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Controlling Transit Bus Emissions and Improving Management

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Contents

Foreword

The first five papers in this Record, which are about various aspects of the diesel fuel emissions control problem now facing the public transit industry as a result of new Environmental Protection Agency emissions standards (40 C.F.R. Part 86) for heavy-duty engines, are introduced by Andrle and Santini. Between 1991 and 1994 these standards place lower particulate emissions requirements on buses than on trucks. It is doubtful that the transit industry's traditional two-stroke diesel engine can be modified to meet the requirements. Because this engine can meet the 1991 requirements if it is methanol powered, the issue of alternate fuels is inextricably intertwined with that of bus compliance with emissions requirements. There are many issues associated with and points of view on this controversial topic. The introduction highlights the major technical, health, and regulatory factors involved and helps to place the papers in context for readers who are new to this topic.

In his paper, discussed by Morlok, Bajpai addresses the economics of bus maintenance contracting. Bajpai concludes, on the basis of cost comparison analyses undertaken for 5 competitively awarded turnkey service contracts and 16 maintenance jobs, that contract hire of bus maintenance may prove a cost-saving option for many systems.

Morlok points out that "contracting out on a comparative basis is an effective tool for public agency managers to use to control their costs, and its use is likely to increase rapidly in the future." However, he also cautions that management and overhead costs such as those of inspection and administration should not be overlooked in comparisons of this nature.

Maze recommends objectives for a transit bus fleet management data, information, and knowledge exchange. Such an exchange was recommended by attendees at a 1982 TRB conference on bus maintenance. The need has been recognized by other organizations as well; for example, the American Association of State Highway and Transportation Officials is currently funding a research project on Interactive Microcomputer Network for Innovative Maintenance Operations and the American Public Transit Association conducts numerous bus maintenance workshops, but, to date, no joint data exchange, of the sort recommended, has become routine and operational.

Introduction to Diesel Particulate Emissions, Alternative Fuels, and the Transit Industry

STEPHEN J. ANDRLE AND DANILO J. SANTINI

The papers presented in this Record are on various aspects of the diesel fuel emissions control problem now facing the public transit industry as a result of new Environmental Protection Agency emissions standards for heavy-duty engines (40 C.F.R. Part 86). From 1991 to 1994, these standards place lower particulate emissions requirements on buses than on trucks. There is considerable doubt that the traditional two-stroke diesel bus engine can, while continuing to use diesel fuel, be modified sufficiently to meet the requirements set by the standards. However, because this type of engine can meet the 1991 requirements when using methanol fuel, the issue of alternate fuels is inextricably intertwined with that of emissions compliance for buses. Further, although it is expected that four-stroke diesel engines will eventually be able to meet the standard, they are not likely to do so when the 1991 particulate standard takes effect for buses. There are many issues related to and points of view on this controversial topic. This introduction highlights the major technical, health, and regulatory factors involved. The authors of the papers assume background familiarity with the overall issue and focus on particular aspects of their work. This introduction is intended to help to place all of the papers in context for those readers who are new to this topic.

As a result of a reevaluation by the Environmental Protection Agency (EPA) of the health dangers associated with emissions from diesel-fueled compression-ignition (DFCI) engines and a reevaluation of the rate at which DFCI-powered buses generate emissions (*1*), the EPA has promulgated strict emission standards for buses and heavy-duty trucks (Table 1). The standard requires that nitrogen oxides and particulate emissions from all newly manufactured heavy-duty engines be progressively reduced to levels well below those allowed in 1987. The new regulations require that engines used in transit buses meet the 1994 truck standard of 0.1 gram per brake-horsepower-hour (g/bhp-hr) for particulates 3 years before trucks are required to do so and meet all other standards on the same schedule as trucks. (*2*)

Particulates and nitrogen oxides are not the only emissions covered by the new regulations. Carbon monoxide, hydrocarbons, and smoke are all regulated. However, from 1987 to 1994, the only changes are for nitrogen oxides and particulates, and the percentage reductions for particulates is far greater than that for nitrogen oxides.

TABLE 1 EPA EMISSIONS STANDARDS FOR BUSES AND HEAVY-DUTY TRUCKS

	Nitrogen	Particulates	
Year	Oxides (g/bhp-hr)[a]	Buses (g/bhp-hr)[a]	Trucks (g/bhp-hr)[a]
1988–1989	10.7	0.60	0.60
1990	6.0	0.60	0.60
1991–1993	5.0	0.10	0.25
1994	5.0	0.10	0.10

[a] g/bhp-hr = grams per brake-horsepower-hour. Brake-horsepower is defined as the effective horsepower of an engine measured by a brake attached to the driving shaft and recorded on a dynamometer. This differs from indicated horsepower, which is the power developed by the cylinders of an engine. One horsepower is the force required to raise 33,000 lb at the rate of 1 ft/min (33,000 ft-lb/min). Definition from Webster's Deluxe Unabridged Dictionary, 2nd ed.

The reason for stricter bus and truck particulates standards is the discovery that "inhalable" particulates in diesel exhaust are far more dangerous than previously thought. Then the EPA discovered that in-use bus emissions are higher than previously thought (*3*, *4*, and paper by Small in this Record) and that public exposure to bus emissions is "very high" (*1*).

Two reasons why buses are mandated to meet an earlier, stricter particulate emissions standards than trucks are that

1. The EPA has found that buses that are in the middle of their life cycle and are used in everyday operation in a downtown area emit particulates at rates far above existing standards and at rates generally higher than trucks.
2. Transit buses operate in cities where high pedestrian densities increase exposure to bus emissions. Buses also concentrate passengers in the vicinity of diesel exhaust, unlike trucks that carry freight.

Three reasons that buses tend to emit particulates at a higher rate than trucks follow:

1. Transit buses most commonly use two-stroke DFCI engines. Four-stroke diesel engines, which have a lower particulates emission, are more common in trucks.
2. The transit bus operating pattern of repeated acceleration and deceleration cycles exacerbates the emissions problem because emissions rates are high during acceleration.

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3. Idling is a high-emissions state for DFCI engines, and the bus duty cycle includes much idling.

Meeting the accelerated particulate emissions standards creates an immediate problem for engine manufacturers, bus assemblers, and transit agencies.

The major health risk attributable to diesel fuel is associated with particulate emissions. The particulates that pose the greatest health danger are inhalable, micron to submicron sized particles. These small particles can be carcinogenic and can aggravate chronic lung diseases. The total particulate mass (small and large particles) of diesel emissions can also impair visibility, soil and damage structures, and cause an offensive odor (*4, 5*).

As the paper by Small in this Record indicates, there is uncertainty about how much of the damage from particulates is due to total suspended particulates and how much is due to sulfate particles, which constitute only a part of total suspended particulates.

Sulfates are a serious but unregulated pollutant from DFCI engines. Sulfates are emitted in particle form, however, so the particulate emission standards for buses and trucks have the beneficial effect of promoting reduced sulfate emissions, which also contribute to acid rain (see papers by Small and by Santini and Schiavone in this Record).

According to EPA estimates, a DFCI bus of 1980 vintage emits 500 times the amount of particulates emitted by an average car (*1* and paper by Santini and Schiavone in this Record). There is little doubt that control of the particulate emissions of buses is highly desirable. However, as Santini and Schiavone indicate, late-model diesel bus particulate emissions measured on a passenger-mile basis are more in line with automobile emissions, so the most important step is to assure that modern bus engines replace old ones. On a passenger-mile basis, old and new buses emit about the same level of nitrogen oxides as do passenger cars.

Nitrogen oxides, which are regulated, constitute a health problem primarily because they are precursors of ozone. The chemistry of nitrogen oxides and ozone is complex. Ozone is the nation's worst air quality problem, so any reduction in emissions of ozone precursors is desirable to the EPA.

The importance of improving air quality is questioned by few, but the exact methods of doing so are challenged by many. The following principal issues drive the discussions in this Record:

- When the EPA standards for heavy-duty engines were adopted, it appeared that trap oxidizers, which would permit existing DFCI engines to meet the particulate emission standard, would be available by 1991. This assumption is now in doubt.
- Because of the strictness of both the nitrogen oxides and the particulates standards for 1991, and the nitrogen oxide–particulates trade-off phenomenon, it is extremely difficult to meet both standards with the DFCI engines now used in transit buses.
- Methanol-fueled engines would probably meet the standards, but many of the "bugs" of the new technology may not be worked out by 1991.
- The costs of adding trap oxidizers or switching to methanol are large. This poses a problem for the budget-constrained transit industry.
- To soften the financial impact, a system of emissions credits may be allowed in the transition years. Such a system would permit engine manufacturers to trade or bank emissions credits from engines that meet the standard against those that do not. The paper by Galef in this Record quantifies the magnitude of savings likely to be achieved through various transition strategies.
- The problem of measurement is inherent in calculating the costs and benefits of various strategies. The paper by Small in this Record investigates various indices that may be used to measure benefits and relates the benefits to the costs of implementation.

TRADE-OFF PROBLEM

The emissions regulations that take effect for transit buses in 1991 cover both particulate emissions and nitrogen oxide emissions. This poses a particularly difficult problem for engine manufacturers because of the particulate–nitrogen oxide trade-off; as emission of one pollutant is reduced with a given engine and fuel, emissions of the other increase. Further, as nitrogen oxides emissions are reduced, fuel economy deteriorates (*6*). It may be possible to meet the particulate emissions standard by modifying existing DFCI engines, but it does not appear likely at this time that such a strategy would be able to meet both standards. Because of this trade-off problem, Santini and Schiavone argue for relaxed bus nitrogen oxide standards in order to make the particulate emission standard achievable with a minimum of disruption to the heavy-duty diesel engine industry and the transit industry.

Bennethum, on the other hand, argues for even stricter nitrogen oxide control in his paper in this Record. Stricter controls would be clearly "technology forcing" because only methanol-fueled engines would be able to meet such standards. Thus the establishment of a standard impossible for the diesel to meet, but achievable with methanol, would send a clear signal to bus engine manufacturers that there would be a sufficient market for methanol engines to make it possible to recoup the capital investment required to develop them. This is an important consideration because it could be to the nation's advantage to have alternatives to oil as transportation fuels. However, with the present regulations, it is simply not clear if the investment is warranted at this time. Small does indicate, however, that the social benefits of such a standard could exceed the costs. Nevertheless, as Small shows, the uncertainties inherent in placing values on these costs and benefits, as well as the uncertainties about the price of diesel and methanol fuel, are great. As a consequence it is not possible to be certain that forcing methanol use in buses is socially desirable.

Small's benefit-cost calculations are based on the value of reducing particulate emissions. Small places no value on the nitrogen oxides reductions, which would be far smaller on a percentage basis. Given the small nationwide contribution of nitrogen oxide from buses to the ozone problem, it is doubtful that a completely successful bus program would, by itself, bring any area into compliance with the regulations. Thus reduced nitrogen oxides from buses will not make much difference to ozone problems. On the other hand, heavy-duty truck sales (>14,000 lb gross vehicle weight) in 1985 were about 100 times transit bus sales. Consequently, if the desire is to reduce ozone precursors such as nitrogen oxides, then strict regulation of nitrogen oxides emissions from diesel trucks is far more important than strict regulation of such emissions from buses.

PROPOSED SOLUTIONS AND THEIR LIMITATIONS

In this Record Santini and Schiavone discuss a number of proposed solutions to the diesel engine emission problem that could be in place in or relatively soon after 1991:

- Low-sulfur diesel fuel,
- Particulate traps on standard diesels,
- A combination of particulate traps and low-sulfur fuel,
- A combination of catalysts and low-sulfur fuel,
- Modified diesel engines, and
- New or modified engines using alternate fuels.

There are three problems with each of the proposed solutions—technical feasibility, cost, and timing. Each of the papers in this Record addresses these issues to varying degrees.

It has been proposed that low-sulfur diesel fuel could reduce particulate emissions because sulfates are a major component of diesel particulate emissions. The efficacy of this strategy is discussed at length in the paper by Small who finds that he can unequivocally recommend that the sulfur content of fuel be reduced to 0.05 percent.

Particulate trap technology, presumed to be in place by 1991, would permit the particulate emission standard to be met. This technology uses ceramics or wire mesh to restrict the flow of particles and to burn them in a process called regeneration (*6, 7*). The higher the temperature used in the trap regeneration process, the more efficiently the particles are burned off. However, the higher temperature increases the rate of nitrogen oxide formation—the trade-off problem.

Because of uncertainty regarding the effectiveness of traps, some negative experience with traps in transit application (*8*), and the small size of the bus market relative to the truck market, work on traps appears to have slowed recently. Further, because of the small size of the bus market, there might not be a ready nationwide supply of low-sulfur diesel fuel in 1991 if only buses need it. Neither trap technology nor low-sulfur diesel fuel may be available in 1991 for the bus market, but they might be available by 1994 because of their introduction for the larger truck market.

Other potentially useful changes to existing two-stroke diesel engines in buses include

- Turbo-charging;
- High-pressure electronic fuel injection;
- Computer engine controls;
- Spark assist for alternative fuels;
- Four-stroke diesel engines;
- Ignition enhancers for methanol engines; and
- Catalysts with methanol or low-sulfur fuel, or both.

The most promising research on diesel engine modification includes low-sulfur fuel, catalysts, particulate traps, cylinder modifications, redesigned fuel injection systems, and electronic controls. In his paper in this Record Duggal discusses some of the problems encountered in developing modified engines. The jury is still out on whether these modification strategies will be able to extend the life of the diesel engine in a more or less traditional form.

Methanol is the most promising of the alternate fuels under consideration. Past cost-benefit research on the introduction of methanol-fueled compression-ignition (MFCI) engines in buses (*4, 9,* and paper by Small in this Record) and the availability of buses that already meet the standards (*10*) have caused the EPA to encourage switching to methanol fuel for urban transit buses (*11*). In his paper in this Record Bennethum discusses the progress of Detroit Diesel in developing a heavy-duty methanol engine, and Duggal describes work at Cummins Engine Company in his paper in this Record. The Detroit Diesel 6V series engine is the most common U.S.-manufactured bus engine, and the Cummins L10 series is the next most common.

The benefits of substituting MFCI engines for DFCI engines would include sharp drops in nitrogen oxides, particulates, and reactive hydrocarbon emissions from buses. Nationally, the benefit from switching to methanol buses would be small, because transit buses consume only about 525 million gallons of fossil fuels annually (*12*), about 0.4 percent of national transportation consumption. In central business districts, however, the benefits of particulate reduction could be substantial because of the relative concentration of buses there; ozone benefits resulting from reduction of ozone precursors (nitrogen oxides and reactive hydrocarbons) would be limited, partly because the effects tend to be far more spatially diffused than are those of particulates. This is recognized in existing benefit-cost studies, which only claim particulates benefits (*4, 9,* and paper by Small in this Record).

In his paper in this Record Small evaluates the costs and environmental benefits associated with methanol-fueled engines in addition to examining low-sulfur diesel fuel, particulate traps, and combined traps and low-sulfur fuel. In most cases, Small finds that the incremental cost of methanol is higher than that of the three diesel fuel–based options that he examines. He does show that methanol's benefits may exceed its costs under some plausible assumptions.

Methanol's benefits would come at the expense of a new emissions problem caused by increased production of aldehydes. A safety problem would also be introduced in bus maintenance facilities because of the volatility of methanol. Indoor fueling and storage would be more dangerous than with diesel fuel because of the fire hazard. These problems, however, are expected to be manageable. The safety of methanol is roughly equivalent to that of gasoline, so methanol is not unsafe compared with the typical U.S. fuel.

AVERAGING, TRADING, AND BANKING OF EMISSIONS CREDITS

Regardless of the strategy or strategies that are adopted to meet the 1991 transit bus emissions regulations, engines that satisfy the regulations are likely to be more costly to produce and operate than traditional diesel engines. To reduce the burden on manufacturers and users of heavy-duty engines, the EPA is modifying its traditional method of imposing emissions standards to allow engines to meet the standard on average instead of individually. The precise mechanism for such flexible strategies has not been determined, but averaging, trading, and banking of emissions credits are being considered. Emissions credits can be created when an engine does better than the standard for an individual pollutant.

Averaging of emissions credits applies to engines of a certain class (yet to be defined) produced by a single firm. If some modified engines perform better than the standard requires, other engines will be permitted to produce emissions greater than the standard allows as long as, on average, all of the engines produced in a model year satisfy the regulation.

Trading is an industrywide concept that would allow firms producing engines that perform better than the standard to sell credits to firms producing engines that violate the standard. This approach would result in industrywide compliance without making existing engines obsolete overnight.

Banking of credits is an intrafirm strategy that would allow credits that accrue from overcontrol of emissions in one model year to be credited against future model years. This strategy is most appropriate when regulations become progressively more restrictive.

Another option that will be available to bus manufacturers is the payment of noncompliance penalties for violation of the standard, enabling sales of noncomplying engines to continue.

The challenge to industry faced with such flexible regulations is to optimize production strategy such that a least-cost mix of engines is produced. The economics of the problem revolve around the marginal cost of reducing emissions using the various compliance technologies available. Galef discusses the economics of flexible control strategies in this Record.

CONCLUSION

As this introduction to the topic of diesel fuel emissions and alternate fuels attests, the transit industry has no clear solution to the problem of compliance with the 1991 nitrogen oxide and particulate emissions standards. The papers in this Record represent various points of view: those of the transit industry, engine manufacturers, and the interested academic community. It is hoped that this exchange of ideas will assist in the development of a compliance strategy that is in the best interests of the public in general and the transit customer in particular.

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Technical Problems and Policy Issues Associated with the 1991 Bus Emissions Standards

D. J. SANTINI AND J. J. SCHIAVONE

An overview is presented of the problems that may be created for transit systems if the strict 1991 bus particulate and nitrogen oxides emissions standards remain in force. The problems created for manufacturers of diesel bus engines by the standards' tighter technology development schedule for buses than trucks are reviewed. Introducing the perspective that emissions from transit buses should be thought of in terms of emissions per passenger mile calls into question the need for the 1991 standards to be stricter for buses than trucks. The unique spatial relationships among buses, downtown pedestrians, and metropolitan places of residence are taken into account when evaluating the differing effects of bus emissions of nitrogen oxides and particulates. There appears to be far less justification for significant reductions of nitrogen oxides emissions from buses than for reductions of particulates. The more stringent the nitrogen oxides standards, the more costly and difficult it becomes to meet any given particulates standard. By analyzing the likely decisions of transit operators under the existing standards, an argument that slightly less strict standards would actually have the effect of causing lower total particulate emissions is developed. Accordingly it is argued that the Environmental Protection Agency should reconsider and slightly revise upward the 1991 standards. The 1994 standard, which is identical for buses and trucks, is not challenged.

The Environmental Protection Agency (EPA) has promulgated strict emission standards for all newly manufactured heavy-duty engines. These standards require reduction of nitrogen oxides and particulate emissions to levels well below those allowed in 1987 (*1*). In the case of particulate emissions, transit buses must meet the 1994 truck standard of 0.1 gram per brake-horsepower-hour (g/bhp-hr) in 1991, three years before trucks are required to do so, and meet all other standards on the same schedule as trucks (*2*). Trucks are given the opportunity to phase in particulate emissions reductions in two steps, but buses must achieve the 83 percent reduction from the 1988–1990 standards in 1 year. Transit buses and trucks must also meet a stricter standard for nitrogen oxides (NO_x), amounting to 5.0 g/bhp-hr in 1991, a 53 percent reduction from 10.7 g/bhp-hr in 1989. At present, the only demonstrated way for buses to meet both the NO_x and particulates standards in 1991 is through the use of methanol-fueled heavy-duty (MFHD) engines (Figure 1) (*3*). Although natural gas–fired heavy-duty (NGHD) engines can meet the 1991 bus particulate standard, it is proving very difficult to also meet the NO_x standard. Figure 1 shows the positions of current engine-fuel combinations relative to one another and to the 1991 NO_x and particulate standards for buses. Because the truck and bus standards converge in 1994, transit operators have a legitimate reason to expect that suitable diesel-fueled compression-ignition (DFCI) engines and diesel fuels will be available then, allowing them the option of purchasing DFCI engines that meet the standards in 1994 and after.

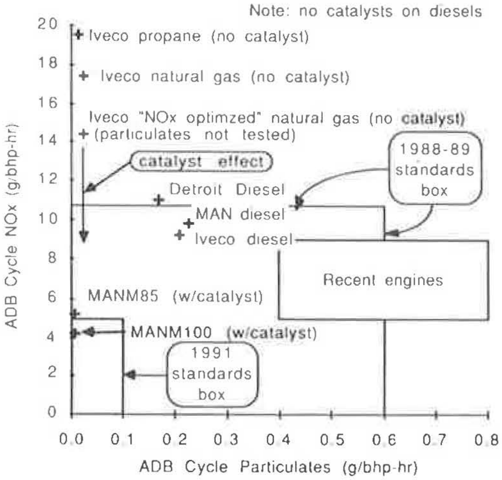

FIGURE 1 Advanced design bus cycle emission rates of various engines in Canadian tests versus EPA standards and recent late-model diesel engine emission rates (*1, 3*).

There are good reasons for trying to cause a reduction of particulate emissions from buses earlier than from trucks. EPA tests indicate that the 6V series General Motors engines, which are typically used in central business district (CBD) service in transit buses, have high particulate emissions rates after a few years of service. Walsh cited EPA-estimated emissions rates of 4.3 g/mi for these buses (*4*). Theoretically, the standard will cause better than a 95 percent reduction from these levels if the old, high-emitting buses are scrapped when new buses meeting the standard are purchased. In practice, for reasons that will be discussed later, the reductions are not likely to be this great.

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The General Motors 6V series engines are typically used in buses, but they are not frequently used in trucks. The 6V series engines are two-stroke engines, which are inherently more polluting than four-stroke engines that are normally used in trucks. Even so, the 0.1 g/bhp-hr standard will be difficult for even four-stroke diesel-fueled engines to meet. From one point of view, setting the standard at 0.1 g/bhp-hr could be expected to cause the offending transit bus engines to be cleaned up or replaced as soon as possible, which is a desirable result given the high particulate emission rates that they exhibit after a few years. Unfortunately, as we will show, the standard could actually have the opposite effect for a number of reasons not considered or anticipated when the standard was set.

Presented here are plausible bus replacement decision-making scenarios for transit operators given the standards, the costs and benefits of introducing methanol buses, and the probable state of DFCI engine control technology in 1991 and 1994. If the assessment is correct, the existing standard will probably have the perverse effect of keeping emissions high for a longer period of time than would a slightly relaxed bus emissions standard, which would allow DFCI engines with substantially improved emission characteristics to be sold to transit operators from 1991 to 1994. Presented for consideration are three possible modifications to the existing bus standard.

One of these would be to retain the strict particulate emissions schedule for buses but allow higher NO_x emissions. This would allow diesel engine manufacturers to take advantage of the inherent trade-off between NO_x and particulates (Figure 2).

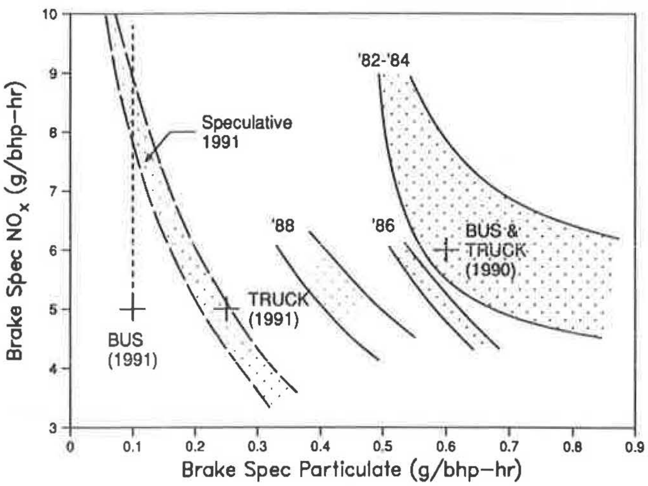

FIGURE 2 Past, present, and speculative future examples of the particulates-NO_x trade-off for heavy-duty diesel engines (1982–1988 curves from Duggal).

A second option would be to relax the bus particulate standard from 1991 to 1994 to the level required for trucks. Estimates are developed that indicate that this would make little difference in the amount of emissions improvement obtained by replacing old uncontrolled buses with new, strictly controlled buses. Third, the estimates can also be used to support some relaxation of both the NO_x and the particulates standards for buses from 1991 to 1994.

AIR QUALITY EFFECTS OF THE STANDARDS

In its recent discussions of the desirability of the bus standards the EPA has emphasized two points (*1*). The first of these points involves the high in-use transit particulate emissions rates found in EPA tests of six buses pulled out of everyday transit use. The tests of these buses resulted in an estimate of a ratio of bus-to-passenger-car particulate emission rates of 500 (Figure 3). This leads to the second point made by EPA, that "equity" now requires that stricter controls be placed on buses so that they will be treated more fairly relative to cars. To illustrate the slight but important differences between the authors' position and that of EPA, a concept of equity believed to be fairer than that used by EPA will be introduced, and the determination of the 500:1 bus-to-car ratio will be reexamined.

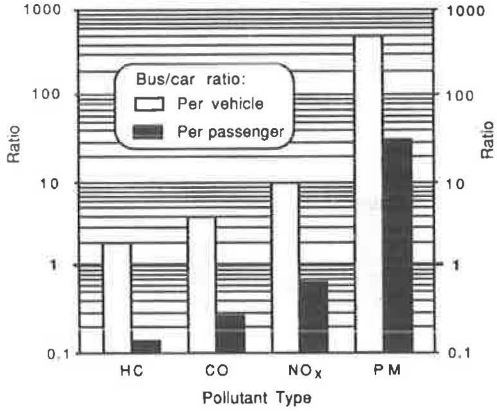

FIGURE 3 Ratio of uncontrolled bus emissions to passenger car emissions, 1980 vehicles (log scale) (*1*).

From the point of view of a passenger car driver, an individual bus is at a disadvantage relative to an individual car. Because a bus is a larger vehicle with an engine that works far harder, it tends to emit more exhaust gases than a car, even when controlled at the same rate per brake-horsepower-hour as a car. Thus, on the basis of a vehicle-to-vehicle comparison, a bus has an inherent disadvantage. Because of its inherently higher amount of exhaust fumes at the tailpipe, the bus is likely to be perceived by a pedestrian as a worse polluter than a car. Indeed, for an individual pedestrian at a given distance from a bus tailpipe, the bus will cause higher exposure than a car. Placing exhaust outlets at the roof of the bus away from the curbside tends to control this effect.

The bus-to-car ratios given by EPA for particulates, NO_x, hydrocarbons (HC), and carbon monoxide (CO) are shown in Figure 3 (*1*). This figure shows clearly that the particulate problem is by far the most severe. EPA has been using the vehicle-to-vehicle comparison in its recent presentations. The present authors suggest that a more appropriate basis for measurement of emissions rate equity for buses and passenger cars would be emissions per passenger mile. Figure 3 shows an emissions per passenger mile recomputation of the EPA's ratios, assuming that a car carries two passengers and a bus carries 30 persons. At peak hours in CBDs of major cities, this ratio probably overstates the per passenger emission rates of buses. Typical buses have about 50 seats. During peak hours every seat can be filled and a number of standees can be on the bus as well. With the assumptions used, a bus remains a worse particulate polluter than a car, but a lesser polluter in every other respect (Figure 3). Thus, if this view of emissions equity is used, there remains a strong reason to control particulates, but no reason to require reduction of the other three pollutants. However, although the bus engine standards for HC and CO do not change from now through 1994, the NO_x standard is tightened. Because of the inherent trade-off in a given engine between particulate control and NO_x control (Figure 2), tightening the NO_x standard makes it more difficult to meet the particulate standard. Thus, if the EPA had not chosen to tighten the bus NO_x standard, the technical challenge involved in meeting the particulate standard would be slightly less severe.

BUS NITROGEN OXIDES CONTROL AND OZONE CONCENTRATIONS

One of the potential advantages of reducing NO_x emissions from buses would be a reduction of ozone concentrations in metropolitan areas. Because nitrogen oxides are ozone "precursors," their reduction ultimately reduces ozone. On the surface this appears to be an advantage, especially when it is recognized that violations of the ozone standard represent the most frequent violations of National Ambient Air Quality Standards (NAAQS) (*5*). However, ozone formation is a very complex process whose interactions with NO_x require careful examination.

Figure 4 is a simple illustration adapted from an EPA explanation of the process. This figure is intended to convey some of the complexities of the process in general and of the situation of buses in particular. First, the concentration of NO_x emissions from buses is greater in the center cities and CBDs of metropolitan areas than in the suburbs. In the immediate vicinity of buses and other vehicles, the emissions of NO_x actually scavenge ozone molecules, thereby reducing nearby ozone concentrations. Figure 5, adapted from an EPA study near an expressway, illustrates this effect (*6*). As the NO_x disperses into the surrounding mass of air, it moves along with the air mass and "cooks" with solar radiation, ultimately increasing the amount of ozone in the atmosphere. Because this interaction with sunlight takes some time to occur, peak ozone concentrations tend to occur in the afternoon and downwind in the suburbs (Figure 4).

Statistics from a recent study of London illustrate this phenomenon. In the "rural areas downwind of London" the 1984 concentrations of ozone were 221.6 mg/m³, while the concentrations in the center of London were 176.6 mg/m³ (*7*). This does not imply, however, that the generally prevalent afternoon ozone concentrations in a CBD cannot be high enough to be a potential problem for persons outdoors. The 176.6 mg/m³ figure for London's CBD was well above the background level of about 115 mg/m³.

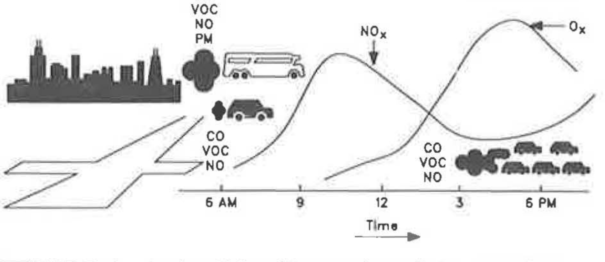

FIGURE 4 A simplified illustration of the complex process of NO_x and O_x chemical reactions [adapted from Wilson (*5*)].

It has been argued in comments to the EPA that increases in emissions of NO_x from cars and trucks should be allowed in urban areas because of the scavenging effect (*8*). This is generally a dubious argument because the scavenging effect is quite localized. Figure 5 shows that there is little reduction from background levels a few hundred feet from an expressway. In a CBD environment, street-level ozone concentrations are depressed relative to regionwide averages while concentrations a few floors above (>100 ft) are the same as or even higher than the regionwide background. Thus, persons outdoors in back yards of suburban homes or on decks in tall apartment buildings would not benefit by increasing NO_x. Further, ozone is a regional problem in which long-range transport is important. Increases of NO_x in one metropolitan area can ultimately increase ozone concentrations hundreds of miles away.

Nevertheless, in the case of buses alone the argument for increased NO_x might have some merit. By their nature, buses are used more than any other type of vehicle in downtown areas. On downtown streets in the afternoon, local NO_x emissions from buses are a small but significant part of local, street-level, NO_x emissions. In those locations measurable increases in ozone should occur as a result of decreases in bus NO_x emissions. In the previously cited London study, a pattern of regulation that initially increased NO_x emissions from cars was estimated to decrease CBD ozone concentrations, so the argued effect is predicted by one model of ozone formation. In the London case, a 38 percent increase in NO_x from new cars relative to the 1984 fleet was associated with a year-2000 decrease in London CBD ozone amounting to 20 percent but an increase in downwind areas of 2.6 percent (*7*). Higher NO_x emissions from buses alone would obviously have a smaller effect in both locations, but the relative concentration of buses in the CBD would probably tip the ratio of CBD reductions to downwind increases even more in favor of the CBD. The question then would be how much the small ozone increase in downwind areas would injure persons there relative to the benefits of the far larger ozone reductions for persons in the CBD. A rough idea of the possible size of CBD effects versus metropolitan area effects is given by the calculations that follow.

Even if it could be unequivocally said that the reduction of NO_x would reduce ozone concentrations at every location, the effect of the NO_x standard for buses from 1991 to 1994 would be insignificant for the average metropolitan resident. Nationally transit buses consume only about 525 million gallons of fossil fuels annually (*9*). Large as this quantity is, it is only about 0.4 percent of total transportation fuel consumption. Thus, if all bus engines were instantly replaced with engine-fuel combinations that emitted at 50 percent of current NO_x rates, average national ozone concentrations would probably normally drop by less than 0.1 percent because transportation emissions account for well under half of the emissions of all ozone precursors (*5*). Further, because the authors of this paper

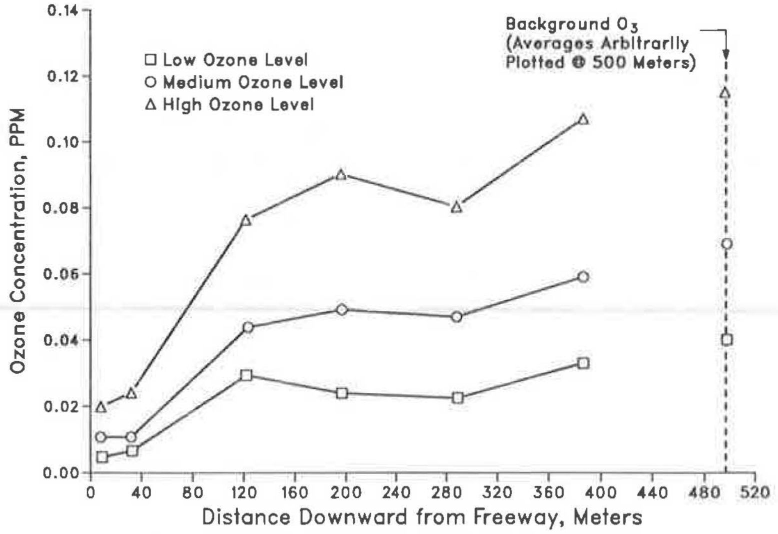

FIGURE 5 Ozone (O_3) data from the EPA's 1979 NO_2/O_3 sampler siting study (*6*).

do not argue for any changes of the standard after 1994, the time interval in question is only 3 years. Using 12 years as the average lifetime of a bus, a change allowed over this 3-year period would only amount to a change for 25 percent of the fleet. Thus an increase of the NO_x standard for 3 years would only increase ozone concentrations by 0.025 percent (relative to a case in which buses meeting the existing standard are assumed to be sold at a normal rate).

As has been emphasized, the contribution of buses to CBD air quality in particular is far greater than to national air quality on the average. Some computations for the CBD of Dallas help to put this into perspective. In Dallas the transit bus share of passenger miles is slightly under 25 percent that of automobiles and other personal vehicles. Assuming about a one-to-one ratio of NO_x emissions per passenger mile for cars and buses (Figure 3) and allowing for the emissions of trucks and other service vehicles, the NO_x emissions of buses can be roughly 15 percent of the mobile source inventory (*10*, Table 4-5), and perhaps around 8 percent of the total CBD inventory (*11*).

Further, as far as street-level emissions are concerned, mobile sources are probably more important than stationary sources. If the average contribution of buses to street-level emissions loading in the CBDs of major U.S. cities is about 8 percent, then the approximately 50 percent reduction in NO_x emissions that could be caused by the bus standard over a decade or so could indeed allow a significant increase in CBD street-level ozone concentrations, perhaps on the order of 4 percent or more. Obviously, the detrimental ozone effect in the physically small but densely occupied CBD would be far greater on an incremental basis than the very small detrimental effect in the suburbs.

BUS EMISSIONS AND PARTICULATE CONCENTRATIONS

The figures presented by the EPA and shown in Figure 3 imply that the contribution of buses to the national particulate problem would probably be far worse than the contribution of nitrogen oxides to the formation of ozone, and the estimates that follow support this implication. In the Los Angeles air basin, Frederick et al. estimated that the basinwide reduction of particulates that would result from complete replacement of diesel buses with methanol buses would be 0.43 percent and that of sulfates 0.23 percent (*12*). Using national statistics, a similar number is obtained. Using the 1985 vehicle miles of travel for all buses of 6,931 million miles (*13*), the Walsh value of 4.3 g/mi for in-use urban buses (*4*), and the national total of 7.0 million tons of particulate emissions in the United States (*5*), a 0.47 percent reduction in national particulate emissions is estimated if all bus emissions are completely eliminated. A 95 percent reduction, as projected by Walsh, would lead to a 0.45 percent reduction. Although buses are assumed here to emit particulates at a far greater rate than cars, the overall contribution to particulate reduction that can be made by buses is limited because transportation accounts for only 19 percent of the nation's particulate emissions (*5*).

However, in the case of the Dallas CBD, if the ratio of bus-to-car emissions per passenger mile were about 40:1, and if all other emission rates remained unchanged relative to cars, then buses could account for as much as three-fourths of the total particulate loading in the CBD. This would probably not be the case in practice, however, because particulate emissions from diesel combustion in general tend to be far higher than from gasoline engines. Consequently, diesel-fueled trucks, generators, and boilers all would contribute relatively greater amounts to the particulate loading in a CBD. In research on the stationary source fuels used in large U.S. urban areas, Santini found that CBDs tend to be unusually oil dependent compared with the city and metropolitan area as a whole (*14*). In CBDs, oil systems were used instead of natural gas systems to replace old coal systems because the cost of digging up streets could be avoided. In any case the bus contribution to the CBD particulate problem is undoubtedly quite substantial.

The EPA, by citing its tests of old buses using a CBD-type driving cycle, implicitly recognizes that the importance of the bus contribution to the particulate problem is greatest in CBDs of large cities (*1*). Walsh cited and used a value of 4.3 g/mi for uncontrolled diesels in his cost-benefit study (*4*). Elsewhere in this Record, Small cites the testing of three buses at the Southwest Research Institute, giving a value of 6.24 g/mi. In comparison, the 0.1 g/bhp-hr 1991 standard would theoretically allow maximum emissions of 0.23 g/mi from a new bus [EPA suggests a rough conversion factor of 2.3 to convert g/bhp-hr to g/mi (*6*)]. In practice the emissions of new buses in CBDs would be higher than 0.23 g/mi because the driving cycle under which the buses would be certified is not as severe as CBD driving.

Because the EPA's 500:1 ratio apparently involves a comparison of uncontrolled used buses on a CBD cycle with a fleet of controlled cars on an average driving cycle, it tends to be quite misleading about the degree to which particulate emissions from new, controlled buses will exceed those of cars. By using 1985 EPA estimates of emissions from a late-model Cummins engine tested on more typical heavy-duty engine cycles (*15, 16*), and comparing them with published emission rates for cars, Saricks of Argonne National Laboratory obtained a ratio of bus-to-car emissions in the neighborhood of 40:1. This 40:1 ratio still means that a late-model bus would have to carry more than 20 passengers before it would emit particulates at a lesser rate than cars with two passengers. Further, if engines, and therefore particulate emissions rates, of diesel buses deteriorate more in CBD use than do those of cars, then the 40:1 ratio would understate the rate of emissions of buses relative to trucks. Nevertheless, on the basis of this latter comparison, far different conclusions would be reached about the urgency of reducing particulate emissions from buses than with the EPA's ratio. It might easily be concluded that late-model buses with Cummins diesel engines loaded to capacity at rush hour would result in lower emissions than cars carrying a similar number of passengers.

The EPA has already done a study of future bus versus car emissions in large cities (*17*). The results of that study are noteworthy for this discussion:

> The impact of switching from heavy use of automobiles to the increased use of bus and rail transit is a net improvement in projected TSP [total suspended particulate] levels. It was found that a large improvement in the TSP contribution from the automotive mode of transportation correlated with a very minor increase in the TSP contribution from buses. This is primarily due to the large capacity of buses, which can accommodate 40–100 commuters in scenarios involving a modal shift. The VMT of automobiles can be reduced by about 50 miles for each 1 mile increase in bus VMT experienced in a modal shift. Despite the higher TSP emission rates for buses compared to automobiles, their use for commuting contributes to a significant reduction in TSP contribution from the transportation sector in the central cities. In all scenarios, contributions from buses represented a significant portion of future ambient TSP levels.

This 1979 study, which projected emissions to the year 2000, was probably pessimistic with respect to the future central city emissions rates from buses because it used a value of 0.9 g/mi for diesels. The 1991 bus standard would require a rate of about 0.23 g/mi, as would the truck standard in 1994. Even allowing for particulate emission increases due to CBD cycle use and deterioration as buses age, the 0.9 g/mi assumption appears to be pessimistic for the end of the 1988–2000 interval because new buses would have been certified at the 0.23 g/mi rate for several years by that date. The particulate emissions rate from post-1975 automobiles in that study was 0.0087 g/mi, so the ratio of bus to car emissions was 103, a value intermediate between the present authors' optimistic 40:1 estimate for the newer Cummins engine and the pessimistic 500:1 ratio cited by EPA for the old GM 6V series engine. Incidentally, the ratio between Walsh's cited value of 4.3 g/mi for in-use buses and Paul's EPA study value of 0.0087 for cars is 494, very close to the 500:1 EPA figure.

The basic point established by the reexamination of the ratio of bus to passenger car particulate emissions is that the establishment of the 0.1 g/bhp-hr standard specifically for buses in 1991 is not as urgent as is implied by the EPA's citation of a ratio of 500:1. When it is recognized that an analysis of the future should compare late-model controlled bus engines with cars and when emissions are considered on the basis of passenger miles of travel, it can even be argued that the standard penalizes buses relative to cars. The 1991 standard requires achievement of about 0.23 g/mi. If future cars emit at 0.0087 g/mi on average, then the ratio of bus to car emissions would be 26. This is far less than the ratio of 103 that was used in the study by Paul (*17*). A rollback of the standard to 0.25 g/bhp-hr would still leave this critical ratio well below 103.

If the same argument is applied to particulates that was applied to nitrogen oxides, then a change in the bus particulate standard to 0.25 g/bhp-hr (instead of 0.1 g/bhp-hr for the 3 years from 1991 to 1994) would decrease the absolute value of the reduction factor computed at the introduction of this section by 0.000041 through 2003. In other words, the amount of reduction would diminish from 0.446 to 0.442 percent. Given the likely understatement of CBD emissions inherent in the certification process, this number is on the low side. Nevertheless, it does illustrate that a minimal amount of increase in particulate reduction is obtained by making the 1991 particulate standard stricter for buses than for trucks.

COSTS AND BENEFITS OF MEETING THE STANDARD WITH DIFFERENT TECHNOLOGIES

What appears to be nearly certain at this time is that the seemingly small differences in standards between buses and trucks can make a considerable difference for those considering purchasing buses from 1991 to 1994. As Figure 1 shows, the only way to meet the 1991 bus standard with today's technology is with methanol-fueled buses. Bennethum's paper in this Record implies that the standards are near a technological barrier that diesel-fueled engines may not be able to cross. By suggesting that a tightening of the NO_x standard in 1994 would make additional work on methanol bus engines worthwhile for the leading manufacturer of bus engines, Bennethum implies that not even the best four-stroke diesel engines will be able to compete with a successful MFHD engine. On the other hand, he also implies that diesel engines will meet the standard in 1994 and that those diesels will take away the market that a methanol bus engine might enjoy from 1991 to 1994 with the existing standard. Small (see paper in this Record) shows that plausible sets of numbers drawn from the literature support a decision to force methanol buses into the market, providing some support for Bennethum's argument. However, Small shows that other plausible numbers support a decision not to do so.

The reexamination of bus control technologies by Small illustrates that, at 1987 methanol and diesel fuel prices, methanol is not the most cost-effective way to reduce particulate emissions from buses. Small examines diesel fuel sulfur reduction, particulate traps, a combination of diesel fuel sulfur reduction and particulate traps, and methanol. The option that he does not examine, however, is the combination of diesel fuel sulfur reduction and catalysts. Catalysts, which are cheaper than particulate traps, will only work if fuel sulfur content is reduced (*18*). Small does a good job of presenting a range of possible damage coefficients, thereby illustrating that a level of uncertainty exists in the estimates that he is able to present. Uncertainty about both the health damage estimates used by Small and the price of methanol versus diesel fuel in the next few years makes it reasonable to question whether Small's study should be used to justify forcing methanol into the transit bus market. Small does not contend that his study implies such a policy, but he does correctly point out that his results are positive enough to "warrant further development of the hardware and further refinement of the benefits." The authors of this paper would not want their position misconstrued in this regard. Although there is reason to question a standard that would have the effect of forcing methanol on all transit properties, the present authors support a reasonable standard and encourage further development and refinement of MFHD bus engine technology and continued evaluation of its benefits as additional confidence in the technology develops.

The cost-benefit studies used by Walsh and Small used base case methanol prices per gallon that were 76 to 71 percent of those of diesel fuel. Small estimated that methanol would have to cost about 55 percent as much as diesel fuel to make methanol a better control strategy than particulate traps (presumably post-1994 traps) or diesel fuel sulfur reduction, or both. In response to the recent recovery of the U.S. chemical industry as the result of the recent drop in the dollar, the domestic price of chemical grade methanol has increased substantially and the price ratio of methanol to diesel has moved in favor of diesel. In late March 1988, the Gulf Coast spot price was quoted at about 60 cents per gallon (*2*). The average nationwide wholesale prices of No. 2 diesel, which is probably available to most transit operators, ranged from 50 to 60 cents per gallon in 1987 (*3*). Recent price ratios of methanol to diesel fuel are therefore not favorable to the introduction of methanol buses, even if the cost-benefit ratio is based on a comparison of the value of metropolitan environmental benefits with transit operators' costs.

The studies of Small and Walsh were "grand-scale" studies that considered the ultimate economic value of the environmental benefits of complete replacement of diesel buses with methanol buses. If a transit operator is to introduce methanol buses, things like construction of new refueling facilities, modification of maintenance pits and equipment, and retraining of mechanics must be paid for before the first methanol bus leaves the transit operator's site. If these costs are included, it is likely that a cost-benefit study done by a transit operator would result in an estimate that required per gallon methanol costs to be less than half those of diesel fuel before methanol would be the preferred option. This assumes that the transit operator includes estimates of the value of environmental benefits of reduced emissions from methanol buses that are similar to those used by Walsh and Small. If these benefits are not included, the transit operator will probably require that fuel savings pay for any costs of introducing methanol buses. In such a case the per gallon cost of methanol would probably have to be substantially less than half the cost of diesel fuel before methanol would be the preferred option.

These points should not prevent transit operators from reasonably evaluating the risks of another round of sharp diesel fuel price increases in the 1990s. The recent ratios of methanol to diesel fuel prices are probably a historical aberration. Indeed, the diesel prices are part of a strategy by OPEC to keep oil consumers from implementing alternatives to oil.

TECHNICAL ATTRIBUTES OF METHANOL HEAVY-DUTY ENGINES

Both Small and Walsh present a range of benefit-cost ratios on either side of 1.0 (where benefits equal costs). Both conclude that additional work on methanol bus technologies is desirable. Walsh uses higher initial costs of methanol buses than does Small, but he attempts to quantify more benefits. Walsh's closing remarks bear repeating. Walsh (*4*) asserts that, before a strategy of converting diesel vehicles to methanol vehicles is adopted,

> some questions need to be answered—how much will the fuel actually cost, how durable will the engines be, can the aldehydes be kept to current levels or lower through the use of oxidation catalysts, what will the actual fuel economy be? In addition, many practical problems will need to be resolved. These include assuring a secure, reliable supply of fuel, deciding how broad the fuel distribution network needs to be, etc.

McNutt et al. (*19*) have examined the methanol fuel distribution problem. Their work implies that a significant minority of major U.S. cities would not be within economic range of a likely initial methanol distribution network. They correctly anticipate that some oil companies will not be interested in selling a product that competes with oil and allow for this effect, selecting only terminals with "advertised public access" and examining truck shipments within 100 mi of these terminals. Although most of the United States would be covered by such a system, that significant minority of cities that are not could be faced with substantial economic penalties if methanol were the only option for new buses.

One concern with the cited cost-benefit studies and the EPA cost-effectiveness study justifying the standard is that they are too technologically optimistic, underestimating the difficulty of developing new technology or ignoring some of the true costs of introducing an incompletely refined technology, or both. The EPA's 1985 cost-effectiveness study stated that "developing a trap-oxidizer system for transit bus use may be considerably easier than for most HDE applications" (*8*, p. 2-69), ignoring the severe duty cycle for buses and the severe emissions control difficulties that exist because of "partially burned and unburned fuel including soot during idle, part load, acceleration and deceleration," each of which occurs quite frequently in bus driving cycles (*20*). In the trap manufacturers' recent upbeat statements about the feasibility of traps, optimistic statements about the potential for traps to meet the 1991 bus standards were conspicuously absent (*21*). The EPA also appeared in its earlier cost-effectiveness study to assume that the industry would accept reliability and durability problems when it stated that "durability and reliability requirements would not be nearly as strict as for most other types of heavy-duty vehicles" (*8*, p. 2-69).

Schiavone (*9*) has noted that many existing buses are "load limited" and that the addition of the heavy tankage and fuel loads to buses for methanol or compressed natural gas could reduce allowable passenger capacity. Economists recognize the indirect effects of load-carrying capability, because it affects labor (driver) costs per passenger carried at peak periods. Peak periods determine how many drivers and buses a transit operator must employ.

The problem of adding weight without adding sufficient compensating power exists for NGHD-engined buses. This power-to-weight problem may not apply for 1991 MFHD-engined buses. However, the problem of trading off added weight for allowable passenger-carrying capacity may well exist for the Detroit Diesel–engined methanol bus. The "Golden Gate" experimental methanol bus with a 6V-92TA engine weighed 1,940 lb more than the diesel version, with 775 lb of this being accounted for by fuel (*6*). Perhaps instrumentation added some weight. In any case, if city authorities restricted the peak number of allowable passengers on the basis of total vehicle weight, the carrying capacity of the methanol bus would be from 6 (fuel weight only) to 13 (full fueled weight difference) fewer passengers, assuming 140-lb passengers. This theoretical effect, assuming a 73-passenger loaded diesel bus [this was a test value used by Duncan (*22*) in tests of 1977 GM buses converted to natural gas] would amount to a capacity cost of from 8 to 18 percent. Using $160,000 as the cost of a new bus, the cost of capacity lost because of added weight would be from $13,000 to $29,000. In the former case, this cost of capacity lost as a result of a switch to methanol would be twice as much as the base switching cost assumed by Small. In the latter case, the cost of lost capacity would be about 60 percent greater than the base value assumed by Walsh. Obviously, if this type of accounting for full switching costs were used, the methanol benefit-cost ratios would drop sharply. More than likely, however, these effects would be ignored as long as adequate power was available to carry the passenger loads originally carried in the diesel versions of these buses. In such a case, a full social accounting of the costs would have to incorporate road damage due to the added axle loading on the back axle of the bus and more frequent axle, brake, and tire replacement costs.

Because methanol and natural gas have less energy content per unit volume than diesel fuel, it will take longer to refuel MFHD- and NGHD-engined buses unless added, more costly, fast-fill techniques are implemented. This problem is especially severe for natural gas. Longer times to refuel will mean fewer hours available for other service operations. In the case of methanol, the dangers thought to be involved in refueling have so far caused refueling facilities to be outdoors and at some distance from the diesel fueling location. In Canada, an experiment with a propane-fueled bus required outside garaging, probably for safety reasons related to fueling (*23*). The fuel use patterns by month in this experiment showed that in cold climates outside garaging requirements will be detrimental to on-road fuel economy.

Another problem that generally exists when technology is "forced" into the marketplace is a lack of reliability of early models. Santini has studied the role of fuel price shocks in forcing new vehicle technologies and has observed that reliability of newly developed models with the greatest fuel savings is typically quite poor (*24*). Generally, the most fuel-efficient models do not succeed in their first market tests. Decades can pass between the first experiments and widespread application. In cases in which environmental standards forced technology on the market, lags in widespread application also occurred and initial models were unreliable economic failures. For example, the earliest diesel locomotives, which were pushed into urban switching markets in the 1920s to eliminate steam engine smoke, were unreliable and uneconomic, though they did prove to be durable (*24*). Widespread implementation of diesel locomotives did not occur until after World War II. After regulation of passenger car emissions in the early 1970s, reliability problems emerged in the 1974–1975 period (*9, 20*) until catalytic converter technology was perfected. Further, in 1974, the year before the fuel efficient catalytic converter emissions control technology was introduced and just after the first OPEC oil price shock, automobile fuel economy reached a postwar low (*24*). This was due in part to emissions control technology that robbed performance and fuel economy. [Note that the NO_x standards for buses (*18*) and particulate traps (*9, 21*) also reduce bus fuel economy.] Automobile sales dropped sharply in 1974 and 1975 as the transition to more fuel efficient catalytic converter emissions control technology took place. The decline in automobile sales and the transition to fuel-efficiency-promoting catalytic converters were undoubtedly helped along by the oil price shock of 1973–1974. It had to be accomplished in conjunction with a fuel transition from leaded to unleaded gasoline. As Springer (*20*) points out, manufacturers did not adopt oxidation catalysts for gasoline cars until it was in their interest to do so—in other words, not until gasoline price increases made the fuel-conserving catalytic converter desirable.

One point here is that energy and environmental technical transitions in vehicles are not easily accomplished—side effects during the transition often include reluctance to purchase newly changed vehicles. Another point is that if losses in sales by vehicle manufacturers were included in cost-benefit studies it would become more difficult to justify the transitions. However, all of the transitions just discussed proved to be in the long-term interests of society. Thus the argument here is for more cautious management of the costs of fuel transitions, not evasion of the transition. Possible remedies to these side effects could include better prior development of the technology and slower, more flexible introduction schedules.

The costs of lack of reliability can be incurred in two ways. First, if it is known that more frequent scheduled maintenance is needed for a new technology to keep it as reliable as the old technology, then higher routine maintenance costs should be incorporated into the economic evaluation of the technology. Second, if on-road failure rates of new technology are greater than those of existing technology, even when the maintenance department does everything known to be needed to assure reliability, then time costs to passengers and drivers will be incurred. Such problems can occur with new technology simply because there is little experience with it. An unanticipated problem of this type occurred when multiport fuel injection was introduced by U.S. automobile manufacturers and widespread injector fouling occurred. As is often the case, the problem was relatively easily resolved after the negative experience in the marketplace. The problem was eliminated when the oil industry put more detergents into gasoline, but in the meantime many customers lost much of their valuable time because of increased, unanticipated frequency of maintenance of fuel injectors. Experimental methanol buses have exhibited injector fouling and deterioration problems and frequent catalytic converter failure problems, both of which would cause higher on-road failure rates and higher maintenance costs if such buses were introduced at this time. If high reliability of these components is not demonstrated by 1991, average U.S. transit operators will be far less likely to opt for methanol buses. It should be recognized, however, that the EPA is now doing a good job of promoting methanol bus demonstration fleets and this would eliminate many of the most glaring reliability problems.

Although evidence compiled on full driving cycles confirms that methanol engines have the potential to considerably reduce average bus emissions (Figure 1), the information also indicates that MFHD engines are not inherently good performers at idle and low load (*3*, *25*, *26*, and J. Bennethum, unpublished information). In CBD use, buses spend relatively more time at idle and low load, situations in which a methanol bus would apparently not be at its best. There are not any published studies breaking out emissions for methanol buses in a CBD-type driving cycle, so at this time the environmental advantage that would result if methanol buses replaced diesel buses in CBDs cannot be established. It does appear likely that significant improvements relative to old diesel buses would remain, if separate analysis of the CBD portions of driving cycles were completed, but the correct comparison would be between state-of-the-art diesel buses in CBD use and state-of-the-art methanol buses in CBD use. There are no data of which the authors are aware that are sufficient to answer this question at this time. The performance of the six experimental 6V92TA advanced-design methanol buses introduced in New York City in April 1988 will help to answer this question.

DECISIONS OF TRANSIT OPERATORS

Transit operators will be faced with several possible alternative actions in the 1990s in response to the existing standards:

- Option 1: Assume that methanol buses will be the only way to meet the standard from 1991 to 1994 and that methanol will be the cheapest option thereafter. Make a complete commitment to a long-term switch to methanol starting with normal rates of bus replacement in 1991.
- Option 2: Do nothing differently, assuming diesel buses that meet the standard will be available in 1991.
- Option 3: Assume that methanol buses will be the only way to meet the standard from 1991 to 1994 but that diesel buses will more cheaply meet the standard thereafter.
  - –Option 3(a): Respond positively to environmentalist pressures; purchase methanol buses at the normal rate from 1991 to 1994, switch to diesel thereafter.
  - –Option 3(b): Respond weakly to environmentalist pressures; purchase some methanol buses and extend the operating life of some old, uncontrolled diesels.
  - –Option 3(c): Let other operators introduce the new technology—do not purchase buses from 1991 to 1994. Extend the operating life of old, uncontrolled diesels in order to get to 1994, when new diesels will be purchased.
  - –Option 3(d): Place a high probability on an oil price run-up relative to methanol (and natural gas or propane, or both) in the 1990s, making methanol (and natural gas or propane, or both) buses instead of diesel buses desirable at that time. Hedge bets—purchase some methanol buses and extend the operating life of some old, uncontrolled diesels. Develop experience with the methanol technology as an energy crisis risk management strategy, preparing to go with diesel or methanol in the mid-1990s. Keep an eye on natural gas and propane costs and research and development to see if buses using these fuels and meeting the standard become available.

Obviously, the authors think that assumptions under Options 1 and 2 are unwarranted but concede that some transit operators will make these assumptions. The assumption under Option 1 is the same assumption that is necessary to support leaving the standard in place. It is conceded that there is a small probability that it is the best assumption and course of action. However, it is a theoretical ideal based on the hopes of methanol advocates rather than reality. Under this assumption the environment gets cleaned up and the transit operators switch completely to a new fuel in a little more than a decade. From an environmental point of view, Option 3(a) is almost identical to Option 1. In both cases old, polluting buses are removed from service and replaced by clean buses meeting the standard. It is the remaining decisions and behavior patterns, however, that are considered more likely. These may even make bus emissions temporarily worse from 1991 to 1994, the time when the more strict bus standards would theoretically benefit pedestrians near buses more than pedestrians near trucks.

The judgment of the authors is that if Option 2 is exercised it will prove to be a wrong option and the operator will soon be forced by circumstances to curtail bus purchases until catching up on methanol technology. Actual behavior of this type of transit operator would probably be that described in category 3(c), because the operator would most likely be resistant to change. The effects on 1991 to 1994 aggregate bus emissions under Options 3(b) and 3(d) (which are behaviorally identical from 1991 to 1994) are uncertain, but emissions would clearly be greater than under Options 1 and 3(a). Option 3(c) is environmentally the worst, and it may be the most common response, depending on the path of diesel fuel and methanol prices from now until 1994. In Option 3(c), the old, egregiously polluting buses that the standard is designed to eliminate stay on the road for 1 to 3 years longer than they otherwise would. Indeed, because the Urban Mass Transportation Administration requires a 5-year extension of bus life before it will release funds for rehabilitation, any bus rehabilitated instead of retired by "foot dragging" transit operators would stay in service for 5 years (*27*). Such actions hardly appear to be the desired result of the standards, but, if this assessment of the probable relative costs is correct, this is likely to often prove to be the most economic option for transit operators.

DECISIONS BY EPA AND INTERVENORS

Assuming that the proper legal steps to challenge an EPA standard are taken by parties interested in a revision of the standard, four outcomes (decisions) would be possible on the basis of the arguments in this paper:

1. Leave the existing standard in place.
2. Relax the 1991–1994 NO_x standard for buses but not the particulates standard (both NO_x and particulates standards for buses would be different than for trucks—NO_x emissions greater for buses, particulates less).
3. Relax the 1991–1994 particulates standard but not the NO_x standard (make the truck and bus standards identical).
4. Relax both 1991–1994 bus standards—the particulates standard to truck levels and the NO_x standard for buses only (the particulates standards for trucks and buses would be the same but buses could emit more NO_x).

Although the authors can only offer informed judgment concerning the consequences of each of these four outcomes, they suspect that each of the last three would lead to greater sales of new buses with low emissions relative to old buses, causing more rapid replacement of old buses and lower total emissions than would the existing standards. Outcomes 2 and 4 would be most likely to allow natural gas– and propane-fueled buses, which have emissions like natural gas engines (*3*), into the market (Figure 1). Outcome 2 might still prove to be too restrictive for DFCI engines in 1991, but it would greatly increase the chance that they could meet the revised standard. Outcome 3 would probably keep natural gas– and propane-fueled buses out of the market, but it would be very likely to allow DFCI bus engines to be sold. All outcomes would allow MFHD-engined buses.

From the point of view of low energy prices, secure energy supplies, and fuel efficiency of buses, the fourth outcome is best, but these benefits would obviously come as a result of the highest allowable emissions for individual new buses. Nevertheless, because buses in this case would be cheapest to operate, bus sales might be greatest. The subsequent level of replacement of old, uncontrolled buses might therefore cause this to be the option for which average emissions from 1991 to 1994 are lowest. With all of the last three options there would be a possibility for using the cost-reducing effects of inter-fuel emissions trading as explained in this Record by Galef. In principle, if Galef's proposal were used, new bus sales and emissions reductions as a result of the replacement of old buses would be even greater.

CONCLUSIONS

One issue here is whether transit operators should be put in the situation of being the first vehicle users to make significant use of methanol. To persons advocating the widespread use of methanol (*28, 29*), this might appear to be an excellent opportunity to push into the marketplace a fuel that will ultimately be necessary to solve U.S. energy security and environmental problems. It is certainly appropriate for the EPA to take actions that force the introduction of technology when the agency estimates that it will improve air quality at reasonable cost. However, because the present authors view the problem from a different perspective, and have found some reasons to fault the increase in stringency of NO_x standards (in the case of buses only) and the incremental increase in strictness of the particulates bus standards relative to trucks, they find it appropriate to question the wisdom of forcing MFHD engines on transit operators. Although they believe that the use of methanol and other alternative fuels can bring benefits to the economy and the environment (*9, 29*), they would like to see them introduced in the right place, at the right time, and at the right rate. It is hoped that a transition to methanol will occur smoothly and steadily over a number of years and not in inefficient booms and busts of activity. After conducting ad hoc decision analysis based on Keeney's methods (*30*), the authors see the potential for such boom and bust activity in the transit industry in the first half of the 1990s with the existing bus emission standards.

The present authors would like to see standards that adequately protect the public from the health and economic costs of particulates, but that make fair allowance for the fact that buses get nitrogen oxide–emitting cars off the highways. It is argued that, given the apparent reductions in total emissions that can be achieved when commuters ride late-model buses rather than late-model cars (*17*), it is in the EPA's interest to keep the costs of transit as low as possible, subject to acceptable health risks. To this end, a standard whose NO_x level would (with adequate protection of air quality) allow transit operators to select among any of the DFCI, MFHD, NGHD, or propane heavy-duty engines being researched would be ideal. Such flexibility would help to assure adequate, inexpensive fuel supplies for transit well into the future and would provide transit with some future protection from oil shortages or price shocks, or both. A fringe benefit for engines below the particulate standard would be the opportunity to use the extra allowance of NO_x emissions to increase fuel economy. Gill has estimated that in a heavy-duty diesel engine "a change from 6.0 g to 4.5 g NO_x increases fuel consumption by approximately 8 percent" (*18*). There is a good chance that, if all of these options were available, a number of them would be used, depending on the costs of fuel in the transit operator's area.

Although there is not substantial geographical variation in the price of diesel fuel, there are large differences in natural gas and methanol prices. In some geographic areas these two fuels are readily available, but in others there is no market at all. Recognition of this implies that, with a slightly less strict but environmentally sound bus engine standard, the most cost-beneficial future fuels for transit would probably vary across the country. Although the quantities of fuel consumed by transit are small, the potential value of transit to consumers in the event of restricted fuel supplies is great. The introduction of a diversity of domestically available fuels would do a great deal to assure security of critical transportation services in the event of a future restriction of oil imports.

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Reducing Transit Bus Emissions: Comparative Costs and Benefits of Methanol, Particulate Traps, and Fuel Modification

KENNETH A. SMALL

The cost-effectiveness of three strategies for reducing particulate and sulfur oxide emissions from diesel transit buses is investigated. The strategies, in order of increasing effectiveness, involve low-aromatic fuel, particulate traps, and methanol fuel. All three are evaluated under optimistic assumptions. Three alternate indices of emissions are considered: one equal to total particulates (including those formed in the atmosphere from emitted sulfur dioxide), one based on California's ambient air quality standards, and one based on statistically estimated effects on mortality. At the fuel prices considered most likely, methanol is far more costly than the other strategies per unit reduction in total particulates, but this disadvantage is greatly reduced according to the other indices. In addition, methanol achieves the greatest absolute reduction in emissions. With the mortality-based index, the incremental cost of the methanol strategy over that of particulate traps in the Los Angeles basin comes to $1.6 million per incremental reduction in expected deaths.

Two recent policies on air pollution and energy have combined to focus attention on urban transit buses. First, new federal emissions standards for diesel-powered vehicles are especially strict for transit buses and will probably force early decisions on technologies with substantial start-up costs. Second, a broad interest in methanol as a motor fuel brings attention to transit buses as a test case and possible starting point for methanol conversion: reasons include easily regulated public agencies, central fueling facilities, high current emissions of particulates and sulfur oxides (two of the most well-established health hazards), and emissions at street level in places with high population exposures.

An earlier study (*1*) found evidence that reducing the number of deaths from cancer associated with particulates and sulfates may by itself justify the likely costs of converting transit buses in the Los Angeles air basin from the low-sulfur diesel fuel now required there to methanol. Sulfate reduction accounted for about two-thirds of the estimated benefits.

However, alternative means of reducing diesel emissions such as cleaner fuel and trap oxidizers (also known as particulate traps) must also be considered. Weaver et al. (*2*) review these and other technologies and compare the costs of reducing particulates by various methods assuming successful technological development. Several findings are noteworthy.

First, they find that lowering the sulfur content of diesel fuel to that now required in Southern California (0.05 percent by weight, about one-sixth the national average) more than pays for itself in reduced engine wear and less frequent changes of lubricating oil, and that refiners would find it to their advantage to simultaneously lower the fuel's aromatic content. (Aromatics are compounds containing a benzene ring.) As a bonus, this would reduce emissions of sulfur oxides, particulates, hydrocarbons, and nitrogen oxides. They also estimate that refiners could lower aromatic content still further at a small extra cost. These results are controversial and hard to reconcile with the authors' expectation that, absent government regulation, the quality of diesel fuel will deteriorate. Nevertheless, low-sulfur fuel is an attractive strategy even under much more pessimistic assumptions. For these reasons, it appears best to include 0.05 percent sulfur fuel as part of a base case for analyzing any more ambitious strategies.

Weaver et al. also find that once low-sulfur, low-aromatic fuel is adopted as a baseline, trap oxidizers offer a cheaper means than methanol of removing additional particulates from the air. The cost estimates are $4.71 and $10.34 per kilogram of particulates for two different trap designs, compared with $13.03 for methanol under their most optimistic assumptions.

In this paper, such cost-effectiveness comparisons are further explored by introducing several variations and refinements to the analysis of Weaver et al. First, as just noted, low-sulfur fuel is adopted as a baseline, but with less optimistic assumptions about engine wear and aromatic content. Second, sulfur-oxide (SO_x) emissions are incorporated into the effectiveness measure, and the consequences of various estimates of their noxiousness relative to that of particulates are explored. Third, the incremental cost-effectiveness of using a methanol strategy to achieve reductions beyond those achieved by clean fuel or particulate traps, or both, is examined. Finally, the price of methanol fuel is varied. The results are a confirmation of the promise of particulate traps and a clearer delineation of the potential role of methanol.

Relatively optimistic assumptions are adopted throughout for both particulate traps and methanol, assuming success of current efforts to overcome technological barriers. Data from

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the Los Angeles air basin are used for many of the needed parameters, though the comparisons of pollution control strategies should be representative of most U.S. urban areas.

MEASURES OF EFFECTIVENESS

Three different methods of weighing the damaging effects of particulates and SO_x are considered. [Nitrogen oxides (NO_x) are not considered because of their more complex role in photochemical-oxidant formation.] The first is the measure of "total particulates" that Weaver et al. use in the findings discussed previously; it incorporates the fact that SO_x become particulates in the atmosphere, a phenomenon they term "indirect particulates." The second weighs each emission according to its contribution to causing any of the ambient pollution standards to be reached in the air basin, a concept introduced by Babcock (*3*). The third weighs them according to their relative contributions to mortality, using the statistical evidence of Lave and his coworkers (*4, 5*). Each of these is discussed in the subsections that follow.

All of these measures ignore distinctions among particulates of different sizes. It is now known that the most damaging particulates are the smaller ones (*6*). Indeed, California has replaced its ambient particulate standard with one for particles of 10 microns or less in diameter. Because diesel emissions fall mainly in this size category, the severity of their effects is probably greater than implied by the methods used here. This would make particulate traps relatively more attractive compared with methanol. On the other hand, omission of methanol's NO_x reductions biases the results in the other direction (presuming that any local ozone-scavenging benefits of NO_x are more than offset by its contribution to areawide smog). Both of these limitations can be overcome through further research.

Total Particulates

Total particulates are the result of both direct particulate emissions and atmospheric reactions involving gaseous emissions. The sulfur in diesel fuel is emitted in oxygenated compounds known collectively as sulfur oxides (SO_x). A small portion of these emissions, mainly consisting of sulfuric acid droplets, belongs to a category of particulates known as sulfates. The rest of the SO_x emissions are sulfur dioxide (SO_2), a gas that reacts in the atmosphere to form additional particulates of the sulfate class, including sulfuric acid and ammonium sulfate. On the basis of atmospheric modeling (*7*), the California Air Resources Board staff estimates that each gram of SO_2 emitted produces 1.2 g of particulates in the atmosphere (*8*, pp. 60–63). Citing this estimate, Weaver et al. (2) define

$$\text{Total particulates} = P + SO_4 + 1.2(SO_2) \tag{1}$$

where P, SO_4, and SO_2 denote direct emissions of carbonaceous (i.e., nonsulfate) particulates, sulfates, and sulfur dioxide, respectively, from a transit bus.

Severity Index

This index is based on California's ambient air quality standards and is constructed somewhat analogously to the federal Pollutants Standards Index, as described in the U.S. Code of Federal Regulations (40 C.F.R. Part 58, Appendix G). The idea is simply to assume that all relevant effects, such as health, visibility, and damage to plants and materials, have been incorporated in setting these standards. Hence the relative severity of a pollutant is measured by the increase in ambient concentration, as a fraction of the relevant standard, that it causes. Computing this requires not only knowledge of the standard but a model of the relationship between emissions and ambient concentrations.

That relationship is complicated because ambient standards are set for both sulfates and SO_2 and because the standard for SO_2 consists of two joint standards, one with particulates and one with NO_x. The latter is ignored here, but the joint standard for SO_2 and particulates, based on a well-established synergism (*9*, p. 16), is accounted for in the same way as in the Pollutants Standards Index: by assuming that the standard establishes a degree of severity for the product of the two concentrations.

The specific assumptions follow:

1. Ambient concentrations of total suspended particulates are proportional to the "total particulate" emissions as defined in the previous subsection (except that, for simplicity, the slight difference between the two components of SO_x is ignored here):

$$C_p = a_p E_{tp} \tag{2}$$

$$E_{tp} = E_p + 1.2E_{sox} \tag{3}$$

$$E_{sox} = E_{so4} + E_{so2} \tag{4}$$

where C_p is ambient particulate concentration and E designates total emissions of a pollutant throughout the air basin.

2. Ambient concentrations of sulfates and of SO_2 are each proportional to SO_x emissions, with different proportionality constants:

$$C_{so4} = a_{so4} E_{sox} \tag{5}$$

$$C_{so2} = a_{so2} E_{sox} \tag{6}$$

3. The damage from an ambient concentration according to a given standard is proportional to the ratio of the concentration to the standard, for each of the following three standards: $\overline{C_p}$, $\overline{C_{so4}}$, and $\overline{C_{pso2}}$, the latter being the product of the particulate concentration and the SO_2 concentration that together define the standard. Furthermore, the damage from these three ratios is additive, and the amount of damage that occurs when any of the three standards is reached is the same. Denoting damage by D and a proportionality constant by b, this implies that

$$D = b\,[(C_p/\overline{C_p}) + (C_{so4}/\overline{C_{so4}}) + (C_p \cdot C_{so2}/\overline{C_{pso2}})] \tag{7}$$

By substituting Equations 2–6 into Equation 7, the relative severities of the two types of emissions (particulates and SO_x) can be calculated as the partial derivatives of D with respect to E_p and E_{sox}. Dividing by b, denoting the results by D_p and D_{sox}, and using Equations 2, 5, and 6 to eliminate the proportionality constants yields

$$D_p = (1/E_{tp})\ [(C_p/\overline{C_p}) + (C_p \cdot C_{so2}/\overline{C_{pso2}})] \tag{8}$$

$$D_{sox} = (1.2/E_{tp})\ [(C_p/\overline{C_p}) + (C_p \cdot C_{so2}/\overline{C_{pso2}})] + (1/E_{sox})\ [(C_{so4}/\overline{C_{so4}}) + (C_p \cdot C_{so2}/\overline{C_{pso2}})] \tag{9}$$

The three standards are those that applied in California in July 1983, just before the new fine particle standard went into effect. In all three cases the averaging period is 24 hr (when there is more than one standard for the same pollutant, only the 24-hr average is used). Ambient concentrations are taken to be the highest 24-hr average observed at the downtown Los Angeles monitoring station during 1985. Emissions are those estimated for the South Coast Air Quality Management District, which includes Los Angeles and Orange counties plus those parts of San Bernardino and Riverside counties that are geographically part of the basin; unfortunately, emissions data are for 1983 because 1985 estimates are not yet available.

Table 1 gives the data. Note that neither of the standards involving sulfur was violated, though they were violated at monitoring stations further inland. Hence the proportionality assumption, which implies that a given increase in concentration is just as damaging whether or not any particular threshold has been reached, is important. This assumption is supported by several lines of evidence. First, most epidemiological studies have failed to find thresholds [e.g., Lave and Seskin (*4*, p. 51)], though some possible evidence is noted by Lipfert (*13*, p. 208). Second, beliefs in thresholds have failed to hold up under scrutiny by four separate panels of the National Academies of Sciences and Engineering for four separate pollutants (*14*, pp. 6, 190, 366–367, 400). Third, even if thresholds exist for individuals, averaging over time, space, and people with varying sensitivities will tend to remove the threshold effects from aggregate population responses. See Small (*15*, pp. 111–112) for further discussion.

The resulting values have the ratio $D_{sox}/D_p = 4.17$. Hence,

$$\text{Severity index} = P + 4.17\ (SO_x) \tag{10}$$

Mortality Index

The statistical work reviewed by Frederick et al. (*1*) indicates that particulate and sulfate concentrations affect mortality across U.S. metropolitan areas. The results are measured as elasticities of .0119 and .0500, respectively. Particulate concentration is assumed to be proportional to carbonaceous particulate emissions, and sulfate concentration to SO_x emissions. Hence the proportional rise in mortality ($\Delta M/M$) cause by bus emission of particulates and SO_x is:

$$\Delta M/M = .0119\ (P/E_p) + .0500\ (SO_x/E_{sox}) \tag{11}$$

Total emissions (*E*) in the air basin are again taken from the last two rows of Table 1, resulting in

$$\Delta M/M = 54.4 \times 10^{-12}\ [P + 17.0\ (SO_x)] \tag{12}$$

Hence,

$$\text{Mortality index} = P + 17.0\ (SO_x) \tag{13}$$

Note that all three of the indices are defined in units of kilograms of carbonaceous particulate emissions.

SCENARIOS

Five scenarios, a baseline and four control strategies, are analyzed. Each is described in a subsequent subsection. The resulting parameters are summarized in Table 2.

Baseline

Weaver et al. (2) make a persuasive case that low-sulfur fuel similar to that already required in Southern California is an attractive measure for any area with an air pollution problem. Using the U.S. Department of Energy's Refinery Evaluation Modeling System, a linear programming model of refinery operations, they project the additional cost to be well within the 3 cent per gallon differential now observed between Southern California and other areas (2, p. 234). This projection allows diesel fuel to be segregated from residual oil in the refining process, but it does not permit the sulfur content of residual oil to be increased; instead, the extra sulfur is recovered and sold. Because of this segregation, it becomes feasible (and, according to the model's results, even cheaper) to lower the aromatic content of the diesel fuel by about 8 percentage points, providing possible side benefits of better cold starting and lower emissions of particulates, hydrocarbons, and NO_x. Furthermore, recent laboratory evidence suggests that lowering sulfur content would substantially reduce engine wear and associated maintenance requirements. Finally, the lower sulfur content improves the operation of particulate traps by permitting catalytic oxidation of hydrocarbons without creating excessive sulfates (2, p. 236).

The findings on both engine wear and aromatic content are novel and await verification, but even without those advantages, desulfurization is an attractive control strategy because of its simplicity, ease of introduction, and applicability to all existing diesel vehicles. Hence, in this paper it is assumed that

TABLE 1 DATA FOR SEVERITY INDEX[a]

	Standard ($\overline{C}$)	Actual (C)	Ratio ($C/\overline{C}$)
Concentrations			
Particulates (*p*)	100 µg/m³	208 µg/m³	2.08
Sulfates (*so4*)	25 µg/m³	20 µg/m³	0.80
Particulates and SO_2 (*pso2*)	(100 µg/m³) × (.050 ppm)	(208 µg/m³) × (.021 ppm)	0.874
Emissions (*E*)			
Particulates (*p*)	218.6×10^6 kg/year		
Sulfur oxides (*sox*)	54.1×10^6 kg/year		

[a] SOURCE: South Coast Air Quality Management District for standards (*10*, pp. 14, 44); concentrations (*11*, pp. 41, 42, 45); and emissions (*12*, p. 17).

TABLE 2 ASSUMPTIONS

	Baseline	Fuel Modification	Particulate Traps	Fuel Modification and Particulate Traps	Methanol
Extra vehicle cost					
Capital ($)	0	0	1,100	1,100	5,200
Maintenance ($/yr)	0	0	315	315	582
Fuel quality					
Sulfur (%)	0.05	0.05	0.05	0.05	0.00
Aromatics (%)	28.70	17.00	28.70	17.00	NA
Fuel economy (mi/gal)	3.81	3.81	3.70	3.70	1.81
Fuel price ($/gal)	0.78	0.791	0.78	0.791	0.55
Emissions (g/mi)					
Carbonaceous particulates	6.080	4.256	0.608	0.304	0.304
SO_4	0.026	0.026	0.080	0.080	0.000
SO_2	0.836	0.836	0.809	0.809	0.000

NOTE: Annual mileage = 34,115; real interest rate = 8.0 percent; bus life = 12 years; and capital recovery factor = 0.1296. NA = not applicable.

any area giving serious consideration to methanol would first adopt the 0.05 percent sulfur standard for diesel fuel, and all strategies are analyzed relative to that standard. Neither the reduction in aromatics nor the increase in engine life suggested by Weaver et al. is assumed because those benefits have not yet been confirmed. Included, however, are the reduced maintenance requirements that they estimate: an $8,000 engine overhaul at 234,000 instead of 180,000 mi, plus a $35 oil change every 6,500 instead of every 5,000 mi.

It is assumed that each bus runs 34,115 mi per year and lasts $T = 12$ years; this was the case for Southern California in 1984 (*16*), and is similar for other areas of the United States. Following Weaver et al., the baseline fuel economy is set at 3.81 mpg. A real interest rate (r) of 8 percent per year compounded continuously is also assumed; thus expenses occurring at t years are discounted by the factor e^{-rt}, and an initial capital expense is annualized by the capital recovery factor $r/(1 - e^{-rT}) = 0.1296$.

Virtually all sulfur in the fuel is emitted as some sulfur compound. According to Weaver et al., about 2 percent of the sulfur (atomic weight 32) is emitted as sulfates, mainly H_2SO_4 (atomic weight 98); the rest is emitted as sulfur dioxide (SO_2, atomic weight 64). With fuel weighing 3.249 kg/gal and containing 0.05 percent sulfur by weight, a bus burning 1 gal every 3.81 mi therefore emits 0.026 g/mi sulfates and 0.836 g/mi SO_2.

Emissions of carbonaceous particulates, in contrast, depend greatly on engine design, fuel, age, maintenance policies, and method of measurement. The most appropriate data for present purposes are from buses in actual use, tested with the Environmental Protection Agency's (EPA's) transient bus cycle. Three buses measured in this way by the Southwest Research Institute had particulate emissions averaging 6.24 g/mi (*17*, Table 12). Subtracting 0.16 g/mi of sulfates (obtained by the same method but for fuel with 0.3 percent sulfur) yields carbonaceous particulate emissions of 6.08 g/mi.

Low-Aromatic Fuel

As already noted, Weaver et al. find that some reduction in aromatics, to 20.3 percent, would occur as a by-product of producing low-sulfur fuel. They also analyze a fuel in which aromatics are lowered still further, to 17 percent, and find that this adds only 0.3 cent per gallon to the cost. Extrapolating linearly to estimate the cost of reducing aromatic content from the baseline value of 28.7 percent to 17.0 percent yields 1.1 cents per gallon as the extra cost of this low-aromatic fuel. Refiners surveyed by the California Air Resources Board (*8*, pp. 74–79) were more pessimistic, but the basis for their estimates and their assumptions about sulfur requirements are unclear.

Other properties of low-aromatic fuel are taken directly from Weaver et al. No change in engine life or maintenance is attributed to the reduction of aromatics. Fuel economy tends to be lower during steady operations but higher during warm-up, so it is assumed to be unchanged on average. Carbonaceous particulate emissions are reduced 30 percent, based on engine tests (*18*).

Particulate Traps

Weaver et al. analyze two types of traps now under development: ceramic monolith and wire mesh. Although the ultimate comparative advantages of these and other types are still in doubt, Weaver et al. find the ceramic monolith to be both cheaper and more effective. Their estimates for the ceramic monolith with a catalytic afterburner (permitted by the low-sulfur fuel) are therefore adopted as representing a realistically optimistic strategy.

These estimates are $1,100 capital cost; $350 maintenance cost every 45,500 mi; 3 percent degradation of fuel economy; 85 percent reduction in carbonaceous particulates from the trap and an unspecified reduction from the afterburner, which is taken to be an additional 5 percent; and a 4 percentage point rise in the portion of sulfur emitted as sulfates, caused by oxidation of SO_2 in the afterburner.

Low-Aromatic Fuel and Particulate Traps

This scenario combines the extra cost of low-aromatic fuel with the extra vehicle costs and fuel economy penalty of particulate traps. Weaver et al.'s estimate of a 95 percent reduction in carbonaceous particulates is used.

Methanol

In this scenario, use of methanol fuel in buses is made possible either by retrofitting during engine overhaul or by purchasing new buses designed for methanol. The extra cost for a new bus has been estimated at $6,000 to $7,000 by General Motors, assuming regular production (*19*, p. 125). Of course, further refinement of the technology may reduce this differential. Weaver et al.'s "optimistic" estimate of $5,200 is used here.

The effects on engine life, routine maintenance, and frequency of engine overhaul are not yet known because of the brevity of field tests of methanol-powered buses. However, there is good reason to fear that methanol's corrosiveness will cause at least as much piston wear and degradation of lubricating oil as does current high-sulfur fuel. This is what Weaver et al. adopt as their optimistic case; with the assumptions outlined in the baseline scenario, this adds $582 per year to the annualized cost of upkeep.

Weaver et al.'s "optimistic" fuel economy of 1.81 mpg for methanol is adopted. Because methanol's energy content is about 45 percent that of diesel fuel, this is equivalent to assuming that a methanol engine is about 7 percent more efficient than a diesel engine—a figure probably at the optimistic end of the range of reasonable claims. Weaver et al.'s optimistic estimate of a 95 percent reduction in carbonaceous particulates is adopted; sulfur oxides are entirely eliminated.

Fuel Prices

The comparisons to be made here are quite sensitive to the price differential between diesel and methanol fuel. Because world markets are in flux, this differential is quite uncertain and its effects on the cost-effectiveness comparisons are explored later. In this section, however, it is useful to use a single price for each scenario.

The price of No. 2 diesel fuel delivered directly by refiners to large end users has varied widely; it ranged between 40 and 86 cents per gallon in 1985–1987 and was in the neighborhood of 55 cents for most of 1987 (*20*, Table 9.7). The future price will probably show a long-term upward trend as petroleum becomes scarcer. Hence a reasonable price for scenarios with 12-year time horizons is somewhat above the midpoint of the 40 to 86 cent range. The figure of 75 cents plus 3 cents for desulfurization is used.

The market for methanol is even more uncertain. The industry is currently depressed, with a lot of excess capacity. Chemical-grade methanol has recently been purchased for California fleets at delivered prices of from 55 to 60 cents per gallon. A significant increase in demand would help relieve the excess capacity and could force the market up a rising short-run supply curve; along with a general upward trend in world energy prices, this would tend to raise the price of methanol. On the other hand, economies of scale in transportation (which accounts for a substantial portion of the delivered price) and the marketing of a lower-purity fuel-grade product would have the opposite effect. Hence, for the optimistic scenario, a price equal to the lower end of the recent range, 55 cents per gallon, is adopted. Note that when energy content is corrected for, this is $1.22 for the amount of energy contained in 1 gal of diesel fuel; hence the price differential assumed here is $1.22 – $0.78 = $0.44 per diesel-equivalent gallon.

RESULTS

Cost-Effectiveness

Table 3 gives the extra cost, compared with the baseline scenario, of each of the four control strategies under the previously discussed assumptions. It also gives, for each of the three alternate effectiveness measures, the percentage reduction in that measure and the cost per unit of reduction, labeled "cost-effectiveness." Recall that, in each index, a change of one unit produces pollution damage equivalent to one kilogram of particulates; hence the indices may be thought of as being in units of "particulate-equivalent kilograms."

These comparisons verify at least two of Weaver et al.'s findings. First, lowering the aromatic content of fuel is the most cost-effective way to achieve relatively small pollution reductions, even starting with low-sulfur fuel as a baseline. This is true for all three measures, despite the pessimistic assumptions about the cost of reducing aromatics. However, this strategy does not achieve a very high degree of control, especially when sulfur oxides are given high weight.

Second, particulate traps achieve pollution reductions at lower unit cost than does methanol. Again, this is true using any of the three measures. Using Weaver et al.'s total-particulates measure, for example, particulate traps cost $3.63 per kilogram removed, whereas methanol conversion costs nearly $20. By way of comparison, the California Air Resources Board estimates the cost of reducing emissions of fine particulates from industrial boilers and oil-fired utility boilers at from $1.59 to $2.67/kg (*8*, pp. 89–90).

Nevertheless, the use of weights reflecting the damaging potential of sulfur emissions substantially reduces the cost disadvantage of methanol relative to other strategies. For example, the mortality index is reduced at a cost of $3.95/kg by particulate traps or $6.65/kg by methanol.

Incremental Cost-Effectiveness

No matter which effectiveness measure is used, control stringency and cost-effectiveness both increase from left to right in Table 3. To determine whether the more stringent strategies are justified, the incremental cost of achieving a higher degree of stringency must be examined and compared with the social benefit of further control or with the cost of achieving the same reduction in other ways.

The rows labeled "incremental cost-effectiveness" show, for each strategy, the per unit cost of reducing an emissions index below its value for the next most stringent strategy. These figures show the classic rising marginal control cost presented in the standard economic theory of pollution control (*21*, p. 89). There is one exception: using the mortality index, the per unit incremental cost of adding fuel modification to a particulate trap strategy is higher than that of going to methanol (which is $7.53/kg relative to particulate traps alone, not shown in the table).

TABLE 3 RESULTS OF THREE COST-EFFECTIVENESS MEASURES

	Fuel Modification	Particulate Traps	Fuel Modification and Particulate Traps	Methanol
Cost increase per bus ($/yr)	98	674	776	4,638
Total particulates				
Emissions reduction (%)	25.7	76.7	80.9	95.7
Cost-effectiveness ($/kg)	1.58	3.63	3.95	19.98
Incremental cost-effectiveness ($/kg)	1.58	4.65	9.79	107.70
Severity index				
Emissions reduction (%)	18.9	55.4	58.5	96.9
Cost-effectiveness[a]	1.58	3.69	4.02	14.51
Incremental cost-effectiveness[a]	1.58	4.77	9.79	30.53
Mortality index				
Emissions reduction (%)	8.8	24.1	25.6	98.5
Cost-effectiveness[a]	1.58	3.95	4.28	6.65
Incremental cost-effectiveness[a]	1.58	5.30	9.79	7.49
Expected mortality reduction (deaths/yr)	1.28	3.51		14.33
Incremental cost-effectiveness ($/$10^{-6}$ death)	0.34	1.14		1.62

[a] Cost-effectiveness is expressed in dollars per unit reduction in the index [i.e., in dollars per reduction in pollution that is equivalent (as measured by that index) to 1 kg of particulates].

Using total particulates or the severity index as measures, the additional reduction involved in going from particulate traps (with or without low-aromatic fuel) to methanol comes at a markedly higher cost than previous reductions. With the mortality index, however, the figures exhibit a modest upward progression from fuel modification to particulate traps to methanol. The incremental cost of reducing the mortality index from 76 percent of the baseline value to 1.5 percent of the baseline value by means of methanol conversion is about $7.50/kg, only $2.20 more than the incremental cost of particulate traps themselves.

Cost-Effectiveness of Mortality Reduction

Because the mortality index is derived from estimates of reduced mortality, its results can be restated directly in terms of reduced risk of death to residents of the air basin. Multiplying Equation 12 by the Los Angeles air basin's annual mortality rate of 8,025 per million, and by its population of 10.62 million, gives the change in expected annual deaths due to a unit change in the index. The result, 4.64×10^{-6}, is used to compute the last two rows of Table 3. (Because the combination of particulate traps and fuel modification does not appear promising using this index, it is omitted as a control strategy in these two rows.) The reduction in expected mortality from controlling a single bus is multiplied by 4,432, the number of buses operating (*16*), in order to express it as the reduction in expected annual deaths in the air basin. For example, converting the entire fleet to methanol would reduce deaths in the basin by an expected 14.33 deaths per year.

These numbers make it possible to assess the value that would have to be placed on a small reduction (Δp) in an average person's annual risk of dying in order to justify each increasing degree of control stringency for transit buses. This value, divided by Δp, is called the "value of life," somewhat misleadingly because it is not the amount that a person would pay to avoid certain death (*1*, *22*). Freeman (*23*, p. 39) calls it the "value of statistical life." The data in Table 3 imply that fuel modification is worthwhile if the value of statistical life is between $340,000 and $1.14 million; that particulate traps are warranted if the value of life is between $1.14 million and $1.62 million; and that methanol conversion is warranted at values above that.

By way of comparison, recent studies of labor markets carefully reviewed by Kahn (*24*) suggest that workers in the United States are willing to forgo about $800 per year in order to reduce their risk of fatal injury by 1 in 10,000 per year. This implies a value of statistical life of $8 million. This value of statistical life would amply justify the most stringent control strategy considered here, namely methanol. Another way to view this number is to multiply it by 4.64×10^{-6}, the estimate derived of change in expected deaths per kilogram of particulates removed, to obtain a social value of particulate reduction of $37/kg. The corresponding value for SO_x is $630/kg.

At the more conservative $2 million value of statistical life recommended by Viscusi (*25*, p. 106), methanol is still justified if the estimated costs and mortality reductions are correct. It must be remembered, moreover, that these figures include only particulates and SO_x; that they include mortality but not sickness, material damage, impaired visibility, or other adverse effects; and that they ignore the higher population exposures caused by transit buses' proximity to crowds of people. Hence the overall effectiveness of the control strategies may be substantially higher than indicated here.

Effect of Methanol-Diesel Price Differential

The cost of the methanol strategy presented here is dominated by its higher fuel cost. At the prices assumed, methanol costs 56 percent more than diesel for the same amount of energy. Even with a more efficient engine, this leads to an extra fuel cost of $3,382 per year per bus, nearly three times as much as the annualized extra vehicle cost. Hence, any comparison of strategies is sensitive to fuel prices, which are very uncertain.

Table 4 gives just the comparison of particulate traps and methanol, but with the methanol-diesel price differential ranging from zero to $1.11 per amount of energy contained in a

TABLE 4 EFFECTS OF VARYING METHANOL PRICE

	Particulate Traps	Methanol		
Methanol price ($/gal)		0.35	0.55	0.85
Methanol-diesel price differential ($/diesel-equiv gal)		0.00	0.44	1.11
Cost-effectiveness ($/kg)				
Total particulates	3.63	3.74	19.98	44.33
Severity index[a]	3.69	2.72	14.51	32.20
Mortality index[a]	3.95	1.25	6.65	14.77

[a]Cost-effectiveness is expressed in dollars per unit reduction in the index [i.e., in dollars per reduction in pollution that is equivalent (as measured by that index) to 1 kg particulates].

gallon of diesel fuel. A zero price differential could occur, for example, if methanol could be made from coal at 71 cents per gallon as estimated by Gray and Alson (*19*, p. 27) and if diesel fuel prices were to rise to $1.29/gal, about 30 percent above their 1981 level.

If the energy-equivalent price differential were to fall to zero, particulate traps would become a distinctly less desirable strategy because methanol conversion would equal or dominate it on all three effectiveness measures. Even at the highest methanol price shown, methanol's cost per unit reduction in the mortality index is a moderate $15/kg, well below the estimated social value of $37. (Methanol's incremental cost-effectiveness relative to particulate traps, not included in the table, is $18/kg at that price.) Hence a strong case can be made for methanol even at this substantially higher price if mortality reduction is believed to be worth the amount suggested by the preceding discussion.

Low-Sulfur Baseline

The same methodology can be used to check the internal consistency of the argument that low-sulfur fuel is a sensible baseline scenario. As discussed earlier, a pessimistic estimate of the cost of reducing sulfur content from the current national average of 0.29 percent (2, p. 232) to 0.05 percent is only 3 cents per gallon. Making no allowances for offsetting savings in maintenance or engine life, this strategy still costs only $269 per year per bus; it reduces annual emissions of SO_4 and SO_2 by 4.3 and 136.9 kg per bus. This produces very favorable cost-effectiveness values: $1.59 for total particulates, $0.46 for the severity index, and an astonishing $0.11 for the mortality index. The latter implies a cost of only $24,000 per statistical life "saved." Even using the total-particulate measure, which assigns no more damage to sulfates than to any other particulate matter, low-sulfur fuel has a cost-effectiveness as good as that of any of the strategies considered in the rest of this paper, and better than particulate traps or methanol.

There can be little doubt that reducing the sulfur content of diesel fuel, at least to 0.05 percent, is a sound first step for control of particulates and sulfur compounds. The case is so strong as to immediately suggest the need to carefully estimate the cost of reducing it even further. Such a strategy might turn out to be more cost-effective than any of the strategies considered here. And as noted earlier, it has the additional advantages of simplicity, ease of introduction, and applicability to existing vehicles.

CONCLUSION

The comparison of strategies for reducing diesel emissions depends critically on the weight placed on sulfur oxides relative to carbonaceous particulates. If account is taken of particulates only, even including those produced indirectly in the atmosphere from gaseous emissions, methanol appears a far more costly strategy than either low-aromatic fuel or particulate traps. No seriously proposed estimate of benefits would justify the incremental cost of $108/kg entailed in going from particulate traps to methanol. Only if methanol prices drop nearly to par with those of diesel fuel would particulate reduction alone justify a methanol strategy, assuming a particulate trap strategy is feasible.

If sulfur is taken into account, however, the picture changes. The incremental cost of using methanol to reduce noxious emissions by the equivalent of 1 kg of particulates is either $30.50 or $7.50, depending on which of two estimates of sulfur's noxiousness is believed. The latter is well within the range that could justify a methanol strategy. Furthermore, if methanol's price were to drop so that it was the same as diesel's on an energy-equivalent basis, its cost-effectiveness would become more favorable than that of particulate traps using either measure, and a higher degree of control would be achieved as well.

Lowering the aromatic content of diesel fuel has promise for achieving modest reductions in particulates. This is especially important because of the possibility of immediate application to the entire vehicle fleet, without waiting for old vehicles to be replaced, and because it can also be applied to trucks without disrupting fueling arrangements or incurring administrative costs. However, the estimates used here of the cost and effectiveness of lowering aromatic content need confirmation. It would also be worthwhile to investigate the cost of reducing sulfur content even below Southern California's limit of 0.05 percent.

These results give considerable support to both particulate traps and methanol as possible strategies. The promise of each warrants further development of the hardware and further refinements in assessing the benefits. The wide range of possible outcomes in such an assessment supports the adoption of emissions regulations that are flexible enough to permit either strategy to emerge as the "winner" as more evidence accumulates.

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Effects of Applying Emissions Averaging, Trading, and Banking to Transit Buses

BARRY GALEF

In the interests of reducing the burden on heavy-duty vehicle manufacturers imposed by air pollution standards yet preserving the improvements in air quality made possible by them, the Environmental Protection Agency is modifying its traditional method of imposing the emissions standards to allow engines to meet the standards on average instead of individually. In this paper the concept of programs with this kind of flexibility is introduced, and how their value depends on differences in the marginal costs of emissions reduction across the set of engines whose emissions may be averaged is demonstrated. These concepts are applied to the problems facing manufacturers of transit bus engines in meeting the strict standards proposed for 1991. It is concluded that flexible regulatory approaches can make a significant contribution to helping bus engines meet the standard, partly by encouraging the introduction of methanol-fueled and other innovative engines. However, the advantages of the flexible regulatory programs could be offset by unintended increases in emissions. The problem of estimating the total reduction in costs resulting from increasing the flexibility of the regulations can be solved using standard techniques of constrained optimization and incremental emissions cost functions derived from engineering analyses. Sufficiently flexible regulatory programs are shown to have the potential to save as much as $174 million per year without affecting air quality. Savings will be radically lower, however, if strict limitations are imposed on the types of engines included in the programs.

The intent of this paper is to examine the potential effects of including urban buses in a regulatory program allowing emissions averaging, trading, and banking. It is based on work done at the request of, and with funding from, the Environmental Protection Agency's (EPA's) Office of Policy Analysis and Office of Mobile Sources in 1986 (*1*). The purpose of that work was to estimate the effects on the costs of meeting the 1991 emissions standards for heavy-duty (HD) vehicles if the EPA were to allow the averaging, trading, and banking of emissions ("flexible regulations"). That work applied only tangentially to transit buses because the EPA was not considering including buses in these programs. That position has changed; thus, after an introduction to the concepts of averaging, trading, and banking, the implications of these alternative programs for meeting the 1991 standards for transit buses are discussed. The discussion shows that averaging, trading, and banking could be valuable in helping transit buses meet the standards—but possibly at some cost in terms of air quality.

The discussion is followed by a formal demonstration of the way in which emissions trading programs allow the reduction of emissions control costs for given levels of emissions and some discussion of the potential magnitude of the savings for variations of the programs.

HOW FLEXIBLE EMISSIONS PROGRAMS CAN RESULT IN COST SAVINGS

The EPA will be requiring tight emissions standards for heavy-duty vehicles in 1991: 0.25 grams per brake-horsepower-hour (g/bhp-hr) (0.1 g/bhp-hr for urban buses) for particulate matter (PM), and 5.0 g/bhp-hr for oxides of nitrogen (NO_x) (regulations promulgated March 15, 1985). These standards will force manufacturers to aim at even lower target levels to allow for deterioration of emissions control performance and for engine-to-engine variability. These standards would be troublesome to meet individually; together, the difficulties are compounded because some strategies for reducing NO_x can increase PM emissions.

Compliance costs, taking increases in fuel consumption into account, are estimated to range up to several thousand dollars per vehicle (*1*, Exhibit V-7, p. 36). These costs could be much higher for some vehicles than for others. (See section entitled Estimation Procedures for details.)

In the interests of reducing the burden imposed by these regulations while preserving the improvements in air quality made possible by them, the EPA is modifying its traditional method of imposing emissions standards to allow greater flexibility. For most emissions regulations, the EPA has applied the standards to each individual engine or vehicle, requiring every engine to be at or below the numerical standards. Because the ease with which the standards can be met varies widely for different types of engines, the burden of a given set of standards will fall unevenly across engines and manufacturers. Allowing some engines to emit at levels greater than the standards, on the condition that their excess emissions are balanced by extra emissions reductions by other engines, can help reduce the burden of the regulations while maintaining the desired level of air quality. For example, a naturally aspirated engine would be allowed to emit an extra ton of NO_x during its life if a turbocharged engine emitted 1 ton less than the standard required.

The concept of allowing one engine's excess emissions reductions to cancel out the excess emissions of another can be implemented in a number of ways. A basic choice to be made in designing a program of this type is the definition of which groups of engines may be included within the same set for purposes of emissions averaging. In a restrictive program, a given engine's emissions could be averaged only with other

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engines in the same family (or model), made by the same firm, in the same year, and using the same fuel. Less restrictive variants might allow averaging with other engine families in the same size class, with all engines using the same fuel and built by the same manufacturer, with all engines using the same fuel built by any manufacturer ("trading"), with all engines of any sort built in the same year, or even with engines built in later years (often referred to as "emissions banking").

Emissions averaging allows manufacturers to save money in two ways, which can be referred to as "windfall" savings and "efficiency" savings. Windfall savings arise when firms are given transferable credits for emissions reductions that would have occurred in any case. The firms can then save money by allowing emissions to increase through the use of the credits. Efficiency savings, in contrast, arise when the same emissions reduction comes about at reduced costs as a result of more rational allocation of emissions control efforts.

As an example of windfall savings, the standards could lead to control of PM emissions at a level below that required. Because of the on-off character of PM traps, all engines might be fitted with traps that pull emissions below the PM standard. Emissions averaging could eliminate this overcontrol. Firms could remove traps from enough vehicles to hit the target without overshooting, using credits generated by the engines with traps to compensate for the excess emissions of the engines without traps.

An example of an efficiency savings arises if an extra ton of emissions can be removed more cheaply from some engines than from others. In this case, reallocating emissions control efforts will increase efficiency. Every ton of emissions "shifted" (through changes in the allocation of emissions control effort) from the high-marginal-cost engine to the low-marginal-cost engine results in savings equal to the difference in marginal costs per ton removed.

INCREASING EFFICIENCY THROUGH FIRM-WIDE EMISSIONS AVERAGING

The source of efficiency savings is shown in Figures 1 and 2. Figure 1 shows the marginal costs per ton removed at different NO_x levels for two engines. (The concepts shown also apply, with some changes, to PM control.) Engine A is expensive to control "at the margin" in that each extra ton removed below 5.0 g/bhp-hr costs $4,000. Engine B is cheaper to control at the margin, costing only $2,000 per extra ton at 5.0 g/bhp-hr. For each engine, these marginal costs per ton rise as emissions are reduced because more and more costly methods are used to eliminate portions of the last few units of emissions.

Under traditional regulatory regimes, each engine would have to meet 5.0 g/bhp-hr exactly (ignoring the need to allow for deterioration and variability). Under averaging, Engine B could be overcontrolled and Engine A could be undercontrolled at considerable aggregate savings. This reallocation of emissions control effort is shown in Figure 2. Engine A now emits 5.5 g/bhp-hr; Engine B now emits 4.6 g/bhp-hr; and these changes are assumed to balance each other in terms of total emissions (because of differences in brake-horsepower-hours per truck and sales volumes). The marginal costs of control are now equal, at about $3,000 per ton, and the total savings are proportional to the difference between the cost decrease for Engine A (the large trapezoid) and the cost increase for Engine B (the small trapezoid).

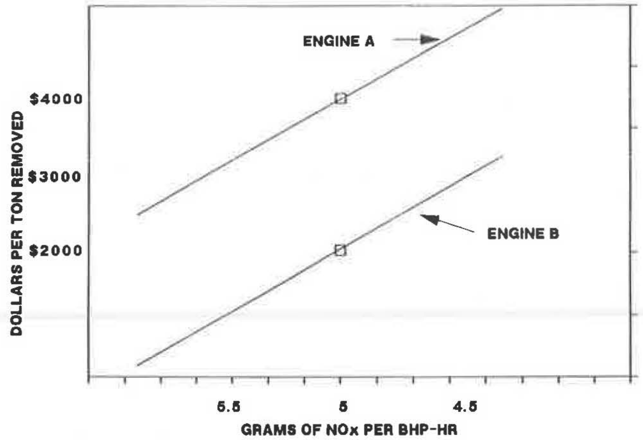

FIGURE 1 Schematic illustration of marginal cost per ton of NO_x removed.

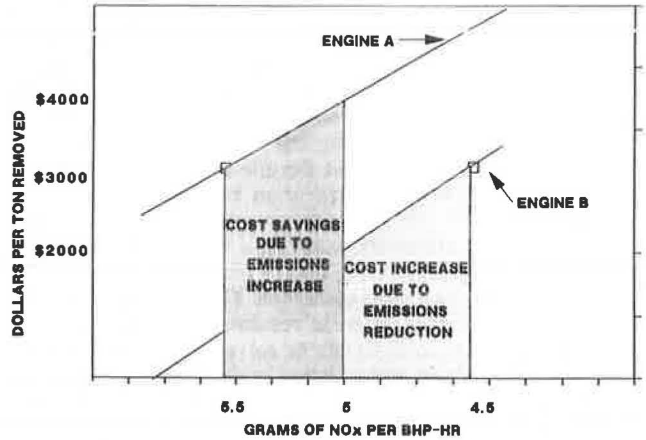

FIGURE 2 Changes in costs under averaging.

INCREASING EFFICIENCY THROUGH INDUSTRY-WIDE EMISSIONS TRADING

The EPA also plans to permit averaging across the entire industry, awarding credits to manufacturers whose engines more than meet the standards overall and letting them trade the credits to firms whose engines do not meet the standards. This type of program is known as emissions "trading."

Trading can save money in the same way that reallocating emissions reductions can save money for one manufacturer, as long as the marginal costs of control at the standard differ from one manufacturer to the other. The simplest case with which to illustrate these savings is if each firm sells only one type of engine. Then, savings arise in the way shown in Figure 2 except that Firm B's increased costs will have to be compensated by selling emissions reduction credits to Firm A.

Figure 3 shows trading between the builders of Engine A and Engine B. The levels of emissions each reaches are the same as in Figure 2, but Firm B is compensated for reducing its emissions. Ideally, the compensation to Firm B is X tons' worth of credits at the marginal cost of $3,000 per ton. (This price is ideal because it results in the greatest total savings. In the real

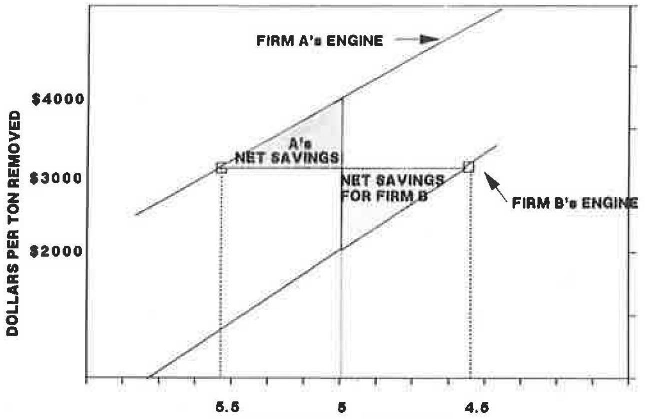

FIGURE 3 Savings under trading.

world, prices of credits could be set in various ways, and prices above or below marginal costs of any market participants would lead to lower total savings and a different allocation of the savings. If the market for credits were sufficiently broad to approximate the operation of a competitive market, however, economic theory predicts that credit prices would tend toward their ideal level.) These credits cost less than X × $3,000 for Firm B to produce, but they are worth more than X × $3,000 to Firm A. This leads to substantial savings for each firm, as indicated by the triangles shown in Figure 3.

An examination of Figure 3 reveals that the total savings are much greater for curves that are far apart—that is, for engines with very different emissions control properties. This becomes particularly important when the effects of flexible regulations on the potential introduction of new transit bus engine technologies, including methanol- and compressed natural gas–fueled engines, are considered.

EMISSIONS BANKING

Emissions banking is yet another flexible program in which credits for engines of one model year are traded to engines of other model years. Savings can arise under banking just as they can under averaging or trading, when engines with low marginal control costs are overcontrolled to allow engines with high marginal control costs to be undercontrolled. These programs are most likely to succeed when standards are expected to be tightened in the future. In that case, firms can overcontrol before standards are tightened, building up credits that ease the transition to the tighter standards.

CALCULATING THE SAVINGS

A procedure for making realistic estimates of the savings that are possible from averaging, trading, and banking is outlined in the section entitled Estimation Procedures. A key part of this procedure is the identification of the shape and position of the marginal emissions control cost curves for each type of engine analyzed. For the work on which this paper was based, the cost curves were based on point estimates of fuel-NO_x and PM-NO_x trade-offs provided by Christopher Weaver of Sierra Research (then of ERC, Inc.), an automotive engineer with extensive experience in emissions control technology. Hyperbolic functions were fit to these point estimates, allowing marginal cost functions to be obtained by differentiation. The marginal functions are shown in Figure 4 for a number of different classes of engines.

The reader will notice that the marginal cost functions for most of the engines (the direct-injection diesels) are not far apart at just under 5.0 g/bhp-hr. This means that the potential savings under an averaging program are quite small for firms selling neither gasoline nor indirect injection (IDI) diesel engines because the marginal cost differences those firms will be able to exploit will be small. Under trading, though, these firms can show substantial savings if they trade with firms selling IDI or gasoline engines. In general, the more unusual an engine is, the greater potential gain it provides under averaging or trading.

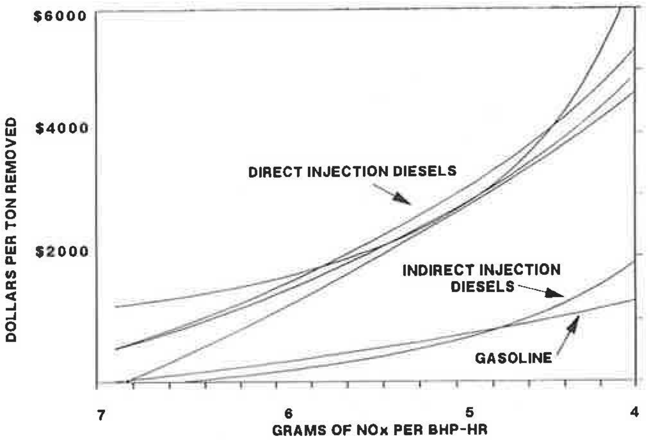

FIGURE 4 Actual marginal cost per ton of NO_x removed (based on data in Tables 2–5 and Figure 5).

ESTIMATED SAVINGS FROM AVERAGING AND TRADING FOR HEAVY-DUTY TRUCKS

Estimates of the cost-saving potential of averaging and trading for heavy-duty trucks showed that averaging within firms could save as much as $230 million per year, an amount equal to almost 4 percent of the total revenues from heavy-duty engine sales (*2*, pp. 6–9). Of this total, approximately $151 million would be attributable to windfall savings associated with removing traps from some engines (thereby allowing an increase in PM emissions over a baseline without averaging), and the other $79 million would be due to increases in the efficiency of meeting given air quality goals. Interfirm trading could allow the saving of as much as an additional $95 million, all of it related to increases in efficiency. Thus total savings could be $325 million, including $174 million in efficiency savings.

The maximum efficiency savings are based on the assumption that averaging and trading would be allowed to operate freely. Only if no constraints were imposed on the types of engines that could be used in emissions trading would averaging and trading lead to the reallocation of control efforts from the types of engine most difficult to control to those least difficult to control. The analysis showed that if the regulations prevented averaging and trading between gasoline and diesel trucks, the efficiency savings would decline by more than 70 percent (to under $50 million from $174 million), because emissions trading could be done only among engines with fairly similar marginal emissions control cost functions. A proposed restriction on trading across truck size classes would prevent most emissions trades between indirect and direct injection diesels. This would eliminate almost all efficiency savings, cutting them to below \$0.1 million per year. These findings underscore the contribution of disparate engine types to the cost savings potential of averaging and trading programs.

IMPLICATIONS OF AVERAGING, TRADING, AND BANKING PROGRAMS FOR TRANSIT BUSES

The EPA is now considering the extension of flexible emissions regulations to transit bus engines. This may affect both the cost and the difficulty of meeting the standards for transit buses, as well as the quality of air in cities.

Making reliable predictions of the effects on transit buses of flexible emissions regulations involves engineering analyses beyond the scope of this paper. The engineering issues actually become more difficult when averaging, banking, and trading are allowed because there are more degrees of freedom: it is necessary to know not only what the costs would be of meeting a given standard with given technologies, but also how much more it would cost to overshoot or undershoot the standard. Still, some possibly useful observations can be made.

Even if all engines used in buses were quite similar,

- If a trap would let one bus get significantly below the standard, averaging would allow manufacturers to reduce the number of traps used, leading to considerable savings. These are the windfall type of savings.
- Second, traps reduce one of the disadvantages of tighter NO_x control (by capturing most of the added engine-out PM emissions). Firms would therefore have the incentive to overcontrol engines with traps for NO_x, thereby generating valuable NO_x reduction credits.
- Third, buses could be overcontrolled for NO_x and PM in the years before 1991, building up banked credits. These credits would allow buses in the 1991–1993 period to exceed the standards, at significant cost savings.

Even greater benefits, though, could come with the introduction of different engine types, assuming (as has been proposed) that "cross-fuel" trading and averaging would be allowed:

- Sales of a small number of low-emission methanol engines could make it easier for diesels to meet the standards by selling diesels enough PM credits to let them avoid using traps or catalysts, or by selling enough NO_x credits to lower their engine-out PM levels. The introduction of methanol engines would be encouraged by allowing them to gain from selling the credits that they might generate in any case. Small, in his paper in this Record, when analyzing the relative costs and values of different PM reduction techniques, for example, did not consider the value of NO_x credits that methanol engines might be able to generate—for a vehicle exerting 500,000 bhp-hr over its life, each g/bhp-hr would be worth half a metric ton of emissions reduction—or about \$1,500 (Figure 4).
- Even gasoline engines could become attractive, because PM and NO_x credits could be sold. These engines could generate enough credits for manufacturers to allow them to be sold at deep discounts, offsetting their poorer fuel efficiency and durability.
- Compressed natural gas engines would also be encouraged and would help meet the standard.
- Additional advantages would arise if NO_x credits purchased from truck manufacturers could be used for bus engines. Buses are not permitted to trade with trucks because of the need to keep emissions from rising in cities where air quality is lower and there is greater exposure. (With unlimited averaging and trading, PM emissions credits would be generated outside cities and used inside. The tighter standard for buses would be rendered almost meaningless.) However, Santini and Schiavone, in their paper in this Record, point out that avoiding increased NO_x emissions in cities is much less important than avoiding increased PM emissions. Thus it might be acceptable to allow NO_x credits to be traded between buses and trucks. It could be beneficial for bus manufacturers to purchase NO_x credits and increase the NO_x levels of buses somewhat while meeting the PM standards more easily. (It might be even better to let bus manufacturers trade PM credits for NO_x credits—resulting in a pure economic and air quality gain. This has not, however, been discussed by the EPA.)

IMPLICATIONS FOR AIR QUALITY

The advantages of flexible regulations will not come entirely without cost, however; air quality goals could be compromised to some degree by allowing manufacturers of buses to average and trade. Some of the ways air quality could be affected follow:

- There will be a net increase in emissions to whatever extent the flexible regulatory programs generate windfall savings and allow firms to reduce the extent of overcontrol. Fewer traps and excess reductions from other types of engines (gasoline, methanol, and CNG) that will be cashed in for credits instead of going to cleaner air are both potential sources of this problem.
- Bus purchasers will naturally exploit differences in their usage patterns. Purchasers intending to use a bus intensively will prefer to buy engines with higher emissions if they get better mileage as a result. In contrast, purchasers with less intensive applications, who are less sensitive to fuel consumption costs, will be willing to accept lower-emitting, higher-fuel-consumption engines if they are given a discount by the manufacturer. If the regulations are set up to assume that both types of buses will be used with the same intensity, then total emissions will go up: 200,000 mi of use of a bus that emits 1 g/bhp-hr below the standard will not make up for 400,000 mi of use of a bus that emits 1 g/bhp-hr above the standard.
- Pollutants not included in the averaging and trading system may grow in importance. These pollutants, including aldehydes from methanol engines and carbon monoxide and hydrocarbons from the largest gasoline engines, are either unregulated or underregulated at present, partly because the types of engines that emit these substances are not sold in large enough numbers to warrant regulation. If manufacturers are given incentives to produce these engines, however, their uncontrolled or undercontrolled emissions could become more serious.

CONCLUSION

It is difficult to predict how much could be saved through the application of flexible emissions regulations to transit bus engines. If predictions for heavy-duty trucks could be assumed to be applicable to transit buses, the predicted savings might be in the range of several percent of the value of the engines themselves. Because of differences in the PM standard for transit buses and trucks, and because the transit bus engine market differs substantially in size and structure from the truck engine market, the truck engine results cannot be expected to be a reliable guide to possible savings for bus engines. The general results, however, especially the prediction that quite significant savings can arise if different engine types are included within an averaging or trading program, suggest significant cost-saving potential and strong incentives for introducing new types of engines.

In addition to contributing to substantial cost savings, implementing a relatively unrestricted program of emissions averaging, trading, and banking for transit buses could be the deciding factor in helping engine manufacturers meet the 1991 standards for transit buses. To avoid undercutting the social benefits to be derived from these programs, however, regulators must be sensitive to the tendency for flexible regulations to lead to increases in emissions.

ESTIMATION PROCEDURES

In this section the introductory discussion of the potential savings from averaging and trading is placed in a more rigorous framework, and the methods used to generate the estimates of cost savings are documented. The intention is to demonstrate that flexible regulations amount to relaxing some of the constraints on the industry's ability to meet given levels of air quality at minimum cost. It is also demonstrated that the savings offered by flexible programs can be analyzed by measuring the difference between costs that have been minimized under differing constraints.

To simplify the discussion, and because the analytical issues are not changed appreciably by limitations in the scope of flexibility allowed, only two cases are considered and compared:

- Averaging, in which emissions from any heavy-duty engine may be averaged with emissions from any engine produced in the same year by the same firm, and
- Trading, in which emissions from any heavy-duty engine may be averaged with emissions from any engine produced in the same year by any firm.

Other variants, including cases in which additional restrictions are imposed on averaging and trading and cases in which intertemporal averaging (banking) is allowed, are discussed only briefly.

Given data relating emissions characteristics to costs for various types of engines, and information about market shares of the different engine types by firm, estimates can be made of the potential resource savings provided by allowing trading in addition to averaging. In the sections that follow the types of engines analyzed, the firms examined, and the general ways in which costs are related to emissions of NO_x and PM are introduced. The conditions necessary for an efficient allocation of emissions reduction activities are discussed, and how the gains attributable to allowing trading in addition to averaging can be derived is demonstrated.

After the theoretical analysis, the actual cost functions used in the analysis are presented. The solution method used is then described, and some results of the analysis of cost savings are presented.

Elements of the Analysis

The analysis of resource savings is based on differences among eight types of heavy-duty engines, nineteen engine manufacturers, and two pollutants.

Engine Types

On the basis of an engineering analysis done for the EPA by Christopher Weaver, the heavy-duty engine industry has been divided into eight types or classes of engines with technically distinct emissions characteristics: light heavy-duty gasoline engines (LHDGE), medium heavy-duty gasoline engines (MHDGE), light heavy-duty diesel engines employing indirect fuel injection (LHDDE-IDI), light heavy-duty diesel engines employing direct fuel injection (LHDDE-DI), naturally aspirated medium heavy-duty diesel engines (MHDDE-NA), turbocharged (or "premium") medium heavy-duty diesel engines (MHDDE-TC), heavy-duty diesel engines intended for line-haul applications (HHDDE-LH), and heavy-duty diesel engines for vocational or non-line-haul applications (HHDDE-NLH).

The greatest distinctions among these types are between the two gasoline-fueled types (LHDGE and MHDGE) and the diesels. Although gasoline-fueled engines are less efficient and durable, they emit virtually no particulate matter and are simpler to control for NO_x emissions. Similarly, the LHDDE-IDI is less efficient and less durable but lower in NO_x emissions than the other diesels. Other distinctions among the classes are smaller in magnitude, or reflect differences in intensity and duration of service more than differences in emissions.

The quantitative analysis requires assumptions about a number of engine cost and usage characteristics (Table 1).

Firms

Nineteen domestic and foreign engine manufacturing firms were included in the analysis. They are distinguished analytically not by differences in their abilities to control emissions from a given type of engine but solely by their patterns of market shares of the types of engines. Although it is likely that some differences will exist in the costs related to emissions reduction among firms for the same engine types, there was no solid engineering basis on which to predict these differences for the future period covered by the analysis. Interfirm differences for given engine types would tend to increase the potential resource savings for trading compared with averaging. Table 2 gives the market shares assumed for each of the nineteen numbered firms. (Projected annual sales for each engine type are given in Table 1.) The firms vary widely not only in overall shares but in their degree of specialization in different types of engines. It is this latter variability that provides the basis for savings under emissions trading.

TABLE 1 DATA BY ENGINE TYPE (*1*)

Engine Type	bhp-hr per Useful Life of Truck (*Be*)	Annual Sales	Percentage Efficiency of Traps ($Etrap = 1 - q$)	Capital and Maintenance Cost per Trap ($)	Increase in Fuel Use Caused by Trap (%)	Dollars per 1% Increase in Fuel Consumption (*FCe*)	Total Cost per Trap ($)
LHDGE	78,540	361,907				51	
MHDGE	164,450	63,866				105	
LHDDE-IDI	86,460	178,801	80	370	1.25	54	438
LHDDE-DI	86,460	504	80	370	1.25	54	438
MHDDE-NA	338,365	44,839	80	448	1.25	259	772
MHDDE-TC	364,820	58,301	80	448	1.25	259	772
HHDDE-LH	788,800	114,468	80	574	1.25	705	1,455
HHDDE-NLH	788,800	30,627	80	574	1.25	705	1,455

TABLE 2 SALES SHARE BY FIRM NUMBER AND ENGINE TYPE

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
LHDGE	8.2%	26.8%	0.0%	0.0%	0.0%	0.0%	65.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MHDGE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LHDDE-IDI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	35.5%	63.6%	0.0%	0.0%	0.0%	0.5%	0.0%	0.3%	0.0%	0.1%	0.0%	0.0%	0.0%
LHDDE-DI	0.0%	0.0%	90.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	9.3%
MHDDE-NA	0.0%	0.0%	0.0%	37.3%	0.4%	0.0%	27.1%	32.3%	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	1.4%	0.0%	0.0%
MHDDE-TC	0.0%	3.6%	0.6%	14.7%	5.2%	0.2%	17.4%	44.3%	0.4%	0.5%	0.0%	0.0%	0.5%	0.3%	0.5%	0.1%	1.1%	3.0%	7.5%
HHDDE-LH	0.0%	0.0%	60.2%	12.4%	0.1%	0.0%	7.2%	0.0%	0.0%	0.0%	19.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%
HHDDE-NLH	0.0%	0.0%	35.4%	18.2%	0.0%	0.5%	34.7%	0.0%	0.0%	0.0%	10.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	0.0%

NOTE: Based on certification data. Firms are identified by number to preserve confidentiality.
SOURCE: Office of Mobile Sources, Environmental Protection Agency.

Pollutants

Two pollutants are considered in the analysis: PM and NO_x. Under the regulations, manufacturers are expected to try to limit emissions of PM to 0.22 g/bhp-hr and of NO_x to 4.2 g/bhp-hr. (It is unclear whether gasoline-fueled engines, which emit virtually no PM, will be included in PM averaging along with diesel engines. For the purposes of this analysis, they are assumed to be excluded from PM averaging and required to have zero PM emissions.)

The costs of controlling these pollutants were modeled in a somewhat simplified way, designed to capture only the most important relationships among resource costs and the pollutants. Reductions in NO_x emissions (beyond those achievable by altering the basic design of the engines and of the add-on devices, such as turbochargers, and the use of electronic controls) are assumed to be obtained by changing engine operating parameters—notably fuel injection timing. These changes will have adverse effects on fuel consumption that become progressively more severe at low NO_x emissions levels. These changes will also worsen the problem of PM emissions; again, engineering analysis predicts that the PM-NO_x trade-off worsens at lower levels of NO_x emissions.

Given PM emissions levels that have been reduced as much as possible by changes in engine and turbocharger design and operation, and have been adversely affected by efforts to lower NO_x emissions, it is assumed that PM emissions can be brought down only by the addition of a mufflerlike exhaust filter known as a trap oxidizer (or, simply, a trap). Traps are expensive to manufacture, install, and maintain and increase fuel consumption slightly, but they can reduce the PM emissions from an engine (the "engine-out" emissions) by about 80 percent.

Traps can be put on or removed from any given engine family, or any individual engine within a family, but their efficiency is not considered to be a variable. Thus the addition of a trap to control PM emissions has a binary, on-off character. For every engine sold to meet a moderately tight PM standard, it might be necessary for every engine to be fitted with a trap that pulls emissions down well below the standard. Under averaging schemes, however, traps could be removed from some percentage of engines, allowing the standard to be reached exactly while saving the costs of traps for many of the engines.

Defining the Least-Cost Method of Achieving Given Emissions Standards

Under traditional regulations requiring each individual engine to meet a numerical emissions standard, and given costs per trap and functions relating NO_x levels to changes in fuel costs and engine-out PM emissions, estimating the total cost of imposing the standards can be calculated in a straightforward way. NO_x emissions for each engine are set at the standard (or at a target slightly below the standard to allow a cushion for deterioration and variability), which determines the increase in fuel consumption for that engine. The NO_x emissions level, along with the engine's basic characteristics, determines the engine-out PM level. If this level is above the standard (again, adjusted to provide a cushion), a trap must be fitted, adding to costs by a set amount. Assuming the costs of reduced fuel efficiency can be calculated, applying these procedures to all engines results in estimates of the total resource costs of meeting the standards for each firm and the industry.

Under averaging or trading, finding the lowest total cost for meeting the standards is more complex. The added flexibility of averaging across engines can allow for resource savings but requires that a separate level of emissions be chosen for each distinct engine type while keeping total emissions below the standards.

Choosing a set of values to reduce costs as much as possible while meeting an overall target is a natural application of the techniques of constrained optimization (*3*, pp. 376–382). To apply these techniques, it must be possible to define the independent variables, the objective function, the constraints, and the dependence of the objective function and the constraints on the levels of the independent variables.

The independent variables for a given firm are as follows:

$NOXiet \equiv$ NO$_x$ levels in g/bhp-hr

where

i = one of the 19 firms,
e = one of the eight engine types, and
t = the engine is fitted with a trap;

$NOXien \equiv$ NO$_x$ levels in g/bhp-hr

where n indicates that the engine is not fitted with a trap; and

$TRAPie \equiv$ Percentage of engines of type e sold by firm i that are fitted with traps.

Additional variables needed for the analysis are

$PMiet \equiv$ Engine-out PM emissions in g/bhp-hr for engines of type e sold by firm i and fitted with traps

where

$$PMiet = f(NOXiet),\quad f' < 0,\ \text{and}\quad f'' > 0.$$

$PMien \equiv$ Engine-out PM emissions in g/bhp-hr for engines of type e sold by firm i and not fitted with traps

where

$$PMien = f(NOXien),\quad f' < 0,\ \text{and}\quad f'' > 0.$$

$Etrap \equiv$ Efficiency of traps in reducing engine-out PM emissions

$q = 1 - Etrap \equiv$ Remaining percentage of engine-out PM in exhaust with a trap

$CTRAPe \equiv$ Discounted cost of a trap per vehicle, including initial cost, maintenance cost, and cost of increased fuel use over the life of the vehicle

$NFUELien$ and $NFUELiet \equiv$ Increase in fuel cost per vehicle where $NFUELien,t = f(NOXien,t)$; $f' < 0$; and $f'' > 0$.

$Vie \equiv$ Sales for firm i of type e

For simplicity, sales are assumed to be constant in this analysis. Indeed, however, depending on manufacturers' pricing decisions and purchasers' attitudes, the introduction of flexible emissions regulations could change sales patterns substantially. This issue is of particular importance for new types of engines the potential market penetration of which may be changed radically by the opportunity to trade emissions with other engine types.

$NOXTONSien \equiv$ Tons (metric) of NO$_x$ emitted by a single engine of type e built by firm i, without a trap $= NOXien * Be * 10^{-6}$

where Be is the total bhp-hr exerted by a truck with engine type e over its useful life, and 10^{-6} is the number of metric tons per gram.

$NOXTONSiet \equiv$ Tons of NO$_x$ emitted by a single engine of type e built by firm i, with a trap $= NOXiet * Be * 10^{-6}$

$PMTONSien \equiv$ Tons of PM emitted by a single engine of type e built by firm i, without a trap $= PMien * Be * 10^{-6}$

$PMTONSiet \equiv$ Tons of PM emitted by a single engine of type e built by firm i, with a trap $= PMiet * Be * 10^{-6} * q$

$TPi \equiv$ Total tons of PM emitted by all of firm i's engines

$TNi \equiv$ Total tons of NO$_x$ emitted by all of firm i's engines

For a given firm i with eight types of engines (e = 1 to 8), the objective function can be specified as follows:

$$TCi = \sum_{e=1}^{8} Vie * \{[NFUELien * (1 - TRAPie)] + [(NFUELiet + CTRAPie) * TRAPie]\} \qquad (1)$$

The constraints to be met on emissions, expressed in tons of total emissions, can be defined as follows:

$$Ypmi = \sum_{e=3}^{8} Vie * Spm * Be * 10^{-6} \qquad (2)$$

and

$$Ynoxi = \sum_{e=1}^{8} Vie * Snox * Be * 10^{-6} \qquad (3)$$

where Spm is the PM target for diesels in g/bhp-hr; $Snox$ is the NO$_x$ target in g/bhp-hr; and e = 1 and e = 2 are gasoline-fueled engine types, which are assumed to emit no PM and to be excluded from PM averaging, and e = 3 through e = 8 are diesel engines. Including the gasoline engines in the PM averaging program (as may be the case for transit buses) would, clearly, have the effect of increasing $Ypmi$ and relaxing the PM constraint.

Total PM emissions must be less than or equal to $Ypmi$, and total NO$_x$ emissions must be less than or equal to $Ynoxi$. These constraints can be written as follows:

$$Ypmi \geq TPi = \sum_{e=3}^{8} Vie * [PMTONSien * (1 - TRAPie) + PMTONSiet * TRAPie] \qquad (4)$$

and

$$\mathit{Ynoxi} \geq \mathit{TNi} = \sum_{e=1}^{8} \mathit{Vie} * [\mathit{NOXTONSien} * (1 - \mathit{TRAPie}) + \mathit{NOXTONSiet} * \mathit{TRAPie}] \tag{5}$$

To find the least-cost set of independent variables for firm *i*, the following lagrangian expression is established:

$$\begin{aligned} \pounds = {} & -\mathit{TCI}\ (\mathit{NOXiln} \ldots \mathit{NOXi8n}, \mathit{NOXilt} \ldots \mathit{NOXi8t}, \\ & \mathit{TRAPi3} \ldots \mathit{TRAPi8}) - \lambda \mathit{pi} * [\mathit{Ypmi} - \mathit{TPi} \\ & (\mathit{NOXiln} \ldots \mathit{NOXi8n}, \mathit{NOXilt} \ldots \mathit{NOXi8t}, \\ & \mathit{TRAPi3} \ldots \mathit{TRAPi8})] - \lambda \mathit{ni} * [\mathit{Ynoxi} - \mathit{TNi} \\ & (\mathit{NOXiln} \ldots \mathit{NOXi8n}, \mathit{NOXilt} \ldots \mathit{NOXi8t}, \\ & \mathit{TRAPi3} \ldots \mathit{TRAPi8})] \end{aligned} \tag{6}$$

Changing the sign on the total cost term implies that the expression should be maximized. The determination of the first-order conditions would be as follows, if the variables were unconstrained:

$$\begin{aligned} & 0 = -\mathit{TCi}'_{\mathit{NOXiln}} - \lambda \mathit{pi} * \mathit{TPi}'_{\mathit{NOXiln}} - \lambda \mathit{ni} * \mathit{TNi}'_{\mathit{NOXiln}} \\ & \cdot \\ & \cdot \\ & \cdot \\ & 0 = -\mathit{TCi}'_{\mathit{NOXi8t}} - \lambda \mathit{pi} * \mathit{TPi}'_{\mathit{NOXi8t}} - \lambda \mathit{ni} * \mathit{TNi}'_{\mathit{NOXi8t}} \\ & 0 = -\mathit{TCi}'_{\mathit{TRAPi3}} - \lambda \mathit{pi} * \mathit{TPi}'_{\mathit{TRAPi3}} - \lambda \mathit{ni} * \mathit{TNi}'_{\mathit{TRAPi3}} \\ & \cdot \\ & \cdot \\ & \cdot \\ & 0 = -\mathit{TCi}'_{\mathit{TRAPi8}} - \lambda \mathit{pi} * \mathit{TPi}'_{\mathit{TRAPi8}} - \lambda \mathit{ni} * \mathit{TNi}'_{\mathit{TRAPi8}} \end{aligned} \tag{7}$$

$$\mathit{Ypmi} \geq \mathit{TPi} \tag{8}$$

$$\mathit{Ynoxi} \geq \mathit{TNi} \tag{9}$$

Rearranging yields

$$\lambda \mathit{ni} = (\mathit{TCi}'_{\mathit{NOXien,t}} + \lambda \mathit{pi} * \mathit{TPi}'_{\mathit{NOXien,t}}) \,/\, \mathit{TNi}'_{\mathit{NOXien,t}} \tag{10}$$

$$\lambda \mathit{pi} = (\mathit{TCi}'_{\mathit{TRAPie}} + \lambda \mathit{ni} * \mathit{TNi}'_{\mathit{TRAPie}}) \,/\, \mathit{TPi}'_{\mathit{TRAPie}} \tag{11}$$

This can be simplified for purposes of explanation in two ways. First, $\mathit{TNi}'_{\mathit{NOXien}}$ is a constant, equal to the change in the number of NO_x tons per g/bhp-hr of emissions, and related simply to the number of bhp-hr exerted by all trucks using engines of type *e* sold by firm *i*. Dividing all of the terms on the right side of Equation 10 by this constant yields

$$\lambda \mathit{ni} = \mathit{TCi}'_{\mathit{TNie}} + \lambda \mathit{pi} * \mathit{TPi}'_{\mathit{TNie}} \quad \text{for all } e \tag{12}$$

which implies that the marginal cost per reduced ton of NO_x, plus the shadow price of PM removal times the change in PM per unit of NO_x, should be the same for all engine types.

Second, the effects of a change in *TRAPie* can be examined for cases in which *NOXien* = *NOXiet*; that is, for cases in which the NO_x levels are the same for the same engine with and without traps. If this were the case, changing the percentage of traps used on one type of engine would not change the NO_x emissions levels for that type of engine. Thus, $\mathit{TNi}'_{\mathit{TRAPie}}$ would be zero, and the first-order conditions would then state that

$$\lambda \mathit{pi} = \mathit{TCi}'_{\mathit{TRAPie}} \,/\, \mathit{TPi}'_{\mathit{TRAPie}} \quad \text{for } e = 3\text{–}8 \text{ (i.e., diesels)} \tag{13}$$

implying that the ratio of the added costs per trap to the number of tons of PM that the trap removes should be the same for all diesels.

More realistically, it can be shown that *NOXien* will be greater than *NOXiet*. This is because, if the two values are the same,

$$\mathit{TCi}'_{\mathit{TNien}} + \lambda \mathit{pi} * \mathit{TPien}'_{\mathit{TNien}} \quad \text{would be greater than}$$

$$\mathit{TCi}'_{\mathit{TNiet}} + \lambda \mathit{pi} * \mathit{TPiet}'_{\mathit{TNiet}}$$

because $\mathit{TCi}'_{\mathit{TNien}}$ would equal $\mathit{TCi}'_{\mathit{TNiet}}$, and $\mathit{TPien}'_{\mathit{TNien}}$ would exceed $\mathit{TPiet}'_{\mathit{TNiet}}$ by a factor of $1/q$. This difference would result because the trap would limit the change in PM emissions accompanying changes in NO_x levels for engines with traps. For the first-order conditions to be met, then, $\mathit{TCi}'_{\mathit{TNien}}$ would have to be smaller than $\mathit{TCi}'_{\mathit{TNiet}}$, implying that $\mathit{NOXiet} < \mathit{NOXien}$. The common-sense interpretation of this is that it is worth exerting the effort to control NO_x to a greater degree on engines with traps, because the traps mitigate some of the adverse impact of the more stringent NO_x control.

The differences between *NOXiet* and *NOXien* levels for trap and nontrap engines complicates the first-order conditions for *TRAPie*-values somewhat. They become

$$\lambda \mathit{pi} = (\mathit{TCi}'_{\mathit{TRAPie}} + \lambda \mathit{ni} * \mathit{TNie}'_{\mathit{TRAPie}}) \,/\, \mathit{TPi}'_{\mathit{TRAPie}} \quad \text{for } e = 3\text{–}8 \tag{14}$$

Substituting the expression for $\lambda \mathit{ni}$ from Equation 12 yields

$$\lambda \mathit{pi} = [\mathit{TCi}'_{\mathit{TRAPie}} + (\mathit{TCI}'_{\mathit{TNie}} + \lambda \mathit{pi} * \mathit{TPi}'_{\mathit{TNie}}) * \mathit{TNie}'_{\mathit{TRAPie}})] \,/\, \mathit{TPi}'_{\mathit{TRAPie}} \tag{15}$$

which, after solving for $\lambda \mathit{pi}$, becomes

$$\lambda \mathit{pi} = [\mathit{TCi}'_{\mathit{TRAPie}} + (\mathit{TCi}'_{\mathit{TNie}} * \mathit{TNie}'_{\mathit{TRAPie}})] \,/\, [\mathit{TPi}'_{\mathit{TRAPie}} - (\mathit{TPi}'_{\mathit{TNie}} * \mathit{TNie}'_{\mathit{TRAPie}})] \tag{16}$$

which must hold for all *e*. Finally, the two constraints must be met.

Thus, if the independent variables could take on any values, and if the functions had the proper curvature to ensure that all of the ratios could be set equal, the solution to the problem would be the familiar one that the ratios of the marginal costs of emissions reduction actions to the changes in emissions they produce should be equal for all actions. This appears to be the case for NO_x control. For PM control, however, the problem is that

$$\mathit{TCi}''_{\mathit{TRAPie}} = 0$$

and

$$\mathit{TPi}''_{\mathit{TRAPie}} = 0$$

for all *e*, and that it is necessary that $0 \leq \mathit{TRAPie} \leq 1$ hold. That is, both the cost per added trap and the reduction in total PM emissions per added trap are constants for any engine type, so the ratios of the two will also be constant. It is extremely unlikely that these constant ratios will be equal by chance; thus the simple technique of setting all of the ratios equal cannot be employed. In addition, the percentage of traps on any given type of engine must be between 0 and 100 percent. This means that the proper framework for finding the lowest cost solution is one with two added inequality constraints for each type of engine with a trap, modifying the first-order conditions to take the new constraints into account. Applying the Kuhn-Tucker conditions (*3*, pp. 704–710) to the problem then yields the intuitively reasonable answer: for all types of engines with *TRAPie* between 0 and 1 (that is, those for which the added constraints do not bind), the cost-effectiveness of every trap (the expression in Equation 16) must equal λpi, the shadow price of PM reduction; for types of engines with *TRAPie* = 0, the cost-effectiveness must be greater than the λpi; and for all engine types with *TRAPie* = 1, it must be less than λpi.

In other words, those types of engines on which traps are unusually cost-effective should all have traps; those types of engines on which traps are not cost-effective should not have any traps. For at least one type of engine, and probably for exactly one type, the cost-effectiveness of traps will equal λpi. This type of engine can be referred to as the marginal engine type because any marginal adjustments in the level of PM emissions will have to be made by changing the trap percentage for this type of engine.

Given fixed *NOXien*- and *NOXiet*-values, the least-cost solution for each firm can be found by steadily removing traps from engines starting with the types of engines with the lowest trap cost-effectiveness until the PM constraint is exactly satisfied. The cost-effectiveness value for the marginal type of engine then provides the value of λpi, the shadow price of PM removal, that is used in calculating the shadow price of NO_x removal. Adjusting the levels of *NOXien* and *NOXiet* appropriately will then allow the first-order conditions to be met for NO_x control. The minimum-cost solution is found by repeating the process of allocating traps and iterating.

Summing the minimum costs under averaging for all firms yields the minimum industrywide cost for this program.

Analysis of Trading

A similar analysis can be used to show that achieving the minimum cost for the entire industry of 19 firms requires that the shadow cost of removing a ton of NO_x be equalized across all firms as well as all engine types and that, as is the case for a single firm, traps should be allocated first to those types of engines with the lowest ratio of cost per ton of PM removed.

The constraints for PM and NO_x emissions are expressed in terms of the industrywide total allowed, rather than on a firm-by-firm basis. That is, instead of individual constraints for each firm,

$$Ypmi \geq TPi$$

and

$$Ynoxi \geq TNi \quad \text{for all } i$$

the constraints become

$$\sum_{i=1}^{19} Ypmi \geq \sum_{i=1}^{19} TPi$$

and

$$\sum_{i=1}^{19} Ynoxi \geq \sum_{i=1}^{19} TNi$$

This means that some firms' engines could emit more under trading than under averaging, as long as some of the engines of other firms emitted less. The difference in tons emitted by each firm's engines in the averaging case and the trading case indicates the number of tons of emissions reduction credits the firms must exchange for bookkeeping purposes.

The total costs under trading will be no more than those under averaging, and will generally be less, because under averaging the marginal costs of emissions reduction will usually differ from one firm to the next; the trading analysis indicates that under those circumstances total costs cannot be at their minimum from an industrywide perspective. Whether firms actually traded the correct number of units of credits under a trading system to reach the optimal solution would probably depend on the credit pricing system that was developed. If prices in a credit market were set competitively, and if there were no transactions costs, it could be expected that the prices would come to equilibrium at the shadow prices of emissions reductions for each of the two pollutants.

Cost Functions and Data Used

The relationships between NO_x levels and increases in fuel consumption and engine-out PM emissions used in this paper are based on point estimates for a number of NO_x emissions levels provided by Christopher Weaver in work for the EPA (Tables 3 and 4). To transform these points into continuous, differentiable functions for use in the optimization analysis, hyperbolic functions were fit through the points. The form and parameters of the functions fit to the point estimates are given in Tables 5 and shown in Figure 5; they track the point estimates closely over the relevant range of NO_x-values (Tables 6 and 7).

Data on trap costs, the resource costs associated with changes in fuel consumption, and bhp-hr per truck by engine type are given in Table 1. This information was provided by the EPA's Office of Mobile Sources and is based on data from the Regulatory Impact Analysis of the 1988 emissions standards (*4*). Some observers have predicted significantly higher costs and fuel consumption penalties related to trap oxidizers (see paper by Small in this Record); the use of higher cost estimates could lead to higher estimates of savings.

Optimization Program

The cost minimization concepts developed in the beginning of this section were made operational by using the data inputs in Tables 2–5 and Figure 5 and an optimization program implemented in Lotus 1-2-3. The program begins by calculating the PM and NO_x constraints; estimating costs per ton of PM removed for each type of engine (provisionally assuming each engine exactly meets the NO_x target) and sorting from high to low; lowering the percentage of engines using traps (starting with those engines with the highest cost per ton of PM removed) until the PM constraint is met; calculating the marginal costs of NO_x removal for each engine type, and adjusting NO_x levels until the marginal costs are equal. The program then inserts the newly computed NO_x-values into the routine for estimating PM removal costs and iterates until the process converges.

This process is repeated for each of the 19 firms, using the sales share distributions of each firm to weight the results. The

TABLE 3 PERCENTAGE INCREASE IN FUEL CONSUMPTION OVER BASELINE LEVELS, POINT ESTIMATES (*1*)

	NOXe (g/bhp-hr)							
Engine Type	2.5	3	3.5	4	4.5	5	6	8
LHDGE	6.5	5.0		2.5		1.0	0.0	0.0
MHDGE	6.5	5.0		2.5		1.0	0.0	0.0
LHDDE-IDI	15.0	8.0		2.0		0.0	0.0	0.0
LHDDE-DI			12.0		6.0		1.0	0.0
MHDDE-NA			16.0		7.0		3.0	0.0
MHDDE-TC			12.0		6.0		1.0	0.0
HHDDE-LH			8.0		4.0		0.5	0.0
HHDDE-NLH			10.0		5.0		1.0	0.0

TABLE 4 *PMe* LEVEL AS A FUNCTION OF *NOXe* LEVEL, POINT ESTIMATES (*1*)

	NOXe (g/bhp-hr)							
Engine Type	2.5	3	3.5	4	4.5	5	6	8
LHDDE-IDI	0.60	0.52		0.46		0.45		
LHDDE-DI			0.65		0.50		0.34	0.30
MHDDE-NA			0.75		0.60		0.44	0.40
MHDDE-TC			0.58		0.44		0.32	0.28
HHDDE-LH			0.45		0.37		0.28	0.25
HHDDE-NLH			0.54		0.40		0.30	0.27

NOTE: Units are g/bhp-hr.

TABLE 5 PARAMETERS FOR FUNCTIONAL RELATIONSHIPS (*1*)

Engine Type	X1	X2	X3	X4	X5	X6	X7
LHDGE	−59.37	500	6	3			
MHDGE	−59.37	500	6	3			
LHDDE-IDI	−11.6	24	−1.5	1	0.407	0.134	−1.8
LHDDE-DI	−115.9	800	4	6.15	0.15	0.85	−1.9
MHDDE-NA	2.41	15.3	−2.5	−0.63	0.29	0.65	−2.1
MHDDE-TC	−115.9	800	4	6.15	0.18	0.6	−2.1
HHDDE-LH	−427.8	7,100	15	15	0.16	0.6	−1.5
HHDDE-NLH	−369.1	6,200	15	12.5	0.15	0.67	−1.8

TABLE 6 PERCENTAGE INCREASE IN FUEL CONSUMPTION BASED ON FUNCTIONAL RELATIONSHIPS (calculated from data in Figure 5 and Table 5)

	NOXe (g/bhp-hr)							
Engine Type	2.5	3	3.5	4	4.5	5	6	8
LHDGE	7.0	5.2		2.6		1.1	0.3	0.3
MHDGE	7.0	5.2		2.6		1.1	0.3	0.3
LHDDE-IDI	14.9	7.4		2.0		0.3	−0.3	0.1
LHDDE-DI			12.3		5.9		1.0	−0.0
MHDDE-NA			15.5		7.2		3.0	0.2
MHDDE-TC			12.3		5.9		1.0	−0.0
HHDDE-LH			8.4		3.7		0.2	0.8
HHDDE-NLH			9.8		5.1		1.1	0.4

TABLE 7 ENGINE-OUT PM LEVELS BASED ON FUNCTIONAL RELATIONSHIPS (calculated from data in Figure 5 and Table 5)

	NOXe (g/bhp-hr)							
Engine Type	2.5	3	3.5	4	4.5	5	6	8
LHDDE-IDI	0.60	0.52	0.49	0.47	0.46	0.45	0.44	0.43
LHDDE-DI			0.68		0.48		0.36	0.29
MHDDE-NA			0.75		0.56		0.46	0.40
MHDDE-TC			0.61		0.43		0.33	0.28
HHDDE-LH			0.46		0.36		0.29	0.25
HHDDE-NLH			0.54		0.40		0.31	0.26

NOTE: Units are g/bhp-hr.

NO_x-control-related increase in fuel consumption (percent):

$X1e + X2e * (NOXie + X3e) \wedge{-1} + X4e * NOXie$

NO_x-control-related increase in fuel cost, by *NOXie* level:

$[X1e + X2e * (NOXie + X3e) \wedge{-1} + X4e * NOXie] * FCe$

Marginal change in fuel costs per one unit change in *NOXie*:

$X2e * -(NOXie + X3e) \wedge{-2} + X4e] * FCe$

NO_x-control-related increase in fuel costs per ton of NO_x:

$$[X2e * -(NOXie + X3e) \wedge{-2} + X4e] * FCe * Be^{-1} * 1{,}000{,}000$$

PMie (in g/bhp-hr) as related to *NOXie*:

$X5e + X6e * (NOXien + X7e) \wedge{-1} = PMien$

Marginal change in PM tons per NO_x ton:

$X6e * -(NOXien + X7e) \wedge{-2} = PMien'NOXien$

Total with trap:

$[X5e + X6e * (NOXiet + X7e) \wedge{-1}] * q = PMiet$

Marginal with trap:

$[X6e * -(NOXiet + X7e) \wedge{-2}] * q = PMiet'Noxiet$

FIGURE 5 Assumed functional relationships based on point estimates (values of parameters *X1* through *X7* are given in Table 5).

total costs for each of these firms are summed to produce the estimated costs of emissions control for the industry under averaging. To estimate the total costs under trading, the optimizing program is rerun as though the sales of the entire industry were accounted for by firm, thereby taking advantage of the fact that trading is essentially interfirm averaging. Finally, the incremental savings provided by trading are found by subtracting the costs under trading from the costs under averaging.

Analysis of Other Regulatory Options

The framework developed to compare averaging with trading under the assumption that emissions of any engine may be traded with those of any other engine can be extended easily to examine regulatory programs with various restrictions. As one important example, a program without any averaging can be simulated by establishing separate emissions constraints for each individual engine and forcing each to meet the standards individually. Comparing the costs under this no-averaging case with the costs under averaging then yields an estimate of the savings attributable to averaging alone.

Changing the structure of the constraints makes possible analysis of related regulatory programs. For example, emissions banking can be modeled by establishing a single constraint for total emissions over a number of years instead of one constraint for each year. Realistic results of an analysis of banking, however, would require knowledge of how emissions control technologies will change over time.

TABLE 8 SAVINGS COMPARED WITH A BASELINE WITHOUT AVERAGING OR TRADING (*1*)

	Averaging Without Trading ($ millions/ yr)	Trading and Averaging ($ millions/ yr)
Including Windfall Savings Due to Removal of Some Traps		
No restrictions	230	325
Fuel restrictions (gasoline and diesel kept separate for NO_x as well as PM)	191	199
Subclass and fuel restrictions (gasoline and diesel kept separate, and size classes kept separate)	151	151
With Estimated Windfall Savings of Approximately $151 Million Removed		
No restrictions	79	174
Fuel restrictions (gasoline and diesel kept separate for NO_x as well as PM)	40	48
Subclass and fuel restrictions (gasoline and diesel kept separate, and size classes kept separate)	(<1)	(<1)

More restrictive cases of averaging or trading may also be modeled by changing the structure of the constraints. Gasoline engines may be separated from diesel engines by forcing each fuel class to meet its own emissions constraints. This restriction may be combined with "subclass" restrictions, forcing each of the three subclasses of diesels (light, medium, and heavy heavy-duty diesels) to meet separate emissions constraints. Each added constraint reduces the potential gains from regulatory flexibility.

Results

Table 8 gives the results of the analysis of the cost-saving potential of flexible regulations for a number of different regulatory programs. Total emissions control costs in the absence of averaging or trading were predicted to fall in the range of $1.1 billion per year; thus flexible programs offer potential savings of as much as 30 percent of baseline costs.

Incremental savings from trading (that is, over and above those attributable to averaging alone) are greatest in the unrestricted case, at approximately $95 million per year. These incremental savings are, however, extremely sensitive to the restrictiveness of the trading program. If manufacturers of gasoline engines are prevented from selling NO_x credits to manufacturers of diesel engines (all of the analysis assumes that gasoline engines do not generate PM credits), the savings from trading drop to about $8 million. Further restrictions (on trading between truck size subclasses) virtually eliminate the incremental savings from trading, cutting it to only about $0.07 million per year.

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Strategic Review of Heavy-Duty Engine Emission Regulations and Alternate Fuels

J. E. Bennethum

Reviewed in this paper are the heavy-duty diesel engine emission standards and related issues that will determine the engine technology available in the marketplace in the future. The concerns identified need to be discussed and resolved in the light of what the industry and government agree to accomplish in the years ahead. This involves such major issues as U.S. energy and environmental policy. Alternate fuels could play a role in meeting the tougher environmental standards and in reducing U.S. dependence on imported petroleum. However, this may happen only if industry is given better information and direction on which to base the business decisions that will ultimately result in the commercial development of alternate fuel technology.

The future emission regulations facing the heavy-duty diesel engine industry generate concerns about the technology and business strategies that will result in viable production plans for the future. Although these regulations are firm, there are questions remaining about the availability of technology and details, such as nonconformance penalties, that need to be known before optimal choice can be made. This makes it difficult, if not impossible, to develop strategies that an organization can use for developing products that will meet the regulations, satisfy the customer, and make a profit. These uncertainties affect not only the engine manufacturer, they also affect the customers who will ultimately have to deal with the new equipment and meet the challenges posed by tougher regulations.

This paper is based on a presentation to the American Gas Association meeting, On the Road with Natural Gas, held in Indianapolis, Indiana, in September 1987. The purpose of the presentation was to point out that even though alternate fuels may satisfy the tougher emission standards, there is no guarantee that a viable business strategy can be developed to move these fuels into the marketplace. Until the U.S. government can provide a more definitive energy policy, the windows of opportunity for alternate fuel technology may not be as "open" as might be desired. Industry will require long-term guarantees that new technologies can be sold and provide a return on the investment, or adopting these technologies will prove to be a poor business decision and they will never be brought to production.

Although many questions remain, Detroit Diesel has made the decision to develop methanol engine technology for the 1991 urban bus market. However, depending on decisions made by the U.S. government on energy policy and long-term emission regulations, a negative business decision may still keep the engine out of the marketplace.

HEAVY-DUTY DIESEL ENGINE EMISSION REGULATIONS

Table 1 gives the current heavy-duty diesel engine (HDDE) emission standards. The purpose of this EPA regulatory program is to encourage manufacturers to build durable emission control systems that comply with the prescribed standards. This program increases recall liability, extends durability testing for system deterioration rates, and affects design targets. These standards pertain to engines tested on the federal transient emission test (TET) on an electric dynamometer. Details of the test and regulations are available in the *Code of Federal Regulations* (*1*). This table is constructed to show changes that will occur by calendar year. Therefore, only the emission standards that change are shown. For example, the hydrocarbon (HC) and carbon monoxide (CO) standards remain at 1.3 and 15.5 g/bhp-hr, respectively, for the entire period and are only listed in calendar year 1987.

TABLE 1 U.S. HEAVY-DUTY DIESEL EMISSION STANDARDS

Model Year	Regulated Pollutant	Standard (g/bhp-hr)	Approximate Design Target (g/bhp-hr)
1987	HC	1.3	1.2
	CO	15.5	15.3
	NO_x	10.7	10.2
1988	Particulates	0.60	0.5
1990	NO_x	6.0	5.0
1991	NO_x	5.0	4.5
	Particulates		
	Trucks	0.25	0.16
	Buses	0.10	0.05
1994	Particulates	0.10	0.05

The design targets in the last column represent the estimated level of individual emissions required for the engines to be capable of passing an end-of-line audit and a field audit. End-of-line audits must take into consideration the variabilities in

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new engine builds as well as measurement variabilities. The Environmental Protection Agency (EPA) reserves the right to request production line audits that, if not passed, can cause the production line to be shut down until the manufacturer proves that the production engines meet the standard. Because of the statistical nature of these data, a target mean engine emission value ($\overline{X}$) that is lower than the standard is necessary.

The field audit mileages for the different diesel engine classifications are given in Table 2. The certification/recall mileage, or full useful life of the engine, shows the length of service during which field recalls can be made and engines are required to meet the standard. The surveillance mileage is the planned field audit mileage. Minor hardware changes can occur with use, and it is the responsibility of the manufacturer to determine the magnitude of any potential emission deterioration resulting from these changes over the full useful life of the engine in service. Because this would require years of field testing, a shorter dynamometer durability test is run in the laboratory and extrapolated to the hours associated with the full useful life in the field. The deterioration factor (DF) must then be subtracted from the mean production engine emission level to establish the design target. This can be expressed by a simple equation:

$$\overline{X} = (A - DF)/KS$$

where

$\overline{X}$ = population mean;
A = emission standard;
DF = deterioration factor;
S = standard deviation; and
K = a factor related to the sample size, confidence level, and other statistical information.

TABLE 2 REGULATORY PROVISIONS (full useful life)

Vehicle Classification	Certification/ Recall (mi)	Surveillance (mi)
Light-duty trucks	120,000	90,000
Light heavy-duty engines	110,000	82,500
Medium heavy-duty engines	185,000	138,750
Heavy heavy-duty engines	290,000	217,500

Beginning in 1988 (Table 1), the HDDE will have to meet a particulate emission standard measured on the TET. The value will be 0.6 g/bhp-hr. In 1990 the HC, CO, and particulate standards will remain fixed, but the nitrous oxide (NO_x) standard will drop from 10.7 to 6.0 g/bhp-hr.

In calendar year 1991, both NO_x and particulate standards will be reduced. The NO_x standard will drop from 6.0 to 5.0 g/bhp-hr. Particulate reductions will differ for two categories of HDDEs, urban buses and all other HDDE applications. Urban buses, as defined in the *Code of Federal Regulations* (*1*), must meet a 0.1 g/bhp-hr standard, and all other engines must meet a 0.25 g/bhp-hr standard. In 1994 all HDDEs must meet the more stringent 0.1 g/bhp-hr particulate standard.

In the following discussion of business and emission technology strategies, the period through 1990 is referred to as the near term, 1991 through 1993 as the midterm, and 1994 and beyond as the far term.

NEAR-TERM CONSIDERATIONS

In the near term known technologies can be used to meet the new emission standards for HDDEs. These technologies include various combinations of aftercooling, injection timing control, air-fuel ratio control, and improved combustion systems. Engines that have not been developed to meet these emission standards will most likely be dropped from production because the standards will be getting tougher and high-emission engines will not be marketable in the future. In the midterm all HDDE applications, excluding urban buses that fall into Category 2, will be important.

MIDTERM CONSIDERATIONS

Category 1

The HC and CO standards remain unchanged, but the NO_x standard drops from 6.0 to 5.0 g/bhp-hr. Because of prior experience with the 5.0-g NO_x standard in California, the technology necessary for this reduction is already in use. The particulate standard is also reduced from 0.60 to 0.25 g/bhp-hr, which creates a new challenge. Development to date suggests that state-of-the-art engines with air-to-air charge cooling, high-pressure electronically controlled injection systems, excellent engine oil control, and low-sulfur fuel will be able to achieve the design targets necessary to certify and sell these engines in the midterm.

There are three options for production engines that cannot be modified economically to meet this new standard:

1. Apply aftertreatment devices to reduce particulates,
2. Pay nonconformance penalties, and
3. Burn alternate fuels that can reduce both NO_x and particulates.

Option 1 does not appear feasible because no commercial aftertreatments devices are available today, and it would require a significant effort to have them available by 1991 even if the technology were well defined today, which it is not. However, it is possible that aftertreatment could become commercially available before the end of the midterm.

Option 2, pay a nonfonformance penalty (NCP), can probably be exercised only for a year or possibly two because of the escalating penalties that are typically assigned. The NCP concept is explained in the *Code of Federal Regulations* (*1*). Unfortunately, the details of the particulate NCPs are as yet unknown, which makes it difficult to develop a business strategy including this option.

Option 3 would require developing an alternate fuel strategy for a wide variety of HDDE applications. This will be difficult if any commercial engines are capable of meeting the midterm standards without aftertreatment or NCPs.

Given current fuel prices, present environmental regulation alone does not guarantee a profitable market for heavy-duty engines using alternative fuels. The market is more likely to be "opened" for alternative fuels primarily on the basis of fuel prices, not environmental regulation. Because future fuel prices are so uncertain, industry cannot afford the risk of developing alternative-fueled engines without some form of guarantee of an ongoing market for these engines.

Given the likelihood that some engines will meet the midterm standards, all engines in this category must meet the standards without resort to any of the three options or they will be noncompetitive. The exception could be the older production engine that could survive in the marketplace if the manufacturer paid a minimal NCP for a year or two. This can only be determined for sure when the details of NCP for particulates are made available and examined as a potential business strategy.

Category 2

The second category of importance in the midterm is the urban bus. All emissions standards are the same as for Category 1 except that the particulates standard is much lower, 0.1 g/bhp-hr. Attaining this particulate level does not appear to be possible without aftertreatment. The same three options are available. Because it is believed that commercial aftertreatment devices will not be available until possibly late in the midterm, aftertreatment devices can be only part of a viable business strategy. NCPs are expected to start at a level approximately equivalent to the cost of technology to meet the standard in 1991, and therefore paying NCPs could be a viable business option for the first year of the midterm. However, an acceptable business strategy would also depend on the introduction of commercial aftertreatment devices in 1992 or 1993 to allow the engine to continue to be sold competitively. If that did not happen, the NCPs could prove to be a competitive disadvantage in 1992 and would certainly be a disadvantage in 1993, leading to dropping such engines from the product plan.

The third option, using alternate fuels in the urban bus market, provides a potential advantage over the options available for diesel-fueled engines. As will be shown later, the Detroit Diesel methanol bus engine can now meet the midterm emission standards for urban buses. If this engine can be shown to meet all of the other customer criteria by 1990, it can be a viable commercial candidate for this market. Obviously, there are other issues and technology strategy decisions that must be considered.

FAR-TERM CONSIDERATIONS

In the far term all HDDEs must meet the lower particulate standard of 0.1 g/bhp-hr. Assuming no commercial diesel fuel–burning engines that reach this particulate level can be developed by that time, the same three options are available. It is certainly possible that a commercial aftertreatment device could be available by 1994 or earlier. If this happens, the only reason to consider Option 2 would be that a life-cycle cost analysis of engines sold in 1994 and succeeding years showed some advantage to paying NCPs. Because details of the NCP are not available for analysis, this option is unclear at this time. However, if the rationale for NCPs is properly applied, this should not prove to be a good business decision, certainly not after 1994, the first year of the introduction of the tougher standards for all HDDEs.

However, even engines that produce 0.25 g/bhp-hr will require 80 percent efficient traps to reach the 1994 design target of 0.05 g/bhp-hr. Engines that meet the 1991 design target of 0.16 g/bhp-hr could reach the 1994 design target with a 35 percent efficient aftertreatment device. This becomes important because completely different aftertreatment technologies could be developed depending on the efficiency required. If high-efficiency traps are not available, higher particulate emitting engines would not be capable of meeting the standard.

Another possibility that must be considered is that trap technology may not prove to be commercially viable by 1994—for reasons of economics or durability. This leads to the possibility that diesel-burning engines could become very expensive as NCPs rise. Obviously, the federal government could act to delay or change the standards rather than legislate diesel engines out of the marketplace by causing them to be at an economic disadvantage. However, if engines burning alternate fuels can achieve these standards, the government could force the industry to switch fuels to achieve the environmental objectives for which these standards were developed.

MIDTERM IMPLICATIONS OF TRAP DEVELOPMENT

If aftertreatment becomes available in 1994 or before, there is a business concern in developing alternate fuel engines for urban bus use for the midterm. The development costs of such an effort must be offset by future product sales.

In the worst-case scenario, it can be assumed that the diesel engine could be sold in the urban bus market with NCPs in 1991 and that aftertreatment devices would become available in 1993. This suggests alternate fuel engine sales would be viable for only 1 year, involving the sale of only a few thousand engines, before diesel-fueled engines again would become a competitive product. One year of sales would not be adequate to justify a positive business decision for alternate fuels on the part of either the engine manufacturer or the transit authorities. This leads to questions about the interrelationship of U.S. policies on environment and energy. If the United States is to reduce its dependence on petroleum-based fuels, a decision must be made soon that will lead to the introduction of an alternate fuel into the U.S. commercial marketplace. Methanol is currently the fuel of choice, and the environmental issues could provide the means of introducing it.

A review of the emission standard scenarios suggests that, in limited market segments, the emission standards could be used to encourage the use of alternate fuels while improving the environment. For example, if the NO_x standard were reduced in the far term for the urban bus, the possibility of meeting the lower standard with diesel fuel would be diminished. An NO_x level of 2.5 g/bhp-hr might be a feasible value for consideration. This would ensure a market for the alternate fuel for a sufficient period of time to encourage engine manufacturers to make the business and technology development decisions necessary to bring these engines to the marketplace. It would also require transit authorities to seriously consider the numerous decisions that must be made if alternate fuels are to be used. Obviously, there are a number of other technology-forcing scenarios that could be brought to bear on this dilemma by various government agencies.

SUMMARY

The future emission standards are not only presenting new technical challenges, they are also raising difficult business concerns. As long as the needed technology for the basic engine, and especially particulate traps, is uncertain and the necessary information about NCPs is unavailable, both technology and business strategies are difficult if not impossible to formulate with any confidence.

For example, strategies for meeting the midterm urban bus emission standards include the possibility of using alternate fuel technology, but uncertainty about future sales of such products has complicated the business decision to proceed with this development. As has been discussed, the possibility of using NCPs and the uncertainty about the availability of commercial particulate traps during the midterm do not support the investment necessary for alternate fuel development. What needs to be done is to guarantee future sales of alternate fuel technology in the United States by supporting it either as part of a U.S. energy policy or as a means of providing a cleaner environment. A lower NO_x standard for selected applications, such as the urban bus in the far term, could provide an ongoing market for alternate fuel technology.

Detroit Diesel has decided to proceed with development of the 6V-92TA methanol engine for commercial applications in 1991. This decision is based on involvement in the bus market, the competition, the potential for meeting the difficult urban bus emission standards with this technology, and the belief that both U.S. energy and environmental policies should support this decision in the future. Obviously, information is still lacking, but technology development is proceeding while all of the alternatives are reviewed.

DETROIT DIESEL'S METHANOL ENGINE

Detroit Diesel selected methanol as the most likely alternative to petroleum-based fuels should another energy crisis occur. Since that decision, which was the result of a General Motors Corporation study of alternative fuels, many others have adopted this fuel for similar reasons. However, in the last few years the availability of petroleum and its price have led to the selection of methanol for another reason—its ability to produce low emissions and improve the quality of the environment.

In the early 1980s, Detroit Diesel developed a 6V-92TA methanol-burning two-stroke engine that appeared to have a commercial advantage over other methanol engine configurations. Because the two-stroke engine is the market leader in transit bus sales in the United States and most of North America, it became a natural contender to satisfy the midterm emission standards for urban buses.

The engine modifications necessary for operation on methanol are shown in Figure 1. Descriptions of this engine, the urban bus installation, and vehicle performance in revenue service are given elsewhere (*2–4*). For several years engine development was curtailed by the depressed economic state of the HDDE business. However, in an agreement reached with the EPA, several consumer groups, and General Motors, the opportunity was provided to continue the development of the two stroke methanol engine. Results from the initial year of effort have been quite encouraging, as shown by the modified engine test results given in Table 3 and shown in Figures 2–4. The emission data in Table 3 indicate that the modified engine easily meets the NO_x and CO standards for the 1991 urban bus and, therefore, the 1994 standards for all HDDEs. Currently, the HC TET results are above the 1.3 g/bhp-hr standard. The most recent weighted hot-cold cycle numbers are approaching the standard, but more improvement is necessary. The particulate emissions of the modified engine are already near the design target level of 0.05 g/bhp-hr. All of these emission levels were achieved without any exhaust aftertreatment device.

Although currently there is no aldeyhde standard, the EPA agreement identified an aldeyhde goal of 0.1 g/bhp-hr for this development program. To date, aldehyde levels of between 0.3 and 0.4 g/bhp-hr on the TET have been achieved without aftertreatment, but, unfortunately, all catalyst systems tested to date have increased the aldehyde levels rather than decreased them on the TET. The effort to identify and select an appropriate catalyst continues, but it must be paralleled by a similar

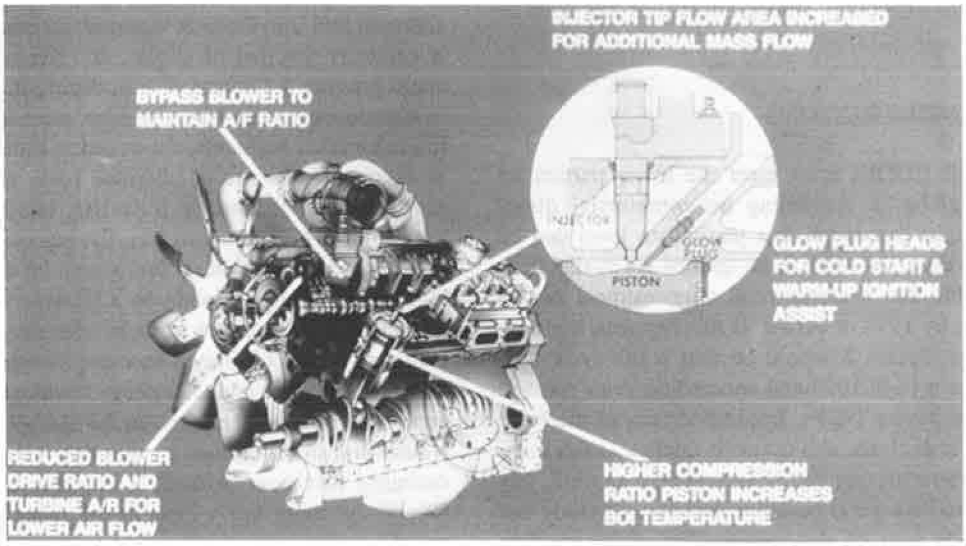

FIGURE 1 Engine modifications necessary for methanol operation.

TABLE 3 MODIFIED METHANOL ENGINE EMISSIONS AND FUEL CONSUMPTION

	Baseline	Modified	Diesel (1987)	Goal
NO_x	1.6–2.0	1.3	4.85	5.0
CO	6.4–7.0	7.2–7.3	1.2	15.5
HC	9.4–10.1	2.2–2.5	0.6	1.3
Particulates	0.23–0.24	0.056	0.32	0.1
Volatile fraction of particulates	–0.21–0.23	0.051	–0.08–0.12	
Aldehydes	0.4			0.1
Idle aldehydes (g/min)	0.5–0.14			0.05
Idle CO (%)	0.4			0.05
Cycle BSFC (lb/bhp-hr)	1.037–1.050	0.968–0.977	0.448 0.958[a]	

NOTE: Units are grams per brake-horsepower-hour unless otherwise noted.
[a] Methanol equivalent.

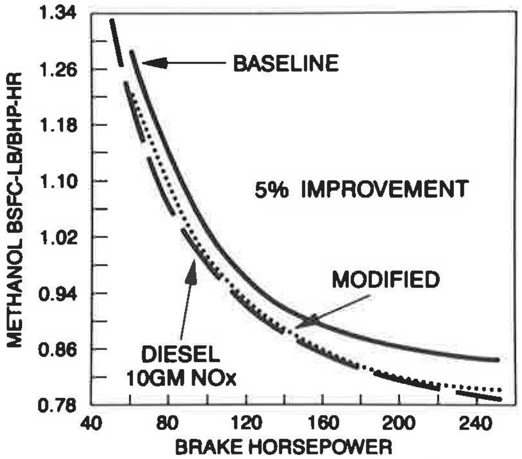

FIGURE 2 Methanol engine BSFC improvement at 2,100 rpm.

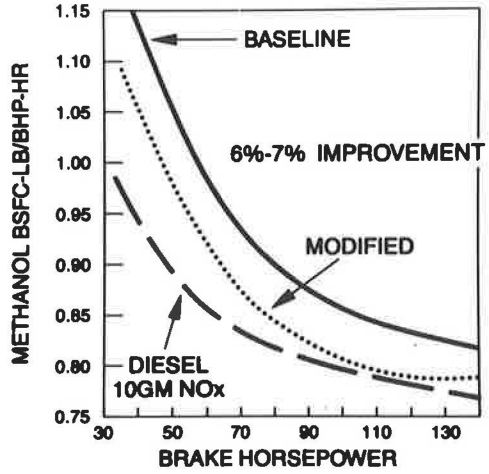

FIGURE 3 Methanol engine BSFC improvement at 1,000 rpm.

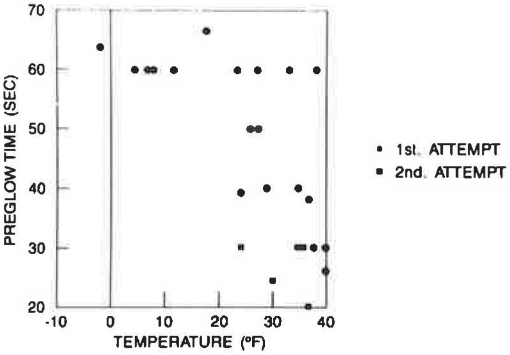

FIGURE 4 Methanol cold-start program (circles = first attempt; boxes = second attempt).

study to establish what aldehyde levels are acceptable in the environment. As Figures 2 and 3 show, the modified 6V-92TA methanol engine is now approaching the brake specific energy consumption of an equivalent diesel engine. Improvements in the brake specific fuel consumption (BSFC) of the modified engine range from 5 to 7 percent at various speeds and loads. More improvement is necessary at low speeds and light loads, and the effort is continuing to accomplish this. (At the time this paper was submitted, further development had resulted in meeting all program emission targets without aftertreatment.)

Cold-start data are shown in Figure 4. The goal for the urban bus engine in the EPA agreement was set equivalent to a diesel. This was interpreted to be a start at 30°F with 1 min of glow plug "preglow" and less than 30 sec of cranking. As Figure 4 shows, this goal was exceeded by starting at lower temperatures, even below 0°F, and at preglow times as short as 40 sec.

Another business aspect of this technology is that it could be applied to autoignite other fuels, such as gasoline, jet petroleum, and ethanol (Figure 5). Althouth the 6V-92TA is not now a competitor where these fuels enjoy a significant market, this potential will be considered in making the business decision to produce this engine for commercial sale in 1991.

CONCLUSIONS

Detroit Diesel has committed to the development of commercial methanol technology for the 1991 urban bus market. The rationale for this decision is based on the following considerations.

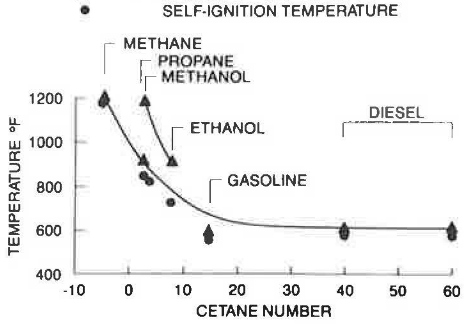

FIGURE 5 Minimum temperatures at beginning of injection (BOI).

1. Detroit Diesel's position as the leading supplier of bus engines in North America,
2. Status of Detroit Diesel methanol engine technology relative to that of the competition and the potential to meet the 1991 urban bus emission standards,
3. Transit authorities' reaction to the use of alternate fuels for bus fleets,
4. Federal and state support of alternate fuel programs to improve the environment, and
5. Need for a U.S. energy policy to encourage alternate fuel use and simultaneously develop an environmentally superior fuel.

All of the information needed to support a firm business decision is not currently available. Lacking are

1. Information on particulate NCPs for the HDDE;
2. Forecast of the availability of particulate traps for the HDDE;
3. A firm U.S. energy policy supporting alternate fuel use; and
4. Information about lower emission standards in the far term that could result in alternate fuel technology sales in specific markets (i.e., NO_x reductions for urban buses).

The technology Detroit Diesel is developing also could provide business opportunities where autoignition of other fuels (e.g., gasoline, jet petroleum, and ethanol) may prove advantageous to the custoner.

Finally, unless something positive is done by the government to encourage the development of alternate fuel strategies for the United States, the future of alternate fuel engine technology will be quite unpredictable and dependent on politics and business decisions based on the information that is available when these decisions have to be made.

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Meeting Bus Emissions Standards—A Perspective

V. K. DUGGAL

Concern for the urban environment has resulted in strict particulates emissions requirements for bus diesel engines beginning in 1991. Similar standards become applicable to on-highway truck engines in 1994. Current technological developments suggest that bus heavy-duty diesel engines manufactured in 1991 are unlikely to meet the standards. Combustion of methanol and natural gas in internal combustion engines results in low particulates emissions and may present an opportunity to meet these limits. In this paper the characteristics of these fuels relative to diesel and technologies for alternate fuel engines are discussed, and emissions and performance trade-offs are highlighted. The criteria such engines must meet to gain customer acceptance are also developed.

Heavy-duty diesel engines predominate in the commercial transportation sector because of their excellent performance with regard to fuel economy, reliability, and durability. The Environmental Protection Agency (EPA) has promulgated emissions standards for heavy-duty diesel engines including bus and truck applications (Table 1). Diesel fuel consumed by transit buses is a small part of total diesel fuel consumed by heavy-duty engines in the transportation sector. However, concern for the urban environment and public visibility have been used as a rationale for much stricter particulates requirements for 1991 bus engines. The same strict requirements apply to heavy-duty truck engines in 1994.

TABLE 1 EPA HEAVY-DUTY DIESEL EMISSIONS REGULATIONS

Emissions (g/bhp-hr)	1988	1990	1991	1994
Hydrocarbons	1.3	1.3	1.3	1.3
Carbon monoxide	15.5	15.5	15.5	15.5
Oxides of nitrogen	10.7	6.0	5.0	—[a]
Particulates	0.6	0.6	0.25 (0.10 bus)	0.10

[a] Not yet promulgated.

In the regulatory environment described, manufacturers of diesel engines are faced with the challenge of practically eliminating particulates in bus exhaust. Alternate fuels may offer an opportunity to meet these requirements. Furthermore, the development of alternatives to hydrocarbon fuels also offers strategic benefits. These include energy security and economic advantages of using indigenous fuels. Technologies for burning alternate fuels in heavy-duty engines cleanly and efficiently may offer access to overseas markets where such fuels may be preferred.

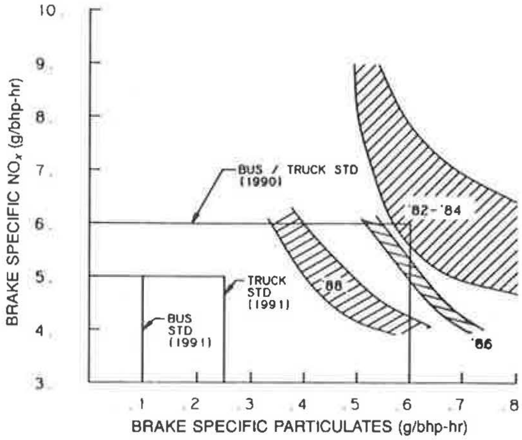

FIGURE 1 NO$_x$-particulate trade-off.

Evaluated here are potential alternate fuels, engine technologies, and emissions prospects for heavy-duty engines. Also highlighted are the criteria or parameters against which these engines should be judged for acceptance.

DIESEL ENGINE EMISSIONS TRADE-OFF

Diesel engine nitrogen oxides (NO$_x$) and particulate emissions follow a classic trade-off curve (Figure 1). Significant progress has been made in the 1980s in shifting this relationship so that lower particulates are emitted for a given NO$_x$. As combustion-generated particulates emissions are lowered, the contribution by lubricating oil and fuel contaminants (e.g., fuel sulfur) becomes a significant portion of the exhaust particulates. To meet the EPA requirement of 0.1 g/bhp-hr particulates (including deterioration factor, production tolerance variability, selective enforcement, etc.), the design target has to be lower than 0.1 g/bhp-hr. Current technological developments suggest that this may not be feasible if diesel fuel is used in the engine.

Technologies for aftertreatment of particulates are being developed. These require collection of particulates in a trap and their controlled oxidation or regeneration. The reliability and durability of trap systems have yet to be demonstrated. These systems also increase engine costs and add a fuel consumption penalty. Trap technologies may not be feasible for 1991 buses.

CHARACTERISTICS OF ALTERNATE FUELS

Some alternate fuels exhibit particulate emissions characteristics that make them attractive for use in heavy-duty engines.

Cummins Engine Co., Box 3005, Columbus, Ind. 47202.

These include natural gas, methanol, and propane. Natural gas is a primary fuel that is not tied to a petroleum base. Methanol can be derived from various feedstocks including natural gas, coal, and biomass. Major production of methanol currently uses natural gas as the feedstock, and its current oversupply is due to the abundance of this resource material. Propane is essentially produced by refining and cleaning up natural gas. Its longer-term availability is therefore limited.

Various characteristics of these fuels (energy density, combustion efficiency, safety, and infrastructure) are compared with those of diesel fuel in Table 2. Where possible, quantitative comparison is shown (e.g., energy density and thermal efficiency). The qualitative comparison uses an indicator of 1 if the parameter is similar to diesel; >1 if the parameter is better than diesel, and <1 if it is inferior to diesel. The table highlights differences in the characteristics of alternative fuels with respect to diesel fuel.

TABLE 2 FUEL CHARACTERISTICS

Characteristic	Diesel	Methanol	Natural Gas	Propane
Energy density	1	0.5	0.35 CNG 0.65 LNG	0.8
Combustion efficiency	1	1	0.83	0.83
Safety	1	<1	<1	<1
Toxicity	1	<1	1	
Infrastructure	1	<1	<1	<1

NOTE: Diesel equivalent = 1; better than diesel = >1; worse than diesel = <1; CNG = compressed natural gas; LNG = liquefied natural gas.

Energy Density

Energy density of methanol is about one-half that of diesel fuel. Either twice the fuel volume needs to be carried on board for equivalent range or the vehicle needs to be refueled more often. Because methanol is a liquid, this does not present a major issue. Natural gas has very low energy density and needs to be carried in a highly compressed state (2,500 to 3,000 psi) or as a liquid in cryogenic tanks (LNG). As compressed fuel, its energy density is about one-third of that of diesel for the same fuel tank volume. In the liquefied state, the range is about two-thirds of the diesel fuel range. On-board storage and refueling of natural gas require significant additional tank size and longer refill times. Propane exhibits energy density about 0.8 that of diesel fuel. Because it is a liquid, refueling logistics would be similar to those for diesel fuel.

Combustion Efficiency

The efficiency of methanol heavy-duty engines is similar to that of diesel engines because the principle of operation [direct injection (DI) of fuel, high compression ratio, and unthrottled] is preserved. The natural gas and propane engines in this analysis are a conversion of the diesel engine to spark ignition (SI) so their efficiency is lower than that of the DI methanol engine for which the fuel and air are mixed externally in the intake system and carburated. A spark plug (in place of a fuel injector) ignites the fuel. Intake restriction or throttling is used to control power output of SI engines. Throttling losses and necessary lower compression ratios contribute to a lower engine efficiency compared with diesel.

Safety

Methanol flame is invisible because of the lack of carbon in its combustion. Therefore methanol-related fires may be difficult to detect. Also, methanol is miscible with water, and any leak from storage tanks may disperse into and contaminate groundwater. Natural gas is lighter than air so any leaks are likely to disperse upward. Propane is heavier than air and can be hazardous if leaked in enclosed spaces.

Toxicity

Methanol is known to be toxic if ingested. It can be absorbed through the skin and may be ingested because it has a pleasant taste, as does ethanol, in contrast with diesel fuel. Propane and natural gas do not show any known toxicity.

Infrastructure

This may be defined as the ability to readily deliver fuel with existing distribution systems. Methanol and natural gas both suffer from a lack of infrastructure. Methanol can be transported; however, large-volume availability and storage systems do not exist.

Natural gas may be available in most urban areas, but the required compressor stations for vehicle fueling do not exist. Propane is available in most places and may be delivered reasonably easily compared with methanol and natural gas. It may be suggested that propane fuel exhibits better infrastructure than do the other alternatives to diesel fuel.

ALTERNATE FUEL ENGINE TECHNOLOGIES

In recent years, various engine developments have been reported to adapt heavy-duty diesel engines to burn methanol or gaseous fuels (*1–6*). The rationale for and results of developments at the Cummins Engine Company using some of these alternate fuels are described, and a current technologies perspective on the use of these fuels is offered.

Engine Technologies

Methanol Fuel

Methanol fuel has very low ignition qualities as indicated by its cetane number. Technical options for methanol engines include

- Direct injection,
- Engine modifications
  –Ignition aids (glow plugs, spark plugs) and
  –Pilot diesel,
- Fuel modification (ignition improvers), and
- Carburation and external mixture preparation.

Gaseous Fuel

Natural gas does not exhibit compression ignition qualities (cetane rating) suitable for diesel engines. Its high octane rating makes it most suitable for a spark ignition engine. Technical options for natural gas engines include

- Spark ignition—carburation and external mixture preparation,
- Dual fuel—pilot diesel injection and gas through the intake system, and
- Direct injection of natural gas—ignition aids in combustion chamber.

Dual-fuel technologies add the complexity of carrying two fuel systems on board but, more important, have not demonstrated a potential to meet the low particulates requirements. Direct injection of natural gas is at the concept evaluation stage and is not yet a technology available for consideration.

The spark ignition technical option for heavy-duty engines is the same as for automobile engines; the fuel and air are mixed in the intake system and ignition is with a spark plug in the cumbustion chamber. Spark ignition engines operate at a lower compression ratio than do diesel engines because of knock limitations. Intake restriction or throttling is a means of controlling the output of SI engines. These differences in design and operation (i.e., lower compression ratio and throttling losses) contribute to the lower efficiency of SI engines.

TECHNICAL APPROACH AND RESULTS

Ongoing technology evaluation programs for methanol and natural gas engines are described in this section. The base engine modified for this work is a Cummins L10 (10-liter swept volume) engine that is used and well accepted in transit bus applications.

The objective of the work reported here has been to demonstrate a methanol engine with minimum engine change and develop a performance and emissions data base. The base diesel engine selected for this work is currently used in both bus and truck applications. The strategy adapted was that of modifying fuel properties, such as ignition and combustion characteristics, to make them similar to those of diesel fuel. Ignition as well as lubrication additives are added to methanol fuel. The engine modifications were limited to injection system changes to deliver larger fuel quantities and material changes for methanol fuel compatibility. Specifically, changes were made to the fuel pump, cam, and injectors. Because of the lower energy density of methanol fuel, nearly twice the volume of methanol fuel needs to be injected to develop power similar to that of a diesel engine.

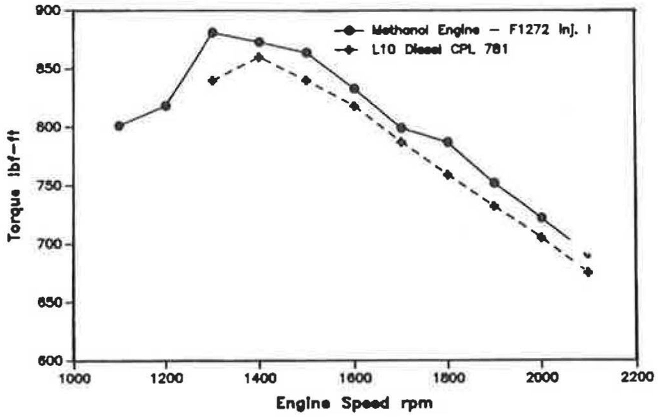

FIGURE 2 **L10 methanol torque curve.**

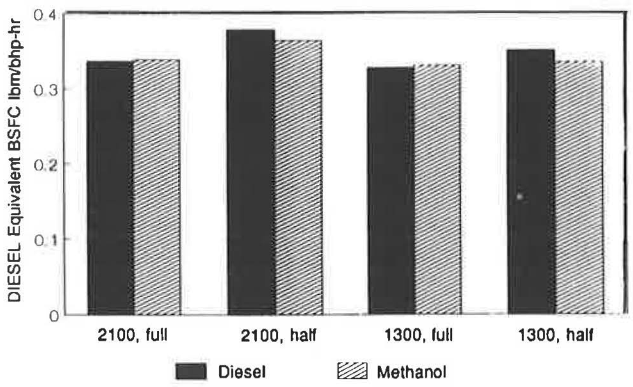

FIGURE 3 **Diesel-equivalent BSFC comparison.**

The results for this prototype engine are shown in Figures 2–7 in which the performance and emissions of the engine are compared with those of the base diesel engine. The torque developed with the methanol engine is similar to that of the base diesel engine (Figure 2). There is a potential to develop higher torque at lower speeds than is practical with diesel engines because of smoke concerns. Brake specific fuel consumption (BSFC) (Figure 3) for methanol and diesel engines is identical under key performance conditions (rated and peak torque speeds/loads). The cylinder pressure developed with the methanol engine is similar to that of the base turbocharged diesel engine (Figure 4).

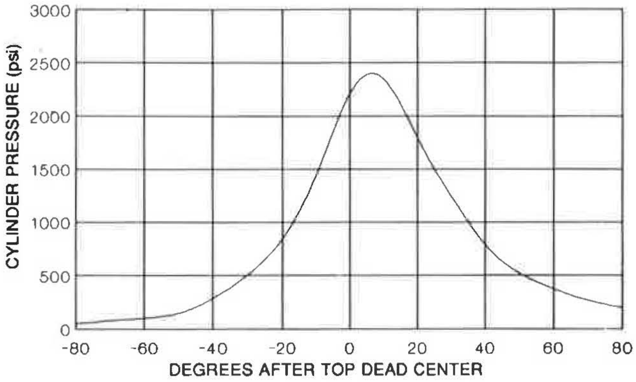

FIGURE 4 **Cylinder pressure (5 percent Avocet, 1,300 rpm, 970 ft-lb).**

Limited emissions data on a steady-state basis have been gathered for this engine. Figure 5 shows the NO_x emissions at 1,300 and 2,100 rpm for the methanol engine and base diesel engine. A point worth making is that the nitric oxide emissions are a function of ignition timing (residence time of combustion products at high temperature). The two engines compared here are not at the same injection timing because of differences in their injection characteristics. Nitric oxide emissions of the methanol engine will increase when the injection timing is advanced to be similar to that of the diesel engine.

Figure 6 shows unburned fuel emissions from the two engines. The hydrocarbons from the methanol engine have not been corrected for Flame Ionization Detector sensitivity differences between hydrocarbon and methanol fuels. The increase in unburned fuel emissions is due to the combination of mismatched injector cups in the methanol engine and long injection duration of the cam used to demonstrate concept feasibility. It is expected that further developments including an

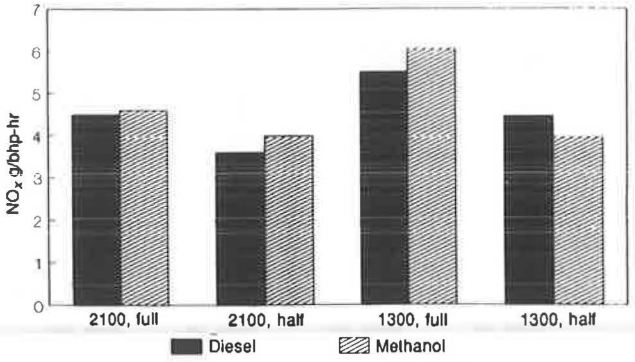

FIGURE 5 Comparison of NO_x emissions.

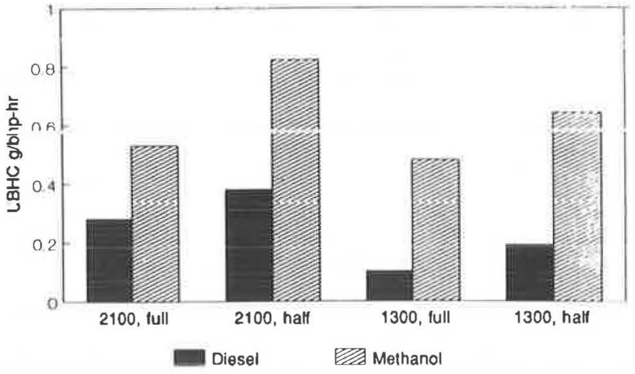

FIGURE 6 Comparison of unburned fuel.

optimized injection system (cam, injector, and injection characteristics) will overcome most of the deterioration observed in these results.

Figure 7 shows a comparison of particulates from diesel and methanol engines developing the same power. Particulates from the methanol engine are 5 to 10 times lower than from the diesel engine, which clearly demonstrates the rationale for considering methanol fuel for heavy-duty engines. Combustion of methanol contributes greater amounts of aldehydes to the exhaust than does diesel fuel. The qualitative data suggest that to be the case. Aldehydes are not regulated at present, but the focus of manufacturers of methanol engines has got to be on lowering this constituent below diesel levels. In the technical concept described previously, the in-cylinder temperatures are such that aldehydes may be oxidized further in the combustion space to a level below that of diesel emissions.

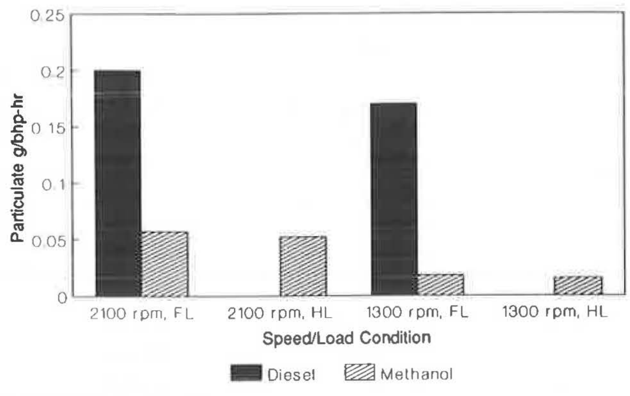

FIGURE 7 Particulate comparison.

Natural Gas Engine

An L10 engine has been modified to burn gaseous fuels (both natural gas and propane). Some of the critical engine components such as valve and valve seat materials have been modified to be compatible with higher (than diesel) combustion temperatures. Also, turbo machinery has been engineered that will optimize fuel economy for the bus operating cycle. These projects are in an early stage of development. Combustion and emissions data from these engines have not yet been developed for comparison with the methanol engine. However, on the basis of work reported elsewhere (7), the following qualitative evaluation can be made of natural gas engine emissions.

The homogeneous charge operates with fuel-air mixtures that are richer than those used for diesel fuel. As a consequence, these engines tend to emit much more NO_x in the exhaust. A comparative analysis of natural gas and propane engine emissions (Table 3) indicates that spark-ignited gas engines produce particulates an order of magnitude lower than similar diesel engines. The NO_x emissions of gas engines increase by a factor of two in these naturally aspirated engines. The HC and CO emissions are not much different. These data indicate that the NO_x needs to be controlled to acceptable levels, which may be feasible by employing lean-burn concepts—operating the engines at an air-to-fuel ratio that is leaner than chemically correct mixtures.

TABLE 3 COMPARATIVE ALTERNATE FUELS EMISSIONS DATA FOR EXPERIMENTAL BUS DRIVING CYCLE

Engine (fuel)	Particulates	HC	NO_x	CO
6V71 (diesel)	0.17	1.36	10.8	1.92
IVECO (diesel)	0.21	0.99	9.2	2.01
IVECO (propane)	0.015	1.17	19.2	2.07
IVECO (natural gas)	0.028	1.6	17.1	1.27
IVECO (optimized natural gas)		3.0	14.5	1.75

NOTE: Units are g/bhp-hr.

PERSPECTIVE ON ALTERNATE FUEL ENGINE TECHNOLOGY

A perspective on engine technologies is given in Table 4, including various performance characteristics and status of current diesel, methanol, and gas engines. The major issue with diesel engines is exhaust particulates. Methanol engines present the added issue of aldehydes in the exhaust. The reliability and durability of these engines are as yet unknown. It is anticipated that these engines will cost considerably more than current diesel engines. Gas-fueled engines are cleaner combustion engines except for their higher NO_x emissions. These engines also have inferior fuel consumption, specific output, and cost compared with modern diesel engines.

To gain wider customer acceptability, alternate fuel products need to meet diesel-like performance (reliability, durability) and cost standards.

TABLE 4 PERSPECTIVE ON CURRENT ENGINE TECHNOLOGY

Characteristic	Diesel	Methanol	Natural Gas
Reliability (unscheduled downtime)	Excellent	?	High
Durability (life to overhaul)	Long	?	?
Specific output	High	High	Mid
Fuel economy	High	High	Mid
Cost	Low	High	High
Emissions			
NO_x	Mid to low	Low	High
Particulates	Mid	Low	Low
Aldehydes	Low	High	Low

SUMMARY

Technological developments for methanol and natural gas engines are ongoing. Each of these technologies presents issues that need to be carefully evaluated, and trade-offs need to be developed. Fuel availability, life-cycle cost, maintenance, operator acceptance, and legislative requirements are the most appropriate criteria against which to judge alternate fuel engines.

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Economic Evaluation of Bus Maintenance Contracting

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The economics of contracting with private service providers for maintenance of transit buses is examined. Cost comparison analysis undertaken for 5 competitively awarded turnkey service contracts and 16 maintenance jobs suggests that contract hire of bus maintenance can prove a cost-saving option for many systems.

Recently, contracting has been widely advocated as a cost-effective way of providing service delivery and injecting the spirit of competition into the transit industry. A few studies in the past (*1*, *2*) have supported this and illustrated that contracting transit service delivery offers the potential for savings. However, no similar evidence has yet been established for vehicle maintenance (VM), even though the notion of contracting in this area is not new.

The economics of contracting with private bus maintenance service providers is examined. To this end, a cost comparison between public in-house maintenance cost and contractor's bid for the two major modes of private-sector participation, contracting for overall fleet maintenance and for specific maintenance jobs (or services), was undertaken. The approach to and results of these cost analyses, which included evaluation of 5 competitively awarded turnkey service contracts and 16 maintenance jobs contracts, are discussed (*3*).

EVALUATION OF CONTRACTING FOR OVERALL BUS FLEET MAINTENANCE

Unfortunately, no clear-cut example of an urban public transit agency that has contracted out all of its fleet maintenance work is yet available. However, in the case of several recently awarded turnkey fixed-route service contracts, total maintenance of the vehicles involved in the particular service has been an integral part of the overall contracted functions. For cost comparison analysis, five such cases of competitively awarded turnkey service contracts were chosen: Dallas Area Regional Transit II (DART II, Dallas, Texas); Snohomish County Commuter Bus Services (Everett, Washington); Huntington Station Feeder Bus Services (Fairfax County, Virginia); Johnson County Services (Olathe, Kansas); and Yolobus Services (Woodland, California).

Approach to Maintenance Cost Comparison

The calculated magnitude of difference in the unit VM cost ($/revenue vehicle mile) of a private service provider and the average unit VM cost of public systems operating under similar conditions is considered here to indicate the potential level of cost savings. Statistically, it is a crude measure of savings because either each data point or the average value of a very small sample (five in this case) is compared with the average value of larger samples representing public transit systems. This particular limitation must be kept in mind when interpreting the results of this analysis. Moreover, positive cost differences cannot be treated as real savings because there are several expense items principally related to general administration of maintenance that remain unavoidable in the short run even though maintenance is partly or entirely contracted out.

Estimating Unit VM Cost of Private Service Providers

Under the assumption that the bid price represents the true value of a private service provider's fleet maintenance cost, cost proposals, including line item budgets and service agreements, of each of the five cases of service contracting were the main sources of information for estimating unit VM costs of each contractor. Because maintenance is a subfunction of the overall turnkey service contract, two major problems were encountered in separating the fleet maintenance costs of each service provider from the cost proposal.

The first problem arose in cases in which no explicit definition of certain line item expenses was available or expense items were lumped together and presented under a specific category such as maintenance subcontract cost. For each case under consideration, explanations provided by the contract manager were taken into account and, to some degree, personal judgment was exercised, both in interpreting the cost of each line item and in deciding whether to include it under the vehicle maintenance function.

The second problem was encountered when treating the line item expenses that are either unique or not incurred by a private service provider. Because taxes, profit, facility rental, and depreciation are unique to the private sector, first a "leveling of the field" exercise was undertaken for a fair comparison of public and private costs. According to the UMTA guidelines on fully allocated cost analysis (*4*) the profits charged by the private provider and the taxes and fees paid by the private provider are common costs of doing business with a private carrier, and therefore these were included in the private carrier's bid.

The cost of using capital assets such as facility, garage, and equipment become significant for private service providers.

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Because public operators usually have access to low-interest capital, they can receive a federal grant to match up to 75 percent of their fund requirement. Moreover, in many cases, such capital expenses remain unreported under the maintenance administration function of the Section 15 reports submitted by public transit systems. Hence, for a fair comparison, it was thought that it was essential to isolate this expense item from the contractor's bid under consideration.

Only in the case of Johnson County was the facility rental cost explicitly specified. Under the Fairfax County contract, this expense is not incurred by the contractor because a well-equipped maintenance facility and garage are provided by the county. In the remaining three cases (DART II, Snohomish County, and Yolo County) the contractors' bids did not clearly specify either the rental or depreciation cost of capital facility and equipment use. Therefore, for the analysis, adjustments to the bid costs of these three contracts were made on the basis of a gross estimate of capital required to build a new facility with bus storage space and essential equipment (*1*). It was assumed that in each case the private service provider would contract out all body work, major overhauls, and paint jobs. For the estimation of capital cost, a unit area cost of $\$52/\mathrm{ft}^2$, derived from the Fairfax County estimates for a new facility, was applied.

Considering the current volatile nature of the insurance market, the premium for liability insurance is mostly treated as a pass-through expense item by private service providers. Hence, even though it is incurred by the contractor, usually it is neither declared in the cost proposal nor included under VM. However, under Section 15 reporting, the VM cost estimate for each public transit system includes the premium for physical damage insurance of revenue vehicles. Therefore it was essential to first estimate the premium expense incurred during 1984 by public transit systems and then to isolate its effect from the estimated cost difference.

For the estimation of liability premium rates during 1984, a sample of 45 public transit systems was taken from the 1984 Section 15 data. There is a wide variation in the premium paid per bus. Many transit systems (almost 26 percent of the sample) did not declare any premium expense, which may be due to the self-insurance option or the transit system's being covered under the umbrella insurance of the city or county it serves. However, for transit systems with fleets of fewer than 200 buses it was found that the annual premium ($/bus) varied within a range of from $340 to $800. There can be numerous reasons for the wide variations such as fleet size, risk management, liability limits, state laws, and insurance procurement policy. However, it appeared to be reasonable to assume that 6 percent of unit VM cost was physical damage (PD) insurance premium cost during 1984. The estimated premium rate was close to the rate indicated by the Wisconsin Municipal Insurance Commission for 1984 [i.e., $0.0324 per revenue vehicle mile (RVM)].

For the estimation of average unit cost over the contract period, first total bid cost was adjusted by deducting the rental/depreciation cost of the capital facility and equipment. Calculated yearly unit costs were then adjusted to 1984 prices.

Finally, the private service provider's unit VM cost (in $/RVM) was calculated after the effect of two important expense items was incorporated: PD insurance premium (6 percent of VM cost) and contract monitoring cost incurred by a contracting agency (5 percent of VM cost).

Estimating Unit VM Cost of Public Transit Systems

For the estimation of the average maintenance cost of public transit systems, the VM cost data of only those public transit systems that closely replicate the operating condition of the private service provider were considered. Using 1984 Section 15 report data, all single-mode properties were selected initially as the study group in order to avoid the complications of joint expenses that could be found with multimode properties.

The next step was to identify major factors influencing VM cost so that each private operator could be compared with similar public transit systems. Identification of the major factors that explain the intersystem variation in VM costs has been a subject of inquiry in the past. Though most of the attempts have been limited to the experiences of public transit systems, their findings have been generic in nature and hence applicable to general causes of VM cost differences. Earlier studies (*5–7*), generally based on statistical analyses (mainly regression analysis), have shown partial success only because the quantifiable factors included in these analyses explained no more than 50 to 60 percent of variation in the VM costs. Major factors identified as influencing the VM cost have been fleet size, mechanics' wages, speed of operation, peak-to-base bus requirements, and fleet age.

However, in recent years, the focus of such investigations has shifted toward issues related to maintenance management (*5, 8*), which are difficult to quantify but considered extremely important to the overall performance of the fleet maintenance function. Elements of internal maintenance management, such as preventive maintenance policies, management information systems, supervision, workload levels, skill of mechanics, training programs, management structure, and recruitment policies, have been recognized as issues that cannot be ignored.

Effects of geographic factors such as climate and terrain on maintenance cost have also been investigated. In the case of aggregated system data analysis, however, the overall impact of climatic factors is uncertain (*6, 7*).

Among the factors that influence VM cost, scale of operation and fleet age are the only two that could significantly influence the operating condition of a transit property. Because management is considered the key aspect of comparison between private and public service performance, no adjustments were necessary to exclude its effect on the average VM cost estimation of public transit systems. It is assumed that the effect of geographic features such as climate and terrain would be neutralized among transit systems and be insignificant if a large sample of transit systems representing both "sun belt" and "rust belt" regions was considered.

The diseconomies inherent in the scale of operations of bus services are considered applicable to both the public and the private sector. Similarly fleet age impact on overall VM cost appears to be important because, under all five turnkey service contracts, new fleets are in operation. Therefore, for the purpose of cost comparison, the average unit VM costs of public transit systems belonging to various fleet sizes and age groups were calculated using 1984 UMTA Section 15 report data.

Comparing Private and Public Transit Maintenance Costs

Approach 1

Under the first approach, the VM cost per RVM of the contractor's bid is compared with the estimated average VM cost per RVM of public transit systems that have fleets of similar size and average age.

A glance over the estimated cost differences, given in Table 1, indicates that in four of the five cases of contracting considered, maintenance contracting shows a lower cost. The level of savings is observed to be as great as 43 percent. Only in the case of Johnson County does the contractor's unit cost appear to be a little higher than the observed average unit cost of public transit systems. In the cases of Yolo County, Fairfax County, and Snohomish County, which are all less than 55-bus operations, the observed cost differences lie within a range of 20 to 43 percent. For the DART II contract, which is the largest (204 buses) service contracting experience in the county, the estimated difference is almost 12 percent. Because there was only one public transit system that had a fleet less than 5 years of age and was in the 200 to 400 fleet size group (i.e., Salt Lake City system), the age restriction was relaxed and the industrywide average unit cost for a 200 to 400 bus operation was used for estimating cost differences with respect to DART II operation.

TABLE 1 ESTIMATED UNIT VEHICLE MAINTENANCE COST DIFFERENCES

System and Location	Fleet Size	Approach 1[a]	Approach 2[b]	Approach 3[c]
Yolo Bus, Yolo County	14	32.63	29.10	46.33
Huntington Feeder Service, Fairfax County	33	19.90	12.60	69.80
Commuter Service, Snohomish County	53	43.14	32.54	49.94
Commuter and Intra-County Service, Johnson County	21	−3.76	−6.90	43.70
DART II, Dallas	204	11.81		
Average		21.70	16.84	54.95

[a] Percentage savings: private operation versus public systems of similar age and fleet size.

[b] Percentage savings: private operation versus public systems in state with similar fleet sizes.

[c] Percentage savings: private operation versus nearest regional public system.

With only one observation available, it is difficult to infer that the level of savings drops with an increase in the scale of operation, but it is true that in large-scale operations like DART II contractor's expenses for procurement, storage, and distribution of parts and supplies and maintenance of maintenance information system data are substantial. Because these expenses are not excluded from the contractor's bid price, the level of savings in the case of DART II may be to some degree underestimated. However, comparison of average unit costs of all private operations with those of comparable public agencies indicates a potential savings of 22 percent.

According to the contract manager of Johnson County, the main reason for the higher initial unit price is its fixed value for the next 6 years. Because the contractor absorbs the risk of future price fluctuations and provides a quality of service (bus cleaning and regular maintenance) perceived by the county to be better than that provided by the previous service providers (a private contractor and Kansas City Transit), the county considers it a reasonable price. Moreover, the county believes that there are significant savings in comparison with the service cost of its regional transit system.

Approach 2

Under the second approach, the unit VM cost of the contractor's bid is compared with the estimated average VM cost of similar sized public properties located within the same state. The effect of the interstate wage differentiation is thus eliminated. Another important controlling variable, average fleet age, was dropped in this case because of the small sample size.

Under Approach 2, though the level of cost differences has declined for each case, they remain consistent with the findings of the previous approach. The range of average savings in the cases of Yolo County, Snohomish County, and Fairfax County is observed to be 13 to 33 percent, whereas in the case of Johnson County the contractor's proposed VM cost emerges 6.9 percent higher than the average unit cost of similar systems in the state of Kansas (Table 1). Because there is no public transit operation in the state of Texas comparable to DART II, no cost difference was estimated in this case. Comparison of average unit costs of four county operations with those of public agencies with similar fleet sizes in their respective states illustrates that private operations, on average, can be 17 percent lower than public operations.

Approach 3

Under the third approach, the economic performance of the private service provider was measured in comparison with the performance of the nearest regional transit agency that could have provided the same service. This notion is pertinent in light of the recent practice of "opting out" from regional transit systems adopted by many counties (e.g., Fairfax County, Johnson County, Snohomish County) to cut their transit-related expenditures. Therefore, under this approach, the VM costs of the contractor's bid and the regional public transit agency located in the vicinity of the case study site have been compared.

Under this approach, the cost savings in the cases of all four county-sponsored private services are between 44 and 70 percent (Table 1). Comparison of average unit cost of all four county operations with the average of regional systems suggests that, on average, the cost of private operation is 55 percent lower than that of the regional public systems.

EVALUATION OF CONTRACTING FOR BUS MAINTENANCE JOBS

The practice of contracting out maintenance jobs is prevalent among public transit operators. Major overhauls; rebuilding various components; and, in some cases, cleaning and servicing of buses are considered good candidates for contracting. The frequently cited reasons for contracting these jobs have been economic in nature, for instance, cost saving, backlog of work, and nonavailability of special equipment and facilities or skilled manpower. However, contracting decisions are usually conditioned by a manager's or supervisor's perception of these factors instead of any ongoing procedure for conducting an in-house economic evaluation for all major maintenance jobs.

An attempt was made to estimate, in gross terms, the level of potential savings that may be attained by contracting out engine overhauls, bus cleaning and servicing, and certain component-rebuilding jobs. Six public transit operators, who have in the past contracted out these types of maintenance jobs, were contacted. The approach taken to the cost comparison analysis is briefly discussed next.

Approach to Cost Comparison Analysis

The principle underlying the approach taken to cost comparison analysis is based on the guidelines of fully allocated cost analysis prescribed by UMTA (*4*). According to these guidelines, the total cost, including the direct cost of undertaking a job or service and a portion of the shared cost of the management, administration, and underlying infrastructure supporting that particular job or service, should be attributed to that particular job or service. In addition, it was recognized that when calculating the cost savings for a job, it is important to consider the amount of future resources used or saved by contracting out that particular job. This is particularly relevant for capital-intensive jobs such as major overhauls, painting, and certain machining work. Moreover, under the internal resource constraint (e.g., manpower) situation, a transit system might have to hire one or more specialized mechanics to bring in a currently contracted-out job. On the completion of that particular job, if the newly recruited staff is suboptimally utilized, the potential cost of keeping them on the payroll is considered as a resource loss cost. Because the magnitude of these costs is directly linked to the scale of production and the efficiency of resource utilization, the average unit cost of capacity expansion and lost resources will depend heavily on specific internal factors of individual transit systems.

The in-house cost of producing a unit of currently contracted-out service or job can be expressed as follows:

In-house cost/Unit = Unit direct costs + Unit shared costs + Average incremental cost of capacity expansion + Average cost of resource loss

Direct costs include labor and material costs directly consumed in producing a unit of a particular job. They are calculated in the following manner:

Unit direct costs = Direct labor hours/Unit × Hourly wage × (1 + Fringe benefits costs/\$Labor) + Average material costs/Unit

The shared costs per unit of production are calculated by allocating a portion of the maintenance overhead (OH) costs, maintenance administration (MADM) costs, and systemwide general administration (GA) costs to the job under consideration using the following expression:

Unit shared costs = Direct labor hours/Unit × 1/MAINTHR {MADM/VEH No. VEH + GAM} + OH/\$Labor × Unit direct labor cost

where

MAINTHR = total hours spent by mechanics and servicers for vehicle maintenance, inspection, and servicing during a year;
No. VEH = total number of revenue vehicles operated by a system;
GAM = amount of systemwide GA allocated to the vehicle maintenance function; in this case, total GA expenses were split among three functional areas: operation, vehicle maintenance, and nonvehicle maintenance, according to the operating budgets.

Other variables could also be used to allocate systemwide GA expenses. Many private industries, especially those with a high capital-to-labor input ratio, often allocate their GA expenses to various cost centers on the basis of the value of capital used by each cost center. However, because of the absence of such information and the labor-intensive nature of transit operations, no attempt was made to test the sensitivity of this allocation variable in the estimation of public in-house cost.

In cases in which the in-house production of a particular service necessitates additional capital outlay, for instance, for purchase of specialized equipment or plant expansion, the depreciation of this additional capital asset is taken into account. This is particularly relevant for systems that are currently contracting out certain jobs because of either the capacity constraint (e.g., backlog of work) or the absence of required equipment or facilities.

The average increment cost (AIC) of capacity expansion can be expressed as

$$\mathrm{AIC} = \left[\sum_{i=0}^{t} I_i \,/\, (1-r)^i\right] \Big/ \left[\sum_{i=L}^{L+t} \Delta D_i \,/\, (1-r)^i\right]$$

where

I_i = the investment in year i;
r = the discount rate (e.g., the opportunity cost of capital used);
t = the planning horizon;
D = the change in work demand; and
L = the average time delay between investment and commission data of the new facility.

Sources of Data

Most of the information on the in-house direct costs of undertaking a contracted-out job was collected through interviews of maintenance staff at each site. Staff responsible for monitoring specific jobs were contacted. Using personal judgment, these persons provided a reasonable estimate of average labor hours required to accomplish a specific job, the wage rates and the fringe benefits of the mechanics assigned, and the cost of material and supplies expected to be consumed in that job. No inherent bias in favor of contracting, and thus underreporting of direct labor hours, was noticed. In most cases the interviewee was not involved in contracting decision making and took pride in handling work in house.

At all case sites, severe difficulty was encountered in collecting information on maintenance overhead costs and administrative costs. Such information was usually not available in the desired form. Overhead costs representing the expenses associated with supporting maintenance personnel and facilities are particularly difficult to isolate in cases in which facility use is shared. On the other hand, maintenance administration–related expenses may generally be available in a well-defined manner in large properties but difficult to identify for small sized properties. This is because administrative personnel in small systems may perform multiple functions including those unrelated to fleet maintenance.

To overcome this constraint, a sample of transit systems that have reported data on their maintenance overhead and administration under Section 15 was drawn. Though few systems report in such detail, it was possible to get from this sample reasonable estimates of the average ratio of overhead to direct labor costs and the average maintenance administration cost per vehicle. Because system size typically influences these costs, they were estimated for different sized properties.

Information on the systemwide GA expenses of individual case study systems was also derived from the 1984 Section 15 report. Each system's GA expenses were first allocated to the maintenance function in proportion to the share of its total operating budget devoted to maintenance. The GA allocated to maintenance (GAM) was further attributed to direct labor hours using the reported annual labor hours of mechanics and servicers devoted to maintenance, inspection, and servicing of vehicles in that particular system.

For estimating the cost of private service providers at each case study site, the bid price for each chosen contracted-out job was collected. Staff members of the maintenance and, in some cases, procurement divisions were contacted.

Comparing Private and Public Costs

For the cost comparison analysis a sample of 16 contracted-out jobs from 7 public transit systems was selected. These can be broadly grouped into three categories: engine rebuilding, bus cleaning, and rebuilding various components. In the absence of any information on the current and future magnitude and pattern of individual job work load for each case study, an accurate needs assessment for the capital and manpower resources cannot be made. However, in recognition that among these three categories only engine rebuilding work necessitates the use of major capital equipment and shop facility, initially it was assumed that all jobs could be handled in house without any investment. Thus the average unit cost of each job comprised only unit direct costs and shared costs. For the engine rebuilding job, however, the effect of additional capital equipment, facility expansion, and manpower utilization on the average unit cost at each level of output (number of rebuildings per year) was evaluated separately. A range of potential savings was established for different scales of in-house production.

Results

The estimated cost differences between the contractors' bids and the calculated in-house costs are given in Table 2. A glance over the estimated savings suggests that, in 15 of the 16 cases of contracting considered, costs of private service are lower than public costs. In the following subsections, results are discussed for each of the three categories of maintenance jobs.

TABLE 2 ESTIMATED SAVINGS IN CONTRACTING OUT CERTAIN MAINTENANCE JOBS

System	Job Description	Private Bid Cost ($)	Estimated Public Cost ($)	Cost Savings (%)
	Engine rebuilding			
A	8V-71	5,834.00	6,675.60	12.61
B	8V-71	7,286.00	5,780.00	–26.06
C	6V-92TA	6,000.00	6,760.00	11.24
D	8V-71	7,100.00	9,076.00	21.77
F	8V-71	5,500.00	6,859.00	19.81
	Cleaning			
B	Clean graffitti	10.00	24.30	58.85
E	Nightly coach servicing	2.50	12.00	79.17
F	Cleaning of interior, windows, and doors	45.00	97.20	53.70
	Rebuilding various components			
D	A/C compressor	524.00	1,073.70	51.20
B	Bendix Tuflo 700	213.00	332.70	36.00
G	Air compressor	240.00	300.40	20.11
F	24V alternator	540.00	629.40	14.20
F	Marine pumps	102.00	153.00	33.33
F	A/C alternator	164.00	355.00	53.80
F	Starter motor	123.75	277.60	55.42
G	Injector	19.00	32.60	41.72

Engine Rebuilding

Engine rebuilding (or overhaul) is one of the major drivers of maintenance cost during the life span of a bus. It is long-periodicity preventive work and therefore can be planned and scheduled well in advance. A complete overhaul consists of dismantling, cleaning, washing, and replacing all defective parts and assemblies; reassembling; testing; and, on satisfactory completion, reinstalling the engine in the bus. This work demands an adequate shop facility and capital equipment such as dynamometer, valve and seat machine, line-boring bar, and injector tester.

The results of cost comparisons analysis, given in Table 2, clearly indicate that the decision to contract out rebuilding of engines can lead to savings for many public transit systems. In four of five cases, the estimated savings fall in the range of 13 to 22 percent. In only one case (i.e., B) the private bid was found significantly (26 percent) higher than the estimated in-house cost. Two major explanatory factors in this particular case could be (a) higher contractor's price, which may be due to the small size of the overall contract (only four engines), and (b) low value for average in-house shop hours reported by the staff (only 45 hr compared with the normally observed standard of 55 to 60 hr).

As mentioned earlier, in individual cases of contracting, if account is taken of the host of internal factors that influence costs (e.g., magnitude and pattern of current and future engine rebuilding workload, existing plant capacity, availability of skilled manpower, inventory), the estimates of savings may be somewhat conservative. To illustrate this, a hypothetical case based on information on the five cases is presented.

The following assumptions were made to generate the illustrative average unit cost curve shown in Figure 1:

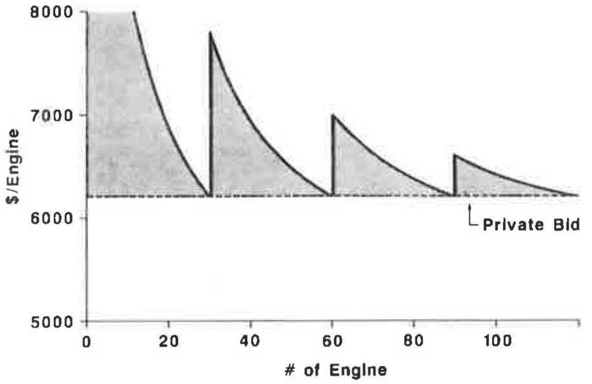

FIGURE 1 Average cost curve for engine overhaul.

- The capacity expansion plan will include addition of a dynamometer bay (1,719 ft^2) and an overhaul shop (2,324 ft^2) and purchase of a dynamometer, a line-boring bar, a valve and seat machine, and an injector tester.
- The expected life of garage facility and equipment will be 30 and 25 years, respectively. Straight line depreciation is assumed for the estimation of capital asset costs.
- The standard time for accomplishing each rebuilding job will be 55 hr, and the average cost of material and supplies consumed in each unit will be $4,500. The mechanic's wage rate and the overhead multiplier will be $12/hr and 2.5, respectively.
- A full-time mechanic will accomplish a maximum of 30 engine rebuilding jobs a year assuming 1,504 productive work hours in a year (27.7 percent unavailable time).

Although the private per unit bid price usually declines somewhat with increasing magnitude of a contract, it was assumed that it will remain fixed at $6,200 per unit. The shaded area in Figure 1 represents the potential savings that could be realized at various levels of output. The discrete jumps at 30, 60, and 90 overhauls per year are caused by the addition of a mechanic at these levels.

Figure 1 clearly shows that, in order to spread the costs of capital assets and to use manpower efficiently, a certain scale of production must be maintained. Most transit systems, particularly small and medium-sized ones, face lumpy and noncontinuous demand patterns for engine rebuilding, so it is difficult for them to attain an economy of scale. To establish a regular workload of 30 engines per year, a bus fleet of from 150 to 200 buses with an evenly distributed age appears to be necessary. Systems with erratic workload patterns will not find it economical to have overhaul facilities. Contracting out such work will be cheaper even when high utilization of a facility can be achieved in the near term. Moreover, specialized work such as engine rebuilding requires considerable management attention, skilled mechanics, and separate training. For instance, according to Figure 1, on average, 21 percent savings can be achieved for 0 to 30 overhauls per year. Average savings for between 30 and 60 overhauls per year appear to be 16 percent and can vary between 0 and 21 percent.

In three of the five cases considered in the analysis, the number of units contracted out was less than 11. Therefore, these systems did benefit substantially by avoiding capacity expansion. Table 3 gives the level of savings these three systems attained in their respective contracting decisions. Even System C, which handles such jobs at a significantly lower cost (26 percent below the contractor's price), realizes substantial savings (almost 54 percent) by deciding to send out its four engine-rebuilding jobs. No significant change in the level of savings of Systems A and F occurs because they contracted out more than 50 overhauls.

TABLE 3 ESTIMATED SAVINGS IN CONTRACTING OUT ENGINE AND POWERTRAIN REBUILDING

			Savings (%)	
System	Job Description	No. of Units Contracted Out	Without Capacity Expansion	With Capacity Expansion
A	8V-71 engine	>50	12.61	12.61
B	8V-71 engine	4	–26.05	53.76
C	6V-92TA engine	10	11.24	32.61
D	Powertrain with 8V-71	11	21.77	39.23
F	8V-71 engine	>50	19.82	19.82

Bus Cleaning

Bus cleaning and servicing consume a significant portion of overall maintenance manpower (almost 20 to 25 percent). Thus economy in this area can substantially affect the maintenance budget. In the three cases of contract hiring considered, the estimated savings fall between 54 and 79 percent (Table 2). The factors that contribute to the lower cost of these contractors are lower wages and efficient utilization of labor. Because facility, equipment, and materials for cleaning were supplied by the transit systems, no effect of capital investment was considered.

Use of part-time nonunionized labor gives contractors great flexibility in deploying the labor force; lower wages are typically paid as well.

Rebuilding of Various Components

In all eight cases of rebuilding or exchange of remanufactured components, such as compressors, alternators, pumps, starter motors, and injectors, the in-house cost of undertaking the jobs is higher than the contractor's price. The estimated levels of savings range between 14 and 74 percent (Table 2). Rebuilding such components in-house is slowly becoming the exception rather than the rule, principally because firms that specialize in remanufacturing specific components are able to establish a scale of production that can be handled by an assembly line.

Both economies of scale and assembly line mode of production appear to lower the unit cost of production for private firms.

CONCLUSIONS

A cost comparison between the bid maintenance cost of five competitively awarded contracts and average maintenance costs for public systems operating under similar conditions demonstrates that, on average, the total bus fleet maintenance contracting option emerges 22 percent lower in cost than do similar public operations. Only in one of five cases is the maintenance cost slightly higher (in a range of 4 to 7 percent).

The average maintenance costs of four county-sponsored private services among the five cases considered are 44 to 70 percent lower than those of their respective regional transit systems.

In all 16 cost comparisons between the contractor's bid for maintenance jobs (or services) and the estimated cost of undertaking the same jobs in-house, the decision to contract out has proved economical. The calculated levels of savings for engine-rebuilding work, rebuilding various components (including compressors, alternators, pumps, injectors, and starter motors), and bus cleaning and servicing fall in ranges of from 13 to 54 percent, 14 to 55 percent, and 54 to 79 percent, respectively.

Differences between private and public costs are indicative of the level of potential savings that may be attained over a certain period of time by a public transit system. For the contracting of new services, a significant portion of the potential savings may be realized immediately after contracting only if new additional overhead expenses along with the direct costs associated with the contracted services are forgone. However, in cases in which a public agency is considering contracting out its existing in-house services, the difference between the real and potential savings will depend on the extent to which the contracting agency can eliminate, after contracting, both direct and shared costs linked to those particular services. In reality, because of the host of internal factors that impede actions such as layoffs and reductions in plant capacity, an agency may only partly realize overall benefit of contracting in the short run.

Although more data would be necessary to derive any statistically sound conclusions, these cost comparisons indicate that contract hire of bus maintenance can be a cost-saving option for many systems. For this purpose, an agency should maintain close links with private garages and regularly compare the costs of in-house jobs with those of private service providers. This is particularly essential before any service expansion or major capital outlay for facility or equipment is undertaken.

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DISCUSSION

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Contracting out on a competitive basis is an effective tool for public agency managers to use to control their costs, and its use is likely to increase rapidly in the future. Bus transit agencies devote approximately 22 percent of their total expenditures to maintenance (*1*), and thus maintenance is an important area in which to consider using this cost control strategy. This paper is important in shedding light on the potential for cost savings in this area. The main purpose of this discussion is to point out some significant conceptual and methodological issues related to cost savings from contracting and thereby place this paper's results in perspective. The discussion will also include a few specific questions about the numerical values and approach used.

The most important distinction in cost savings is that between monetary or dollar savings and real savings. Real savings refer to actual savings in physical resources, such as amount of labor or material used, and occur independent of the price paid for these items, whereas dollar savings can result from either a reduction in real resources or a reduction in the price paid. From an overall societal standpoint, of course, real resource savings are more significant. However, from the standpoint of a specific agency, the dollar savings are of interest because they release monies for alternative uses (e.g., reduce taxes, expand other services). Like most prior literature, this paper focuses on dollar savings, undoubtedly reflecting a transit industry perspective.

A second issue that must be addressed is the meaning of "saving." In this paper saving is implicitly defined by the equations or procedures used to estimate it, but it is not entirely clear what this saving is intended to represent. In the contracting context, the term "saving" is usually used for the incremental reduction in total cost of producing the same service that results from contracting instead of in-house production. Conceptually this can be explained by reference to Figure 2 (*2*). The total cost of production of all service in-house is A + B. Under contracting, the public agency in-house cost will be reduced by an amount A. In order to have the service provided, the agency enters into one or more contracts for which the (bid) contract price is C. In addition, the agency may incur some additional management or monitoring costs, as a result of contracting out, as indicated by D. Furthermore, there may be some additional costs of producing the remaining service in-house as a result of contracting out; these are indicated by E. Thus the net cost saving would be as indicated in the figure (A − C − D − E).

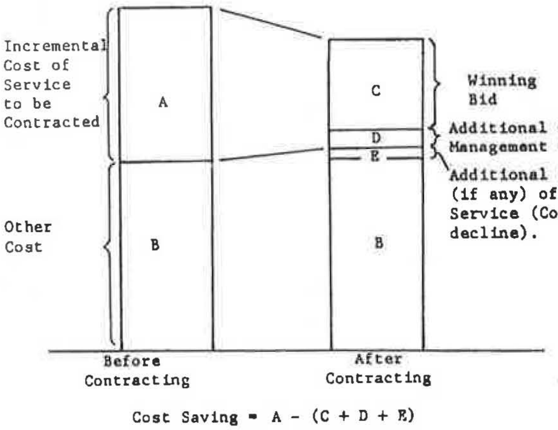

FIGURE 2 Effect of competitive contracting on total costs of transit.

In this paper, reference is made to Elements A, C, and D, but not to E. Whether or not E is properly taken to be zero in the case of maintenance contracting is unclear. In this case, the agency might add some backup capability to its maintenance facility in case the contractor cannot perform as intended, resulting in a positive value of E. Alternatively such in-house backup capability may be reduced, on the premise that the contractor's own backup can be used in a crisis at the agency's facility, so E might be negative.

Note that this saving could represent the incremental saving to the local transit agency alone or to the combination of all agencies that finance the service (local agency plus local, state, and federal governments). Transit agencies are basically responsible for operating and maintenance costs and receive grants for capital equipment from the federal government and other levels of government. Hence savings to the local transit agency would be different from those to government. Also, as noted in the paper, there are significant differences between private firms and public agencies with respect to taxation and user charges for public facilities (e.g., trash, sewers). Although "a leveling of the field" exercise with respect to these items is mentioned, it appears as though the end result is that no correction for taxes and user fees was applied. This biases the estimates in favor of a reduced level of cost savings. Another important distinction is between short-run and long-run costs and savings, and the author of the paper correctly distinguishes between these.

The private-public difference also relates to use of depreciation as a measure of value of capital expenditures. Depreciation itself is an arbitrary procedure for spreading expenditure over the depreciable life of the asset, and it has no real meaning as a true equivalent annual expenditure. This is well documented in engineering economics texts and need not be discussed in detail here [see, for example, Au and Au (*3*, p. 286 ff.)]. Instead of depreciation, the proper cost to use would be the annual equivalent cost based on use of the capital recovery factor (but of course considering the effect of depreciation allowances on taxes and after-tax income). Sufficient detail is not presented in the paper about how depreciation was used to adjust costs, so the impact on overall savings is unclear.

Turning to specific cost issues, the comparison of overall bus fleet maintenance using three different approaches bears comment. Under Approaches 1 and 2 maintenance costs under contracting are compared with the estimated average cost to public systems that are similar in a number of features including fleet size. This would appear to be appropriate only if the public agency that otherwise would have undertaken the maintenance was indeed the same size as the private firm. If, as is more likely, the public agency were larger and contracted only a portion of its vehicle maintenance, then the relevant comparison would be between private contractors and larger public agencies. This suggests that Approach 3 is really the most relevant comparison for purposes of estimating savings.

A second area of concern is certain parameter estimates and equations. Specifically, the estimates of 6 percent of other costs for insurance and 5 percent for monitoring bear discussion. Actual experience with monitoring costs of public services that are similar to public transit indicates that monitoring costs can be as high as 12 percent (*4*, p. 16). Also, the specific equation used for estimating depreciation costs for the "average incremental cost of capacity expansion" (in the section on Bus Maintenance Job Contracting) should be explained. Similarly, the "unit shared costs" in this section are also insufficiently defined. Finally, throughout the paper, when costs had to be estimated from aggregate data, as in the case of vehicle maintenance costs in public agencies, average costs were used on the assumption that costs are proportional to maintenance activity (e.g., vehicle miles). This is a strong assumption, and some discussion of its validity is certainly warranted.

Finally, a major issue in contracting is whether or not the products obtained through contracting and in-house production are indeed equivalent. In transportation it is generally possible to specify clearly and unambiguously what the product should be and to monitor the provision of the product so that deficiencies in quality should not be a problem. However, the discussant wonders whether or not in an area such as cleaning there might be quality differences, particularly when the contractors use lower-paid part-time labor.

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AUTHOR'S CLOSURE

Morlok's discussion of the concept of savings resulting from competitive contracting is commendable. The discussion provides further insight to readers of the paper. The discussant does raise a few questions with regard to certain numerical values used in the cost comparison analysis. The intent of this closure is to provide answers to these questions.

Cost Element E, which represents additional costs of producing the remaining services in-house after contracting out, is likely to be experienced by a transit agency especially after contracting some of the existing services. In cases in which new services are contracted such effects may not occur. The value of E was assumed to be zero in the paper because all five cases represented turnkey service contracts for new services. Similarly, in the cases of maintenance job contracting no attempt was made to quantify such effects. This particular cost element is appealing but difficult to forecast accurately.

In the paper it is explicitly indicated that no correction was applied for taxes and user fees paid by private service providers because they are considered to be common costs of doing business in the private sector. This assumption is in compliance with the recommendations of the Competitive Services Board, which was created to develop cost comparison guidelines on competitive bidding (*1*).

In recognition that public operators have access to low-interest capital and, in most cases, receive federal grants to match up to 75 percent of their capital requirement, it was considered reasonable to isolate and subtract maintenance facility–related expenses from the contractor's bid before cost comparison. Because in three cases (DART II, Snohomish, and Yolobus) private bids were not explicit about such expense items, the annual cost of capital for maintenance facility and storage space was estimated for each case depending on the fleet size. For the purpose, first space requirements were calculated using general space standards for functions to be kept in house. Next, assuming a unit area cost of $\$52/\text{ft}^2$, the capital requirement was estimated and then depreciated over a 30-year period using the straight line method.

TABLE 4 VEHICLE INSURANCE PREMIUM DURING 1984

	Range of Observed Physical Damage Insurance Premium in 1984	
Case Study Sites	$/RVM	Percentage of Contractor's VM Cost
Dallas (DART II)	0.017–0.040	2.58–5.87
Snohomish County	0.027–0.065	5.61–12.52
Fairfax County	0.009–0.022	2.66–6.06
Johnson County	0.014–0.034	2.37–5.43
Yolo County	0.012–0.028	3.48–7.82

The assumption of 5 percent of bid cost as monitoring expenses actually represents the average monitoring costs derived from a nationwide survey of transit contracting (*2*). In general, monitoring costs are observed to vary in a range of from 3 to 10 percent.

The premium for liability insurance paid by public transit agencies with fewer than 200 buses during 1984 was observed to vary within a range of from $340 to $800 per bus. Table 4 gives, for each of the five cases considered, the estimated range of insurance cost per revenue vehicle mile (RVM) and the share it represents of overall maintenance cost. The assumed value of 6 percent falls within the estimated ranges and coincides with the Wisconsin Municipal Insurance Commission rates of 1984 (i.e., $0.0324/RVM).

The quality of service provided by private contractors remains a major concern of public agencies considering contracting as an alternative mode of service delivery. However, in the area of bus cleaning, contrary to the discussant's perception, public agencies generally appear to be little concerned. In both cases of cleaning contracting mentioned in the paper, public agencies expressed satisfaction with the performance of their contractors. Bus cleaning should be considered a good candidate for contracting because it is labor intensive, demands few skills, and is generally a job least preferred by maintenance workers. As pointed out in the paper, substantial savings in this area are experienced by both public agencies.

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Objectives for a Transit Bus Fleet Management Data, Information, and Knowledge Exchange

T. H. MAZE

Exchanges for bus equipment and bus fleet performance data, equipment management information, and fleet management knowledge, following several different formats, have been proposed and attempted. However, the objectives and structure of the proposed exchanges are usually poorly defined. In this paper objectives for an exchange are recommended and data, information, and knowledge that should flow through an exchange are discussed. Highlighted in the paper is the partitioning of exchange flows into levels. Data flows represent the least processed level of exchange, information flows represent processed data, and knowledge flows are the most highly processed level of exchange. The more highly processed the exchange, the less interpretation is required before application. For the exchange to be of maximum value, it should provide information on all three levels.

The purpose of this paper is to provide guidance on an issue of current interest to transit bus fleet managers; bus equipment manufacturers; and mass transportation administrative agencies at the local, state, and federal levels: creation of an exchange for bus equipment and bus fleet performance data, equipment management information, and fleet management knowledge. Although the initiation of an exchange has been a topic of recent concern to bus fleet managers, the recommendations provided in this paper are equally applicable to managers of other public works fleets (transit agencies are considered members of the public works family of service agencies).

INTRODUCTION

The focal point of the paper is a series of recommended objectives for an exchange. The importance of the proposed objectives lies in the direction they provide for structuring an exchange. The exchange of bus equipment and bus fleet performance data, equipment management information, and fleet management knowledge is an attractive concept, and establishing such an exchange has been proposed on several occasions. However, the objectives that proposed exchanges are to achieve are usually poorly defined. In at least one case (and probably in others), a lack of clearly defined objectives caused an attempted exchange to founder during its demonstration. In this paper concepts of exchange level development are defined and specific objectives are recommended for future efforts to initiate an exchange.

MOTIVATION FOR AN EXCHANGE

In 1982 the Transportation Research Board (TRB) organized a conference on bus maintenance (*1*). One of the charges of the conference was to recommend activities that offered the potential of improving the performance of bus maintenance. A highly recommended management tool was the creation of a "national information network for sharing data on major model-specific defects" (*1*, p. 36). A second bus maintenance conference was organized by the TRB in 1984 (*2*). During the second conference the attendees indicated that the single most important issue facing bus maintenance managers was the creation of an "improved information exchange."

Since the 1984 TRB conference there have been several efforts to improve the exchange of information on bus maintenance and bus performance. The American Public Transit Association (APTA) has taken a key role in the promotion of exchange and has organized biannual workshops on bus equipment and maintenance. Periodically APTA devotes a section of its weekly newspaper, *Passenger Transport*, to bus maintenance topics. The Urban Mass Transportation Administration (UMTA) and other organizations (i.e., state or regional transit associations) have also attempted to promote exchange in various fashions ranging from highly structured exchanges of computerized maintenance data to informal discussions of garage-level problems. Universities and research organizations have promoted exchange through formal presentations and classroom-style workshops (*3*). However, all of these efforts are clearly changing with time and they will evolve to different forms and improve in the future.

A discussion of these transitory exchange efforts is, however, outside of the scope of this paper. Many current forms of exchange are likely to shortly change. However, current efforts to promote exchange indicate the industry's recognition of the importance and value of exchange.

The creation of an exchange is an attractive notion, and it has been attempted by other industries. For example, in the early 1970s, the American Public Works Association (APWA) sponsored an attempt to create a national data base to identify the performance of public works equipment (e.g., garbage packer trucks, street maintenance equipment, pickup trucks) (*4*). At the time, pooling of data from several public works agencies appeared to be feasible because many of the agencies used the same service organization to process their equipment management information. Because several public works agencies were already using the same data coding structure and their data

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were processed by the same software package, the service organization believed it could process several agencies' data simultaneously and produce summary information. For example, the service group could compute the average cost per equipment operating hour or maintenance labor hours per piece of equipment using the combined data of all of its client public works agencies. The summary information would serve as a point of reference against which individual agencies could judge their own fleet's performance. Unfortunately, the APWA's attempts failed, mainly because of the lengthy computer processing time required to produce summary statistics using early 1970s computers. However, because of the increased computing speed of current computers (late 1980s), APWA is again interested in developing a similar data pool (private communication with Robert Bugher, Executive Director of the APWA, 1987).

The Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA) have successfully developed an extensive exchange that is operated by the Navy (*5*). Since the early 1970s, many DOD-NASA organizations and contractors have been required to submit data and reports from technical studies that document the costs, reliability, and maintainability of equipment to the Government-Industry Data Exchange Program. Although the Navy does not have an exact mechanism for estimating the benefits of their data exchange system, users are surveyed annually and asked to estimate the costs they avoided as a result of the exchange. In 1985 more than $61 million in savings were reported by the system's users; the operating cost of the exchange was roughly $3 million (*5*). These results have led the Navy to conclude that the savings and cost avoidance accrued through the use of the exchange far exceed the exchange's operating costs and the exchange members' costs for use of the system.

Levels of Exchange

Clearly, exchange can be at many levels ranging from informal discussions of garage floor problems to structured exchange of computerized data. To classify exchange levels, flows are divided into three levels: exchanges of (a) data, (b) information, and (c) knowledge. There are significant differences in the attributes of data, information, and knowledge. These terms are defined [the definitions are adapted from those of Horton (*6*)] as follows:

1. Data: A datum is simply the relationship between some measurable attribute and a specific event. For example, data on failures of a specific bus component (e.g., transmissions) will consist of miles traveled or hours of use (a measurable attribute) until each component failure (the event). Such failure data may be derived by reviewing maintenance work orders or vehicle maintenance history logs. Data are the lowest level of maintenance and vehicle performance flow.
2. Information: Information is processed data and it reduces the uncertainty of future events. For example, if statistical analysis is performed on component failure data, the statistics (i.e., the mean miles between failures, the standard deviation of miles between failure, and other statistical parameters) can help to determine when to expect future failures of the same component. Statistical information reduces uncertainty because it aids in the making of forecasts of future failures.
3. Knowledge: Knowledge is highly processed data, and the creation of knowledge from data requires independent judgment and interpretation of data analysis. For example, if failure data and repair cost data were analyzed, it might be possible to specify a component's minimum cost replacement or overhaul interval (e.g., overhaul engines every 250,000 mi or at failure). Procedures for determining the optimal interval between component overhauls are knowledge. Procedures are one form of knowledge. Other forms involve factual and judgmental knowledge. Factual knowledge requires the study of data sets to derive facts. For example, Duffy et al. (*7*) compared the use of prerun inspections by transit systems and found that transit systems with more thorough prerun inspection procedures tended to enjoy better maintenance system performance as indicated by mechanic labor hours per mile. Judgmental knowledge is derived from observing data without the use of formal data analysis. For example, during their study of prerun inspections, Duffy et al. found that, in the judgment of most maintenance managers, the use of prerun inspections improves maintenance performance (*7*).

The distinctions among data, information, and knowledge are quite important. The value of an exchange will be largely a function of the format, structure, and level of exchange (i.e., data, information, or knowledge). For example, if only raw data are exchanged, then, for the exchange to be valuable to the participants, each participant must have the capability of processing raw data into either information or knowledge. Some sophisticated transit agencies may find a raw data exchange beneficial. However, many others without complex data processing skills are not likely to find raw data worthwhile. Thus it is apparent that the utility and success of an exchange will be dependent on the data, information, and knowledge that flow into and through the exchange and on matching the level of exchange (i.e., data, information, or knowledge) to the requirements of exchange users.

Types of Exchange

Current methods of exchanging bus equipment and bus fleet performance data, equipment management information, and fleet management knowledge are relatively diffused and require quite different development approaches. For example, the APTA conferences on Bus Equipment and Maintenance are largely devoted to the exchange of judgmental knowledge (informal analysis derived from experience). UMTA has promoted, through a demonstration project, the exchange of statistical information through a centralized computer data base that contains maintenance data records from several transit agencies. Each of these represents an exchange of maintenance data processed to different levels (processed to become information or highly processed to become knowledge). The usefulness of each level depends on the user's ability to interpret the materials being exchanged. For example, knowledge requires little interpretation before it can be applied whereas pure data require a good deal of analysis and interpretation. The relative popularity of APTA's conferences, as witnessed by their increasing attendance, leads to the conclusion that many bus maintenance managers find exchange at the knowledge level (particularly judgmental knowledge) quite useful (*8*, p. 6).

Contrasting the various methods of exchange illustrates that no one single means of exchange is appropriate for all users all of the time. Sophisticated users often may only require access to a data bank; they can perform their own analysis to develop information or knowledge. Others may find data processed to the information level, or even data that are highly processed to the knowledge level, more useful. Further, some topics may be appropriately exchanged at only one of the three levels. For an exchange to be of universal utility to all potential users it should contain all three levels.

EXCHANGE RECOMMENDATIONS

The first step in the development of any activity is to establish a management plan. A management plan should include fundamental planning components; objectives to be achieved by the operation of the activity; rules, procedures, and programs; and a budget to govern the activity's operation. Clearly, it is premature to propose operating rules, procedures, programs, and a budget for an exchange. However, it is reasonable to recommend general objectives for an exchange of bus equipment and bus fleet performance data, equipment management information, and fleet management knowledge.

PROPOSED OBJECTIVES

Proposed objectives for an exchange are categorized by their time frame. Some are continuing objectives to be accomplished throughout the life of the exchange. Some objectives can be accomplished with a relatively small amount of historical data; these are short-term objectives (within 1 year). Some can only be accomplished with several years of historical data; these are midterm objectives (1 to 3 years). Other objectives can be accomplished when historical data are available for a long enough period to gain a maintenance profile over a bus's life; these are long-term objectives (5 years or more).

Proposed Continuing Objectives

Clearly there are nontechnical, fundamental goals that should be common to any system, such as deriving the greatest cost savings for the system's users, attracting a large number of regular users, and other standard goals. However, continuous technical objectives for an exchange should include the following items.

Development of Standards

Most transit systems have institutional and environmental differences that, to some extent, make maintenance and operating data from different agencies inconsistent. For example, a transit agency may have mechanics who are more qualified than mechanics at other transit agencies, which, in turn, makes the performance of the agency's maintenance system superior. Differences in mechanic performance may be due to factors that are under the maintenance manager's control (such as mechanic recruitment and training programs). Differences may also be due to institutional factors outside the fleet manager's control. For example, the fleet manager may be unable to offer wages that will attract competent mechanics, or there may be local socioeconomic factors such as a lack of competent diesel mechanics in the local labor pool. The extent of inconsistencies grows even more serious when a comparison is made of local data collection methods, definitions, and data accuracy. Uniformity is further diminished by differences in maintenance procedures, policies, rules, and practices. Comparability is also made even more difficult by variations in environmental and route service factors such as duty cycles, fleet age, the terrain covered by routes, weather, and ridership levels.

Because of the variations among agencies, an exchange should strive to develop standard procedures for data definitions and collection. By minimizing the institutional variations in data definitions and data collection, the exchange can increase the comparability of the maintenance operations of individual users. Thus a continuous objective of the exchange should be to strive for standard definitions and data collection procedures. A first step toward uniformity would be the adoption of a standard job coding system for maintenance and servicing of transit buses. If a standard code were adopted, maintenance and servicing jobs could be recorded by transit agencies using the same alphanumeric codes for job and cost categories. The code could be developed and kept up to date in a manner similar to that used for the American Trucking Associations' *Vehicle Maintenance Reporting Standards* (*9*).

Comprehensive Coverage of Levels of Exchange

UMTA's experimentation with a national computerized bus maintenance data base and information exchange provides an illustration of the need for comprehensive coverage of all levels of exchange (*10*). The primary purpose of UMTA's system was to take data from individual transit systems, merge the data, and derive summary statistics on a national basis (e.g., cost per repair, labor per repair, total maintenance costs) and possibly even identify specific model defects that exist in contributors' bus fleets. An individual system could then use the summary statistics to make comparisons with its own performance.

During the demonstration of UMTA's computerized data base and information exchange system, a liaison board of knowledgeable transit professionals was asked to evaluate the exchange. Members of the liaison board from large transit systems with sophisticated maintenance management information systems and detailed data bases failed to see the value of having access to a national data base because they already had their own detailed performance statistics. In general, a data base with more detail will have a greater number of maintenance job codes, which permits greater accuracy in identifying specific maintenance jobs. When detailed data sets are merged with less detailed data sets, the detailed data sets are condensed and job codes are aggregated; information is lost in the aggregation process. Liaison board members from large transit systems thought that their own sophisticated information systems were likely to provide them with more detail than would a national data base because of aggregation problems.

The specific reason for larger systems being unattracted to UMTA's exchange is probably that the system only exchanged information at one level. The UMTA system provided only summary statistics, using a national data base, that are similar to those commonly produced by individual maintenance management information systems. Further, the data would have to be aggregated into the least common denominator of job codes and classifications used by transit agencies contributing data to make the data from each agency compatible.

The UMTA project foundered during its demonstration because of a lack of clearly defined objectives. After the demonstration phase, UMTA's proposed exchange was shelved. Even at the final liaison board meeting, the board did not fully understand the objective of the exchange system (*10*).

A comprehensive exchange should provide data, information, and knowledge that an individual system could not derive on its own. For example, a national exchange should be able to provide transfer of knowledge through (a) research conducted using a national data base; (b) dissemination of one transit agency's technological innovation; (c) exchange of technological innovations from related industries; and (d) technical, engineering, and management training. Thus the exchange should strive to comprehensively exchange data, information, and knowledge.

Proposed Short-Term Objectives

Short-term objectives are generally those that can be achieved with a modest amount of data on maintenance performance from individual data contributors. Proposed short-term objectives include the following items.

Identifying Model-Specific Defects

The identification of model-specific defects was identified as a primary purpose for the development of a national data base in the 1982 TRB Conference on Bus Maintenance (*1*). A defect is usually identified by premature failures and possibly other performance attributes (e.g., high fuel consumption) that indicate a flaw in design or manufacture. Equipment flaws, or even equipment that performs below expectations, can be brought to the attention of manufacturers so that they may rectify the problem. Also, agencies that own the equipment could be made aware of the defect, its special conditions, and possible ways to design out the defect (e.g., retrofits).

An exchange could identify specific defects with modest amounts of data. As an example, studies could be conducted that are similar to the Transportation Systems Center's (TSC's) reliability study of V730 transmissions in 1982 (*11*). The TSC study successfully identified the poor reliability of early models of the V730 transmission with transmission life data from only a few large transit systems. As one equipment manufacturer pointed out, such field-collected data can be quite valuable to the manufacturer in product improvement because "laboratory and proving ground tests are conducted on a relatively small number of samples due to the great cost involved. . . . Quite often preventive maintenance and service practices tend to be more idealized in proving ground tests. . . ." (*12*). A national data base provides the opportunity to examine a large number of pieces of equipment under actual operating conditions.

Tools, Diagnostic Equipment, and Tests

Methods of conducting maintenance are constantly being improved by the use of special tools, diagnostic equipment, and test procedures. Sessions at APTA's Bus Equipment and Maintenance conference are often devoted to improved methods. Knowledge of these methods should be reported and disseminated through an exchange. The exchange should stress the importance of reporting improvements in standard formats with data that provide evidence of the method's effectiveness and cost savings.

Training

The exchange should seek to facilitate training at all levels: maintenance labor, front-line supervisors, and fleet management. Training can be facilitated through exchange of existing materials, organization of workshops, and preparation of training materials.

Performance Data

In the short term, data on performance measures could be collected from transit properties. The performance measures could serve as a basis for comparing the productivity of individual transit systems with national averages. Of course, individual transit agencies must realize that performance measure averages may not be comparable to their own system.

The idea of creating national averages (standards) for performance is attractive, and efforts to create national fleet performance standards have been made in the past. In 1951 the American Transit Association established a panel of operating executives to establish a set of "transit pars" for transit industry performance (including maintenance) (*13*). The pars were standards for performance measurements, and they were designed to help management test the efficiency of their transit system.

Proposed Midterm Objectives

Midterm objectives are generally those that can be achieved within 1 to 3 years. Midterm objectives may involve the analysis of maintenance system performance of individual contributors of data to derive information and knowledge about the desirability of management practices of individual agencies.

Management Procedures

Maintenance management practices tend to vary dramatically from one transit system to the next. For example, the preventive maintenance activities that are conducted and the frequency of preventive inspections vary greatly even among transit agencies with similar duty cycles and equipment. The frequency of preventive inspections has been commonly observed to vary from 2,000 mi between inspections (2,000-mi inspections are largely for safety reasons) to 8,000 mi between inspections. Presumably there must be significant differences in the cost of preventive and corrective maintenance, and the reliability of equipment, when inspections frequencies vary so widely. However, there exists little information that, through empirical data analysis, identifies the trade-offs and advantages of various preventive maintenance strategies.

A midterm study (between 1 and 3 years) of maintenance performance data and the corresponding practices of individual contributors of maintenance data could identify the trade-offs and advantages of management strategies and policies. Studies could also cover (a) management control systems used by transit maintenance departments to better control labor time allocation, material dispersal, and consumable dispersal (e.g., fuel and oil); (b) maintenance staffing levels and skill distribution and the effectiveness of training programs to update and improve skill levels; (c) the effectiveness of conducting maintenance functions in house versus contracting them out for fleets of various sizes, maintenance labor skill levels, and maintenance facility and maintenance equipment resources; and (d) studies of other maintenance management practices that tend to vary from one system to the next or of practices that appear innovative and timely.

Equipment Innovation

Bus equipment innovation and equipment design issues are being researched by individual transit systems. For example, a summer 1987 "Bus Tech" in *Passenger Transport* reported that 13 transit systems were experimenting with alternative fuel systems (i.e., methanol fuel, compressed natural gas, and propane gas) (*14*, p. 6). Other areas of equipment innovation include the use of new nonasbestos brake blocks, drive line retarders, and emission control equipment. The exchange could set standards for the reporting of experimental results and provide engineering analysis of experimentation that appears to provide a high level of equipment improvement.

Proposed Long-Term Objectives

Long-term objectives are those that may not be achievable without several years of data (5 years or more). Long-term objectives may involve the analysis of maintenance and cost data that cover the entire life of a bus. A proposed long-term objective involves the collection of data to permit life-cycle cost analysis to be conducted.

Because buses have minimum lives that span several years, it is difficult to gain information on life-cycle costs and life performance data (i.e., reliability, maintainability, and availability) over a bus's entire life without a long-term data collection effort. The long-term collection of life costs and life performance data would be of tremendous assistance in the selection and specification of equipment, replacement and bus rehabilitation decision making, and budgeting for future maintenance and capital costs. Knowledge of equipment performance over its life is essential for setting the most cost-effective spare ratio policies. Of course, all cost data must be tempered by the data contributor's unique operating environmental conditions and duty cycle.

CONCLUSIONS

For an exchange to be of the greatest value it should strive to provide exchange at all levels: data, information, and knowledge. This is not an easy task and requires a significant effort and a long-term funding commitment. The performance of the Navy's Government-Industry Data Exchange Program illustrates the benefits of an exchange (*4*). However, its roughly 15-year existence and its approximately $3 million per year operating budget illustrate the significance of the support required to achieve the benefits that are possible through an exchange.

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