rections imprinted in rocks may undergo subsequent spatial rotation, which imposes an additional constraint on the reconstruction of polar paths from paleomagnetic measurements.

A provocative question in plate tectonics is the ultimate source of energy. In this report it is suggested that the differential rotational inertia of continents coupled with pole-plate displacement leads to continental-plate movement and seismicity. Others (*10*) suggest that earthquakes may cause short-term polar (Chandler) wobble and secular polar movement. Munk and Hassan (*11*) conclude that the annual component of polar wobble (making up about one-third the amplitude of polar wobble) is excited by atmospheric loading. This component is large enough to cause significant displacement energy in continental plates and may be the continuous forcing function in plate tectonics. If so, the ultimate energy source would be solar.

MARTIN F. KANE
U.S. Geological Survey, Woods Hole, Massachusetts 02543

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System Approach for Reducing Car Pollution

Abstract. *Federal policy emphasizes more exacting specifications for new cars to combat pollution. Some doubts are cast on this approach, and alternatives are suggested. Ease of maintenance, high reliability, and inspection are essential to pollution control and must be provided for in the specifications. A total system approach to reduce car pollution is outlined.*

There are serious questions as to the most practicable way of reducing automobile pollution. Present federal policy emphasizes tougher emission standards for new cars (*1–3*), but it lacks adequate provisions for the enforcement of suitable standards throughout the life of the cars. My intent here is to cast doubts on this approach and to suggest alternatives.

None of the designs that are now being conceived to meet 1975–76 federal regulations is inherently pollution-free. Without proper maintenance and inspection these cars will be especially liable to excessive emissions.

Ease of maintenance, high reliability, and proper inspection are as important as suitable emission standards, and it is essential that they be incorporated into a general policy, as is the case in the aerospace industry. Our experience with the diesel engine furnishes a case in point. The diesel engine is designed to give a clean exhaust. Yet everyone is familiar with the sight of a diesel emitting a dark smoke or a fog of hydrocarbons. A diesel engine requires careful and skilled (and often unavailable) maintenance if it is to stay nonpolluting. Furthermore, one wonders if the frequent appearance of smoking diesels might not be related to the fact that the highest power output of the diesel engine is favored by conditions that promote excessive emissions. Whatever the exact reason, this example illustrates the need for both maintenance and inspection.

Any attempt to reduce car pollution will prove expensive. Estimates of the cost of the changes needed to meet federal specifications for 1975 vary from \$300 to \$800 for a single car, or \$3 billion to \$8 billion in investment cost for 10 million cars. Decreased fuel efficiency and improved maintenance may each cost \$3 to \$6 billion a year. Fuel modification [suggested by General Motors (*2*)], if adopted, would cost another \$3 billion to \$10 billion a year. It is important that these enormous sums are spent effectively.

What design options can the automobile manufacturer exercise as he endeavors to satisfy compulsory emission standards? In general, he may modify the design and the operation of the present spark-ignition engine, or he may seek new design alternatives.

At present it appears that none of the new designs, such as the steam engine or the gas-turbine engine, will have commercial importance within the coming decade. Further, with the exception of the electric car, all these new designs, like the present spark-ignition engine, will require strict maintenance if their exhaust is to stay clean. As for electric cars, their widespread use might cause the source of pollution to be transferred from the car to the power plant (*4*).

One hopes that future breakthroughs will provide us with a nonpolluting car. In the meantime we should continue to improve the spark-ignition engine. Some significant improvements have already been made, or are in the process of being adopted. These include the elimination of the gases escaping from the crankcase and the reduction of hydrocarbons evaporating from the fuel system. The main problem still remains, namely, the reduction of emissions of hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x) from the exhaust (*2, 3, 5, 6*).

Engine modifications alone would not cut these emissions to the low levels that will become mandatory in 1975–76. Present design proposals envision HC and CO emissions as being reduced by a suitable afterburner and rely on engine modifications to mitigate NO_x emissions. This is mainly due to the inherent limitations of the combustion process itself.

Hydrocarbons and CO are the products of incomplete combustion whereas NO_x is formed in the combustion process. Excess oxygen and higher flame temperatures will promote more thorough combustion; these, in turn, depend on the air/fuel ratio. Figure 1 shows qualitatively the effect of the air/fuel ratio on emissions of HC, CO, and NO_x. Hydrocarbon and CO levels decrease at first as the air/fuel ratio increases. At high air/fuel ratios HC emissions may increase again because dilution lowers the flame temperature. On the other hand, the for-

Table 1. Estimates of total daily emissions from cars in Los Angeles for 1980. The estimates are made for 4.2 million cars, each driving 30 miles per day, and are based on the federal test procedure (FTP) seven-cycle test (1968) (*6*). The 1976 standards have been recomputed to the same basis by dividing by 2.

Basis	Emissions (tons per day)		
	HC	CO	NO_x
1968, 3.5 million cars (*8*)	1700	9500	620
All cars, 1972 standard	200	2500	380
All cars, 50% 1972 standard, 50% Clean Air Act *	115	2410	200
Pre-1975 cars, 50% double 1972 standard, 50% Clean Air Act, reliability level 1 †	340	3400	425
All cars, 50% double 1972 standard, 50% Clean Air Act, reliability level 2 †	460	4120	460
All cars, 50% double 1972 standard, 50% base emission level A *, reliability level 1	350	3530	435
All cars, 50% double 1972 standard, 50% base emission level B *, reliability level 1	375	3800	456
All cars, 50% 1972 standard, 50% emission level B, reliability level 1	275	2520	265

* The specified emissions (in grams per mile) are: 1972 standard (*6*), 1.6 (HC), 20.0 (CO), 3.0 (NO_x); Clean Air Act (*1*), 0.25 (HC), 2.4 (CO), 0.2 (NO_x); base emission level A, 0.5 (HC), 5.0 (CO), 0.4 (NO_x); base emission level B, 1.0 (HC), 10.0 (CO), 0.8 (NO_x). † At reliability level 1, 10 percent of cars have a nonfunctioning evaporative control, 10 percent have a nonfunctioning afterburner (average emissions 15 g/mile for HC, 100 g/mile for CO), 10 percent have deteriorated to 1972 standards, and 10 percent have a nonfunctioning NO_x control (average emissions 3 g/mile). At reliability level 2, twice as many cars are malfunctioning.

mation of NO_x is promoted by higher flame temperatures and is, therefore, at its peak when the fuel mixture is slightly leaner than stoichiometric.

From Fig. 1 it appears that the optimum situation occurs at an air/fuel ratio of about 18. At this ratio, the NO_x level would correspond to 1.5 to 2.0 g/mile (1 mile = 1.6 km) for an average passenger car, that is, less than a third of the NO_x level that present cars cause (6 to 7 g/mile) but considerably above the mandatory 0.4-g/mile level of federal law. Cars have not been designed to operate at this air/fuel ratio before because it is difficult to design an engine that would perform well on lean fuel mixtures. If, in the interest of reducing NO_x emissions further, a leaner fuel mixture was adopted, then the chance of a misfire, causing copious discharge of HC, would increase.

To maintain low emissions by means of lean fuel mixtures will require accurate fuel distribution. This can be achieved by using gaseous fuels, such as liquified petroleum gas; their adoption, however, would present severe distribution and safety problems. A more promising approach would be to use direct fuel injection systems. At present, however, the advantage of direct fuel injection is still contested, as it is difficult to insure that separate air and fuel supplies remain properly adjusted relative to each other.

Emissions of NO_x can be reduced by lowering the combustion temperature and by changing the compression ratio and the spark timing. This also can be achieved by diluting the fuel mixture by recirculating cooled exhaust gases. Most of these measures, particularly changes in the spark timing and recirculation of exhaust gases, will impair the drivability and performance of the car and in some cases will also reduce fuel efficiency. There will, therefore, be a temptation to readjust the engine once the car leaves Detroit, unless of course there is an effective system of inspection. Reduction of the combustion temperature if carried too far would also, in the absence of afterburner, promote discharge of HC.

With rich fuel mixtures (air/fuel ratios of 10 to 12) it is easier to reduce NO_x emissions without hurting the performance of the car. Under these circumstances, HC and CO emissions from the engine increase and failure or faulty operation of the afterburner would cause them to skyrocket, as a glance at Fig. 1 clearly reveals.

Hydrocarbon and CO emissions can be reduced in either a thermal afterburner (which can be regarded as a secondary combustion chamber) or in a catalytic afterburner (*2, 3, 7*). Both afterburners will have a secondary air supply. Catalysts have been developed that can last a considerable time (50,000 miles) and are very efficient under driving conditions. Both types of afterburner do not function well during the start-up of a cold engine (*2, 3*).

A catalyst that can also take care of NO_x emissions would be a boon. However, though such catalysts do exist, none has yet a practical lifetime (*7*), and the development of better catalyst for NO_x decomposition is one of the most urgent needs if a reliable method for reducing NO_x emission is to be found.

Afterburners, in general, do provide us with a promising method of reducing pollution from cars. The problem is how to manufacture afterburners of high reliability and long life. Afterburners are sensitive devices. Any excessive discharge of HC and CO, caused by engine malfunction, will lead to a temperature overshoot that will very likely destroy the afterburner.

This sensitivity can be reduced by increasing the thermal capacity of the system. But high thermal inertia re-

Table 2. Estimates of total daily emissions from cars in Los Angeles for 1990. The estimates are made for 5 million cars, each driving 30 miles per day, and are based on the FTP seven-cycle test [(*6*); 1968].

Basis*	Emissions (tons per day)		
	HC	CO	NO_x
1968, 3.5 million cars (*8*)	1700	9500	620
All cars, 1972 standard	240	3000	450
Clean Air Act	37.5	360	30
Clean Air Act, reliability level 1	325	2100	115
Clean Air Act, reliability level 2	610	3800	200
Base emission level A, reliability level 1	360	2400	140
Base emission level B, reliability level 1	415	3000	185

* For specified emissions levels and an explanation of reliability level, see footnotes to Table 1.

quires a longer warm-up period, which, in turn, will result in increased emissions during cold start. These two factors must be balanced to insure optimal overall performance.

Most catalysts are affected by lead. Lead concentration in the gasoline will, therefore, have to be strongly reduced or eliminated entirely.

Most of the current projections for future improvements of air quality are based on the questionable assumption that engines will only double their initial emissions during their lifetime (6). Half of the new cars are still on the road after 12 years, and their state of maintenance generally deteriorates in the later years. Without compulsory maintenance enforced by periodic inspections, the cars envisioned for 1975 might much more than double their initial emissions because their improved performance is geared to complex control devices. Today's emission-controlled cars require careful tuning to maintain the emission levels for which they were designed. In the 1975 designs CO and HC emissions will probably be reduced by means of afterburners whose reliability may not last 12 years. A faulty afterburner will increase emissions of CO and HC by factors of 10 to 50, depending on engine design, as explained previously. Faulty tuning or engine deterioration could increase NO_x emissions by factors of 10 to 20.

Failure of the emission control will not otherwise impair the performance of the car and might even go unnoticed by the car's owner. In the absence of rigid inspection, the owner will lack the incentive to carry out the necessary repairs.

Under these circumstances, total emissions will be determined largely by the number of cars with faulty emission control and will depend only slightly on emission standards to which new cars may conform. To illustrate this point, consider the situation in Los Angeles. Tables 1 and 2 show estimates of the total daily emission in 1980 based on different standards and reliability levels and compare them to projections based on recent trends (8). The basis for these estimates was chosen on the conservative side and is listed in the tables. The conclusions are strikingly clear and are insensitive to any reasonable changes in the numbers used: Total emissions in 1980 (Table 1) will depend mainly on the number and the performance of the

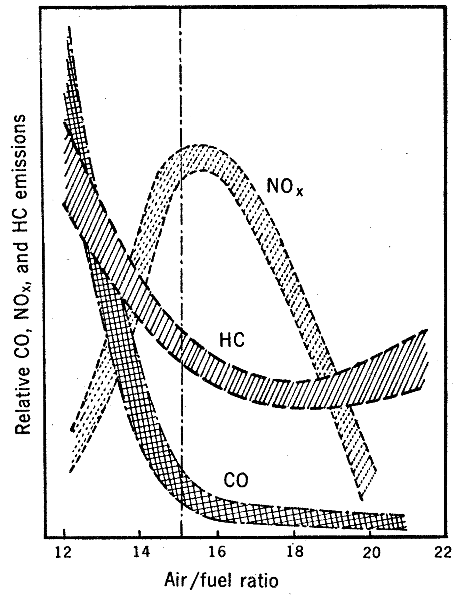

Fig. 1. Effect of air/fuel ratio on emissions. The relative CO, NO_x, and HC emissions are not to scale.

pre-1975 cars, as well as on post-1975 cars with faulty emission controls. The table shows that even if we double the federal emission standards for 1975 total emissions will not be affected significantly. The same is true for the far future (Table 2), in which all the pre-1975 cars have (hopefully) vanished from the roads.

High reliability cannot be achieved solely by design and manufacture. It must be fostered by maintenance and inspection. Any of the proposed new designs will perform well only if the cars are properly maintained. The warranties of the manufacturers are carefully written that way. The average driver, however, does not fulfill the maintenance requirements even if the warranty is conditional to certain maintenance procedures. A large fraction of the drivers will not have their engine tuned up, or the spark plugs changed, as long as their cars can be driven (9). None of the proposed antipollution devices will work when the spark plugs, ignition timing, and carburetion are not properly maintained. At present, the majority of garages are not equipped to undertake the tuning of the sophisticated carburetion and ignition systems required for low emissions, nor are they staffed with personnel that are trained to do these jobs properly.

How significantly pollution can be reduced by proper inspection and maintenance has been demonstrated by several studies. In the Atlantic Richfield Clean Air Caravan (10), 5000 cars were inspected. Adjustment of only the carburetor of 1500 cars reduced HC emissions (calculated for all the 5000 cars) by 30 percent and CO emissions by 10 percent. Other studies (11) show that proper maintenance could lead to a 30 percent reduction in total HC and CO emissions (nitrogen oxides are much harder to control by mere adjustments). Eliminating irreparable bad emitters might improve the possible reduction.

In preparing long-range policies we must also take into account that even with an annual inspection many cars, particularly those in the second half of their lives, will be working at emission levels far above those prescribed by legal standards. In New Jersey there is an annual safety inspection, and approximately 40 percent of the cars fail it once each year and 6 percent fail it twice, despite the fact that a considerable fraction of these cars are repaired before being submitted to inspection (12).

To reduce the number of polluting cars on the road, we have, therefore, to develop more effective inspection programs. Effectiveness and ease of inspection strongly depend on design and must be engineered into the car. None of these goals is taken care of in the present federal law. Furthermore, federal specifications are generally interpretated in a way that makes them quite meaningless for inspection policy. A small number of cars are tested and the results are averaged. We need specifications that not only apply to each individual car but also specify the emission level at which cars will be rejected at the yearly inspection. Cars have to be engineered so that they can be restored to this emission level by reasonable maintenance. This level should be adjusted with the age of the car and at present would have to be considerably higher than the 1976 standards. But the rejection level at the inspection station is the only standard that really matters, and it should therefore be the basis of any emission control.

At any level of technology the specified levels of emissions are going to have complex effects on both design and development of cars. In the absence of existing technology, too stringent emission standards might be self-defeating. The development of promising technical alternatives might be abandoned or slowed down because they have no hope of meeting such standards, despite the fact that they might lead to lower overall emissions than anything else in sight. As an example, the extremely strict NO_x requirements have slowed the development of gas turbines.

Furthermore, the exacting standard of 0.4 g/mile for NO_x emission will undoubtedly force the car manufacturer to base his design on the use of rich fuel mixtures, thereby loading the afterburner with copious amounts of HC and CO that will be produced during the combustion of the rich fuel mixture. This is certain to reduce the reliability of the entire system.

Some of the designs proposed as the most promising to meet the NO_x requirements not only are very complex, but also will perform poorly. What is worse, the performance of the car could be significantly improved by adjustments (such as the ignition timing and air/fuel ratio) that will restore NO_x emissions close to their present levels. Another case in point is the cold-start problem. Research efforts have unduly emphasized the development of an afterburner capable of controlling emissions during cold start. One way of getting the afterburner to respond promptly to cold-start emissions is to decrease its thermal inertia. This, however, would make the afterburner particularly sensitive to any temporary malfunction of the engine. Another way of reducing cold-start emissions would be to add a second afterburner designed for start-up only. This again will increase the complexity of the system and thereby reduce its reliability. Indeed, the importance of the cold-start problem is questionable. In Los Angeles, cold-start emissions, calculated on the basis of two cold starts a day for each car, contribute less than 5 percent of the total HC and CO emissions from cars.

To reliably achieve low overall emissions requires design compromises that take into account the interactions between different requirements. To obtain optimum results by legislative control, the government agencies must therefore develop the proper technical expertise, to provide the total system development guidance to the legislative body.

Effective control of pollution from cars requires a total system approach rather than solely the legislation of emission standards for new cars. Specifications for new cars should:

1) Specify emission levels that each car has to maintain throughout its useful life. These levels will form the basis for an annual inspection.

2) Provide safeguards to prevent unusually high emissions in case of partial failure of the control equipment.

3) Provide guidelines to facilitate ease of maintenance, replacement, and inspection of control equipment.

The present allowable emission levels should be relaxed to enable available technology to furnish reliable solutions. These levels can be subsequently decreased as new technology becomes available. New designs of control equipment and engine modifications should take into account the need for simple maintenance and high reliability.

Solutions that will induce the driver to tamper with the control equipment in order to improve the performance of the car should be avoided. We therefore need a nationwide inspection policy, which will require vastly improved maintenance facilities and properly trained people.

There is still time to take a fresh and rational look at the problem of car pollution before the predictable lack of effectiveness of present measures create a climate of dissatisfaction in which sensible solutions are harder to obtain.

REUEL SHINNAR
Department of Chemical Engineering, City College of the City University of New York, New York 10031

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Jupiter: Observation of Deuterated Methane in the Atmosphere

Abstract. *A positive identification of singly deuterated methane has been made in the 4- to 5-micron spectrum of Jupiter.*

During May 1971 we obtained a number of whole-planet spectra of Jupiter in the spectral region from 1800 to 2200 cm^{-1} at a resolution of 0.55 cm^{-1}, using a Connes type Fourier spectrometer (*1*) at the coudé focus of the 2.7-m telescope of McDonald Observatory, University of Texas. The spectra were combined into a grand average having a signal-to-noise ratio of about 150. Comparison solar spectra were also obtained during the same period with the same instrument configuration in order to identify telluric features and to aid in the definition of continuum levels.

Strongly evident in the spectrum of Jupiter are several J-manifolds in the P-branch of the ν_1 parallel band of CH_3D. We believe this to be the first observation of deuterium in any astronomical source.

We made the identification using the high-resolution laboratory data of Allen and Plyler (*2*), in which the frequencies are accurate to better than 0.03 cm^{-1}. As a consequence of our limited spectral resolution, pressure broadening, and smearing from the high rotational velocity of the planet, the manifolds are not resolved in the astronomical spectra. Furthermore,