ARTICLES

Achieving Acceptable Air Quality: Some Reflections on Controlling Vehicle Emissions

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Motor vehicle emissions have been and are being controlled in an effort to abate urban air pollution. This article addresses the question: Will the vehicle exhaust emission control and fuel requirements in the 1990 Clean Air Act Amendments and the California Air Resources Board regulations on vehicles and fuels have a significant impact? The effective control of in-use vehicle emissions is the key to a solution to the motor vehicle part of the urban air pollution problem for the next decade or so. It is not necessary, except perhaps in Southern California, to implement extremely low new car emission standards before the end of the 20th century. Some of the proposed gasoline volatility and composition changes in reformulated gasoline will produce significant reductions in vehicle emissions (for example, reduced vapor pressure, sulfur, and light olefin and improved high end volatility), whereas others (such as substantial oxygenate addition and aromatics reduction) will not.

The first finding of a recent National Research Council report (*1*) is that "Despite the major regulatory and pollution-control programs of the past 20 years, efforts to attain the National Ambient Air Quality Standard for ozone largely have failed." Many urban areas still exceed the permissible air quality standards, and Los Angeles, the most extreme case, may never be brought into compliance. However, concentrations of ozone have decreased by 8% from 1982 to 1991; ambient carbon monoxide (CO) concentrations in 1991 were about 70% of what they were in 1982 (*2*). Although they are unquestionable signs of progress, these improvements are not nearly as large as the anticipated reductions in emissions suggested.

Congress, in response to this less than satisfactory progress, passed in 1990 a new set of Clean Air Act Amendments in an attempt to achieve more rapid progress. The 1990 amendments, the subject of intense debate over costs, benefits, and regional differences, will continue the downward trend in standards for new car exhaust emissions (Tables 1 and 2); mandate fuel improvements to reduce vehicle emissions further; impose more stringent requirements on stationary sources, both large and small; and introduce specific controls on power plants to reduce acid rain. California has set in place a program of future emissions standards more stringent than those in the 1990 Clean Air Act Amendments that are designed to go by stages to low emission levels, including a requirement that 10% of the new cars in the year 2003 have "zero emissions." Yet, new cars today emit only a few percent of the exhaust emissions that came from autos built before emission controls some 25 years ago. This approach to air pollution control, largely by more strict regulation of emissions from new cars in the future as they leave the production line, is a continuation of policies during the past 25 years that have been less successful than expected.

The most important urban air pollution problem is photochemical smog. Hydrocarbons (HCs), their oxidation products, and oxides of nitrogen (NO_x, which denotes the sum of NO and NO_2), in a few hundred meters of air above our major cities, react in the presence of sunlight to produce strongly oxidizing compounds of which ozone is the most prevalent. At sufficiently high concentrations, these oxidants impair people's breathing capacity, cause eye irritation, and damage materials, vegetation, and crops. A

Table 1. U.S. light-duty motor vehicle emission standards. The emission rates for HCs, CO, and NO_x are by (or adjusted to the equivalent of) the 1975 Federal Test Procedure. The federal standard for particulate matter is 0.60 g/mile for 1986 and 0.20 g/mile for 1987 and 1989 to 1993. The federal and California standards for formaldehyde are 0.015 g/mile for 1993. Abbreviations: mi, mile; Evap, evaporative HCs.

Model year	Federal				California				
	HCs (g/mi)	CO (g/mi)	NO_x (g/mi)	Evap (g/test)	HCs (g/mi)	CO (g/mi)	NO_x (g/mi)	Evap (g/test)	Particulate matter* (g/mi)
Pre-control	10.60†	84.0	4.1	47	10.60†	84.0	4.1	47	
1966					6.30	51.0	(6.0)		
1968	6.30	51.0	(6.0)‡		6.30	51.0			
1970	4.10	34.0			4.10	34.0		6	
1971	4.10	34.0			4.10	34.0	4.0	6	
1972	3.00	28.0			2.90	34.0	3.0	2	
1973	3.00	28.0	3.0		2.90	34.0	3.0	2	
1974	3.00	28.0	3.0		2.90	34.0	2.0	2	
1975	1.50	15.0	3.1§	2	0.90	9.0	2.0	2	
1977	1.50	15.0	2.0	2	0.41	9.0	1.5	2	
1978	1.50	15.0	2.0	6§	0.41	9.0	1.5	6§	
1980	0.41	7.0	2.0	6	0.39‖	9.0	1.0	2	
1981	0.41	3.4	1.0	2	0.39¶	7.0	0.7	2	
1983	0.41	3.4	1.0	2	0.39	7.0	0.4#	2	
1984	0.41	3.4	1.0	2	0.39	7.0	0.4	2	0.60
1985	0.41	3.4	1.0	2	0.39	7.0	0.4	2	0.40
1986	0.41	3.4	1.0	2	0.39	7.0	0.4	2	0.20
1987	0.41	3.4	1.0	2	0.39	7.0	0.4	2	0.20
1989	0.41	3.4	1.0	2	0.39	7.0	0.4	2	0.08
1990	0.41	3.4	1.0	2	0.39	7.0	0.4	2	0.08
1991	0.41	3.4	1.0	2	0.39	7.0	0.4	2	0.08
1992	0.41	3.4	1.0	2	0.39	7.0	0.4	2	0.08
1993	0.41	3.4	1.0	2	0.25	3.4	0.4	2	0.08

*Diesel passenger cars only for all standards of particulate matter. †Crankcase emissions of 4.1 g/mile not included; fully controlled. ‡Emissions of NO_x (no standard) increased with control of HCs and CO. §Change in test procedure. ‖Nonmethane HC standard (or 0.41 g/mile for total HCs). ¶Optional HC standard, 0.3 g/mile, requires 7-year or 75,000 mile limited recall authority. #A 0.7 NO_x optional standard for 1983 and later, but requires limited recall authority for 7 years or 70,000 miles.

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secondary concern is CO, which at moderate levels impairs motor skills and at higher levels significantly impairs the bloodstream's oxygen-carrying capacity. Motor vehicles are the dominant urban source of CO. The air quality standard for CO, the ambient level above which significant health effects can occur, is exceeded periodically in 42 major U.S. cities (2).

An elaborate structure for the regulation of air pollutant emissions exists in the United States. Enormous sums of money have been spent in emission control, of both mobile and stationary sources, and the United States is about to spend considerably more. Methods of control to date have been roughly half as effective as expected in improving urban air quality. Significant progress has been achieved already: Air quality is better in all major urban areas in the United States, which is no mean achievement especially because urban growth during the past 20 years has been substantial. But "only half as well as expected" is not good enough, and much of what is planned for the future will be extremely expensive. Are these plans the right course of action?

In this article we examine why progress to date has been less than expected and then suggest where emphasis should be placed to achieve significant further improvements in air quality. Our overall message is that our government needs to focus on those actions that will make a difference in our ongoing efforts to achieve acceptable air quality and pause to consider the use of strategies of which the benefits are less clear and the potential costs are high.

Table 2. Future light-duty vehicle exhaust emission standards. Light-duty vehicles are those with a loaded weight of less than 3750 pounds. Standards are in grams per mile at 50,000 miles.

Standard type	NMOG*	CO	NO$_x$	HCHO
		Federal		
Tier I† (1994)	0.25 (0.31)	3.4 (4.2)	0.4 (0.6)	
Tier II‡ (2003)	0.125	1.7	0.2	
		California		
Conventional vehicles (1993)	0.25 (0.31)	3.4 (4.2)	0.4	
TLEVs† (1994)§	0.125 (0.156)	3.4 (4.2)	0.4 (0.6)	0.015 (0.018)
LEVs† (1997)§	0.075‖ (0.09)	3.4 (4.2)	0.2 (0.3)	0.015 (0.018)
Ultra LEVs (1997)§	0.04‖ (0.055)	1.7 (2.1)	0.2 (0.3)	0.008 (0.011)

*NMOG, nonmethane organic gas (sum of nonoxygenated and oxygenated HCs) †Standards are for 5 years or 50,000 miles and 10 years or 100,000 miles (in parentheses), to be reviewed by the EPA administrator ‡Standards are for 10 years or 100,000 miles. §Reactivity is adjusted for different fuels according to the following reactivity adjustment factors (RAFs) (allowed NMOG emissions = standard/RAF)· 1.00 for conventional gasoline, 0.41 for M85, 0.98 for transitional low emission vehicles (TLEVs), and 0 95 for low emission vehicles (LEVs) (phase II gasoline). ‖On the assumption that the TLEV RAF holds for LEVs and ultra LEVs

Motor Vehicle Emissions

Auto emissions control has a long history. Exhaust emission standards for new cars were first set in 1968 (1965 in California), after which the standards for exhaust emissions became steadily more strict every couple of years until the early 1980s (Table 1). The strategy adopted to minimize smog was major reductions in unburned HC emissions with lesser reductions in NO$_x$. The strategy was chosen in part from our assessment of how the photochemical smog chemistry responds to changes in HCs and NO$_x$ as well as from the technical feasibility of reducing HCs relative to NO$_x$.

Unburned carbon-containing compounds in the exhaust are fuel HCs and partial oxidation products that escape burning during the normal combustion events that occur in each cylinder of the automobile spark-ignition engine. Carbon monoxide emissions are significant when the engine is operated under fuel-rich conditions—that is, when the air in the fuel-air mixture that enters the engine cylinder is insufficient to convert all the fuel carbon to CO$_2$. Rich mixtures are used as the engine approaches wide open throttle because they give the highest possible power from the engine. They also help with combustion stability during engine warm-up and, in older cars, at idle. Oxides of nitrogen are formed from nitrogen and oxygen in the engine cylinder at the high temperature created during the combustion of the fuel-air mixture and are fixed from the reformation of oxygen and nitrogen by the rapid cooling of the exhaust gases.

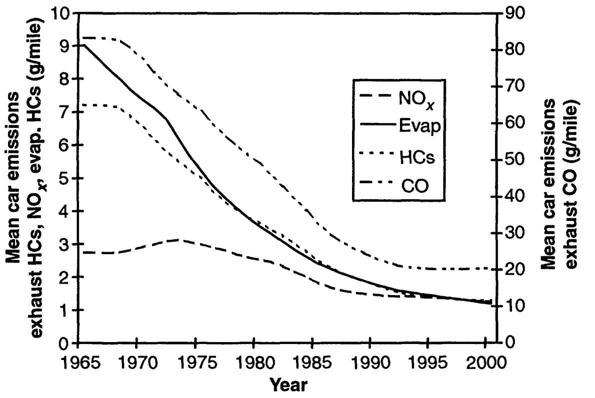
For the last 18 years, catalytic converters in the engine exhaust system have been used to achieve the large additional reductions in emissions required to meet federal standards. In current new vehicles, a properly working catalyst reduces the emissions of each of the three pollutants—HCs, NO$_x$, and CO—that leave the engine's cylinders by a factor of 5 to 10 before the exhaust enters the atmosphere. However, it has taken two decades for the combined catalyst and engine technology to reach this point.

Evaporative HC emissions from motor vehicles fall into three categories: (i) diurnal; (ii) hot soak; and (iii) running losses, generally thought to occur in that order of importance. Diurnal emissions take place as the fuel tank of a parked vehicle "breathes" air in at night as it cools down and breathes out air and gasoline vapors as it heats up during the day. The so-called "diurnal breathing" of the fuel tank can produce evaporative emissions of as much as 50 g of HCs per day on hot days. Hot soak emissions occur just after the engine is shut down and the residual heat from the engine heats the fuel system. Running losses can occur as gasoline vapors are expelled from the fuel tank while the car is driven and the fuel in the tank becomes hot. These losses can be high at high ambient temperatures or for vehicles that are particularly hot while running. Finally, gasoline vapor can escape from the fuel tank when a vehicle is filled at the service station. Evaporative HCs have been captured with carbon-containing canisters that absorb the gasoline vapors from these sources in the vehicle. The absorbed vapors are purged from the canisters into the engine and burned during normal driving. These evaporative controls have met the regulation test requirements for two decades, although some of these systems have not been nearly as effective at controlling evaporative emissions in the field. One reason for this difference is that current test procedures do not adequately represent conditions in the real world. New procedures have been developed to address this problem and are now being implemented. In some areas of the United States, vapor recovery systems at service stations capture refueling emissions.

Emissions inventories. The average emission rate from the total in-use vehicle fleet as well as emissions from all other sources affect air quality. In principle, the average emission rate depends on the age distribution of the in-use vehicle fleet, the number of miles per year vehicles of a certain age are driven (new cars are driven more), the emissions from cars of a given age, the rate of deterioration of emission controls, the effects of tampering, and the reductions of emissions resulting from inspection and maintenance (IM) programs. Ambient temperature, average driving speed, and driving pattern also affect the rate; some data are available to help define how emissions depend on these variables. Evaporative HC emissions can be converted to grams per mile and added to exhaust HC emissions to reach a value of total vehicle HC emissions.

Figure 1 shows a typical output from such a calculation for the light-duty vehicle fleet. On a per car basis, progress looks encouraging: Today's average in-use car has about one-fifth the HC and CO emissions and one-half to one-third the NO$_x$ emis-

Fig. 1. The exhaust HC, NO_x, CO, and evaporative (Evap) HC mean car emissions expressed in grams per vehicle mile traveled for the in-use light-duty vehicle fleet, predicted by EPA's most recent vehicle emissions inventory model, Mobile 5.0. The time period covered is from the late 1960s, when emissions controls were first introduced, to the year 2000. The curves show the effect on average predicted in-use fleet emissions of the introduction of cleaner new cars designed to meet the increasingly stringent federal emission standards listed in Table 1 up to and including tier I.



sions of a pre-control car of 25 years ago. The number of miles driven in major urban areas has gone up, and the emission rate is the product of grams per mile and miles driven. During this same 25-year period, the urban miles traveled in the United States per year went up by 100%, so that part of this decrease in per car emissions (about one-quarter of the decrease in HCs and CO but some two-thirds of the decrease in NO_x) merely offsets this increase in mileage. The predicted future emission rates are based on the assumption that the future purchase of vehicles by consumers will follow the historical trends.

However, there are other major sources of air pollutants. Emissions from stationary sources are included in the total inventory, as are biogenic or natural emissions. Large power plants are major point sources of NO_x. Such major stationary sources are usually quantified specifically for each urban area on the basis of the amounts of fuel used and the permitted levels of stack emissions. Values of air pollutants from smaller but much more numerous sources are estimated differently. Examples of such sources are dry cleaning establishments and auto body shops that use organic solvents, restaurants that cook with oils, and homes that produce emissions from such sources as furnaces, lawn mowers, and barbecues. Such distributed sources are usually included in proportion to population density, with estimates of the emission rates for each type and size of source. Except for large point sources where the exact location, fuel consumption, and impurity generation are reasonably well documented, an accurate inventory of stationary sources is more difficult to develop than is the mobile source inventory because the emission levels are less well defined and the variability from source to source is much greater. Biogenic HC emissions from trees and other vegetation, another part of the total HC inventory, are difficult to estimate because they are a function of the specific vegetative species, temperature, moisture, and other factors (*1*).

To various degrees of detail, all of these data are assembled into emissions inventory models by the Environmental Protection Agency (EPA), the California Air Resources Board (CARB), and other state and regional agencies to compute total emissions of each pollutant for each major urban area. These source inventories are then fed into computer models of atmospheric dispersion and ozone formation chemistry, also to varying degrees of sophistication, to form predictions of ambient concentrations. These predictions are usually calibrated with a specific air pollution episode in the urban area of interest for which data on the concentrations of ambient pollutants are available. The consensus is that the weakest link in this complex calculation is the emissions inventories; although far from perfect, the meteorological and chemical models have less inherent uncertainty.

During the last 5 years a number of independent studies have suggested that inventories of mobile-source HC (and CO) emissions have been understated by as much as a factor of 2. The results of a 1987 field test in Los Angeles, in which measurements of pollutant concentrations in the air flowing out of the Van Nuys road tunnel in California were used to compute actual on-the-road vehicle emissions, surprised the technical community (*3*). Concentrations of CO and HCs averaged 2.7 and 3.8 times higher, respectively, than predicted by the emission inventory models that are the basis for predictions of mobile source emissions. From about the same time as the tunnel study to the present, remote-sensing instantaneous measurements of CO and HC concentrations in the exhaust of vehicles in a variety of cities showed considerably higher emission rates than had been assumed (*4–13*). Comparison of ambient measured ratios of CO and HCs to NO_x in Los Angeles, with emission ratios derived from emissions inventories, broadened and confirmed the results of the Van Nuys tunnel study (*14*). Modeling of Los Angeles ozone by CARB and by researchers at the California Institute of Technology and Carnegie Mellon University (*15*) also suggested strongly that assumed HC emissions were understated.

More recent studies of vehicle emissions at the Fort McHenry (Maryland) and Tuscarora (Pennsylvania) tunnels have provided additional data on the discrepancies between observed in-use emission rates and those predicted by models of current mobile source emissions (*16–18*). These studies show that measured values of HCs and CO are about 1.5 times the predicted concentrations; the measured and predicted NO_x values are closer to each other. Fleet age has a dominant effect on fleet emissions: the older the fleet, the higher the average emissions. There is still considerable uncertainty as to the size of emissions from mobile sources, and there is at least as much uncertainty in the magnitude of stationary-source emissions.

Motor Vehicle Emissions: Key Issues

Recent studies, in which the best currently available emissions inventories and air-quality models were used, have shown that if *all* auto emissions are removed from the emissions inventory in Los Angeles by 2010, ozone concentrations will be only about 10% lower than they are projected to be if current regulations are implemented (*19*). The current path, which includes the somewhat stricter federal standards in the 1990 Clean Air Act Amendments for vehicles built in the 1994 model year and later (tier I, Table 2), relies on cleaner, lower emissions cars displacing older, dirtier cars from the in-use vehicle fleet and enhanced vehicle IM to reduce average emissions. The plan also includes the introduction of reformulated gasoline in the mid-1990s, which reduces emissions (especially HCs) from both new and older cars. If these predictions are right, we have already set in motion the necessary regulations to remove the auto as a serious source of air pollution in the 21st century and beyond. Unfortunately, the improvements in air quality achieved to date are less than what were predicted, and the vehicle emissions data from the Van Nuys tunnel and other studies suggest that removal of this source of air pollution will not be so simple.

Current regulations are effective in the sense that new production vehicles do meet the emissions requirements, through the testing and certification of prototypes over 50,000 miles and through testing at the end of the production line. In actual use, performance is not as good. More recent, in-use model year vehicles have average emissions, determined by the certification test procedure at 50,000 miles, that exceed the standards for HCs and CO by up to a factor of 2; NO_x emissions stay closer to the regulated limits. Older cars have higher emissions rates than those of recent models. This difference is not surprising when one considers the nature and complexity of the product and the uneven commitment of vehicle owners to necessary maintenance.

High emitters. It has become increasingly apparent that most of the mobile source emissions are caused by a small percentage of the vehicles. A compelling body of remote-sensing and roadside data shows, more or less regardless of locale, that about 50% of the CO and HC emissions come from 10% of the vehicles (*7, 8*). Figure 2 shows the CO and HC emissions from the 1989 random roadside survey conducted by CARB. The data set comprises 4400 vehicles sampled at 60 locations throughout the state. These plots show just how significant are the CO and HC emissions from the dirtiest one-fifth of the fleet in each model year. A relatively small amount of the overall emissions comes from the very old cars because they contribute such a small amount to the total vehicle miles traveled. The high emitter problem appears to span all model years and results from dirty vehicles that are driven significant distances. One would expect older cars to have higher emissions, and some have very high emissions (super emitters). What was not expected was the high emission rates detected in the worst 20% of more recent model cars. This evidence of super emitters or of modes of vehicle operation with high emission rates (such as heavy accelerations) that occur more commonly than expected represents the main problem of excessive motor vehicle emissions.

Old cars have high emissions because their standards were higher and they have had a long time either to deteriorate or to be altered somehow. However, why are there so many recent model super emitters? The limited evidence from roadside inspections indicates that several factors are important. A sizable fraction (15 to 30%) of cars have had their emission controls tampered with, by either the owner or a mechanic. The implementation of emission controls 15 to 20 years ago did worsen driveability and fuel economy. However, today's engines have been carefully optimized to combine control of emissions with good fuel economy and driveability. However, when these engines do fail they tend to become fuel-rich, leading to excessive HC and CO emissions. Some proportion of vehicles have been misfueled—that is, used with the often cheaper leaded gas instead of the required unleaded gas. One tankful of leaded gas causes major poisoning of the catalyst. Because leaded gas has essentially disappeared from the U.S. market, this problem is no longer important.

In both older and newer cars, components of emission control systems do malfunction and required maintenance is not always done or done properly. If key engine components (such as the airflow meter or exhaust gas oxygen sensor) malfunction, emissions can increase markedly. Such component malfunctions and failures do occur, with owners who apparently do not notice or ignore service or check-engine warning lights.

The variability of gasolines in use today is of such magnitude that the use of specific fuels plays a role in excessive emissions. Because the effect of fuel vapor pressure on evaporative HC emissions is nonlinear, variations in the fuel's Reid vapor pressure (RVP) (*20*) in the field will increase these emissions above what the average fuel produces. Recent data from the Auto/Oil Air Quality Improvement Research Program indicate that the highest exhaust emission fuels had some combination of T_{50} (the temperature at which 50% of the fuel evaporates) values greater than 110°C, T_{90} (the temperature at which 90% of the fuel evaporates) values exceeding 171°C, or sulfur content greater than 300 parts per million by weight (*21, 22*). According to a 1992 survey, 20% of commercial fuels exceeded these distillation cutpoints and 40% of commercial fuels exceeded the sulfur cutpoint (*23*). Data on intake valve deposits suggest that clean valves can lower exhaust HCs and CO by 10 to 50% compared with values for moderately dirty valves on otherwise clean-running vehicles. Because some of the fuels in use do not have adequate deposit-control additives, their use could also contribute to enhanced emissions. The Auto/Oil program's study of high emitters (*24*) shows gasoline composition effects for this class of vehicles that are comparable to those of more normal emitting vehicles.

Off-cycle operation. The remaining uncertainties in vehicle emissions relate to how driving patterns (the combination of accelerations, cruises, and decelerations), trip length (which affects whether the catalyst gets hot enough to be effective), mean driving speed (which depends on types of roadway and traffic), and ambient temperature each affect average emissions per mile. A number of studies carried out over the past several years have shown that the current models on which calculations from motor vehicle emissions inventories are based need to be improved. The Federal Test Procedure (FTP) is designed for new car certification as a model not necessarily of on-road driving behavior. The FTP is being evaluated in terms of its representation of actual driving, as rapid accelerations and decelerations, responsible for significant fractions of emissions on a typical trip, are probably not adequately included in the FTP cycle. Emissions from one high acceleration event can be approximately one-half those of a cold start. Recent evidence indicates that evaporative emissions from motor vehicles are far higher than had been thought, especially on hot days, when there is the greatest potential for high smog concentrations. Key inputs to travel-demand transportation models that are now based on decades-old data should be updated. Parameters for emissions models are developed by the use of vehicles that are often procured from the public for emissions testing. Procurement procedures have exhibited a bias toward vehicles in good operating condition. Consequently, super emitters

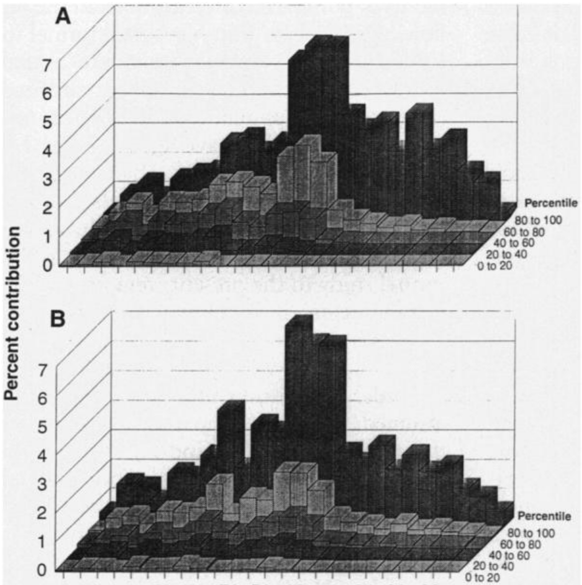


Fig. 2. Estimated contribution to (**A**) CO and (**B**) HC emissions as a function of model year for motor vehicles in California in 1989 (*29*). These plots are based on warm-idle emissions data from 4479 vehicles randomly selected at 60 locations in California in 1989 and represent the product of the measured tail pipe emissions and the population of vehicles of each model year. The five percentiles are calculated for each model year by the division of that vehicle population into five groups of equal numbers.

have not been adequately represented in the tested vehicle populations.

Heavy-duty and off-road vehicles. As emissions from light-duty vehicles are reduced, the effects of heavy-duty and off-road vehicles becomes more obvious. Control of these vehicles has lagged or has been neglected entirely. Diesel engines, which are used in the larger vehicles, are important sources of particles and NO_x but emit relatively low amounts of CO and HCs. Diesel particulate emissions can, over time, be controlled. The control of NO_x is problematic, and an appropriate technology is not available. Lean NO_x catalysts are being pursued but conversion efficiencies remain low.

Motor vehicle emissions may be higher than we think because (i) many vehicles have become super emitters through deterioration, tampering, or malfunction of the emission control system; (ii) driving patterns in the FTP, used as the basis for models of mobile source emissions, are not necessarily representative of actual driving patterns; (iii) evaporative losses are significant; (iv) vehicle fleet and use data may be inaccurate; and (v) in-use fuel is not as clean as certification test fuel. An important question to address is whether the vehicle exhaust emission control and fuel requirements in the 1990 Clean Air Act Amendments and CARB's regulations on vehicles and fuels will significantly affect emissions. Some of what is planned for the next decade makes good sense, but much does not.

Approaches to Reduce Motor Vehicle Emissions

There are four general approaches to reduce motor vehicle emissions: (i) technological improvements and modifications to the motor vehicle, (ii) the use of fuels that reduce mass emissions of pollutants or result in emissions that are less reactive in the atmosphere, (iii) IM programs, and (iv) transportation control measures. We briefly review the first three approaches in their current forms to assess their likely impact in improving air quality.

Improvements in vehicles. There are many opportunities to reduce gasoline engine exhaust emissions, and much work in this area is in progress worldwide. Although good prospects exist for continued reduction in vehicle exhaust emissions during the next decade, this process will nonetheless take time to develop and implement for the benefits in actual use to be significant and durable. The opportunities lie in (i) basic engine improvements (such as improved air and fuel distribution, mixing, and combustion; reduced oil consumption; tighter tolerances on engine design and manufacture; and design of the total exhaust system for low heat loss and fast warm-up), (ii) control system improvements (in the ignition system; in airflow measurement; in the fuel metering and injection system; better integration of the engine, transmission, and catalyst systems; and more precise control of these systems), and (iii) improved exhaust after treatment (such as increased catalyst size and precious metal loading, more effective catalyst formulations, mounting of the catalyst closer to the engine, and special cold-start control techniques). Improvements in these areas over the next decade or so offer continuing reductions in exhaust emissions by factors of 2 to 3 but with generally higher initial complexity and cost.

There are other opportunities. One that is being vigorously explored is electrically heated catalysts. With several kilowatts of electrical power, the catalyst can be heated before vehicle start-up to temperatures at which it effectively removes CO and HCs. This is a technology that might satisfy the regulations but is unlikely to be nearly as effective in use. From what we have seen to date, the technology is not sufficiently robust for its rapid deployment to be useful. A longer term opportunity also being explored aggressively is the lean NO_x catalyst. If an effective catalyst technology that removes NO_x when the engine is operated lean (that is, with excess air) can be developed, then this technology will allow some efficiency gains to be made in gasoline-fueled spark-ignition engines. The technology will also help the diesel emissions problem substantially—there are no other known opportunities available for major reductions in diesel NO_x emissions.

Evaporative HC emissions from gasoline-fueled vehicles can be effectively controlled. New evaporative test procedures have been developed and are being implemented that correspond much more closely to real world conditions, and gasoline vapor pressure is being stringently controlled. More effective control systems for evaporative emissions are under development. These new systems, combined with fuel volatility controls, backup inspection procedures, and attention to fuel-delivery system leaks, should eliminate evaporative emissions in a few years as a major source of HC emissions.

Although the federal tier I requirements should be achievable on schedule and tier II levels should be feasible at the end of this decade (Table 2), which is about the time that the 1990 Clean Air Act Amendments indicate that they could be implemented, it is not clear whether the tier II levels will be necessary nationwide. Both the stage of development of the technology at the individual vehicle level and the production capacity of the industry are important issues in the evaluation of what schedule is feasible. The California transitional low emission vehicle (TLEV) and low emission vehicle (LEV) requirements can likely be met in sequence before the end of this decade. We believe that attainment of the ultra-low emission levels for 100,000 miles is problematic because of the likely complexity of the emission control systems that would be required and their sensitivity to the engine changes that inevitably occur over the full life of the vehicle.

The sale of zero-emission vehicles (ZEVs) in California has been mandated by CARB to begin in 1998 at the rate of 2% of annual light-duty vehicle sales and to rise to 10% of these sales by 2003. The ZEV requirement is tantamount to a mandate for electric vehicles, the principal technology available in the near term to meet the ZEV requirement. Unless the power for electric vehicles is generated by nuclear or other non–fossil fuel sources, they are not actually ZEVs. Because existing nuclear power facilities are generally operating at full capacity, the incremental power needed for electric vehicle charging would presumably come from additional fossil fuel combustion. Over time, electric vehicles will not become super emitters, and with their use the relative mix of HC and NO_x emissions from the vehicle fleet would shift as fossil fuel power plants that provide electricity would emit primarily NO_x. Only nuclear energy has the potential to provide transportation power that is free of air pollution in those urban areas where electric vehicles are used.

The key to the vehicle emissions problem is the inordinately large contribution to emissions from a relatively small fraction of the fleet, the super emitters. If maintenance of the entire current fleet on the current fuels were possible, then the major portion of the vehicle emission problem would be solved. The federal tier I standards, with the use of reformulated gasolines taken into account, should meet the needs of other parts of the country if the problem of super emitters can be solved. California's TLEV and LEV standards are appropriate for Southern California's especially severe air pollution problem. If other parts of the United States do not show the expected air quality improvements over the next several years, then the case for implementing the tier II federal requirements at the end of this decade should be evaluated. However, model studies to date show that the additional improvements in air quality from tier II implementation would be small (*19*).

Improvements in fuels. Although reductions in automotive emissions during the past 25 years have resulted primarily from the implementation of control technology, two important fuel modifications were also enacted. In the early 1970s, the removal of lead from gasoline was begun, with the required sale of unleaded gasoline nationally to meet the needs of catalyst-equipped cars. Limitation of fuel vapor pressure has recently helped to control evaporative emissions. The next phase of fuel changes to reduce emissions follows the two separate approaches of alternative fuels and reformulated gasoline. The introduction and expanded use of alternative, or clean, fuels such as natural gas, liquid petroleum gas, and alcohols have been proposed as part of the strategy to reduce automotive emissions. Another alternative is to improve current fuels. The automotive and petroleum industries have proposed reformulated gasoline—a term that refers to gasoline with modified chemical and physical properties to reduce the mass and the air pollution impact of emissions.

The 1990 amendments to the Clean Air Act establish a Clean-Fuel-Vehicle program that requires the sale of clean fuels and the vehicles that can use them. These vehicles could use a range of fuels, from hydrogen to reformulated gasoline, or electricity. Compared with gasoline, alternative fuels are limited by availability, cost, distribution infrastructure, and vehicles to make use of the fuels. It is unlikely that the advantages in air quality that the use of some of these fuels might have over reformulated gasoline would alone justify their widespread introduction. Natural gas and electricity provide the most certain air quality advantages, but the use of neither is without emissions. Compressed natural gas or liquid natural gas seems particularly promising for use in buses and large-fleet applications. The alcohol fuels, especially when blended with gasoline and used in flexible fuel vehicles, provide little or no air quality advantages beyond the reduction of CO. The high energy density and low cost of gasoline, extensive production and distribution infrastructure, and availability of effective technologies to control emissions make competition from alternative fuels difficult. Long-term strategic justifications for a nonpetroleum-based motor fuel may exist, but air quality considerations alone would not likely justify any large-scale replacement of gasoline.

The 1990 Clean Air Act Amendments specifically require the sale of reformulated gasoline beginning in 1995 in the nine cities in the United States that most often exceed ozone air quality standards. This gasoline must decrease both volatile organic-compound emissions and toxics by 15% in 1995 relative to those of 1990 technology vehicles and fuels and decrease each by 25% in 2000 if the EPA deems these to be technically feasible. Cities that are both ozone and CO nonattainment areas will require year-round oxygenates in gasoline. The wintertime oxygenate concentration is 2.7% by weight, and a 2% oxygen content applies to the summer ozone season. The EPA definition of this fuel is based on a complex model that would allow the use of fuels providing equivalent air quality improvement. All gasoline sold in California beginning in 1996 will be a highly reformulated gasoline defined somewhat differently by CARB (Table 3).

Gasoline is a complex mixture containing hundreds of different HCs; its physical and chemical properties are difficult to describe with a few parameters. Those properties of gasoline that have been considered to reformulate the fuel to decrease exhaust mass emissions or atmospheric reactivity are aromatic content, olefin content, oxygenate content, sulfur content, vapor pressure, and distillation characteristics (for example, T_{90}, the temperature at which 90% of the fuel's mass has been evaporated by distillation). Attempts to reformulate gasoline have generally been carried out with parallel efforts to keep octane ratings constant. In so doing, it is often not possible to vary the individual fuel components independently; if one component is decreased or removed, it must often be replaced with others that maintain octane value.

Gasoline composition and properties affect emissions through a variety of mechanisms including the preparation of fuel-air mixtures, ignition and combustion, the formation of engine deposits, catalyst effectiveness, the durability of engine and emission control systems, and vapor formation in fuel systems. The two changes in fuel properties that appear to have a widespread beneficial effect on emissions from light-duty vehicles are reductions in sulfur content and vapor pressure. The reduction of fuel sulfur increases catalyst efficiency for HCs, CO, and NO_x. The effect is immediate and reversible, indicating that sulfur tends to occupy active sites of the catalyst rather than age the catalyst. The reduction of fuel vapor pressure has a direct effect on the generation of vapor in fuel systems. Evaporative emissions may make up 50% or more of HC emissions from modern automobiles, especially on hot days. Cold start at RVP down to 48 kPa (7 psi) does not appear to be a problem, especially with port fuel–injected vehicles, although cold start at lower RVPs would be. Evaporative emissions tend to be enriched with the fuel components that have lower molecular weight, such as light olefins; it is this fraction that is also most photochemically reactive in the atmosphere. Thus, reductions in light olefins in reformulated gasoline would also be effective.

Aside from reducing CO formation and providing an octane boost to compensate for lowered aromatics, the addition of oxygenates, such as methyl tertiary butyl ether (MTBE) and ethanol, has been found to have little or no effect on the problems of atmospheric reactivity and ozone formation. The addition of MTBE reduces HCs and CO through the formation of lean fuel-air mixtures in older cars and at operating conditions under which the engine is not controlled to stoichiometric operation. Consequently, NO_x emissions are sometimes increased. In refineries, MTBE is generally available at a concentration of about 2% of the gasoline production, from the refining of isobutylene. Current MTBE use in gasoline is about 1% in summer and about 15% in winter in CO nonattainment areas, when its effect on CO emissions is important. Methanol and MTBE, added to HC fuels, increase formaldehyde emissions, and ethanol and ethyl tertiary butyl ether increase acetaldehyde emissions, as would be expected from their chemical structures and reaction mechanisms. Volatility curves for methanol-gasoline blends show some disturbing characteristics. Even if the RVP of the base gasoline (0% methanol) and of M85 (85% methanol and 15% gasoline, by

Table 3. California phase II gasoline specifications (effective 1 March 1996).

Measure	Flat limits*	Average limits*	Cap	1990 California average
RVP (psi)†	7.0	7.0		8.5
Sulfur (ppmw)	40	30	80	150
Benzene (percent by volume)	1.0	0.8	1.2	2.0
Aromatic HCs (percent by volume)	25	22	30	32
Olefin (percent by volume)	6	4	10	9.9
Oxygen (percent by weight)	1.8 to 2.2		2.7 maximum 1.8 minimum	0
T_{90} (°F)	300	290‡	310	330
T_{50} (°F)	210	200	220	212

*Flat limits met by each gallon, and average limits met on a 90-day basis at a refinery or import location. †Applies to summertime only and varies according to location. ‡No single batch in-plant can exceed 310°F.

weight) is 7 psi (the specification of California phase II gasoline) (Table 3), the vapor pressures of M10 to M65 mixtures can be well over 10 psi. Because flexible-fuel vehicles can be expected to operate on a range of mixtures, evaporative emissions from such vehicles could present a serious problem. The addition of ethanol to gasoline is generally counterproductive with respect to ozone formation. Moreover, to accommodate ethanol addition to gasoline, the vapor pressure of the base gasoline must be lowered to compensate for the volatility increase of the mixture, thereby increasing the cost of the fuel.

Benzene is removed from gasoline because it is a toxic substance. Decreases in other aromatics do not appear to have appreciably beneficial effects on the atmospheric reactivity of emissions, except that improving the high-end volatility of the fuel does reduce HC emissions in newer cars. As the T_{90} of the gasoline is reduced, the substantial effect on emissions is related to decreases in the heavy gasoline components, C_8 to C_{10} alkanes and C_6 to C_9 aromatics and alkenes (*25*).

The reduction of RVP, sulfur, T_{90}, and light olefins will have a beneficial effect on lowering both exhaust and evaporative emissions. Aromatic reduction, aside from reducing benzene emissions and T_{90}, and oxygenate addition offer no clear advantages in this regard. Also, a recent study has shown that regulation of gasoline olefins with carbon numbers greater than five will have negligible environmental benefit (*26*).

When the 1990 Clean Air Act Amendments were passed, there was little quantitative information on the relation between fuel composition and emissions, especially regarding oxygenates, on which to base prescriptions for changes in fuel properties that would reduce the ozone-forming potential of emissions. Oxygenate requirements in that act were arbitrary, in a scientific sense, and were partly the result of a political compromise among different interest groups. As data are becoming available, the complex problem of fuel, emissions, and atmospheric reactivity is becoming apparent. For example, in retrospect we see that oxygenates represent a reasonable approach to limit CO emissions and maintain octane ratings in the face of other composition changes but appear to offer negligible benefits in terms of decreasing atmospheric ozone formation. No convincing argument based on combustion or atmospheric chemistry can be made for the addition of ethanol to gasoline. Methanol-gasoline blends such as M85 will probably not prove to be cost effective in ozone reduction when compared with carefully reformulated gasolines (*27*).

Inspection and maintenance programs. Inspection and maintenance programs are intended to reduce in-use vehicle emissions through the identification and repair of vehicles that do not meet exhaust emission standards. Today, IM is typically a measurement of tail pipe emissions at two different engine speeds with no load on the engine. The EPA established guidelines for IM programs, and states were allowed to take a credit for a 25% reduction in vehicle emissions if they had an IM program. Simply having a program in place was sufficient to earn credit for the 25% reduction; no requirement existed to link IM credits to enforcement or actual in-use vehicle emissions. Of the options available for the reduction of motor vehicle emissions, a well-designed IM program is among the most cost-effective. Unfortunately, the performance of IM programs has generally not been subject to the same degree of scrutiny as have other elements in the matrix of motor vehicle emissions controls.

These programs have generally not met their goals for several reasons: (i) evaporative emissions have not been tested, (ii) the repair of too many high-emitting vehicles has been waived because of cost limits, (iii) the tail pipe test on the operation of unloaded engines is not representative of on-road emissions, (iv) testing has often been performed incompetently, and (v) cheating has taken place both through collusion between the tester and vehicle owner and by vehicle owners modifying their vehicles before and after scheduled testing. The EPA has proposed an enhanced IM program that would require a dynanometer test under varying engine loads, would test evaporative emissions, and would raise the repair cost limit substantially. Although these are clearly steps in the right direction, the enhanced IM program still has some serious defects. Most notably, it lacks the necessary component of significant on-road, in situ remote sensing to validate the emissions reductions and to catch cars that have been tampered with between inspections.

An important aid to the maintenance of good emissions control over the useful life of each vehicle is the incorporation of on-board engine and emission control system diagnostics (OBD). These devices are combinations of sensors, computer diagnostics, and warning lights that alert the driver and maintenance personnel to problems that affect the emission control system. Both the 1990 Clean Air Act Amendments and CARB require that during the next few years, extensive OBD capability be built into new vehicles. To be effective, these diagnostics must be robust and the OBD regulations must be stated largely in terms of the requirements for the performance of emission control systems rather than the specification of individual technologies. Unfortunately, the OBD requirements as currently stated by EPA and CARB seem to be excessively detailed and headed in conflicting directions. This potential clash of requirements should be rectified.

Remote sensing. As discussed above, there is considerable evidence from tunnel tests and measurements of off-cycle mobile fleet emissions that suggests real world emissions from the mobile fleet are probably much higher than those produced from the stationary FTP test on individual cars. Thus, an IM program should include the measurement of emissions of the mobile fleet as they occur in actual operation. The remote monitoring of tail pipe emissions of passing cars is a cost-effective tool that can allow the identification of high emitters, which can then be targeted for repair. Monitoring sites, relocated regularly to appropriate positions that are invisible to the drivers, will allow sampling of actual emissions. Notification of the car owner (identified from a license plate photograph) can be given so that a more detailed examination can be made by inspectors, high emissions verified, problems identified, and correction of problems ensured. The combination of remote-sensing programs with IM programs to focus inspection resources on the higher emitting vehicles is an especially attractive strategy.

How to Ensure That Controls Remain Effective

The task of ensuring that controls remain effective is dependent on the development of a scientifically reliable database that can be built from accurate ambient chemical and meteorological data and a reliable emissions inventory of all stationary, mobile, and biogenic sources that impact the region. A comprehensive modeling program is also necessary to the use of detailed chemical and meteorological inputs that allow ongoing tests of the consistency of emissions inventories and of the observed pollutant concentrations. A clear sign of imbalance between the two would stimulate necessary improvements to the methods of the inventories and perhaps to the elements of the models themselves.

Monitoring network. To detect changes in air quality in a given locality, including the potential for ozone generation, we require an accurate, long-time record of the important trace gas precursors of ozone: NO, NO_2, the many reactive HCs, including many alkanes, alkenes, aromatic HCs, isoprene, and terpenes, and their reactive oxidation products such as formaldehyde and acetaldehyde. The existing records of ambient concentrations in most U.S. cities are inadequate to check the accuracy of emission inventories or to establish trends. Present planners of control strategies consider themselves lucky if they have available, for a city of interest, data from one or two episodic events that have occurred during the past several years and for which special efforts were made to document both the ambient concentration levels and the meteorology. Although ozone monitoring has been quite extensive for many years now, these records alone do not provide a scientific explanation for trends in the ozone data. Hence, it is important that we establish a temporal record of the concentrations of the gas species that have been identified as important precursors to ozone generation at representative sites throughout the region. Furthermore, concentrations of the reactive gases near the surface alone are inadequate. Representative measurements should be made as a function of elevation throughout the mixed layer of the atmosphere as well as the air mass lying above the mixed region because ozone and its precursors may be injected from these areas when the temperature inversion breaks. For example, the titration of the ozone by locally emitted NO can depress ground-level ozone concentrations to levels that are not representative of those in the larger region.

Emissions inventories. Accurate emissions inventories are essential to the understanding and control of the ozone problem. The coupling of emissions data with those from an effective sampling network allows a test on the balance between the two. Until a good balance is achieved, we cannot be confident in our predictions about trends of emissions and our decisions about what controls are necessary. An emissions inventory from the mobile fleet in future years should have estimates on the basis of real driving cycles made in local traffic with instrumentation that is carried in the cars tested. Measurements should be made on cars that are representative of those present in the local fleet. Such cars should be picked at random from the existing population and include a proportional fraction of those that are, for whatever reason, high emitters.

A parallel effort is required to improve the accuracy of our stationary and biogenic emissions inventories. As a fraction of total emissions, these sources together are now at least as important as mobile source emissions. However, our ability to estimate these emissions with reasonable precision is almost certainly less well developed than our analysis of mobile emissions. Remote-sensing techniques that have been so valuable in pinpointing the characteristics of motor vehicle emissions seem promising for the surveillance of stationary sources.

Prospects for the Future

Underlying our entire discussion is the concept of cost effectiveness. Air pollution control measures are enormously expensive, and some are much more effective than others. The United States can simply not afford to go down a path that costs the public vast sums of money and achieves little benefit in air quality improvement. Judging cost effectiveness itself is not an easy issue: the major parties concerned, the automobile and petroleum industries and the government, have yet to agree on a consistent methodology by which to judge cost effectiveness. Largely for this reason we have not included explicit cost estimates but have relied on our judgment to determine whether the control strategies discussed have the potential for significant impact on the problem and their relative cost-effectiveness ranking.

Three approaches to reduce motor vehicle emissions have been examined in this article: (i) technological improvements and modifications to the motor vehicle, (ii) use of fuels that reduce mass emissions of pollutants or result in emissions that are less reactive in the atmosphere, and (iii) IM programs. The mobile source emission inventories provide us with a tool for assessing the relative impact of various control strategies on future vehicle fleet emissions. Although these inventories have their problems, they are our only available form of analysis for such predictions. Predictions have been made of total vehicle fleet emissions from 1990 through 2010 (*28*), which identify the reduction in emissions that corresponds to each of the major control strategies that have been proposed in the areas of stricter new car standards, cleaner fuels, and significantly enhanced IM. In agreement with the general findings here, improvements in emissions are predicted to come from more effective IM programs, the federal tier I standards, and phase I fuel improvements. The other strategies evaluated would likely have substantially lesser impacts.

Reformulated gasoline is useful in reducing tail pipe and evaporative emissions and, once in the marketplace, will affect the entire in-use fleet. Some of the proposed gasoline volatility and composition changes in reformulated gasoline will produce improvements (such as reductions in vapor pressure, light olefins, sulfur, and T_{90}) and appear worthwhile; the others (oxygenate addition and aromatics reduction) do not seem worth the cost. The use of methanol and ethanol blended with gasoline in flexible fuel vehicles offers no significant improvement in emissions over the use of reformulated gasoline.

Although the more stringent new car exhaust emission standards and the reformulation of gasoline will make some impact on the vehicle emissions problem, it is the effective control of in-use vehicle emissions that is key to the removal of motor vehicles from the urban air pollution problem. In a sense, the cost of more sophisticated systems of vehicle emissions control and ever more expensive fuel recipes is a subsidy to the relatively small number of vehicles that are responsible for the majority of emissions. The reduction of this source of emissions will require much more effective IM programs than have been implemented to date, realistic upper cost limits for mandated repairs, and in-use surveillance programs to identify high emitters and monitor progress.

The Los Angeles area in California must be recognized as having an ozone air pollution problem that is much more severe and difficult to solve than that of any other area in the United States. In California alone, the continued implementation of more stringent emissions requirements, the use of more extensively reformulated gasolines, and experiments with potentially economically viable alternatives such as natural gas fuel makes sense. The federal tier I standards appear to be sufficient for the other 49 states because the major emissions reduction will come from an in-use fleet with better functioning emission controls. The likely mass emissions improvements from California's requirements of ultra LEVs appear to be small because the emissions from LEVs are already very low. Finally, because motor vehicles are now the source of less than half of the total urban emissions into the atmosphere, major reductions in stationary source emissions will likely be needed to achieve significant improvements in urban air quality.

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Geophysical Investigations of the Tectonic Boundary Between East and West Antarctica

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The Transantarctic Mountains (TAM), which separate the West Antarctic rift system from the stable shield of East Antarctica, are the largest mountains developed adjacent to a rift. The cause of uplift of mountains bordering rifts is poorly understood. One notion based on observations of troughs next to many uplifted blocks is that isostatic rebound produces a coeval uplift and subsidence. The results of an over-snow seismic experiment in Antarctica do not show evidence for a trough next to the TAM but indicate the extension of rifted mantle lithosphere under the TAM. Furthermore, stretching preceded the initiation of uplift, which suggests thermal buoyancy as the cause for uplift.

Our knowledge of the tectonic history of Antarctica is largely based on information from the surrounding continents, ocean basins, and the continental margins of Antarctica. With the exception of the open waters of the Ross and the Weddell seas and a few rock outcrops, Antarctic geology is buried under a thick ice cover and can only be studied by geophysical methods that remotely sense the Earth's crust under the ice. These geophysical methods include the measurement of subglacial topography by radar, the measurement of anomalies in the Earth's gravity and magnetic fields, and magnetotelluric and seismic methods. Ground and aerial radar and magnetic surveys and ground surveys of gravity have been carried out in Antarctica during the past 20 years (*1*, *2*). An integrated survey including radar, magnetic, and gravity measurements from a small aircraft has been attempted (*3*). Although seismic methods are the primary geophysical tool elsewhere in the world, only a few over-snow seismic surveys have been conducted in Antarctica (*4*) because surveys there are limited to crevasse-free areas and can be done only with substantial logistical support.

Stretching and breakup of the continental lithosphere are the fundamental geological process that creates rift basins and, eventually, oceans. The process should be manifested in the crustal structure of the transition zone between rifts and oceans and the stable continent. In Antarctica, the transition from the West Antarctic rift (which includes the Ross Embayment) to the East Antarctica shield involved the formation of a rift-flank mountain range, a phenomenon that is not well understood. Both the area of the rift and the size of the flanking mountains, the 3500-km-long and the 4500-m-high TAM, are among the largest in the world (Figs. 1 and 2). In this article, we present results from Seismic Experiment Ross Ice Shelf (SERIS), a large-scale, modern multichannel seismic reflection and refraction experiment over the snow in Antarctica (Fig. 2). This experiment took place in the austral summer of 1990 to 1991 and examined the geometry of the boundary between the West Antarctic rift system and East Antarctica as well as the causes for the uplift of the TAM.

Tectonic History

Before the breakup of the Gondwana supercontinent in the early Jurassic [~175 million years ago (Ma)], Antarctica lay at the center of this land mass (Fig. 1) (*5*) and so is the key to an understanding of Gondwana geology and plate reconstruction. The continent now consists of two major parts: East Antarctica, a large stable block that has existed relatively intact for hundreds of millions of years, and West Antarctica, an

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