Harvard Center for Risk Analysis

Using Decision Science to Promote Reasoned Responses to Health, Safety, and Environmental Risks

OCTOBER 2003

Volume 11
Issue 4

Risk in Perspective

THE COST OF IMPROVING HEALTH BY REDUCING EMISSIONS FROM PUBLIC TRANSIT BUSES

JOSHUA T. COHEN Ph.D.

JAMES K. HAMMITT Ph.D.

JONATHAN I. LEVY Sc.D.

Introduction

Because improvement of outdoor air quality is a key priority for both the federal government and for some local regulatory agencies, standards limiting tail-pipe emissions by motor vehicles in general and urban transit buses in particular are steadily becoming more stringent.

To address regulatory and public concern over emissions, transit agencies across the United States have been investigating the effectiveness and feasibility of alternative propulsion systems for these vehicles. Alternative propulsion systems represent various changes to engine design, fuel, and exhaust treatment. In this issue of *Risk in Perspective,* we discuss a recent Harvard Center for Risk Analysis (HCRA) study that evaluates two of the most common alternative technologies now in use for urban transit buses - emission controlled diesel (ECD) and compressed natural gas (CNG). For each of these technologies, we quantify both the health benefits and resource costs. We find that CNG has a modest edge over ECD in terms of its health benefits. However, CNG comes at a substantial cost relative to ECD. The complete study appeared in the April 15, 2003 issue of *Environmental Science and Technology.* Our analysis draws on a wide range of information in the scientific literature, and was guided by input from an advisory panel that included members from academia, industry, and public transit agencies.

Alternative Propulsion Technologies Evaluated

We consider a scenario in which a hypothetical transit agency purchasing new buses can choose among three propulsion technologies - conventional diesel (CD), ECD, and CNG. We estimate the health benefits of ECD and CNG by comparing the morbidity and mortality impacts of their emissions to the morbidity and mortality impacts of CD emissions. In particular, we estimate how much opting for ECD or CNG instead of CD would

For more information on HCRA visit our website at: www.hcra.harvard.edu

reduce the number of quality adjusted life years (QALYs) lost as the result of operating a fleet of 1,000 buses, with each bus traveling an average of 40,000 miles annually. We estimate the additional resource costs for each alternative technology relative to CD, including the cost of vehicle procurement, infrastructure improvements, and operations (fuel and maintenance). Emissions from all three types of buses contribute to global climate change, and we include the resulting damages as another monetary cost. Dividing the incremental cost by the incremental QALYs saved yields the cost-effectiveness (CE) ratio. A low CE ratio (fewer dollars spent per QALY saved) is more favorable than a high CE ratio (more dollars spent per QALY saved).

We define the ECD technology as a new conventional diesel bus equipped with both an oxidizing catalyst and a continuously regenerating diesel particulate filter (DPF). A DPF traps particles and uses exhaust gases to oxidize and eliminate the material. To prevent fouling of the DPF, ECD vehicles require fuel with lower sulfur content than conventional diesel fuel. The DPF also requires annual cleaning to remove built-up ash.

CNG burns cleaner than diesel fuel. Because it is a vapor at ambient temperature, CNG must be compressed to around 3,000 pounds per square inch (psi) to carry sufficient quantities onboard, requiring stronger fuel tanks. Compression also requires additional energy and special equipment. Storage, fueling, and maintenance facilities must be equipped with special ventilation and detection equipment to minimize the risk of an explosion if there is a gas leak.

Buses relying on other propulsion technologies could also be considered, including electric buses, hybrid buses that have electric power trains and small fossil fuel engines, hydrogen fuel-cell vehicles (which generate electricity from hydrogen without producing harmful combustion byproducts), and more advanced diesel technologies that address other emission components. We chose to compare only the ECD and CNG technologies, for two related reasons. First, these are the most common alternative technologies used by transit authorities. For example, CNG vehicles represent around 60% of all alternative fuel transit buses purchased and New York City has plans to equip 3,500 vehicles in its diesel fleet with DPFs. Second, because these technologies are the most common, they are the only technologies for which adequate performance data are available.

Because the values of many of the parameters in our analysis are uncertain, we estimate how best case and worst case values for these parameters influence our results. We also estimate how risk may change across the U.S. due to geographic variation in factors such as population density and atmospheric chemistry.

Health Effects and Emissions

Our analysis accounts for the health effects associated with emissions of particulate matter (PM), nitrogen oxides (NO_x), and sulfur dioxide (SO_2). PM is thought to substantially increase mortality due to cardiopulmonary factors. In addition, EPA and other regulatory agencies judge that diesel PM may contribute to lung cancer, whereas it is widely assumed that CNG PM does not. Although these assumptions are both controversial, we accept both for this analysis, biasing our results in favor of CNG.

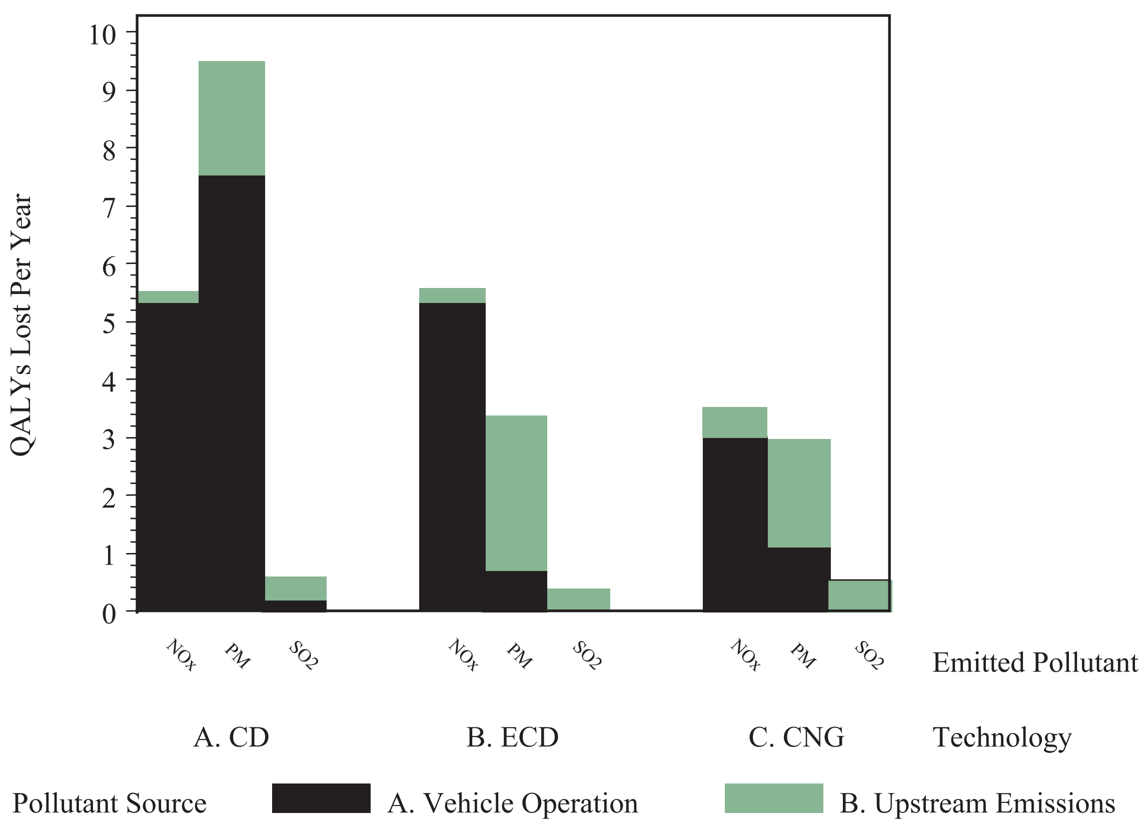
NO_x is important to health because of the chemical reactions it undergoes after leaving the tailpipe. First, NO_x can become a “secondary particulate” when it is converted to nitrate and combined with ammonium, thus adding to PM exposure. Second, when it reacts with volatile organic compounds (VOCs) in the presence of sunlight, NO_x generates ground-level ozone, a contributor to smog. Ozone may contribute to mortality and to the incidence of asthma. Like NO_x, SO_2 also contributes to the formation of secondary PM.

Our analysis takes into account both emissions associated with vehicle operation and emissions generated by “upstream” activities - *i.e.*, the extraction, production, and distribution of fuel. For PM, NO_x, and SO_2, upstream emissions are for the most part far smaller than corresponding emissions from vehicle operation.

Compared with CD, both ECD and CNG reduce PM emissions by approximately three-fourths. For NO_x, CNG reduces aggregate emissions by around one-third, while ECD does not reduce NO_x emissions at all. ECD reduces SO_2 emissions to a greater extent than does CNG, but the baseline emissions are so small that the contribution of SO_2 to baseline health risks is limited.

Taking all the emissions and their health impacts into account, our central estimates are that a fleet of 1,000 new CD buses would result in a loss of 16 QALYs each year. Accounting for uncertainty underlying this calculation, we estimate that this loss might be as little as 0.1 QALYs (best case bounding assumptions) or as much as 85 QALYs (worst case bounding assumptions). Replacing these buses with 1,000 ECD buses would reduce this loss by 6.3 QALYs annually (range: 0 to 41 QALYs), and replacing them with 1,000 CNG buses would reduce the loss by 8.6 QALYs annually (range: 0.01 to 65 QALYs). Figure 1 summarizes these results.

Figure 1: Annual QALYs Lost Due to Emissions from a Fleet of 1,000 Buses



Resource Costs

For each bus, the annualized incremental cost for ECD relative to CD is $1,700 (range: $1,300 to $2,100). The major components of that difference are the amortized cost of equipping the vehicle with the diesel particulate filter and the added cost of ultra-low sulfur fuel. Maintenance of the filter contributes a small amount as well.

The annualized incremental cost for each CNG bus is substantially higher than for ECD, ranging from $15,300 in areas with low land costs (range: $4,800 to $26,000) to $20,500 in areas with high land costs (range: $5,800 to

$36,000). Land costs significantly affect overall CNG costs because of the need to provide adequate ventilation of storage, fueling, and maintenance facilities. Transit authorities can address ventilation requirements by building single-story facilities, which can take up substantial amounts of land. Alternatively, they can build multi-story structures to reduce land requirements, but must include more sophisticated ventilation equipment. In low-cost areas, where land is readily available, we estimate the amortized incremental cost for infrastructure to be $950 per bus. In high-cost areas, the corresponding annualized estimate is $6,200.

In addition, CNG buses themselves are more expensive because of the complexity of the fuel tanks and onboard fuel-distribution system. Amortizing these costs yields an annualized increment of $2,800.

Further, based on the experience of large transit agencies, we conclude that CNG's operating costs are higher than CD. Although CNG fuel is less expensive than diesel (per unit energy content), the lower efficiency of CNG engines means that the annual fuel cost for CNG is around $3,200 higher than for CD. Data from New York City suggest that the annual maintenance cost for each CNG bus is $6,000 higher than for each CD bus. (Some transit agencies have reported that maintenance costs decreased when they purchased CNG vehicles. However, inspection reveals that these agencies were comparing new CNG buses to old diesel buses, or that they reported maintenance costs net of those covered under warranty.)

Finally, the CNG fueling infrastructure (natural gas compressors) must be maintained, adding another $2,300 in costs annually per bus.

Both ECD and CNG generate more greenhouse gas emissions than do CD vehicles. The incremental monetized damage associated with CNG ($200 per year) exceeds the corresponding figure for ECD ($30 per year), but these increments are very small compared with the acquisition, infrastructure, and operational costs for these technologies.

Cost Effectiveness

Compared with CD, we estimate that ECD improves health and reduces mortality at a cost of $270,000 for each QALY saved. For CNG, the corresponding cost is $1.7 million per QALY in an area with low land acquisition costs and $2.4 million per QALY in an area with high land acquisition costs. Directly comparing the two alternatives we considered, the incremental cost effectiveness of CNG relative to ECD is estimated as $5.8 million (low land cost) to $8.4 million (high land cost).

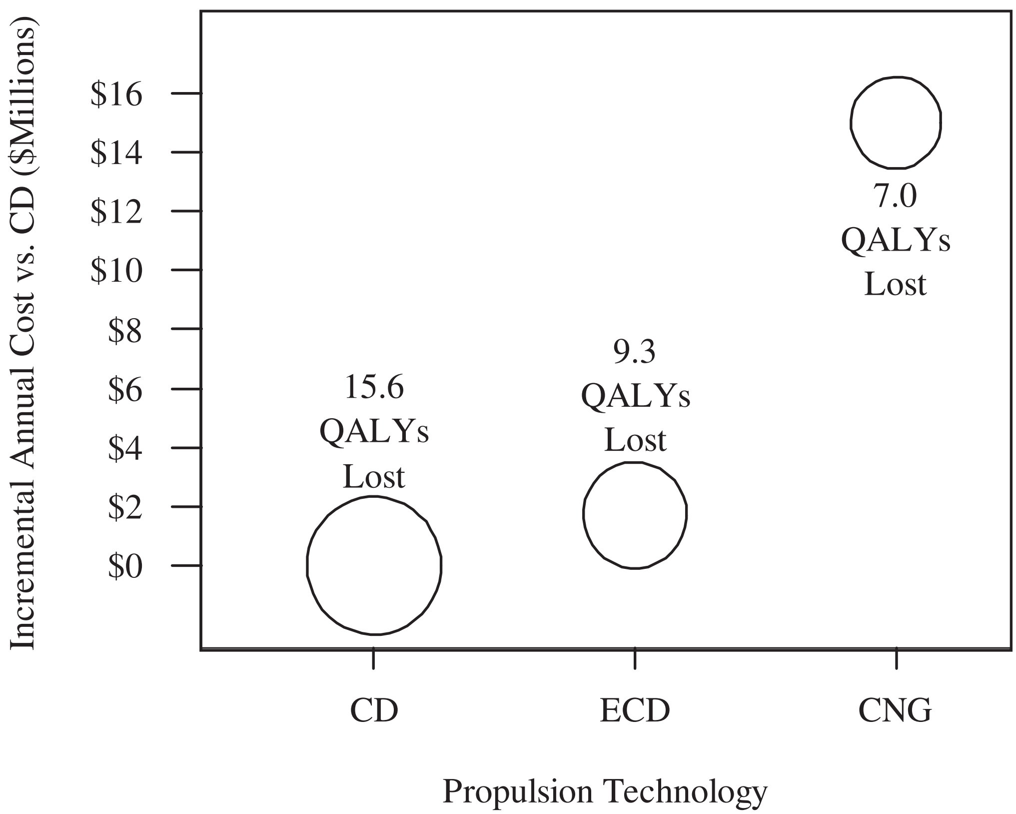
Because of uncertainty about the appropriate values of many of the parameters in our analysis, the ranges of plausible values for the ECD and CNG CE ratios are wide. For ECD, the cost per QALY saved may be as small as $30,000 or infinite (*i.e.*, no health benefits per incremental dollar invested). For CNG, the CE ratio ranges from $70,000 to $2 billion per QALY saved in low land cost areas, and from $90,000 to $3 billion in high land cost areas. We also find that the CE ratios depend on local atmospheric conditions and population patterns, factors that affect population exposure to air pollution.

Interestingly, two issues that garner substantial attention - the effect of diesel exhaust on lung cancer and the contribution of emissions to climate change - contribute little to our quantitative estimates. When measured in terms of lost QALYs, the impact of lung cancer, even if it is caused by diesel exhaust, is far less than the impact of PM on the cardiopulmonary mortality rate. As mentioned above, the estimated monetary value of the incremental effect of ECD and CNG on climate change is small compared with their other costs. Hence, our conclusions are not affected by these factors, no matter what plausible assumptions we choose.

Discussion

As illustrated in Figure 2, the reduction in health damages afforded by CNG compared with ECD is modest and comes at a substantial increase in resource costs. However, while cost-effectiveness provides an indication of the relative efficiency of investing in either of these technologies to improve health, it does not by itself indicate which investment, if either, is desirable in an absolute sense. Conceivably, the gains of both ECD and CNG may both be too small to justify their costs. Alternatively, it is possible that even though the reduction in health damages achieved by CNG is more expensive than the reduction achieved by ECD, this savings of 2.3 QALYs per year may be worth the added annual cost of $13 million (low land cost areas) to $19 million (high land cost areas).

Figure 2: Annual Health Damages and Incremental Costs for a Fleet of 1,000 Buses*



Bubble area is proportional to QALYs lost for each technology. Cost for CNG ($15 million per year) is for areas with low land costs. For areas with high land costs, the annual incremental cost is $21 million.

One way to address this issue is to compare these technologies with other investments that improve public health. Doing so suggests that both ECD and CNG are expensive. QALYs can be saved at a lower cost by investments in the medical prevention of coronary heart disease and cancer, reduction of motor-vehicle injury trauma and fatalities, and the prevention of infectious disease. However, CE ratios for public-health investments often differ substantially across domains. For example, an analysis conducted by HCRA in the 1990s found that the median cost per QALY saved for regulations considered by different agencies were much

Harvard Center for Risk Analysis
Harvard School of Public Health
718 Huntington Avenue
Boston, Massachusetts 02115-5924
617 432-4497
www.hcra.harvard.edu

100% recycled paper, all post-consumer fiber.

PEER REVIEWER:

ANDREW M. WILSON, SC.D.

ADDITIONAL READINGS:

Cambridge Systematics Inc. and Economic Development Research Group (1999). Public Transportation and the Nation's Economy: A Quantitative Analysis of Public Transportation's Economic Impact. Underwritten by the American Public Transit Association. Available at: http://www.edrgroup.com/pages/pdf/Public-Transport.pdf.

Cohen, J. T., Hammitt, J. K. and Levy, J. I. (2003). Fuels for urban transit buses: A Cost-Effectiveness Analysis. *Environmental Science and Technology* 37: 1477-1484.

U.S. EPA (Environmental Protection Agency) (2000). *Regulatory Impact Analysis: Control of Emissions of Air Pollution from Highway Heavy-Duty Engines.* EPA420-R-00-010. Office of Air and Radiation.

higher for EPA ($7.6 million) than for several other agencies (FAA - $23,000, CPSC - $68,000, NHTSA - $78,000, OSHA - $88,000).

When compared within the domain of other clean-air policies, investments in ECD and CNG do not look as expensive. For example, results from another HCRA analysis suggest that controls on stationary air-pollution sources (*e.g.,* power plants) save lives at a cost ranging from tens of thousands to a million dollars per life year. Mobile source controls (*e.g.,* motor vehicles) cost from tens of thousands to four million dollars per life year saved. For ECD, the return per dollar invested falls within both of these ranges, while the return for CNG falls within the range of CE ratios for mobile-source programs only, and is towards the high end of this range.

Of course, economic efficiency is not the only issue that a transit agency must consider in choosing among alternative propulsion technologies. There are aesthetic considerations (diesel buses are often said to be noisy and to generate a strong, unpleasant odor), and safety issues (CNG can explode, while diesel fuel can cause environmental damage if a spill occurs). Moreover, although aggregate population risks may be small, individual impacts may be comparatively large for those who live or work near locations where buses operate. It must also be kept in mind that our results are imprecise, as indicated by the wide range of plausible results described earlier.

Nonetheless, cost is an important issue. Spending more for each new alternative-technology bus may delay the process of replacing older, dirtier buses if a transit-agency's budget is limited. Alternatively, if the number of buses to be purchased is fixed, a more expensive technology drives up the purchase price, potentially taking resources from other investments. For example, spending may be reduced for other mass transportation priorities, such as improving or extending service. A model developed for the American Public Transportation Association suggests that such reductions depress public transit ridership, as people tend to switch to private vehicles in response to a decrease in the quality of public transit service. Increased use of private vehicles increases congestion and air pollution and offsets intended gains.

The increased use of private vehicles is one potential "adverse side effect" of spending on alternative-technology buses. Understanding whether this and other side effects offset the benefit of investing in cleaner buses depends on quantifying the technology's costs and benefits, which is the goal of the type of analysis described in this issue of *Risk in Perspective.* While there are other factors that influence such decisions, consideration of economic efficiency - the health return per dollar invested - is an important part of the discussion.