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

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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.

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

Year	Nitrogen Oxides (g/bhp-hr)[a]	Particulates Buses (g/bhp-hr)[a]	Particulates 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.

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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