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

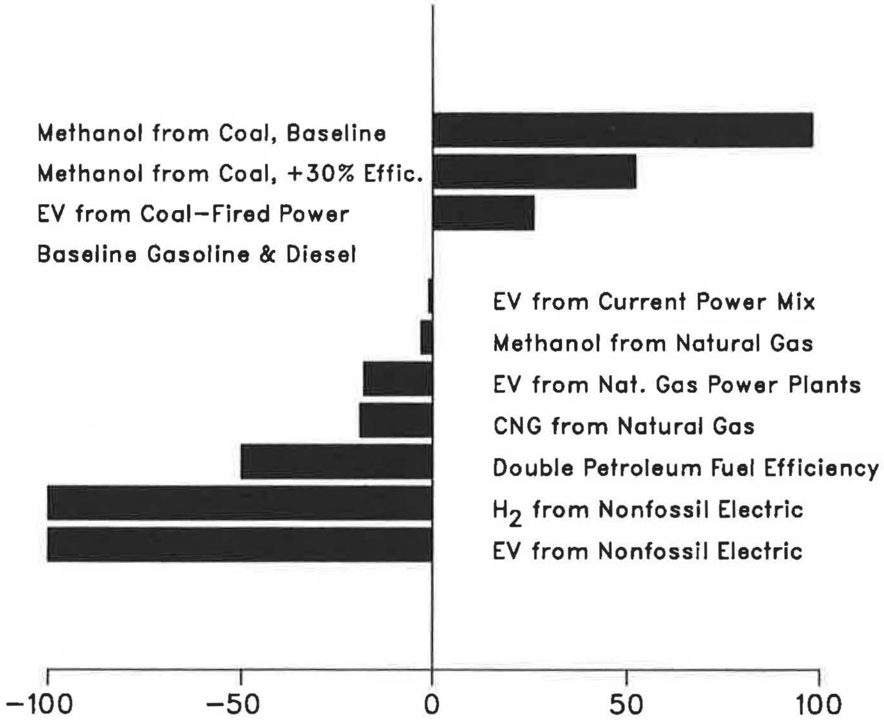

FIGURE 1 Percent change in CO_2 loading relative to petroleum cycle.

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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