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

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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.

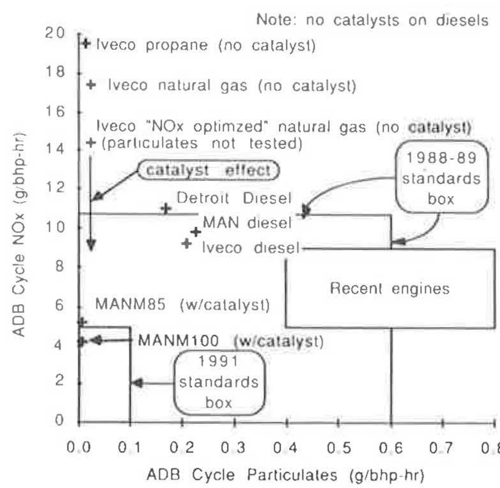

FIGURE 1 Advanced design bus cycle emission rates of various engines in Canadian tests versus EPA standards and recent late-model diesel engine emission rates (*1, 3*).

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).

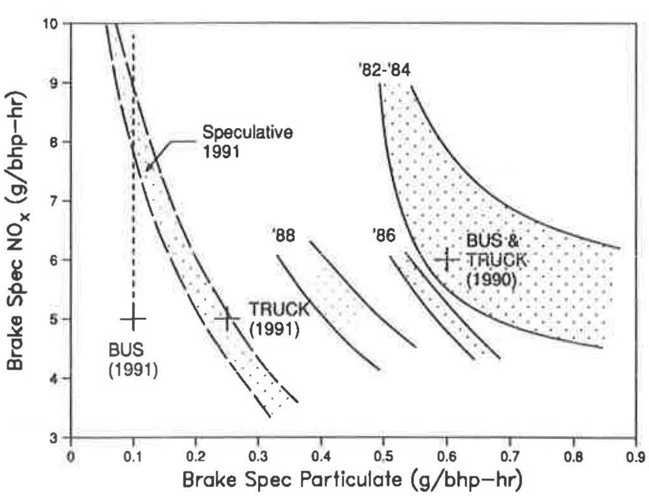

FIGURE 2 Past, present, and speculative future examples of the particulates-NO_x trade-off for heavy-duty diesel engines (1982–1988 curves from Duggal).

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.

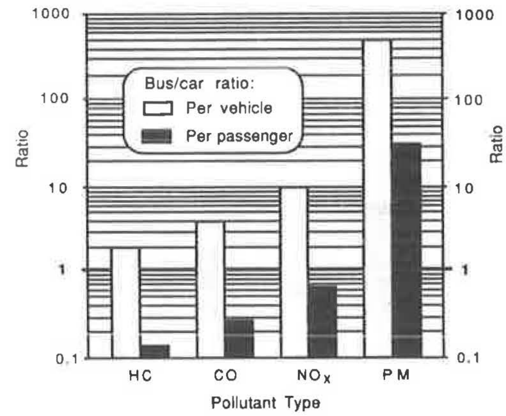

FIGURE 3 Ratio of uncontrolled bus emissions to passenger car emissions, 1980 vehicles (log scale) (*1*).

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/m^3, while the concentrations in the center of London were 176.6 mg/m^3 (*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/m^3 figure for London's CBD was well above the background level of about 115 mg/m^3.

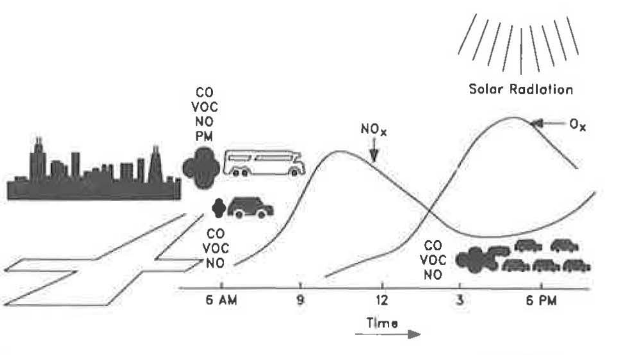

FIGURE 4 A simplified illustration of the complex process of NO_x and O_x chemical reactions [adapted from Wilson (*5*)].

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

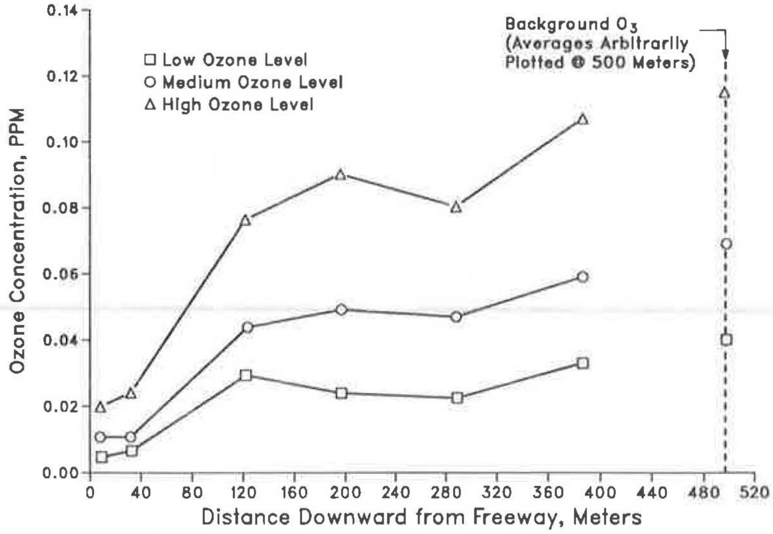

FIGURE 5 Ozone (O_3) data from the EPA's 1979 NO_2/O_3 sampler siting study (*6*).

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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