 31 largest van fleets alone (including government vans) or approximately 3.5 million fleet vehicles nationwide. More important, both surveys indicate that these levels of EV penetration could be increased substantially with relatively minor range increase. Because many fleet vehicles routinely travel over the same roadway and are centrally refueled, they would be good candidates for RPEV replacement. In addition, many fleet vehicles in the surveys required considerable cargo capacity. Thus, the RPEV with its smaller battery may prove a better option than a battery-powered EV.

Location

High-volume urban roadways provide the best location for roadway electrification because the infrastructure cost can be distributed among more users. Approximately 60 percent of all travel in the United States takes place on urban roadways, and 65 percent of all urban interstate travel occurs under congested conditions that imply reduced travel speeds (*57*). This favors roadway electrification because the longer a vehicle is on the powered roadway the more battery charge it can receive and, unlike an ICEV, an RPEV does not waste fuel or pollute while it is immobile.

Roadway electrification would also be plausible on urban streets frequented by the same vehicles. Bus routes present an ideal opportunity for RPEV technology because they often go through heavily populated pedestrian areas that are sensitive to pollution (diesel buses are heavy emitters of highly visible harmful particulate matter). Other environmentally sensitive areas where pollution has more noticeable impacts, such as national parks, would also provide good applications for RPEV technology.

Roadway electrification could be used for intercity trips of moderate length. Long sections of roadway between reasonably close metropolitan areas would be electrified. The electrified lanes would be long enough to allow an RPEV to reach a neighboring city either by charging the battery en route or by replacing battery energy with roadway energy for part of the trip. However, the electrification of long stretches of rural highways is an expensive proposition because the cost would be allocated among fewer vehicles than would the cost of urban roadway electrification.

CONCLUSIONS

The RPEV may be a workable alternative to the petroleum combustion engine and an option for overcoming the main drawbacks of battery-powered EVs. Although there is a great deal of uncertainty regarding the cost of an RPEV, the air quality benefits are conclusive. In addition, an RPEV transportation system could help mitigate global warming.

The initial analysis of RPEV life-cycle costs described here indicates that RPEVs may be less expensive to own and operate than conventional petroleum vehicles even if RPEV users bear the full cost of electric roadway installation and maintenance. Furthermore, RPEV operating costs are less vulnerable to fuel-cost fluctuations and fuel-supply disruptions than are those of a comparable ICEV. RPEV implementation is well justified on the basis of air quality criteria. Wide-scale use of RPEVs would essentially eliminate transportation-generated VOC and CO emissions and substantially reduce NO_x emissions. RPEVs allow air quality benefits far greater than what is feasible with advanced-technology petroleum ICEVs. RPEVs would probably reduce greenhouse gas emissions considerably in addition to reducing regulated emissions. On the basis of the 1988 national fuel feedstock mix for electricity power plants, RPEVs would reduce automobile greenhouse gas emissions by 24 to 51 percent from 1988 gasoline automobile levels.

Battery-powered EVs are already finding their way into the fleet vehicle market and are being promoted as one solution to the air quality problem in southern California. However, even if optimistic expectations of battery technology materialize, EV markets will still be relatively small because of vehicle range limitations. Roadway electrification is a relatively new technology that offers important advantages over battery-powered EVs. A flexible RPEV system that offers a variety of battery sizes to accommodate various driving demands is capable of capturing a significant share of the commuter vehicle and fleet vehicle markets.

Although RPEV technology has been demonstrated and tested, a number of system design considerations must be addressed before the technology can be implemented. Once fundamental system objectives are determined, the technology can be tailored to best meet those objectives. Financing mechanisms also need to be established in the early developmental stages. The potential of RPEVs can only be realized if the uncertainties surrounding the concept are adequately addressed through expanded research and development. Because RPEV technology is in its infancy, there is reason to expect substantial efficiency gains and cost reductions in the near future.

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Funding Transportation Energy Conservation Programs with Oil Overcharge Settlements

MARIANNE MILLAR MINTZ AND ANNE MARIE ZEREGA

Since 1986 states have been receiving restitution funds from oil companies and crude oil producers found to have overpriced or miscertified federally controlled crude oil to avoid price restrictions between 1975 and 1981. As of March 31, 1989, the states had more than \$3.7 billion available for expenditure, including earned interest, and had received federal approval to spend about \$2.2 billion (63 percent). These funds have been earmarked for a wide range of energy conservation programs in residential and commercial structures, industry, and transportation. Because there have been several court judgments and because of the complexities of the project approval process, it is not clear how much oil overcharge money is being used to support transportation energy conservation projects. However, available data suggest that the transportation sector is receiving less than 12 percent of these funds. In 1988, transportation accounted for more than 63 percent of U.S. oil use. Within the guidelines of the court settlements, a variety of transportation energy conservation programs are eligible for funding with oil overcharge funds. The U.S. Department of Energy's administration of oil overcharge funds is discussed and the kinds of projects that state and local officials should consider in successfully developing a conservation program are illustrated.

Since 1974, the United States has made significant progress in improving energy efficiency. The average new car travels more than 10 mi farther on a gallon of fuel, commercial aircraft fly the same number of passenger miles on 30 percent less fuel, and trucks and railroads transport the same number of ton-miles of freight on 20 percent less fuel.

One area of continuing concern, however, is transportation's almost total dependence on petroleum-based fuels. Between 1974 and 1988, transportation's share of U.S. petroleum consumption rose from 51 to more than 63 percent. As domestic oil production declines and the United States depends more on imported oil, this trend is becoming increasingly serious. Energy conservation may be the only feasible near-term alternative for reducing transportation's oil consumption and U.S. vulnerability to disruptions in oil supply. Further, because transportation vehicles are major sources of urban congestion, pollution, and so-called greenhouse gases, saving energy in transportation can have important social, economic, and environmental benefits.

This paper summarizes a report prepared for the U.S. Department of Energy (*1*). That report highlights nearly 50 innovative transportation projects, which portray a range of interesting and unique options that should be considered when states or localities review existing conservation programs or develop new ones. In many cases, the features that make the projects unique can be readily incorporated into existing programs or new initiatives with little disruption to continuing efforts. The report also provides (*a*) the name and telephone number of one or more persons who can provide additional information on each project; (*b*) "scorecards" highlighting the nonenergy benefits of different types of projects; (*c*) the address and telephone number of each state energy office and the name of the individual responsible for administering the programs that have transportation components; (*d*) names, affiliations, addresses, and telephone numbers of individuals who can be contacted for information and assistance on particular types of transportation projects (e.g., transportation demand management); and (*e*) procedures for submitting proposals under the Stripper Well settlement agreement (see below).

Most of the projects described in the report have been supported by or are eligible for support from "oil overcharge" funds. Since 1986, all 50 states have been receiving funds from crude oil producers found to have overpriced or miscertified federally controlled crude oil to avoid price restrictions. As of March 31, 1989, states had received more than \$3.7 billion, a total that includes earned interest. Federal approval has been received to spend about \$2.2 billion, or 63 percent of these funds. Within the guidelines of the court settlements, a variety of transportation energy conservation programs are eligible for funding with oil overcharge funds. Because of the side benefits mentioned above, even more funding may be available from sources focusing on environmental quality, economic development, or congestion relief.

TRANSPORTATION ENERGY PICTURE

The United States enjoys perhaps the finest transportation network the world has ever seen. In particular, the Interstate highway and aviation networks provide an unrivaled source of reliable and inexpensive transportation. The cost of this system, however, is national dependence on petroleum fuels for all but a fraction of U.S. transportation needs.

The implications of this dependence on imported oil were driven home during two exceptional periods—the Arab oil embargo in 1973–1974 and the Iranian revolution in 1979. The unprecedented oil price increases and the market dislo-

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cations that accompanied them spurred major efforts in the industrialized world to reduce energy consumption, increase energy efficiency, and develop alternative energy sources. As a result, significant progress has been made in using energy resources more wisely.

In 1988, the United States used slightly more energy than in 1973 (see Figure 1). Almost 40 percent more energy, an amount equivalent to about 5 billion barrels of oil per year, would have been used if changes had not been made. Part of the reduction in U.S. energy use can be attributed to shifts in the industrial production mix and to changes in consumer awareness and behavior. However, most is related to technological improvements in vehicles, buildings, and equipment. The improvements are largely motivated by higher energy prices. In the transportation sector, factors other than higher prices have influenced current trends in energy use.

Transportation's Share of U.S. Oil Consumption

Figure 1 shows changes in energy consumption by sector; Figure 2 documents changes in petroleum (liquid fuel) consumption over the same period. Together these graphs indicate that all sectors have significantly improved energy efficiency. However, stationary energy consumers (buildings, industries, and utilities) have also rebuilt or replaced equipment to switch from petroleum to other, and perhaps more stable, fuels like coal and natural gas. The transportation sector has failed to switch to nonpetroleum fuels. In 1973 transportation consumed 8.4 million barrels of oil per day (MBPD); in 1988 the comparable figure was 10.2 MBPD, a 20 percent increase. All other sectors reduced their oil use over this period: residential and commercial consumption by 39 percent (from 2.1 to 1.3 MBPD); industrial consumption by 8 percent (from 4.3 to 4.0 MBPD); and electric utilities by 54 percent (from 1.7 to 0.8 MBPD). What emerges from these data is a clear picture of the transportation sector's almost total dependence on petroleum.

Oil consumption would have grown faster in the past and would grow faster in the future were it not for impressive fuel-efficiency gains. As new cars have replaced older "gas guzzlers," the average fuel economy of all cars on the road has increased from 13.3 mi/gal in 1973 to 20.0 mi/gal in 1988 (*3*,*4*). However, gains in fuel efficiency have been offset by increases in the number of vehicles on the highways. There were 45 percent more vehicles registered in 1988 than in 1973. Further, the total number of miles traveled grew by more than 54 percent in that time.

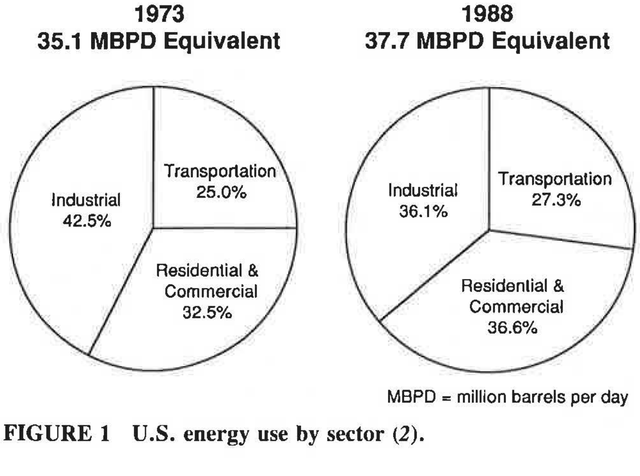

FIGURE 1 U.S. energy use by sector (*2*).

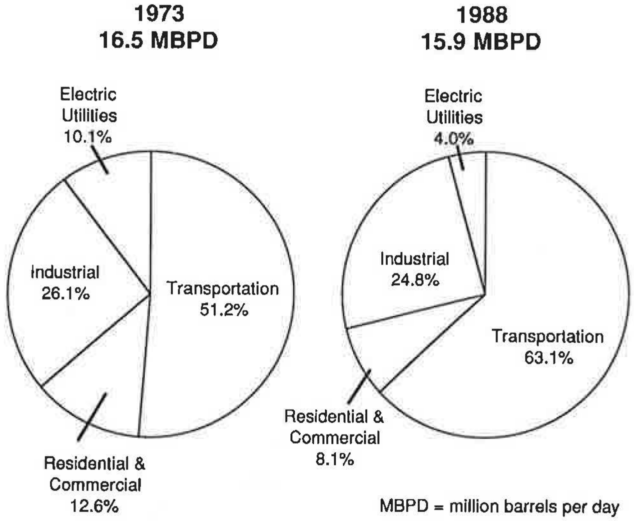

FIGURE 2 U.S. petroleum use by sector (*2*).

Another development having a negative effect on fuel economy has been the increased popularity of light trucks. Light trucks accounted for 14 percent of all new car, van, pickup, and utility vehicle sales in 1971, but for nearly 32 percent of these sales in 1988. They are becoming a large part of the fleet, often being used in place of cars, but having fuel economies 30 to 40 percent less than those of the cars they are replacing. This substitution has significantly affected overall fuel economy.

Because of these three factors—the failure to switch from petroleum-based to nonpetroleum-based fuels, the growth in vehicular travel, and changes in the mix of vehicles on the road—transportation is responsible for a large and growing share of domestic oil *consumption*. In 1973 the sector accounted for 51 percent of domestic oil consumption; by 1988 this figure had risen to 63 percent (see Figure 2), an amount 23 percent greater than U.S. oil *production* in that year. This shortfall is projected to increase to 41 percent in 2000 and to 68 percent in 2010 (*5*).

Transportation's Contribution to Environmental Problems

The transportation sector also contributes to several environmental problems. Of particular import is global warming resulting from increasing concentrations of greenhouse gases in the atmosphere. During the last 100 years, the average global temperature has risen 0.7°C. Increasing temperatures could lead to a rising sea level and climatic changes (for example, severe droughts, flooding, and shifts of growing areas to acreage with thinner soils). Carbon dioxide, the most abundant of the greenhouse gases, is produced by combustion of fossil fuels, including gasoline, diesel oil, and jet fuel. As the number of vehicle miles traveled increases, the transportation sector's contribution to this problem will increase.

Also of concern is the transportation sector's contribution to acid rain and ozone depletion. Vehicle exhaust gases contribute to acidification of the atmosphere, causing increased corrosion of structures and other physical property and damage to ecosystems. Chlorofluorocarbons released by aerosol propellants and refrigerants, including Freon from automotive air conditioners, are a major cause of holes detected in the earth's protective ozone layer.

Traffic Congestion

Urban traffic in the United States is growing by 6 percent per year and is projected to double in many areas by 2000. Increasing traffic congestion translates into increased fuel consumption and tail pipe emissions. Most local officials and transportation planning professionals agree that expanding our roadway system is not always feasible. The space may not be available, or the political and economic costs of land acquisition and highway construction may be too high. Therefore, innovative means must be found to increase the people-moving capacity of existing roadways. Energy conservation is an important side benefit of many of these projects.

TACKLING TRANSPORTATION'S DEPENDENCE ON OIL

Improving Vehicle Technology

Overall automotive fuel economy will continue to improve as older vehicles are retired and newer, more fuel-efficient vehicles take their place. However, even the widespread use of more fuel-efficient vehicles will leave the United States heavily dependent on oil for transportation for the foreseeable future. The most promising technological opportunities for further reductions in oil consumption lie in developing alternative fuels for existing engines or developing new engines that can run on alternative fuels. Although measures like these are being pursued, they are still many years away from tangibly affecting this petroleum-based transportation system.

Improving Transportation System Efficiency

Improving the efficiency of the transportation system is the only feasible near-term option for conserving petroleum in the transportation sector. In the past two decades, the concept of transportation system management (TSM) has evolved to combat traffic congestion and improve air quality. Most TSM measures conserve energy by maximizing transportation system efficiency, and many have found their way into the transportation control plans required by the U.S. Environmental Protection Agency for improving air quality in major urban areas.

Through its state energy offices, the U.S. Department of Energy has promoted TSM and assisted in implementing transportation control plans by funding transportation projects that help meet energy conservation goals. Since 1975, departmental activity has become more visible as a result of legislation establishing a grant program to support energy conservation projects, including ridesharing. By continuing to provide funds for ridesharing and various other TSM measures, state energy offices are the U.S. Department of Energy's principal means of supporting transportation energy conservation.

Energy Conservation Programs of the U.S. Department of Energy

All U.S. Department of Energy funding for state transportation programs is managed by the Office of State and Local Assistance Programs (OSLAP) under the Assistant Secretary for Conservation and Renewable Energy. OSLAP manages the following four energy assistance programs; a fifth—the Low-Income Home Energy Assistance Program (LIHEAP)—is administered by the U.S. Department of Health and Human Services. LIHEAP is structured as a state block grant program to help low-income households pay home energy costs.

1. State Energy Conservation Program (SECP): Congressionally established in 1975, SECP is a cooperative effort of federal and state governments to promote energy efficiency and to reduce growth in energy demand. The U.S. Department of Energy provides grants to states to implement state energy conservation plans. The grants have a 20 percent state matching requirement. Five energy conservation measures are mandatory under SECP: (*a*) lighting efficiency standards for public buildings, (*b*) thermal efficiency standards for public buildings, (*c*) programs to promote ridesharing and mass transportation, (*d*) energy efficiency standards for state procurement activities, and (*e*) programs to permit right-turn-on-red. Once these mandatory programs are funded, the states may fund discretionary programs to conserve energy.
2. Energy Extension Service (EES): The EES is a partnership between federal and state governments to provide small-scale energy users with practical information and technical assistance on energy conservation. The U.S. Department of Energy provides EES grants to the states; in turn, states support a variety of activities, including small business workshops, energy efficiency demonstration programs, weatherization loans, and energy information centers. Although eligible, transportation is not a major component of this service.
3. Weatherization Assistance Program: There are no transportation elements in this program.
4. Institutional Conservation Program: There are no transportation elements in this program.

Since 1982, most of OSLAP and much of LIHEAP funding has come from oil overcharge funds. Deposited in escrow accounts, these funds derive from court judgments against crude oil producers for overcharging purchasers of petroleum products or for not complying with the allocation regulations established before 1981. The escrow accounts contain billions of dollars from a complex network of settlements and are governed by different judgments, regulations, and statutes. To date, more than $3.7 billion has been disbursed to states to be spent on energy programs. (This excludes $1.25 billion in Texaco funds. According to the September 29, 1988, court decision, $534 million of these funds will be distributed to states.) An additional $1.4 billion is in an escrow account held by the U.S. Department of Energy. This account earns about $244 million in interest annually. In addition, approximately $1.3 billion will be available in the 1990s when pending court cases are settled. Thus, significant funds are available to support energy conservation programs, including transportation projects. The states will decide how to spend their oil overcharge funds; the U.S. Department of Energy requires only that the state plans comply with its governing regulations.

There are three major oil overcharge settlements:

- Exxon: The $2.1 billion settlement can be used only for the four programs mentioned above, plus LIHEAP. Exxon funds cannot be used for capital or research and development projects. Most of these funds have been earmarked for specific projects.
- Stripper Well: The $727 million settlement can be used not only for the same five programs as the Exxon settlement, but also for other energy-related activities. This judgment is more open than Exxon's judgment, permitting the funding of existing or new energy-related programs designed to benefit state energy consumers. Although most of this money has been earmarked, much of it has not been spent. States can still reallocate these, as well as Exxon, funds to innovative transportation programs.
- Texaco: Of the $1.25 billion settlement, $534 million will go to states over a 5-year period beginning in calendar year 1989. This judgment is more like the Stripper Well judgment in that funds can be spent under any precedent of any earlier oil overcharge fund settlement. None of this money has been earmarked to date.

In addition to these three settlements, the Petroleum Overcharge Distribution and Restitution Act and the Warner Amendment directed the U.S. Department of Energy to disburse additional funds to the states. The act allows the U.S. Department of Energy to disburse excess funds (up to $200 million annually) from all oil overcharge settlements for five specific energy programs. Between 1987 and 1989, $250 million was distributed under this act. The Warner Amendment is a one-time disbursement of accrued interest from oil overcharge accounts. Under the 1982 amendment, the Department of Energy disbursed $200 million to be spent on the five energy programs specified in the Exxon settlement.

Table 1 summarizes OSLAP data on Exxon and Stripper Well funds distributed to states, territories, and possessions as of March 31, 1989. It also indicates how much had been spent as of that date and how much was still available. (The accuracy and completeness of the OSLAP data base depend on how quickly and completely states report their receipt and use of funds. Thus, data tend to be less current than the accountings of individual states, which should be contacted for a more up-to-date report on fund availability.) Because there have been several court judgments and because of the complexities of the project approval process, it is not clear how much oil overcharge money is being used to support transportation energy conservation projects. However, Table 1 suggests that only 12 percent of the funds is being used for such projects.

Figures 3 and 4 provide, respectively, specific examples of transportation projects eligible for funding and lists of the actual types of transportation projects funded with Exxon and Stripper Well funds as of March 31, 1989.

Clearly, funds are available to support transportation energy conservation. As always, however, effective planning requires identification of measures appropriate to each state or locality and enlistment of the support of constituent agencies. The process can take time and fortitude. Agencies that can be consulted for guidance and support when developing transportation energy conservation measures include state energy, transportation, and environmental management departments, as well as metropolitan planning organizations. These agencies have considerable knowledge and expertise and can be valuable allies in planning and implementing transportation energy conservation projects.

INNOVATIVE TRANSPORTATION ENERGY CONSERVATION MEASURES

There are many specific strategies for improving transportation energy efficiency and an array of program models incorporating them. Most are eligible for funding under Exxon, Stripper Well, or several of the smaller oil overcharge settlements. Many successful programs are multipurpose—they both save energy and further other local objectives. These other objectives could include economic development, providing special assistance to low-income persons, reducing vehicle emissions, expanding the people-moving capacity of existing transportation facilities, and so forth. Obviously, for any particular state or locality, programs must be tailored to local needs and resources. In some cases, it may be appropriate to design multipurpose programs; in others, such constituency-building techniques may be irrelevant.

Table 2 gives a number of transportation energy conservation programs recently implemented by state and local agencies. Programs focus on one or more basic strategies—improving vehicle occupancy, improving vehicle technical efficiency, enhancing traffic flow, or switching from petroleum to nonpetroleum fuels. The following discussion elaborates on these strategies.

Vehicle Occupancy Improvement

Occupancy improvement strategies focus on promoting ridesharing—by either providing new transit services, encouraging workers to join carpools or vanpools, or otherwise improving the efficiency or attractiveness of high-occupancy vehicles (HOVs). An innovative context for new transit services is in crowded resort areas where such services can reduce traffic congestion, improve air quality, and generally enhance visitor enjoyment. With sufficient ridership and a tight cost structure, they can be virtually self-supporting from farebox revenues.

Rideshare promotion programs can assist in carpool and vanpool formation by providing personalized matching services with regular follow-up and continued assistance or by using mass merchandising techniques (e.g., publishing carpool matchlists like classified advertisements) to reach passive markets of potential ridesharers. Rideshare promotion programs can also focus on reaching particular submarkets (e.g., low-income workers who live in central cities), providing incentives (e.g., discounts on monthly transit passes or payments

TABLE 1 EXXON AND STRIPPER WELL FUNDS DISBURSED TO STATES AND EARMARKED FOR TRANSPORTATION AND OTHER PROJECTS

State, Territory, or Possession	Exxon Settlement				Stripper Well Settlement				Transportation Funding	
			Earmarked				Earmarked			
	Disbursed (Thousand $)	Interest (Thousand $)	Thousand $	%	Disbursed (Thousand $)	Interest (Thousand $)	Thousand $	%	Thousand $	%
Alabama	32,192	NR[a]	19,706		15,443	958	14,819	90.4	13,328.3	38.6
Alaska	8,272	1,334	8,790	91.5	3,894	528	3,555	80.4	0	0
American Samoa	371	32	300	74.4	NR	14	NR	NA[b]	0	NA
Arizona	21,566	3,399	19,487	78.1	10,323	995	3,578	31.6	2,733.0	11.8
Arkansas	25,950	3,290	20,176	69.0	12,807	826	11,639	85.4	5,582.7c	17.5
California	194,717	28,380	82,056	36.8	92,128	8,709	132,784	132.0	58,045.7	27.0
Colorado	22,716	3,741	23,611	89.2	10,821	873	7,851	67.1	3,300.7	10.5
Connecticut	34,900	5,853	7,367	18.1	17,091	1,472	18,269	98.4	5,484.9[c]	21.4
Delaware	9,945	1,422	6,343	55.8	4,778	456	4,074	77.8	103.5	1.0
District of Columbia	4,604	718	2,418	45.4	2,404	333	2,182	79.7	624.8	13.6
Florida	98,115	19,821	59,209	50.2	46,498	4,993	34,080	66.2	13,770.0	14.8
Georgia	46,625	6,302	31,775	60.0	22,411	2,508	22,151	88.9	3,021.5	5.6
Guam	3,100	594	305	8.3	1,483	147	1,483	91.0	46.7	2.6
Hawaii	14,482	1,223	15,810	101.0[d]	6,915	548	NR	NA	1,514.5[e]	NA
Idaho	8,691	958	8,158	84.5	4,130	354	3,365	75.0	1,260.0[c]	10.9
Illinois	96,106	11,377	65,085	60.6	46,224	3,488	46,471	93.5	200.0[c]	0.2
Indiana	51,631	5,113	18,989	33.5	24,789	586	22,836	90.0	29,369.4	70.2
Iowa	27,424	4,437	22,466	70.5	13,113	1,363	23,880	165.0	7,668.1	16.5
Kansas	23,958	1,500	7,866	30.9	11,282	1,237	2,952	23.6	2,830.1	26.2
Kentucky	27,439	1,249	8,331	29.0	12,900	1,256	13,231	93.5	0[c]	0
Louisiana	51,536	4,192	16,224	29.1	23,938	1,471	18,715	73.7	16,500.0[c]	47.2

Maine	15,094	1,166	13,551	83.3	7,398	404	7,330	94.0	50.0[c]	0.2
Maryland	36,416	5,082	33,772	81.4	18,019	1,926	19,798	99.3	461.2	0.9
Massachusetts	70,341	11,493	63,342	77.4	34,451	3,269	39,000	103.0[d]	0[c]	0
Michigan	70,991	8,987	30,228	37.8	34,290	3,467	43,663	116.0[d]	98.3	0.1
Minnesota	36,066	4,072	25,244	62.9	17,464	2,150	16,769	85.5	6,599.4	15.7
Mississippi	28,378	2,637	30,629	98.8	13,742	1,245	12,283	82.0	5,151.2	12.0
Missouri	41,516	4,271	35,377	77.3	19,871	2,080	14,014	63.8	1,069.7	2.2
Montana	9,585	1,115	7,400	69.2	4,555	428	3,664	73.5	2,187.0	19.8
Nebraska	15,505	3,523	4,877	25.6	7,421	791	600	7.3	540.3	9.9
Nevada	8,767	1,291	4,360	43.3	4,076	317	6,599	150.0[d]	5,345.0[c]	48.8
New Hampshire	9,798	1,882	10,152	86.9	4,690	493	4,174	80.5	868.6	6.1
New Jersey	75,433	NR	22,973	30.5[f]	37,150	2,291	34,775	88.2	0[c]	0
New Mexico	13,693	2,758	10,004	60.8	6,592	655	9,000	124.0d	154.6	0.8
New York	159,875	15,405	153,753	87.7	77,928	7,016	65,070	76.6	19,500.0	8.9
North Carolina	47,030	12,139	20,406	34.5	22,588	3,138	21,917	85.2	2,045.0	4.8
North Dakota	7,721	1,308	5,295	58.6	3,689	313	5,500	137.0[d]	1,756.3	16.3
Northern Mariana Islands	192	24	200	92.6	NR	9	25	NA	0[c]	0
Ohio	79,740	17,809	62,878	64.5	37,816	4,592	37,249	87.8	9,003.1[c]	9.0
Oklahoma	26,234	3,852	15,896	52.8	12,429	814	13,595	103.0[d]	1,410.9	4.8

(continued on next page)

TABLE 1 *(continued)*

State, Territory, or Possession	Exxon Settlement				Stripper Well Settlement				Transportation Funding	
	Disbursed (Thousand $)	Interest (Thousand $)	Earmarked Thousand $	Earmarked %	Disbursed (Thousand $)	Interest (Thousand $)	Earmarked Thousand $	Earmarked %	Thousand $	%
Oregon	20,722	2,552	19,931	85.6	9,976	1,109	10,934	98.6	9,727.8	31.5
Pennsylvania	96,804	10,416	28,560	26.6	46,857	1,421	21,288	44.1	0[c]	0
Puerto Rico	20,054	1,187	2,000	9.4	9,587	910	NR	NA	0[c]	NA
Rhode Island	8,005	1,077	6,761	74.4	3,990	317	4,494	104.0[d]	135.0	1.2
South Carolina	25,188	4,880	2,929	9.7	11,998	1,093	10,166	77.7	336.3[c]	2.6
South Dakota	7,502	1,258	6,177	70.5	3,598	216	2,896	75.9	2,211.0[c]	24.4
Tennessee	34,603	2,923	35,724	95.2	16,283	1,072	4,600	26.5	0[c]	0
Texas	157,187	18,363	49,844	28.4	74,246	8,141	65,481	79.5	5,983.0	5.2
Utah	12,454	1,847	8,809	61.6	5,937	546	5,405	83.4	2,198.4	15.5
Vermont	5,005	619	3,720	66.1	2,409	271	1,602	59.8	150.0[c]	2.8
Virgin Islands	9,951	NR	2,112	21.2[f]	4,655	NR	NR	NA	529.3	NA
Virginia	53,377	NR	29,586	55.4[f]	25,828	4,304	21,268	70.6	5,900.0	11.6
Washington	32,122	2,429	24,226	70.1	15,369	1,500	14,438	85.6	10,755.0	27.8
West Virginia	12,903	2,551	6,819	44.1	6,014	464	6,541	101.0[d]	6,994.1	52.4
Wisconsin	36,967	7,617	17,700	39.7	17,707	1,957	18,420	93.7	2,800.0[c]	7.8
Wyoming	8,874	1,237	6,102	60.4	4,104	312	3,173	71.9	0[c]	0
Total	2,098,433	262,705	1,245,809	53	1,006,099	92,139	933,646	85	269,344	12

[a] NR = not reported.

[b] NA = could not be calculated with available data.

[c] Exxon settlement only.

[d] Earmarked funds include expected future interest or expected future disbursements.

[e] Stripper Well settlement only.

[f] Excludes interest.

Sources: J. Duane, F. Weik and E. Guziewicz, unpublished data. For additional detail on state disbursements and allocations see also Ref. 6.

Programs for the general driving public

- Fuel-efficient traffic signals
- Highway traffic management
- Motor fuels recycling
- Highway and bridge maintenance and repair
- Public transportation

Programs for consumers

- Car care clinics
- Fuel efficient driver training
- Ridesharing
- Marketing of state-supported passenger rail and mass transit
- Bicycle promotions

Programs for commercial, industrial, and governmental institutions

- Vehicle fleet maintenance
- Transportation system management assistance
- Remanufacturing and refitting of transit buses
- Computerized school bus routing
- Alternative transportation fuels
- Transit system refitting loans

FIGURE 3 Examples of state restitutionary programs in the transportation sector approved by the Department of Energy [from Department of Energy Stripper Well Exemption Litigation, M.D.L. 378 (May 5, 1986), Exhibit J, U.S. District Court for the District of Kansas].

toward initial van leasing expenses for new vanpools), or removing barriers (e.g., providing reimbursement of taxi fares for emergency midday trips) that can deter workers from participating.

Improving the efficiency or attractiveness of HOVs by either preferential treatment or reductions in operating costs can also increase ridesharing. Exclusive lanes and parking spaces, signal preemption, merge priority at traffic signals, and price discrimination through reduced tolls exemplify the kinds of measures designed to treat HOVs preferentially. Expanding into off-peak charter services, establishing self-insurance pools, and generating additional revenue through the sale of snacks and beverages on subscription routes illustrate the kinds of measures that can control operating costs.

Vehicle Efficiency Improvement

Strategies to improve vehicle fuel efficiency focus on increasing the technical performance of the vehicle or the skill of the vehicle operator. Technical performance of fleet vehicles may be increased by maintenance scheduling and systematic fleet management, especially regular performance monitoring to spot minor problems before they become catastrophic. For

Ridesharing promotion and matching services
Vehicle routing and fleet management
Training in fuel-efficient driving techniques
Training in fuel-efficient vehicle maintenance
Rural transportation
Improved timing of traffic signals
Transportation services for elderly and handicapped persons
Waste oil recycling
Motor fuel testing
Transit vehicle and equipment purchases
Construction and engineering studies of transit and multimodal transportation centers
Transit station and track improvements
Pedestrian and bicycle pathways
Road and bridge repairs
Park-and-ride and park-and-pool lots

FIGURE 4 Types of transportation projects funded with Stripper Well funds.

household vehicles, "car care clinics" can identify such "fuel-robbers" as improperly inflated tires, out-of-tune engines, and plugged air cleaners. More specialized services focusing on engine diagnostics can identify computer control problems that may not be detected in standard tests but that reduce engine efficiency.

Operator skill can be upgraded through training in fuel-efficient driving practices, either as part of high school driver education curricula or in fleet management programs. Videotapes and computer games offer a particularly effective and innovative means of reaching young drivers. Older drivers can be reached through public service advertisements and through schoolchildren who have learned about energy conservation practices (e.g., proper tire inflation) in the classroom.

System Flow Improvement

Optimized traffic signal timing is probably the most widely applied flow improvement strategy. After several years of applied research and field experience (the first project explicitly designed to conserve fuel was initiated in 1982), a number of signal optimization models (e.g., TRANSYT-7, PASSER, SOAP, AAP, MAXBAND) and planning regimes have been developed. Though staff of the local operating agency must tailor these techniques to local conditions and capabilities (i.e., by designing and implementing an appropriate data collection effort, selecting and calibrating the model, and implementing and evaluating the selected timing plan), they provide both a useful reference and a starting point for the project.

TSM strategies may be defined as a host of measures designed to increase the effective capacity of the highway network, particularly during the peak period. Capacity enhancement, in turn, permits existing facilities to accommodate relatively more travel under free-flow conditions, which generally increases vehicle fuel economy. In addition to improved signal timing and priority treatment for HOVs, TSM strategies include improved intersection channelization and striping, peak-period reverse lanes, measures to shift travel demand (both commuters and truck deliveries) from peak to off-peak hours, and various forms of peak-period travel demand reduction.

Because of its potential for dramatic improvements in peak-period congestion, travel demand reduction is gaining increased local attention. Many employment centers, either at the behest of the local community or in response to a widely perceived congestion problem, have formed transportation management organizations (TMOs) to promote ridesharing, flextime, and other options to reduce the share of work trips occurring in single-occupant vehicles during the peak period. Although functions vary in response to local needs and resources, TMOs generally serve as conduits for information on available transit services, areawide carpool and vanpool matching services, and alternative work schedules. Some also collect and main-

TABLE 2 INNOVATIVE TRANSPORTATION ENERGY CONSERVATION PROJECTS RECENTLY IMPLEMENTED BY STATE AND LOCAL AGENCIES (*1*)

Program Name	Type	Sponsoring Agency or Location	Geographic Applicability			Major Innovative Feature	Synergies or Side Benefits
			Urban	Suburban	Rural		
Get In	Ridesharing	Montgomery Co., Md.	X	X		Taxi reimbursement for emergency midday trips	
Share-A-Ride	Ridesharing	Montgomery Co., Md.	X	X		Personalized matching services	
Commuter's Register	Ridesharing	Rideshare Co., Hartford, Conn.	X	X	X	Reaches both active and passive markets	Transit promotion
Innercity Access	Ridesharing	Caravan for Commuters, Boston	X	X		Connects inner-city workers with suburban job sites	Urban economic development
JOBS Bus	Ridesharing	Greater Richmond Transit Co.	X	X		Connects inner-city workers with suburban job sites	Urban economic development
Work Bus	Rural transportation	Berrien Co., Ga.		X	X	Connects rural workers with major job sites	Full cost recovery through concession and charter services
Eureka Springs Transit	Rural transportation	Eureka Springs Transit, Ark.		X	X	Public transportation for recreational area	Tourism promotion
Vanpool Incentive Program (VIP)	Ridesharing	Caravan for Commuters, Boston	X	X	X	Cash incentives to new vanpoolers	Defers highway capacity expansion
Employee Transportation Managers	Ridesharing	Commuter Computer, Calif.	X			On-site, customized rideshare promotion	Turnkey opportunity for private providers
Car Kit	Driver training	Alabama Energy Extension Service	X	X	X	Video and computer games reach young drivers	Training in computer use
Fleet	Fleet management	New York Energy Office	X	X	X	Hands-on, customized fuel management training	Training in computer use
Car Chek	Vehicle maintenance	Virginia Division of Energy	X	X	X	Ongoing engine diagnostic services for the general public	Mechanics' training
CompuCar	Vehicle maintenance	Alabama Energy Extension Service	X	X	X	Ongoing engine diagnostic services for the general public	Mechanics' training; motorist viewing of Car Kit videos
Project Inflate	Vehicle maintenance	Alabama Energy Extension Service	X	X	X	Fun approach to proper tire inflation	School children learn about energy conservation
Fuel Efficient Traffic Signal Management (FETSIM)	Transportation Systems Management	Caltrans and California Energy Commission	X	X		Training and hands-on assistance to local traffic engineers	Improved traffic flow; reduced emissions

(*continued on next page*)

TABLE 2 (*continued*)

Program Name	Type	Sponsoring Agency or Location	Geographic Applicability			Major Innovative Feature	Synergies or Side Benefits
			Urban	Suburban	Rural		
Various projects giving preferential treatment to HOVs	HOV lane model	Oak Ridge National Laboratory, Tenn.	X	X		Bus and carpool travel time reduction	Increased people-moving capacity
	Signal preemption	Santa Clara Co., Calif.	X	X		Increased HOV mode shares	Deferred highway capacity expansion
	Preferential tolls	Caltrans, Calif.	X	X			Reduced emissions
	Project Hero	Seattle Metro, Wash.	X	X			
	Preferential parking and free transit	Portland, Oreg.					
Operation Breezeway	Transportation Systems Management	California Highway Patrol, Caltrans, and California Trucking Association	X			Shift truck delivers to off-peak hours	Peak hour congestion relief; truck accident reduction
Adequate Facilities Ordinance	Transportation Demand Management	Montgomery Co., Md.	X	X		Development continent on adequate transportation; trade-off provisions; bond forfeiture to ensure compliance	Systemwide traffic reduction; transit promotion
Transportation Systems Management Ordinance	Transportation Demand Management	Pleasanton, Calif.	X	X		Annual goals for large employers to reduce single-occupant work trips	Comprehensive data base; transit promotion
Various projects substituting telecommunications for work trips	Transportation Demand Management	Mountain Bell, Colo.	X	X	X	Individually tailored schedules	Improved employee productivity; reduced parking and office space; employment for functionally challenged workers
		State of California	X	X	X	Extensive planning, training, and follow-up support	
Pipeline construction	Modal shifts	Maryland Department of Transportation and Maryland Energy Office	X	X	X	Eliminated truck deliveries of jet fuel to Baltimore-Washington International Airport	Reduced truck traffic; improved reliability
Trawl Efficiency Devices (TEDs)	Nonhighway vehicle fuel efficiency	Georgia Department of Natural Resources			X	Grants for shrimpers to purchase TEDs that reduce drag on nets	Improved competitiveness of local industry; endangered species protection; reduced bycatch and improved marketability of catch

Fishing Vessel Energy Conservation	Nonhighway vehicle fuel efficiency	California Energy Extension Service			X	Information, technical assistance, equipment testing, and low interest loans for efficiency improvements to fishing vessels	Improved competitiveness of local industry
Tractor tune-ups	Nonhighway vehicle fuel efficiency	Utah Energy Office			X	Information and technical assistance on fuel-efficient maintenance of diesel farm equipment	Improved competitiveness of local industry
Dyna-Bite Traction Intensifier	Nonhighway vehicle fuel efficiency	U.S. DOE Energy-Related Inventor's Program			X	Reduced tire friction and ballast requirement for tractors and other farm machines	Improved competitiveness of local industry; enhanced productivity and equipment life
Railmaster™	Nonhighway vehicle fuel efficiency	New York Energy Research and Development Administration			X	R&D on an easily removable underchassis system to convert truck trailers to "rail cars"	Economic development—job creation
Ferry Boat Energy Conservation	Nonhighway vehicle fuel efficiency	Washington State Energy Office	X	X	X	Identified equipment and operating measures to improve fuel efficiency of ferry boats	Operating cost savings to state general fund; crew training
Roadside Rest and Information Centers	Alternative fuels	Maine Department of Transportation		X	X	Solar-powered water and space heat	
Solar-powered highway support facilities	Alternative fuels	Caltrans, Calif.		X	X	Solar-powered irrigation controllers, emergency call boxes, traffic counters, and sign lighting	Cost savings
Various projects testing methanol as a vehicle fuel	Alternative fuels	State of California, U.S. DOE, U.S. DOT (UMTA)	X	X	X	Matched methanol fleets under various climates and service conditions to similarly equipped gasoline control fleets	May stimulate local vehicle industry

tain data bases on work trip travel patterns, actively promote alternative work schedules, and provide in-house carpool and vanpool matching services.

Telecommuting, or substituting voice or data communication for work travel, is an alternative that is receiving increasing interest. Historically, most telecommuting programs have been developed by private-sector employers seeking to expand their work force but not their expenses for office space (and, perhaps, parking). More recently, however, a number of states and localities have begun to investigate telecommuting as a strategy for reducing traffic congestion, improving air quality, and saving energy. Between private- and public-sector activities, a considerable body of knowledge on planning, managing, and evaluating telecommuting programs is being developed.

Off-Road Efficiency Improvement

Although off-road travel accounts for only 28 percent of transportation energy use, it still consumes the equivalent of approximately 720 million barrels of crude oil per year (7). This fuel is used by a wide range of mobile equipment operated under an equally wide range of duty cycles. Thus, overall conservation targets tend to be small compared with those in the road sector, and efforts must be further fragmented to deal with diverse subsectors. However, if program development is tailored to regional conditions and resources, efforts to save energy in the operation of marine vessels, rail equipment, farm tractors, and other off-road vehicles can produce extremely interesting and innovative projects, many of which have the potential for significant economic side benefits.

In the nonhighway sector, energy conservation strategies can be grouped into three broad categories: modal shifts, improvements in the technical efficiency of vehicles, and improvements in vehicle operations. Modal shift strategies are usually from truck to intermodal systems or from truck to rail, water, or pipeline modes. In the past decade, relatively more energy-efficient intermodal systems have captured an increasing share of motor carrier cargo. Today, various types of trailer-on-flatcar, container-on-flatcar, and RoadRailer™ systems are in regular use, and development continues on new systems and improvements to existing systems. Such improvements promise not only enhanced energy efficiency, but also gains in local employment and tax revenue from new manufacturing industries.

Programs to improve the technical and operating efficiency of off-road vehicles can be aimed at a wide range of vehicle types and duty cycles, some of which are usually perceived as transportation (e.g., ferry boats), others of which are not (e.g., farm tractors, fishing vessels, and mining equipment). Depending on local needs and resources, programs can be oriented toward either information and outreach (e.g., by sponsoring tractor tune-up clinics or disseminating information on fuel-efficient designs for vessel propellers) or capital improvements (e.g., by providing low-interest loans). In both cases, programs typically offer the side benefit of improving the competitiveness of local industries.

Alternative Fuels

In the long term, alternative fuels offer the greatest petroleum-displacement potential of any transportation energy conservation strategy. Unfortunately, however, this potential is not without considerable cost—both for technical improvements to enable automobiles and trucks to run on fuels other than gasoline or diesel oil and for a new fuel delivery infrastructure to supply those fuels. In the past decade, a number of demonstration projects have investigated the feasibility of operating school buses, transit buses, and various types of automobiles and light trucks on either methanol or compressed natural gas. Most of these projects have demonstrated acceptable performance, reliability, and safety, but unacceptable cost. Work continues in this area, and the results of demonstration projects should be closely monitored.

In the last decade, advances in photovoltaics have made solar technology competitive with grid-supplied electricity for a wide range of stationary uses. Though generally not perceived as transportation uses, several of these applications should be of interest to state and local transportation agencies. In remote locations, photovoltaics are now being used to power roadside call boxes, traffic counters, and maintenance facilities. Even in urban settings, self-contained photovoltaic lighting systems are often competitive with conventional electric conduit for illuminating new overhead signs.

SUMMARY AND CONCLUSIONS

Since 1986 the states have received more than $3.7 billion in oil overcharge funds, primarily from the Exxon and Stripper Well judgments. In addition to these funds, $0.5 billion from the Texaco judgment will be distributed between 1989 and 1993, and as much as $1.3 billion may become available when pending court cases are settled. Although various restrictions apply to the expenditure of these funds, all settlements share a common intent—to make restitution to petroleum purchasers who were overcharged when domestic oil prices were controlled. Thus, a wide variety of petroleum conservation and assistance programs are eligible for funding under one or another of the oil overcharge settlements.

Because transportation accounts for 63 percent of U.S. petroleum consumption, this sector is a prime candidate for receipt of restitution funds. However, this may not happen unless transportation energy conservation projects are included in the state plans submitted for approval to the Department of Energy. Although much oil overcharge money has not yet been earmarked for specific programs, both the way the settlements are structured and recent funding trends suggest that the transportation sector may not receive its fair share of funding. As of March 31, 1989, transportation projects represented 12 percent of the Exxon and Stripper Well funds that states had earmarked for specific projects.

Under existing court settlements, the states have primary authority for allocating oil overcharge funds. Although each state must submit its plan to the Department of Energy, the department merely reviews the plan to ensure that it complies with whatever restrictions were imposed by the court. Thus, efforts to secure a greater share of oil overcharge funds for transportation programs must occur at the state level. A number of interesting and innovative ideas for transportation energy conservation projects have been presented for consideration by the state planners and policy makers who must develop their state's energy assistance plan. Although the specifics of each plan and each court settlement vary, the projects mentioned here and described by Mintz and Zerega (*1*) generally fall within the guidelines of the major oil overcharge settlements and should be eligible for funding under them.

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