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1988-03-01

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UCI-ITS-WP-88-2

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March 1988

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ABSTRACT

This paper investigates the cost-effectiveness of three strategies for reducing particulate and sulfur-oxide emissions from diesel transit buses. 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 other strategies per unit reduction in total particulates; but this disadvantage is greatly reduced using the other indices. In addition, methanol achieves the greatest absolute emissions reduction. With the mortality-based index, the incremental cost of the methanol strategy over particulate traps in the Los Angeles basin comes to $1.6 million per incremental reduction in expected deaths.

To be published in Transportation Research Record, 1988. This work is supported by a grant from The John Randolph Haynes and Dora Haynes Foundation. The author is grateful to Jane Morrison for research assistance, and to the following people for helpful comments: Stephenie Frederick, Charles Lave, Jane Morrison, Dan Santini, and four anonymous referees. However, responsibility for the results and opinions expressed lies solely with the author.

REDUCING TRANSIT-BUS EMISSIONS: COMPARATIVE COSTS AND BENEFITS OF METHANOL, PARTICULATE TRAPS, AND FUEL MODIFICATION

Two recent directions in policy toward 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 startup 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 to methanol, even starting from the low-sulfur diesel fuel now required there. Sulfate reduction accounted for about two-thirds of the estimated benefits.

However, one must also consider alternative means of reducing diesel emissions such as cleaner fuel and trap-oxidizers (also known as particulate traps). 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, all 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, diesel-fuel quality will deteriorate. Nevertheless, we will see that low-sulfur fuel is an attractive strategy even under much more pessimistic assumptions. For these reasons, it seems 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, I further explore such cost-effectiveness comparisons by introducing several variations and refinements to Weaver et al.'s analysis. First, as just noted, I adopt low-sulfur fuel as a baseline, but with less optimistic assumptions about engine wear and aromatic content. Second, I incorporate sulfur-oxide (SO_x) emissions into the effectiveness measure, exploring the consequences of various estimates of its noxiousness relative to that of particulates. Third, I examine the incremental cost-effectiveness of using a methanol strategy to achieve reductions beyond those achieved by clean fuel and/or particulate traps. Finally, I vary the price of methanol fuel. The result is a confirmation of the promise of particulate traps, and a clearer delineation of the potential role of methanol.

I adopt relatively optimistic assumptions throughout for both particulate traps and methanol, assuming success of current efforts to overcome technological barriers. I also use data from the Los Angeles air basin for many of the needed parameters, though the comparisons of pollution-control strategies should be representative of most U.S. urban areas.

EFFECTIVENESS MEASURES

I consider three different methods of weighing the damaging effects of particulates and SO_x. (Nitrogen oxides, or NO_x, are not considered due to 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 above; 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 toward 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 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 diameter 10 microns or less. Since diesel emissions are mainly in this size category, the severity of their effects is probably larger than implied by the methods used here. This would make particulate traps relatively more attractive compared to 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, belong 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. Based on atmospheric modeling (7), the California Air Resources Board staff estimates that each gram of SO_2 emitted produces 1.2 grams of particulates in the atmosphere (8, pp. 60-63). Citing this estimate, Weaver et al. 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. non-sulfate) 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 CFR 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 by the facts that ambient standards are set for both sulfates and SO_2, and that the latter 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 are:

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

$$C_p = a_pE_{tp} \tag{2}$$

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

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

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

(ii) Ambient concentrations of sulfates and of SO_2 are each proportional to SO_x emissions, with different proportionality constants:

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

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

(iii) The damage from an ambient concentration pertaining 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 damages from these three ratios are 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:

$$D = b\left(\frac{C_p}{\overline{C_p}} + \frac{C_{so4}}{\overline{C_{so4}}} + \frac{C_p \cdot C_{so2}}{\overline{C_{pso2}}}\right) . \tag{7}$$

By substituting equations (2)-(6) into (7), we can calculate the relative severities of the two types of emissions (particulates and SO_x)

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 (2), (5), and (6) to eliminate the proportionality constants, we have:

$$D_p = \frac{1}{E_{tp}}\left(\frac{C_p}{\overline{C}_p} + \frac{C_p \cdot C_{so2}}{\overline{C}_{pso2}}\right) \tag{8}$$

$$D_{sox} = \frac{1.2}{E_{tp}}\left(\frac{C_p}{\overline{C}_p} + 2\cdot\frac{C_p \cdot C_{so2}}{\overline{C}_{pso2}}\right) + \frac{1}{E_{sox}}\left(\frac{C_{so4}}{\overline{C}_{so4}}\right) . \tag{9}$$

The three standards are those applying to California in July 1983, just prior to the new fine-particle standard. In all three cases the averaging period is 24 hours (when there is more than one standard for the same pollutant, I use only the 24-hour average). Ambient concentrations are taken to be the highest 24-hour 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, since 1985 estimates are not yet available.

Table 1 lists 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 (ii), 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. 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, 366-7, 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 (15, pp. 111-112) for further discussion.

The resulting values are $D_p = .0104$ and $D_{SOX} = .0310$, with ratio $D_{SOX}/D_p = 2.97$. Hence we define

$$\text{Severity Index} = P + 2.97(SO_x) \quad . \tag{10}$$

Mortality Index

The statistical work reviewed in (1) finds 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 proportional to carbonaceous particulate emissions, and sulfate concentration to SO_x emissions. Hence the proportional rise in mortality $\Delta M/M$ caused by bus emissions P and (SO_x) is:

$$\Delta M/M = .0119x[P/E_p] + .0500[(SO_x)/E_{SOX}] \quad . \tag{11}$$

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

$$\Delta M/M = 54.4x10^{-12}[P + 17.0(SO_x)] \quad . \tag{12}$$

Hence I define:

$$\text{Mortality Index} = P + 17.0(SO_x) \quad . \qquad (13)$$

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 subsection below. 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, I assume that any area giving serious consideration to methanol would first adopt the .05 percent sulfur standard for diesel fuel, and analyze all strategies relative to that. I do not assume either the reduction in aromatics or the increase in engine life suggested by Weaver et al.'s analysis, since those benefits have not yet been confirmed. I do include, however, the reduced maintenance requirements that they estimate: an $8,000 engine overhaul at 234,000 instead of 180,000 miles, plus a $35 oil change every 6,500 instead of every 5,000 miles.

I assume that each bus runs 34,115 miles per year and lasts $T=12$ years: this was the case for Southern California in 1984 (16), and is similar in other areas of the U.S. Following Weaver et al., the baseline fuel economy is set at 3.81 miles per gallon. I also assume a real interest rate r of 8 percent per year compounded continuously; thus expenses occuring 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 two 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 one gallon every 3.81 miles therefore emits 0.026 g/mi sulfates and .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 our purposes are from buses in actual use, tested with the Environmental Protection Agency (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 as above but for fuel with 0.3 percent sulfur), we have 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 byproduct of producing low-sulfur fuel. They also analyze a fuel in which aromatics are lowered still further, to 17 percent, finding that this adds only 0.3 cents per gallon to the cost. Extrapolating linearly to estimate the cost of reducing aromatic content from our 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 aromatics reduction. Fuel economy tends to be lower during steady operations but higher during warm-up, so is assumed 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. I therefore adopt their estimates for the ceramic monolith with a catalytic afterburner (permitted by the low-sulfur fuel) as representing a realistically optimistic strategy.

These estimates are: $1,100 capital cost; $350 maintenance cost every 45,500 miles; 3 percent degradation of fuel economy; 85 percent reduction in carbonaceous particulates from the trap, and an unspecified reduction from the afterburner which I take 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 scenarios combines the extra cost of low-aromatic fuel with the extra vehicle costs and fuel-economy penalty of the particulate traps. I use Weaver et al.'s estimate of a 95 percent reduction in carbonaceous particulates.

Methanol

In this scenario, buses use methanol fuel 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-$7,000 by General Motors, assuming regular production (19, p.125). Of course, further refinement of the technology may reduce this differential. I use Weaver et al.'s "optimistic" estimate of $5200.

The effects on engine life, routine maintenance, and engine-overhaul frequency are not yet known due to 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 lubricating-oil degradation as 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.

I adopt Weaver et al.'s "optimistic" fuel economy of 1.81 miles per gallon of methanol. Since methanol's energy content is about 45 percent of 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. As for emissions, I adopt Weaver et al.'s optimistic estimate of a 95 percent reduction in carbonaceous particulates; sulfur oxides are entirely eliminated.

Fuel Prices

The comparisons to be made here are very sensitive to the price differential between diesel and methanol fuel. Since 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 have a single price for each scenario.

The price of number 2 diesel fuel delivered directly by refiners to large end users has varied widely, ranging between 40 and 86 cents per gallon in 1985-87, 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 40-86 cent range. I take it to be 75 cents and add 3 cents for desulfurization.

For methanol, the market 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 55-60 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, I adopt a price equal to the lower end of the recent range, 55 cents per gallon. Note that when energy content is corrected for, this is $1.22 for the amount of energy contained in one gallon 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 shows the extra cost, compared to the baseline scenario, of each of the four control strategies under the above assumptions. It also shows, 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 on each index, a change of one unit produces pollution damage equivalent to one kilogram of particulates; hence we may think of the indices 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 my 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 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 \$1.59 - \$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 as we move to the right in Table 3. To determine whether the more stringent strategies are justified, we must look at the incremental cost of achieving a higher degree of stringency, and compare that with the social benefit of further control or with the cost of making the same reduction from other sources.

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 portray the classic rising marginal control cost as portrayed 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).

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 portray 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 per kilogram, 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 8025 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 4432, 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 per year.

These numbers enable us to assess the value that one would have to place 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." Table 3 implies 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 U.S. are willing to forego 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 above 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, materials 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 accounted for 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 large as the annualized extra vehicle cost. Hence, any comparison between strategies is sensitive to these very uncertain fuel prices.

Table 4 presents just the comparison between particulate traps and methanol, but with the methanol-diesel price differential ranging from zero to $1.11 per amount of energy contained in a 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 per gallon, 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 favorable 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 social value of $37 estimated above. (Methanol's incremental cost-effectiveness relative to particulate traps, not shown on the table, is $18/kg at that price.) Hence a strong case can be made for methanol even at this substantially higher price if one believes mortality reduction to be worth the amount suggested by the discussion above.

The Low-Sulfur Baseline

This same methodology can be used to check the internal consistency of my 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; whereas 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, $0.64 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, the low-sulfur fuel has a cost-effectiveness as good as 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 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. Accounting for 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 diesel would particulate reduction alone justify a methanol strategy, assuming a particulate-trap strategy is feasible.

Taking sulfur into account, however, the picture changes. The incremental cost of using methanol to reduce noxious emissions by the equivalent of one kilogram of particulates is either $43 or $7.50, depending on which of two estimates of sulfur's noxiousness one believes. The latter is well within the range that could justify a methanol strategy. Furthermore, if methanol's price were to drop to the same as diesel on an energy-equivalent basis, its cost-effectiveness would become more favorable than particulate traps using either measure, and would achieve a higher degree of control 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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TABLES

Table 1. Data for Severity Index[a]

Concentrations:	Standard ($\bar{C}$)	Actual (C)	Ratio ($C/\bar{C}$)
Particulate (p)	100 $\mu g/m^3$	208 $\mu g/m^3$	2.08
Sulfate (so4)	25 $\mu g/m^3$	20 $\mu g/m^3$	0.80
Partic. and SO_2 (pso2)	(100 $\mu g/m^3$) x(.050 ppm)	(208 $\mu g/m^3$) x(.021 ppm)	0.874

Emissions:	(E)
Particulates (p)	218.6 x10^6 kg/year
Sulfur Oxides (s)	54.1 x10^6 kg/year

[a] Sources:
Standards: (<u>10</u>), pp. 14, 44.
Concentrations: (<u>11</u>), pp. 42,45,41.
Emissions: (<u>12</u>), p. 17.

Table 2. Assumptions

Annual Mileage	34,115	Real Interest Rate	8.0%
Bus Life (years)	12	Capital Recovery Fct	0.1296

	Baseline	Fuel Mod.	Partic. Traps	Fuel Mod. & Partic. Traps	Methanol
Extra Vehicle Cost:					
Capital ($)	0	0	1,100	1,100	5,200
Maint. ($/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):					
Carbon. Partic.	6.080	4.256	0.608	0.304	0.304
SO4	0.026	0.026	0.080	0.080	0.000
SO2	0.836	0.836	0.809	0.809	0.000

Table 3. Results of Three Cost-Effectiveness Measures

	Fuel Mod.	Partic. Traps	Fuel Mod. & Partic. 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
Incr. Cost-Effectvns ($/kg)	1.58	4.65	9.79	107.70
Severity Index:				
Emissions Reduction	21.1%	62.4%	65.9%	96.5%
Cost-Effectiveness (a)	1.58	3.67	3.99	16.31
Incr. Cost-Effectvns (a)	1.58	4.73	9.79	42.86
Mortality Index:				
Emissions Reduction	8.8%	24.1%	25.6%	98.5%
Cost-Effectiveness (a)	1.58	3.95	4.28	6.65
Incr. Cost-Effectvns (a)	1.58	5.30	9.79	7.49
Expected Mortality Reduction (deaths/year)	1.28	3.51		14.33
Incr. Cst-Eff. ($/10-6 dth)	0.34	1.14		1.62

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

Table 4. Effects of Varying Methanol Price

	Partic. Traps	Methanol		
Methanol Price ($/gal)		0.35	0.55	0.85
Meth.-Diesel Price Differnt'l ($/diesel-equiv gal)		-0.00	0.44	1.11
Cost-Effectiveness ($/kg):				
Total Particulates	3.63	3.74	19.98	44.33
Severity Index	3.67	3.05	16.31	36.19
Mortality Index	3.95	1.25	6.65	14.77

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