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Foreword

This Record contains papers on environmental analysis, air quality, transportation-related noise, energy considerations, and alternative fuels.

Achieving a comprehensive environmental review of proposed projects and obtaining the needed public involvement and agency approvals are major obstacles to all forms of transportation improvements. Three papers address various aspects of the environmental review process. One considers expanded alternatives analysis for a rapid transit project. The second summarizes a negotiating process to enable cooperative development of project designs, and the third describes the integrated environmental review procedures used by the New Jersey Department of Transportation.

One of the mandates of the Intermodal Surface Transportation Efficiency Act and of the Clean Air Act is that transportation projects improve air quality in nonconforming urban areas. A major problem in accomplishing this is to accurately analyze and model the consequences of proposed transportation actions. The air quality papers in this Record examine issues of particulate matter and its dispersion near urban roadways, the comparative emissions of electric and gasoline vehicles, the regional emission impacts of electric vehicles on electrified roadways, and remote sensing of carbon monoxide and hydrocarbons from passing motor vehicles.

Transportation noise emissions and control are receiving worldwide attention. Four noise papers deal with noise emissions and barrier effectiveness in the United States and Saudi Arabia. Included in the papers are the development of noise prediction models and evaluations of noise barrier effectiveness, aesthetics, and economic feasibility.

Fuel economy is desirable both for energy conservation and for reducing air pollution. Three papers examine ways and costs of improving fuel economy, vehicle operating characteristics that affect fuel economy, and differences between Environmental Protection Agency-test fuel economy and actual on-the-road experience. One paper examines the cost-effectiveness of converting fleets to compressed natural gas.

PART 1

Environmental Analysis

Expedited Alternatives Analysis for the Dallas Area Rapid Transit Project

DOUGLAS A. ALLEN AND WILLIAM KYLE KEAHEY

Dallas Area Rapid Transit (DART) recently completed an alternatives analysis/draft environmental impact statement (AA/DEIS) and subsequent final environmental impact statement (FEIS) in a little over 2 years. The process was completed under an expedited arrangement with the Federal Transit Administration (FTA). DART's experience and the activities involved in this process are discussed. Lessons are identified that others may be able to use to significantly reduce the time to complete what is often a multiyear effort. The system planning effort that preceded the AA/DEIS is described, since it laid the groundwork for the successful completion of the AA/DEIS in a relatively short time. Among the system planning activities that contributed to a smoother AA/DEIS were the development of the travel forecasting model set, the analysis of corridor-specific alternatives, and the establishment of the federal process as an aid to decision making. The new system plan included a 33-km (20-mi) light rail system. DART was motivated to complete the AA/DEIS/FEIS quickly to begin implementation of the proposed rail system. An expedited arrangement was agreed to by FTA in response to the secretary of transportation's Overmatch Initiatives Program. The expedited treatment limited the reports that needed FTA approval and provided DART with priority in the review process. Additional actions were taken to limit the duration of the AA/DEIS process.

The Federal Transit Administration (FTA), formerly the Urban Mass Transportation Administration (UMTA), has developed a planning process to be followed by applicants for federal funding assistance in the development of major capital investment projects such as rail systems. The cornerstone of the FTA project development (*1*) process is the alternatives analysis/draft environmental impact statement (AA/DEIS). The alternatives analysis examines various alternative solutions to corridor transportation problems. The draft environmental impact statement identifies the environmental impacts associated with each alternative. The AA/DEIS process combines sound planning practices and compliance with federal environmental laws, the most significant of which is the National Environmental Policy Act of 1969 (NEPA).

A substantial amount of time is required to conduct an AA/DEIS. The U.S. General Accounting Office (GAO) has investigated numerous projects to understand the time necessary to conduct an AA/DEIS. Their findings indicate that 13 to 38 months is required to conduct an AA/DEIS. Another investigation by Diridon (*2*) identified a time frame of 32 to 40 months. In 1989 the secretary of transportation announced that an AA/DEIS could be conducted in an expedited manner for projects that provide substantially more than the required local matching funds. This overmatch initiative is intended to encourage more local funding of major capital investments in transit.

The overmatch initiative and the prospect of an expedited process were announced as Dallas Area Rapid Transit (DART) was about to begin the AA/DEIS process for the South Oak Cliff Corridor located in Dallas, Texas. In 1989 DART was highly motivated to begin implementation of the recently developed systems plan that called for, among other elements, a 20-mi light rail system. Therefore, before initiating efforts toward the South Oak Cliff AA/DEIS, DART requested and received an expedited AA/DEIS process agreement with FTA, which permitted an accelerated schedule. With the help of the expedited process, DART was able to complete the AA/DEIS and the subsequent preliminary engineering/final environmental impact statement (PE/FEIS) process in a little more than 2 years.

Studies conducted by GAO and by Diridon indicate that the typical time necessary to perform this work is 32 to 72 months.

This paper is intended to discuss our experiences with an expedited schedule. Numerous lessons were learned from this effort, many of which may be of value to others entering the AA/DEIS process. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) identified possible efficiencies that could be incorporated into the AA/DEIS process. The experiences discussed in this paper are from a process antedating ISTEA but are still applicable under the proposed ISTEA improvement.

BACKGROUND

DART was created on August 13, 1983, when voters in 14 cities and Dallas County cast ballots in favor of regional public transportation. In January 1984 the voter-approved 1 percent sales tax went into effect, and DART began formal operations. In 1984, the DART board chose light rail transit as the preferred mode for its principal fixed-guideway technology. Following several system plan and financial plan revisions, DART scheduled a bond election in June 1988, in which voters were asked to support long-term indebtedness to construct a 155-km (93-mi) light rail system. This bond election failed, sending DART staff back to the drawing board.

Several factors led to the defeat of the bond proposal, especially the public's dissatisfaction with (*a*) the cost of the proposed rail system, (*b*) the reluctance to incur long-term debt to pay for it, and (*c*) the lack of public involvement in the transit authority's planning efforts. Shortly after the bond defeat, DART began to develop a revised system plan.

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It is important to review the preparation of the new system plan, since success of the AA/DEIS can be traced to the system planning efforts that laid the groundwork. The new system plan's development was based on a set of guiding principles established early in the process. Included in these principles was the request to examine all alternatives in each corridor and base the recommendations on cost-effectiveness and public acceptance. This resulted in a consensus on the system plan and elements in the plan.

DART began the system planning process by identifying several candidate projects for each travel corridor, including express buses, high-occupancy vehicle (HOV) lanes, elevated rapid transit (heavy rail and monorail), and surface rapid transit (light rail). A technical analysis of each candidate project was prepared that included cost and ridership estimates and probable environmental impacts. Three alternative system plans were developed that were loosely based on the three basic types of fixed-guideway transit systems: HOV lanes, elevated rapid transit, and surface rapid transit. On the basis of anticipated costs and ridership and the goal of achieving a cost-effectiveness index (CEI) of $10 per added transit trip (based on the FTA CEI formula), a "budget" was identified for each corridor that would ensure that the three plans were all cost-effective and could be financed without long-term debt. A network of community transportation forums was established to solicit comments and receive input on the plans. From these comments a composite system plan was prepared that was approved by the board in June 1989. This revised "New Directions" system plan was adopted by the city of Dallas, Dallas County, and other member cities by October 1989. The revised system plan calls for 110 km (66 mi) of light rail transit, 62 km (37 mi) of HOV lanes, 30 km (18 mi) of commuter rail service, and continued expansion of bus and van services.

The system plan recommended early implementation of a 33-km (20-mi) light rail starter system, along with other commuter rail and HOV lane components. The proposed light rail starter system is made up of three lines: a 15-km (9-mi) line from the South Oak Cliff section of Dallas through the central business district (CBD); an 8-km (5-mi) branch off the South Oak Cliff line into West Oak Cliff; and a 12-km (6-mi) line along the North Central corridor between Park Lane and the CBD. During system planning efforts DART worked with FTA to identify a federal priority corridor. The system plan called for the South Oak Cliff line to be federally funded; the other two lines would be locally funded.

Three activities during the system planning process greatly contributed to completing the South Oak Cliff Corridor AA/DEIS in a relatively short time. Because the system planning process examined alternative technologies and alternative alignments in each corridor, the alternatives to be considered in the South Oak Cliff Corridor AA/DEIS could be screened. This proved to be a significant factor in saving time by limiting the work effort to be a reasonable number of alternatives.

Recently updated travel forecasting models were available to conduct ridership studies and cost-effectiveness analyses during the system plan development. This also was a key factor in keeping the AA/DEIS process moving. No model development was needed during the AA/DEIS, and travel forecasts could begin as soon as the alternatives were sufficiently defined.

FTA's cost-effectiveness formulas were instrumental in establishing a framework for policy makers and citizens to debate and compare alternatives. Using the formulas and ridership projections prepared by North Central Texas Council of Governments (NCTCOG), DART developed its plan to reflect a cost-effectiveness system. This was important during the AA/DEIS because it established cost-effectiveness as an important evaluation issue and helped define reasonable alternatives.

AA/DEIS PROCESS

As noted earlier, DART was highly motivated to complete the AA/DEIS process in a relatively short period of time. We requested and received approval from FTA to initiate the AA/DEIS in the South Oak Cliff Corridor under an expedited status in August 1989. The expedited agreement provided DART with relief on two issues. The first was that the series of standard analysis methods reports would need FTA approval, but the series of technical memoranda, which document the results of the analysis (commonly referred to as results reports), would not need to be approved. Otherwise, the process followed by DART did not deviate from the AA/DEIS standard practices established by FTA. The second time saver was a commitment by FTA to attempt to provide comments on reports within 2 weeks. Whereas the first issue saved time by eliminating the need to get approval on a number of reports, the agreement's real importance was in establishing DART's AA/DEIS documents as a priority over other projects under review by FTA.

Scoping meetings, the initial step in the AA/DEIS process, were held in September 1989. Following scoping, a screening of alternatives was done, which reduced the number of alternatives. Much of the analysis documented during the system plan preparation was useful in this screening activity. This proved to be a key step in reducing the time for the process, since we were able to drop a large set of alternatives through a documented screening process. The screening process also documented our consideration of a large set of alternatives, a stated goal of NEPA. By November 1989 we had developed the list of final alternatives to analyze throughout the AA/DEIS process.

The final set of alternatives included the no-build and TSM alternatives and several combinations of light rail alignments. The South Oak Cliff Corridor was divided into three distinct geographic areas: the CBD, the Trinity River crossing area, and the Lancaster Road area. Within each of these areas, a small number of alternative alignments and station options were considered.

While staff were documenting the results of scoping and the screening of alternatives process, our specialty subconsultants began preparation of the methods reports. Draft methods reports were submitted between December 1989 and April 1990. Approvals of the methods reports were received between February and May 1990. While the methods reports were being prepared and reviewed, staff initiated collection of data, analysis, and documentation efforts for what would become the results reports.

Rather than keeping methods and results report efforts separate from each other, DART initiated analysis before the formal approval of the appropriate methods report. These early efforts were not initiated until an acceptable level of comfort was obtained from FTA staff. Obviously, some risk was associated with initiating these efforts before methodology approval, but the trade-off was an earlier start on the lengthy analysis required to prepare results reports. Since the results reports were oriented to transition into the appropriate DEIS chapter, this early start permitted staff to begin preparation of the DEIS.

During the process we coordinated closely with FTA staff. As work was proceeding on the results reports, questions were raised that led FTA staff to request additional analysis. It was decided early in the process to simply do the analysis rather than take the time to debate whether the analysis was necessary. This seemed to save time as well as provide FTA staff with the information they needed.

The preliminary draft of the DEIS was prepared and forwarded to FTA staff in June 1990. Summer 1990 was spent coordinating with FTA staff regarding the adequacy of the document. To ensure that this review and comment cycle proceeded quickly on this draft and on all previous reports, we attempted to edit the document so that FTA staff would only need to concentrate on the content. By August 1990 FTA staff were satisfied with the AA/DEIS and approved circulation for public comment.

The 45-day period in which public comment on the DEIS is sought began in September and ended in October 1990. As comments were received, either at the public hearings that were held during the comment period or when they were submitted in writing, staff began to document the comments and prepare a response. Also during the comment period we began the final product of the AA/DEIS process: the locally preferred alternative (LPA) report.

The DART board approved the LPA in November 1990. The LPA recommendation coincided with the majority of public comment and support, including the support of the state historic preservation officer and Dallas City Council. By the end of November, FTA had concurred with the LPA and authorized DART to initiate preliminary engineering and the preparation of the FEIS.

PE/FEIS PROCESS

The PE/FEIS process was less structured than the AA/DEIS process. This is reflected in written FTA guidance, which, contrary to the AA/DEIS guidance, provides little direction to applicants. The PE/FEIS process was driven by the need to do more detailed cost and impact analysis and to identify environmental impact mitigation measures for the LPA.

DART was fortunate to retain the AA/DEIS consultant team for the PE/FEIS efforts. This resulted in a significant time savings by beginning immediately where we had stopped with the AA/DEIS analysis and eliminating the inefficiencies of mobilization.

The most significant issue identified during the AA/DEIS was the impact on the West End Historic District, which includes Dealey Plaza, site of President Kennedy's assassination. When the FEIS was initiated, this issue was quickly addressed to allow adequate time to consider the sensitive nature of the potential impact on the area. The impact on this historic district required compliance with Section 106 of the Historic Preservation Act and Section 4(f) of the Department of Transportation Act. Compliance with Section 110 of the Historic Preservation Act was also required by efforts of others to create a national historic landmark to preserve the Kennedy assassination area. Documentation associated with these preservation efforts required coordination with numerous parties at all levels of government. It was the most time-consuming effort during the PE/FEIS process, beginning in January 1991 and concluding in July 1991. Had we waited to begin work on this issue, the completion of the FEIS would have been delayed.

Impact analyses by the specialty subconsultants for the other environmental issues were concurrent with the historic preservation work. Since the historic preservation work had the longest duration of the analyses, we were able to complete the other environmental work relatively early to make adjustments in the preliminary engineering efforts to accommodate mitigation requirements, as necessary.

The draft FEIS was sent to FTA in June 1991. Summer 1991 was spent coordinating with FTA staff and obtaining final approvals for the FEIS, including the Section 106/110 memorandum of agreement and the Section 4(f) statement. By August 1991 FTA staff were satisfied with the FEIS and approved its circulation for public comment.

The comment period ended in October 1991. As the comments were received, responses were prepared and sent to FTA. The record of decision, completing the FEIS process, was issued in October 1991.

REASONS FOR EXPEDIENCE

There are several reasons why DART was able to complete the combined AA/DEIS and PE/FEIS process in a little over 2 years: system planning, scoping/screening, expedited status, and management.

System Planning

During 1987 NCTCOG and DART worked with outside experts to update the travel forecasting models. This process resulted in extensive review and debate over the modeling process and its assumptions, including adequate documentation. Having a recently calibrated model that had gone through this process allowed DART to begin the forecasting work on alternatives early in the process. Because of this preparation, it was not necessary to develop models during the AA/DEIS process.

The unsuccessful bond election in 1988 was the impetus for a new system planning effort that placed emphasis on cost-effectiveness, public involvement, and examination of numerous alternatives in each corridor. The benefit of system planning to the AA/DEIS process was twofold. First, since the federal CEI was used in system planning to screen and compare alternatives, it established the federal CEI and, by association, the entire FTA project development process as a framework for decision making. Second, the documentation of numerous alternatives studied during system planning allowed screening of alternatives early in the AA/DEIS process.

Scoping/Screening

Early in the system planning process several candidate projects were identified for each travel corridor, including express buses, HOV lanes, and rapid transit (light rail and heavy rail). Technical analysis for each candidate project included cost estimates, ridership forecasts, and probable environmental impacts.

Since the system planning process examined alternative technologies and alternative alignments in each corridor, this information was available for the scoping meetings. As a result, staff were able to use this information to screen the alternatives during the scoping process to a smaller, more manageable set of reasonable alternatives, thereby reducing the magnitude of analysis to be performed during the remainder of the AA/DEIS process.

The screening process had the added benefit of documenting that many alternatives were considered, which is one intent of NEPA.

Expedited Status

The principal advantage of the expedited status was that our project was a high priority for FTA administration and technical staff. This allowed DART to get timely responses to documents that required FTA review and approval. A good working relationship was established between DART and FTA staffs. DART provided FTA with draft reports that had gone through a thorough editing and quality control exercise so that FTA could focus on the content of the reports. We also found it expeditious to simply conduct the additional analysis requested by FTA staff without overly debating the merits of what was requested.

Management

Before initiating the AA/DEIS, there was a commitment to complete it as soon as possible while maintaining the integrity of the analysis and the process. To achieve this, the project manager was prepared to address issues in a short time frame to keep the project team moving on schedule. This included taking controlled risks periodically. Staff also attempted to anticipate what would be needed early enough to begin work so that it would not affect the critical path. We started preparation of reports, analyses, forecasts, estimates, and other efforts as soon as possible so that progress would not be slowed.

SUMMARY

The recent allowance of an expedited AA/DEIS process was initiated by the U.S. Department of Transportation and FTA to encourage a stronger local effort to fund major capital transit investments. However, the mere availability of an expedited process does not ensure that an applicant's AA/DEIS process will be performed in a reduced period of time. The expedited process provides an opportunity for an applicant to reduce the time necessary to conduct an AA/DEIS provided that other factors are achieved.

DART's experience with the expedited AA/DEIS process provided two time saving opportunities: the results reports did not require formal approval by FTA, and FTA staff agreed to provide comments on reports requiring approval within 2 weeks. Both of these provisions reduced the time necessary to complete the process, and it was apparent on several occasions that DART's submittals were of a higher priority than other projects being reviewed by FTA staff.

Perhaps a more significant factor in DART's success with the expedited process was the preparation of an adequate foundation provided by the system planning efforts before the AA/DEIS. The use of FTA's CEI during system planning to evaluate each corridor's alternatives was essential in the identification of an affordable system plan. The availability of updated travel forecasting models during system planning eliminated the need to develop these models during the early stages of the AA/DEIS. DART was also able to quickly reduce the number of alternatives considered in the AA/DEIS because of system planning efforts that examined alternative technologies and alignments in each corridor. In addition, extensive community involvement during system planning resulted in a solid base of support for the system plan and, consequently, the AA/DEIS process.

This experience indicates that the expedited AA/DEIS process can decrease the amount of time necessary to conduct these studies. However, it does not significantly reduce the volume of work necessary to complete the studies. Rather, it compresses the time within which these studies may be accomplished.

Therefore, an applicant desiring to pursue an expedited AA/DEIS process must have an understanding of the intensive nature of the compressed AA/DEIS work efforts, the clear advantages provided by thorough system planning efforts, and the commitment of staff efforts necessary to truly result in an expedited process.

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Getting to Yes in Environmental Protection

DAVID T. HARTGEN AND KENNETH C. DRIGGERS

A process for negotiated solution building to defuse environmental concerns about major road proposals in the low country area of South Carolina is summarized. Using a neutral intermediary, the state highway department and citizens developed design solutions that achieved mobility needs and protected the environment. The method is being used on two environmentally sensitive highway projects, both of which involve highway widening and effects on wetlands and the economy. The projects are a section of US-17 in Colleton County and a section of US-21 in Beaufort County. In one case (US-21) a solution has been reached; in the other (US-17) discussions about alternatives continue, and progress is being made.

Perhaps no issue has had such a significant negative effect on transportation investment in the last 20 years as concern for environmental protection. Beginning in the late 1960s and 1970 with the National Environmental Policy Act, states were required to prepare environmental impact statements for highway projects likely to degrade the environment and to take appropriate mitigating actions for protection of environments. During the 1970s, transportation investment was substantially affected by these requirements. The initiation of state environmental action plans in the mid-1970s improved the process by which state highway departments and others jointly planned for mobility, but these documents did not, of themselves, increase concern about socioeconomic, energy, environmental, and other matters. The trend toward increasing regulation has continued into the 1980s and 1990s, with the Clean Air Act and its amendments, procedures for wetland mitigation, and the 1991 Intermodel Surface Transportation Efficiency Act. In all of these laws, procedures for ensuring the adequate protection of the environment while providing cost-effective and necessary mobility are continued. In addition, new issues, such as global warming and future energy constraints, although not necessarily addressed in federal highway law, increase concern about the environment. The conclusion is that concerns about environmental protection in highway investment are here to stay.

Many of the environmental issues relating to highway investment are contentious in nature and often involve legal actions if not outright court suits. This is particularly unfortunate since both highway departments and environmental organizations generally share the same goals. Both want to protect the environment. Generally, both want to maintain and improve mobility. If it is necessary, both want cost-effective mitigation. Both want the benefits of quality accessibility and a quality environment. Differences exist, therefore, not in the goals but primarily on the means. The primary responsibility of highway departments is to maintain and improve transportation mobility, whereas the primary responsibility of environmental organizations is to maintain and protect environmental quality. Both sides, however, recognize the necessity for achieving the other's goals, and in all but extreme cases both sides are willing to work to make that happen.

The spirit of cooperation and coordination, so essential in all walks of human life, is particularly critical in highway project development today. Without it, very few highways can get built without a fight. The alternative is continuous litigation, delays in necessary improvements, considerable expenditures for fundamentally unproductive activities such as litigation, and ultimately solutions that satisfy no one.

This paper reviews several recent projects in South Carolina, which provide useful instructional examples for expansion to a national model. These examples suggest that, through the use of objective intermediaries, groups with initially diverse goals and holding different opinions about the worth of transportation projects can compromise on their positions and identify solutions that are effective. The paper describes how several road projects in South Carolina, contentious when initially proposed, were ultimately defused and are likely to pass through the environmental process relatively unscathed, even after considerable initial opposition. The result was compromise highway proposals that met both the needs of the highway department for improved mobility and the concerns of the community for environmental and community protection.

LITERATURE REVIEW

As might be expected, a great deal has been written to document both environmental impacts of highways and the process to be followed in preparing that documentation. The standard guidelines are legal, regulatory, and procedural documents issued by various regulatory agencies [*1*, *2*, the National Environmental Policy Act (NEPA)], which specify precisely the items to be reviewed in environmental assessments and the process to be followed. Summaries of requirements are available in digests and texts (*3–6*). Each state [e.g., the New York Department of Transportation (*7*)] also has formal processes for environmental review. By their nature, these documents do not discuss simplified or alternative methods or interpret the procedures. Other studies (*8*,*9*) describe streamlined methods, including conversion of DEISs to FONSIs, flexible public input, and planning-stage project development. Other studies (*10*) are essentially background analyses that identify and categorize impacts.

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Measures to smooth the process of environmental review are well developed in the citizen participation literature. Yukubousky (*11*) and Jordan et al. (*12*) each describe about 50 methods to enhance citizen involvement in transportation decision making, varying from simple press/media activities to complex role playing, meetings, and surveys of opinions. In particular, Jordan et al. organize methods according to stage in the planning process, making the document useful for different clients. Citizen participation is also described fully by AASHTO (*13*), which focuses on the need for early open communication:

> Two-way communication (between designers and citizens) is essential if communities are to view the process as legitimate and accept its results. All too often, a project is stopped after a substantial investment of time and money by the agency when it becomes clear that major alternatives and significant points of view did not receive adequate attention. Establishing a two-way communication process at the start of planning provides for a continuous constructive exchange between what could otherwise be adversaries.

A variety of models of public participation and conflict resolutions are reported in the transportation literature. AASHTO (*13*), for instance, identifies the essentials of effective involvement as (*a*) identification of citizens and actors affected, (*b*) two-way communication, (*c*) interaction, and (*d*) program evaluation. The role of citizen participation is to "fully inform citizens . . . and get their perspectives" on proposals, not to justify prior views of proposal worthiness or design. Meyer and Miller (*6*) view the decision process as muddy, confusing, and political, requiring a "bargaining process" to ensure positive outcomes. Concentrating on agency interrelationships, Schick (*14*) notes that very few state regulatory or highway agencies have memoranda of understanding in place for dealing with hazardous waste, preferring an ad hoc approach; there was "little evidence of teamwork" in these activities.

MODEL FOR GETTING TO YES

Figure 1(*a*) shows the conventional model for environmental analysis of transportation projects. In this model, departments of transportation, supported by local development groups, construction organizations, and others in the transportation sector propose improvements for transportation actions that imply by their design or location considerable negative environmental impacts. Opposition to such proposals typically comes from community activist groups initially, broadens to include elected officials and other citizens, and concludes with environmental groups taking legal action to block the project at various stages. The ultimate solution is essentially a legal "yes" or "no" answer, which prevents a compromise by its nature. If the answer is favorable to the highway department, the project is built largely as proposed and the environmental groups in the community are unhappy. On the other hand, if the result of the legal action is favorable to the environmental groups in the community, the project is typically killed and the mobility necessary for that area is often not retrievable. Essentially, therefore, both sides lose no matter what the outcome.

An alternative model is shown in Figure 1(*b*). In this case, rather than engage in legal confrontation, the two parties work together through an intermediary, such as the Palmetto Conservation Foundation, to develop a compromise proposal that both protects the environment and provides the necessary improvements in mobility. In this model, there is no loser, but the extent of the win is less for each side. The requirement for compromise and solution building produces a 90 percent victory for both sides, which allows each to embrace the final product.

CASES

In this section, we discuss two cases that occurred recently in South Carolina, each of which used the "intermediary" model described earlier to develop a solution to a complex problem involving trade-offs between the environment and mobility. The two cases are as follows: (*a*) widening of US-17 through the ACE Basin, a unique environmental coastal wetland; and (*b*) widening of US-21 (Sea Island Scenic Parkway) east of Beaufort, South Carolina, which had both environmental and socioeconomic impacts.

In each of these situations, we describe circumstances surrounding the project, what the transportation department and local citizen's groups initially wanted, the role of the intermediary, specific activities and steps involving projects, and finally the results of the effort.

The South Carolina low country has some of the most beautiful beaches in the country and marshlands and undisturbed forests of unsurpassed beauty. Wildlife is still abundant, as are historic plantations suggesting a life-style as old as the country itself. These attractions have prompted a development boom in the South Carolina low country. Over the past five decades, South Carolina's five coastal counties grew by 140 percent. Since 1970 alone, Horry County has grown by 106 percent and Beaufort by 69 percent. Adding to the explosion along the coast is the impact of tourism, South Carolina's second-largest industry. More than 17 million visitors augment state and local coffers with sales and accommodations taxes each year, with the coastal environment easily the number one attraction.

Balancing the development boom in coastal South Carolina with a protection of natural resources requires a high level of technical expertise. It also requires community relations techniques that promote consensus among groups with a history of adversarial relationships. Whereas this careful approach may at first glance appear to slow progress, it can actually improve the viability of many projects by avoiding community dissension and costly litigation. Nowhere is the need for a careful approach more important than in the construction and improvement of highways. The potential impact of highway projects on cultural and environmental integrity traditionally has fueled some of the most intense disputes in the public works arena. The core aspect of a highway, its ability to link communities together, can also link together groups with mutual goals to oppose it.

Two recent highway proposals in coastal South Carolina have received intense public opposition, demonstrating the need for a new sensitive planning approach. In both cases, an outside intermediary, the Palmetto Conservation Foun-

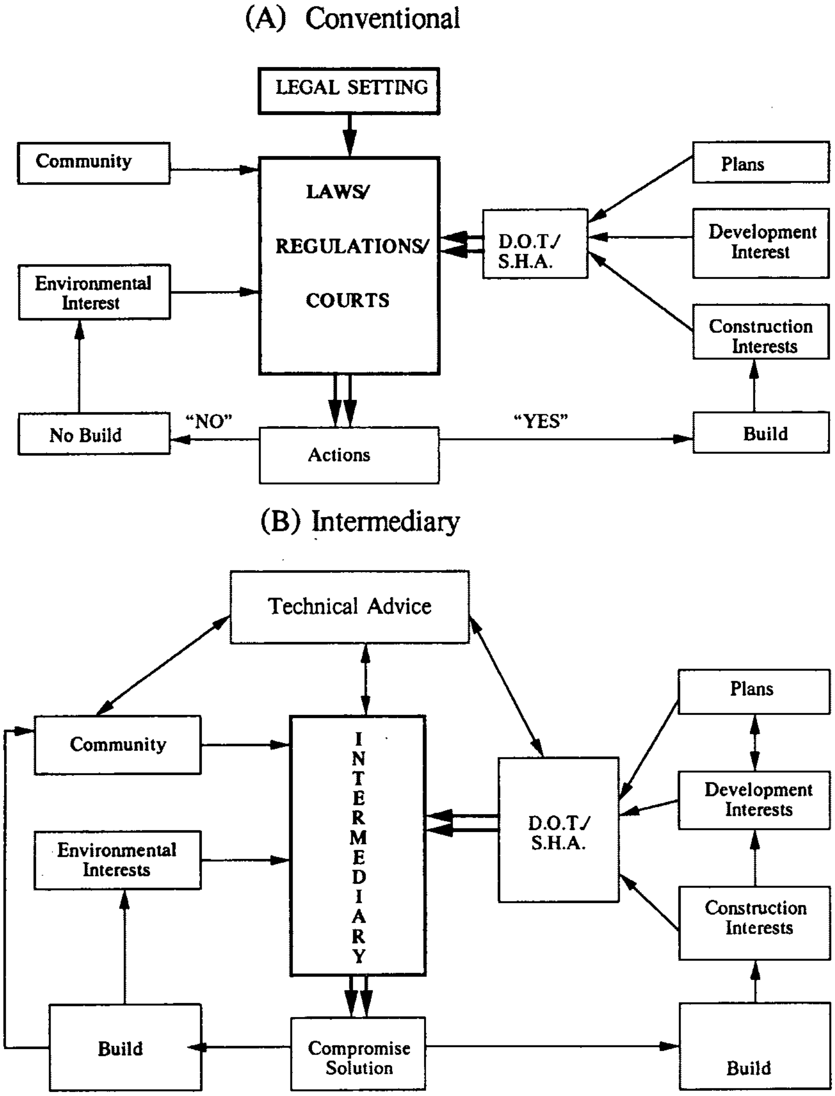

FIGURE 1 Models of environmental highway negotiations.

dation, has attempted to reach a consensus on highway improvements that not only promotes safe and efficient transportation but also respects significant environmental and cultural resources. Perhaps most important, these efforts have brought together groups that too often see each other in an adversarial light.

ACE Basin Scenic Highway

U.S. Highway 17 stretches the full length of the South Carolina coast, serving as a primary route for millions of tourists. The facility has four lanes except for a 17-mi stretch in Colleton County, a still-rural area between Charleston and Beaufort (Figure 2). The South Carolina Department of Highways and Public Transportation proposes to upgrade this remaining segment of Highway 17 by adding two additional lanes.

The proposed improvements would involve a unique natural area known as the ACE Basin. Named for three rivers (Ashepoo, Combahee, and Edisto), the basin consists of 350,000 acres of mostly undisturbed wetlands and wildlife habitat and is the site of a nationally recognized conservation effort by state and federal agencies and nonpublic groups (Figure 3). More than 100,000 acres has been permanently protected. Plans to widen the highway have created a conflict between the goals of transportation efficiency and conservation. The Colleton County Chamber of Commerce decided a middle ground was needed on the Highway 17 debate. The chamber has recommended that the project be converted to a basin "scenic highway." The plan has two primary focuses: first, the design for the highway is to be as sensitive as possible to the unique environment in the basin; second, the chamber plan addresses what to many is the ultimate problem with highway expansion—that rampant strip development will spoil the aesthetic quality of the area.

The foundation set out to influence the department's design for the highway by first conducting its own analysis. This independent analysis placed local groups on sound footing in

FIGURE 2 Location of study area (source: South Carolina Department of Highways and Public Transportation).

working with the department, a position many environmental interests have difficulty reaching. The department agreed to a series of meetings to discuss the project and address local concerns. The foundation represented the chamber of commerce with lawyers, engineers, and landscape architects to counterbalance the department's expertise. The give and take at the meetings proved productive as problems were seen from new perspectives.

The result of the meetings was a highway design acceptable to many of the groups concerned about the highway. The department was able to limit clearing, realign the corridor to protect vegetation, and reduce the slope of the highway. Scenic pulloffs and a wetlands interpretive center were added to the proposal. Perhaps more significant, an undisturbed buffer to the corridor is to adjoin the highway through a Scenic Highway Protection District ordinance. Its effect is to protect the scenic integrity of the corridor by limiting development to a series of commercial nodes around existing small towns. These "rural villages" will be encouraged to provide the commercial activity needed to support the tourist industry. Sign control, landscaping requirements, and vegetative buffers are also integral parts of the regulations.

The ACE Basin Scenic Highway will efficiently move traffic along the coast in an environment of natural beauty. This project protects the scenery and environment of the low country and adds a tourist amenity. One can imagine a visitor to the coast traveling between Historic Charleston and the Beaufort Sea Island via the natural beauty of the ACE Basin Scenic Highway. This drive is more than a trip between two destinations; it is a journey into the beautiful and historic South Carolina low country.

FIGURE 3 *Top*, Cumbahee River Bridge, US-17, South Carolina. *Bottom*, US-17 at Green Pond, South Carolina.

The highway department attempted to meet many of the local concerns about the highway. After experiencing difficulty in gaining the necessary wetlands permits, the department realized that cooperation was its best policy. Its willingness to cooperate put a new face on the project and reduced the tension that was building between the department and environmental groups. It also led the way for an effort by the local government to limit the impact of the roadside development on the ACE Basin.

Sea Island Scenic Parkway

A national monthly magazine recently called Beaufort, South Carolina, one of the 10 best small communities in the United States. The small town has an excellent historic district, abundant recreational opportunities, and an unsurpassed charm. The magazine also referred to Beaufort's proximity to the relatively undisturbed native culture, the Gullah on St. Helena Island, as the primary feature that makes Beaufort unique. The growing development on St. Helena Island led the South Carolina Highway Department to propose improving the main transportation artery, U.S. Highway 21, from two to five lanes (Figure 4). These improvements, however, will significantly disturb the resources that make the culture unique, specifically wildlife-supporting wetlands (Figure 5), the historic native community, and the Emancipation Oak, the site of the freeing of Sea Island slaves. Once again, the conflict between progress and community integrity came to a head over a highway. A group of Beaufort citizens organized the Sea Island Coalition, promoting an alternative to the five-lane proposal that would not only move traffic but unite the community through bike and pedestrian paths. The citizens made it clear that they did not oppose highway improvements outright but that a five-lane facility was not acceptable.

Once again, the Palmetto Conservation Foundation served as an outside intermediary on behalf of the citizens group. The intermediary tactic came at an excellent time in the process—the draft environmental assessment had not been finalized, and the project was in the design phase. After careful review of the traffic data, the foundation noted that the plan as proposed would probably not pass review for the necessary permits, especially in light of the public opposition. However, it also realized that no one's interest would be served by time-consuming and costly litigation. It offered an alternative to the department's plan, the Sea Island Scenic Parkway, that would serve the most immediate transportation needs and satisfy local opposition to the highway. Amenities such as bike and walking paths were added to the proposal. Most significantly, the alternative plan is more likely to pass environmental review, moving the project forward and easing confrontation. The highway department cooperated in the preparation of the alternative, making its data available to the foundation. Care was taken not to cast the alternative in a way that would be critical of the department. Rather, the stance was, Can we work together to solve this problem? The

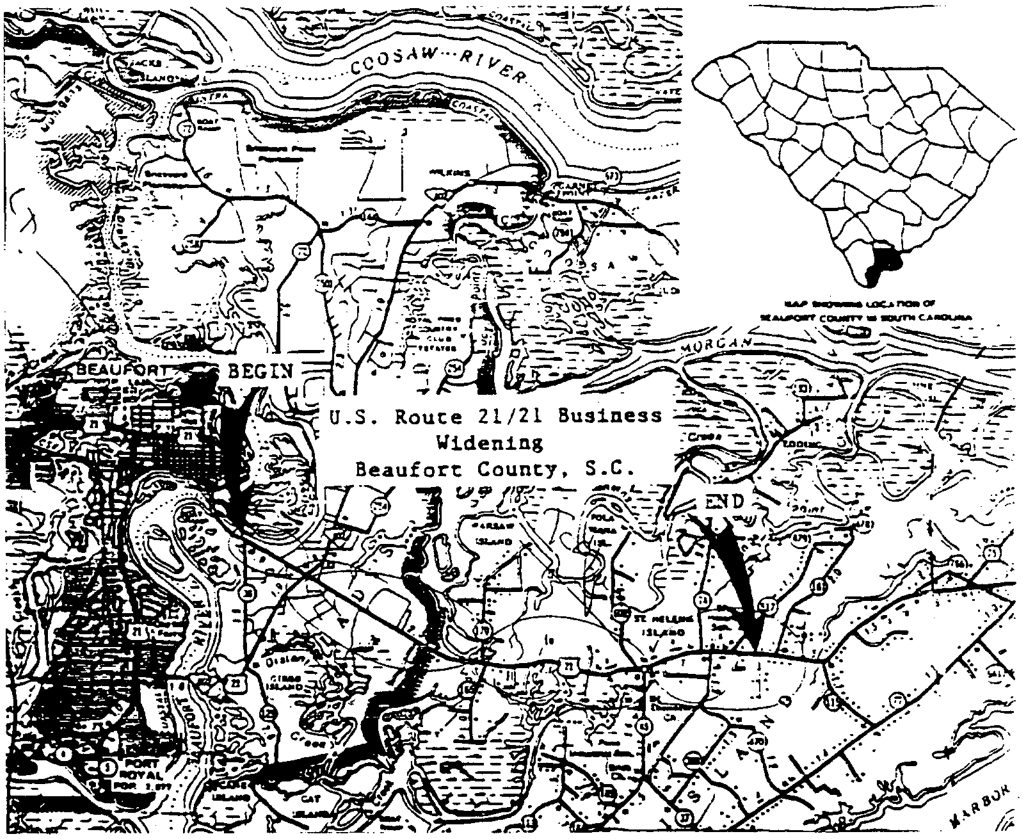

FIGURE 4 US Route 21/21 Business widening, Beaufort County, South Carolina.

FIGURE 5 ***Top*, US-21 (South Carolina). *Bottom*, wetlands along US-21 (South Carolina).**

Beaufort County Council carefully considered the alternative proposal and decided the best approach was to downsize the highway along the lines of the foundation's recommendation, because it offered the best chance for immediate implementation. The highway department has reviewed the proposal and is willing to bring its final plan toward the alternative. Many of the alternative plan recommendations are now part of the official project.

Efforts at compromise on the ACE Basin Scenic Highway and Sea Island Parkway demonstrate that highway planning in sensitive areas need not be a "bloody, winner take all" proposition. If both sides consider competing perspectives and slow down the process before confrontation reaches crisis proportions, reasonable and mutually acceptable solutions can be reached. Negotiation before confrontation is always the best policy.

OBSERVATIONS

These cases provide useful principles that may apply in other circumstances. Getting to yes in environmental protection is generally in the best interest of highway departments and environmental groups. Waging public battles over infrastructure programs not only slows progress on needed projects but also erodes public confidence in government's responsiveness to citizen concerns. Building an early consensus on the need and scope of projects can avoid costly litigation and community divisiveness.

Going Slow To Go Fast

Little is to be gained by rushing through an environmental review in the highway design process if, when released, that review or process is successfully challenged and the highway proposal is stopped by environmental opposition. A more sensible process is one in which the project proceeds slowly at first, gathering extensive information from the community on what kind of mobility improvements are needed and how best to protect the environment in the course of providing them. Citizen participation methods in transportation planning are extensive and well documented, and numerous methods have been used in a variety of environmental settings. The principle of open slow communication initially, gaining support for the need for mobility improvement as well as the need for environmental protections, is critical to later solution building.

Too often, highway planners fail to recognize early in the process that not every interest group in a community is going to welcome new highway projects. This realization is particularly important in areas with sensitive resources like wetlands, historic districts, or protected land. Slowing the process early in the design phase to register citizen concerns can bring many groups into the discussions and help demonstrate that a project is needed and can be accomplished in a sensitive manner. More often than not, local groups have substantial problems with a project as proposed. After all, they often have a defined vision of how they want the community to develop and what resources are important in achieving this vision. In working on projects likely to arouse public concern, highway planners are well advised to bring as many interest groups into the process as possible. This negotiation process needs to take place well before the first design has been drawn and any concept released to the public. Conservation groups, historic preservation advocates, and community organizations should be made to feel part of the design team. The time required to extend the planning process will be well spent if it avoids intense confrontation at a later date.

Nonconfrontational Data Review

Initially, information concerning the project will be limited and often open to challenge. Environmental groups typically challenge highway projects on the basis of conformity with legal process, less successfully on justification or need. This is because federal law and most state laws do not require that projects be justified in a technical sense, but only that the process for highway project development be followed carefully. As a result, much less attention is paid to the numbers underpining the need for the project or its appropriate design than to the process by which the project has moved forward. Data review, focusing on technical assumptions underpining the project, often will produce a recognition on both sides that the need for the project is different, not necessarily less, than initially articulated. Careful review of project need is almost always an essential step in determining a good project solution. Essentially, when project need is firmly established, solutions can be found. When project need is not firmly established, proposed solutions often look unnecessary.

To begin the search for an alternative acceptable to many diverse groups, a professional review of the information justifying the project should be undertaken. If this information becomes available first in the draft environmental assessment, the rallying cry to defeat the proposal has usually been sounded by this point. A wise move is to offer the information earlier in the process to get any possible disagreements on the table before extensive time and money have been spent. This review of the data should avoid confrontation. Highway departments should recognize that all information belongs to the public and deserves fair review. Citizen groups should respect reasonable time frames and the professionalism of the highway planners. In short, the data should not cause dispute, only conclusions drawn from it.

Thorough Technical Analysis

Closely related to the preceding point is the requirement that technical assessments for projects, with respect to both need and impact, be thorough and accurate. These assessments need not be precise, however, since in many cases it will be impossible to determine the effect of a particular proposal on the environment with great certainty. Once again, open and objective assessment in a nonadvocacy setting is likely to yield the greatest value for information provided by either side initially.

Neutral Review

We have found that it often helps to have both parties work with an independent and neutral reviewer. The reviewer may be from out of town or out of state or may occasionally be local, but it is particularly important that the reviewer not have a stake in the outcome of the study. An unbiased view is too often missing in the highway location process. Governmental officials naturally feel an ownership of their plans and are skeptical of outside interference in their domain. Citizen groups too often lack the expertise to professionally critique plans or offer alternatives. This schism is often the cause of the two sides' inability to negotiate an acceptable policy. Skepticism is pervasive.

An outsider's perspective can help promote an acceptable compromise. This individual or group should assist both sides in a potential dispute, speaking in terms of mutual understanding and clearing away the mistrust that too often surrounds these situations. Highway planners too often fail to grasp the community's vision. Local citizens can be mystified at the engineering principles and design regulations that direct construction of a highway. An outside professional can get the participants working together toward a solution of the problem. Who is to play the role of the outsider is key. The outsider should be a true outsider, who not only has no direct interest in the outcome but also can confront unpopular decisions. The outsider must be professional, with an understanding of highway design, state and federal regulations, and community planning techniques. Most of all, the outsider must possess the talent to negotiate good-faith answers to tough problems. Because a great deal of professional competence and mutual trust is needed, careful attention should be given to the selection. Going slow in making this selection and giving the outsider a chance to negotiate can make the difference between a highway welcomed by the community and a major confrontation.

Know Your Stuff

It is particularly important for the intermediaries to become familiar with the issues surrounding the project in detail. Essentially, they must develop and maintain the credibility of both sides. This means that the intermediaries must have a thorough understanding of the project and its impacts and of the views of the various parties concerning the value of the project. (The value of the project is not the same as information concerning its actual impacts.) Virtually nothing substitutes for this technical knowledge since, without it, the credibility of the intermediary is reduced. It goes without saying that an intermediary must be impartial throughout the process, encouraging both sides to work together to develop a solution that they can each accept. The intermediary is not an arbitrator or an imposer of solutions, but rather a facilitator of communication.

Firm but Polite

Respect is most easily gained and maintained if the intermediary takes control of the process, but not the project itself. The project must remain the property of both sides; otherwise there will be failure to negotiate in good faith. The intermediary responsibility includes organizing and hosting meetings, maintaining decorum and professionalism, and ensuring that all groups continue to work in a spirit of cooperation. This may require a firm but subtle grip on the tiller.

It is easy for each side of a highway dispute to see the other as obstructionist. But it is important for each side to respect the integrity of the other. Citizen groups must recognize that highway planners are seeking to accomplish a valid public goal in moving traffic efficiently and safely. On the other hand, citizen groups have a right to push for their solutions. Conservation is also a valid public purpose, and one too often missed in the rush toward progress through infrastructure expansion.

The need for mutual respect should not be taken too far. Old habits need to be reexamined, and this often does not occur unless aggressive tactics are used. Citizen groups need to make highway planners understand from the beginning that they intend to pursue all available options at their disposal. Public input is good for the process and should be as aggressive as necessary. But the worst possible approach for a citizen group in seeking to influence a highway design is to respond in purely emotional terms. "We just don't want the highway" is not an acceptable attack against professionally prepared plans. This leads highway advocates to think that opposition is coming from emotion and too often elite interests that resist all attempts at progress. Responses should be based on rational analysis that searches for a better way to solve a problem. Emotional responses are also not fair to highway planners. Fulfilling the maze of highway design requirements, not to mention securing necessary funding, is at best a difficult job. To ask a highway planner to respond to every individual memory of how the landscape used to be would slow the process beyond an acceptable limit. Good arguments, based on hard data, should be presented to influence highway design.

Highway Design Process

Whereas highway design may appear from the outside to be rigid and federally mandated, it is in fact a combination of art and science without imposed federal guidelines. Most state highway departments use the AASHTO Design Manual as a basis for their own highway design manuals. Within highway design manuals, there is almost always room for compromise and flexibility in design and in the specifics of design. In addition, highway designs change over time, typically becoming more stringent for roads of particular functional classifications. Thus, at any given time, there may be certain elements in a highway project that are substandard with respect to design but that are at the same time functional and safe. It may be ideal to improve all such elements at the time of construction, but it is not always necessary and certainly not always required. Understanding that design is flexible is the key to proposing solutions that are effective from a mobility point of view and also satisfactory to the community. Willingness to compromise on highway designs without compromising safety or mobility will usually produce a considerably lower-cost solution. Another example of flexibility in highway design would be in the calculation of the number of lanes required to provide a certain capacity for a projected road. Assuming that agreement has been reached on forecasts of traffic, the capacity required to serve it must be estimated using a host of different factors involving peak-hour rates, design-hour volumes, directional flow, traffic mix, and other factors. Virtually all of these are unknown and open to question. It is not surprising, therefore, that the use of slightly different but nevertheless reasonable assumptions concerning input parameters may result in a different design for a given need than was originally proposed by either side.

Communication

Frequent meeting and communication are the key to improving trust and reaching compromise. It is impossible to compromise without communication. Therefore the intermediary's role is to ensure that communication between both sides is frequent and polite, either directly or through the intermediary. Whereas projects can and sometimes do get into an "over-meet" situation, we have found that more rather than less discussion and meeting are generally good for project development.

No compromise is easy, and negotiations take time. The time to achieve meaningful compromise should be built into the process as surely as design and right-of-way acquisition. Any time used to build consensus will be compensated for by the lack of litigation and public battles. Open communication must be based on trust. This trust can only be developed through good-faith, face-to-face negotiations. Small problems can often be settled before opposition becomes intense when they are talked through by both sides.

Low Media Profile

Perhaps nothing is as detrimental to the process of negotiation as extensive external coverage. This is not to say that such negotiations should go on in secret. On the contrary, open meeting laws and numerous other constraints in most states prevent that from happening, and even if such activities could go on in secret, we do not believe that they should. On the other hand, there is a difference between conducting meetings openly and in a spirit of cooperation as opposed to a series of meetings in which the media are invited to attend and participate every step of the way. We have found that in generally low-key meetings, the media are the most productive. In the event that media issues get in the way of the project, openness is generally the best approach. Often media will respond positively to the argument, "Look, we're trying to work this out and we are at a particularly sensitive stage right now, so we would very much like to have your cooperation in helping us to reach these solutions in an uncharged manner."

Willingness To Compromise

Of course, no cooperative solution will be possible if either side is unwilling to move from its initial stated beliefs or positions. The fundamental underlying assumption of the process is that both sides recognize the need to achieve, in whatever degree, some of the goals of the other side. That will normally be the case, since environmental groups and transportation planning and development agencies typically have similar goals, even if they may have different weights. We have generally found that both environmental and transportation investment organizations understand the importance of compromise in achieving mutually acceptable goals.

POLICY APPLICATIONS

As NEPA did in the 1970s, the 1991 ISTEA and the Clean Air Act Amendments of 1990 are likely to have significant negative effects on transportation investment in the 1990s unless transportation investment agencies and environmental organizations begin to work together to overcome barriers to achieving their mutual goals. Highway development is not dead, nor is it dying, but it is at risk. Transportation investment agencies need to understand that business as usual is no longer possible and that new mechanisms for cooperation are necessary. Environmental organizations are not antihighway, by and large, but proenvironment. Similarly, highway development agencies are not antienvironment but promobility. If the attention is placed on the common reality of both goals, that is the intersection rather than the diversions of their paths, each can be comfortable with the responsibilities of the other.

Transportation agencies need to open their environmental processes much earlier, typically, than they do now. Environmental review should start not when projects are moved into the pipeline for TIP funding or similar state-level activity, but rather when projects are initially proposed for consideration. Environmental review, including the identification of likely environmental impacts, should be conducted as part of the initial scoping of project proposals, even those beyond the range of the TIP and indeed occasionally beyond the range of the 20-year horizon (*15*).

Traditionally, the federal government's position on environmental analysis has been to wait and review formally submitted documents for consideration with the intent of issuing a FONSI or requiring a full EIS. In our view, this position encourages litigation because it places the federal government in position of decider. Essentially, if the environmental community loses the battle in the request for a FONSI, it has no recourse except to the courts. In our view, the cause of highway development would be much better served if FHWA expanded its involvement in project selection and development early in the process, both requiring and encouraging citizen involvement in particular projects and in the process by which projects are developed. It is not necessary for FHWA to take positions on individual projects; the time for that is at the end of the environmental review, but that step is not all under environmental planning. If compromise is explored and reached early in environmental review, the federal government's review will be considerably less charged.

We agree with those analysts who believe that the relatively calm waters of highway development are likely to get considerably more stormy in the next decade as further regulations are imposed. We do not agree, however, that they need toss the boats around. By combining two small boats, each on stormy waters, into one larger craft, both environmentalists and highway investment agencies can weather the storm together in safety.

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From Planning Through Construction: An Overview of New Jersey Department of Transportation's Integrated Environmental Procedures

ANDRAS FEKETE

A centralized environmental organization structure, including a newly created project scoping team, integrated policies and procedures, and adequate staffing provide the means for full consideration of environmental issues at all major decision points involving New Jersey Department of Transportation project development and implementation. Results of preliminary environmental screenings are used in making planning decisions and in development of short- and long-range programs. New project starts are "scoped" by the preliminary engineering and environmental units to produce environmentally compatible project proposals that comply with the National Environmental Policy Act and are ready for final design. Environmental project managers play a critical role in integrating services provided by the environmental bureau with other departmental functions. During final design, procedures ensure that environmental commitments are incorporated into project plans and specifications. Environmental reevaluations are done on all projects as a prerequisite to FHWA authorizations for right-of-way acquisition and construction advertisement. Follow-up environmental functions involving environmental construction permits, archaeology salvage, hazardous waste, and noise barriers are carefully coordinated and integrated during design and right-of-way decision making. Environmental Commitment Reports, summarizing all environmental concerns addressed in final project plans, are reviewed with construction personnel before construction. Compliance with environmental specifications is monitored during construction, and follow-up evaluations are performed on the success of environmental mitigation and enhancements.

April 20, 1990, marked a significant milestone for the environmental movement and for transportation. It was the 20th anniversary of Earth Day and the signing of FHWA's Environmental Policy Statement, stressing "the need to fully integrate environmental considerations into agency policies, procedures and decision making" (T. D. Larsen, keynote address, National Conference on Highways and the Environment, 1990). Mainstreaming environmental considerations has become a federal mandate and a challenge for transportation professionals. Obtaining speedy approvals of environmental documents and simply mitigating impacts is no longer good enough. There must be a genuine responsiveness through all stages of program planning and implementation to build and operate transportation systems that consider and incorporate contemporary environmental values. Good environmental documents are not the end result of the environmental process; good projects are. Therefore, the environmental process must be comprehensive and include all stages of project evolution and provide continuous opportunities to incorporate appropriate environmental values. The result should be "transportation facilities that fit harmoniously into communities and the natural environment" (T. D. Larsen, keynote address, National Conference on Highways and the Environment, 1990).

The environmental process must be carefully managed. Because it involves compliance with multitudes of shifting regulatory programs and evolving environmental values, the activities collectively referred to as the "environmental process" must be well integrated and carefully managed to produce good results. The consequences of mismanaging this process can include serious erosion of agency credibility, exposure to successful litigation, unpredictable schedules, and increased project cost.

In the past 20 years, the New Jersey Department of Transportation (NJDOT) evolved its environmental process to include all stages of project planning and implementation. There can be many different ways to successfully integrate environmental considerations into project development and implementation. This paper presents a summary of NJDOT's version and illustrates how the department has prepared itself to meet the rigorous transportation and environmental challenges of the 21st century.

EVOLUTION OF NJDOT'S ENVIRONMENTAL PROCESS

In 1972 the Bureau of Environmental Analysis (BEA) was created as a planning unit. Initially staffed with a handful of professionals, its sole purpose was to write environmental documents mandated by the National Environmental Policy Act of 1969 (NEPA) (P.L. 91-190, January 1, 1970, as amended by P.L. 94-52, July 3, 1975, and P.L. 94-83, August 9, 1975) to obtain FHWA approvals for projects already designed and otherwise ready for construction. After NEPA compliance was achieved, there was little, if any, further involvement by environmental staff during the remaining steps of project implementation.

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The increased restrictiveness of state and federal environmental regulations during the late 1970s, especially involving wetlands, and the need to follow up on environmental commitments made in NEPA documents and environmental permits created opportunities for environmental specialists to assume active roles in construction plan and specification development. Aside from the obvious environmental benefits, the process had another significant value. It marked the beginning of a strong partnership between NJDOT environmental and engineering staff.

By 1988 BEA was assigned lead responsibility for obtaining all environmental approvals, including construction permits. A formal environmental reevaluation process was also implemented, requiring BEA sign-off on every federally funded project before FHWA authorizations for ROW purchase and project advertisement. These two important functions placed BEA directly in the mainstream of project development. Implementation of review procedures for compliance with environmental commitments and permit conditions during and after construction by environmental staff further extended opportunities to incorporate environmental values into the final stages of project implementation. It also fostered a closer relationship between construction and environmental staff.

The recognition that environmental considerations must be fully considered during the earliest stages of program planning and project development, and that only environmentally feasible projects should be pursued, led to the current organization of the environmental function in NJDOT. In addition to providing environmental services during design and construction phases, BEA is now also working with a newly created unit, the Bureau of Preliminary Engineering (BPE), to "scope" new projects. A scoped project has an environmentally compatible preliminary design, all significant environmental approvals, public support, and credible project cost estimate and is ready for final design without the need for additional alternatives analysis.

The term "project scoping" as officially designated in NJDOT policy and used in this paper is different from scoping defined in the Council on Environmental Quality regulations (*1*) involving NEPA compliance. The latter is a technique recommended to solicit early involvement in large projects by other agencies and the public. NJDOT's project scoping process will be described in a subsequent section.

ENVIRONMENTAL STAFF WITHIN THE NJDOT ORGANIZATION

The primary unit for providing environmental services to NJDOT is BEA. It is located in the Division of Project Development, along with BPE, which provides engineering services for project scoping and project location. The division reports to the assistant commissioner of policy and planning as shown in Figure 1. All environmental staff are located centrally in Trenton, within easy travel distance to any work site.

The 67 staff in BEA are organized into three sections: project management, technical, and permits/ecology. Additional field support is provided by 20 environmental professionals located in the Construction and Maintenance Bureau. Figure 2 shows the functions performed by each section of BEA.

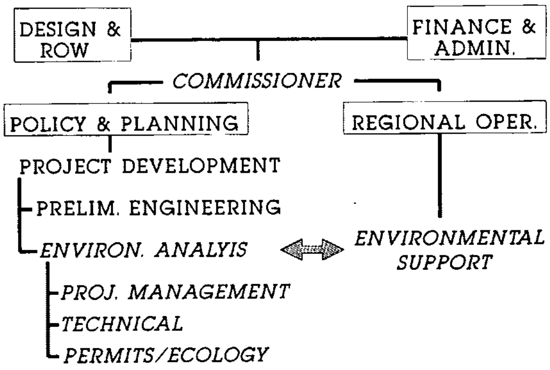

FIGURE 1 Placement of environmental staff in NJDOT organization.

<u>PROJECT MANAGEMENT</u>
- Organized by regions, located in Trenton.
- NEPA & 4(f) document preparation & approvals.
- Project coordination with FHWA and within NJDOT.
- Project schedules, tracking, reporting.
- Environmental "generalists".

<u>PERMITS & ECOLOGY</u>
- Organized by regions, located in Trenton.
- Environmental permits & natural resources assessments.
- Permit coordination with agencies.
- Permit schedules, tracking, reporting.
- Environmental "specialists".

<u>TECHNICAL</u>
- Organized by technical functions, located in Trenton.
- Section 106 approvals, air, noise, hazmat, contracting.
- Coordinate with agencies & FHWA.
- Schedules, tracking, reporting.
- Environmental "specialists".

FIGURE 2 BEA functions by section.

INTEGRATION OF ENVIRONMENTAL CONSIDERATIONS DURING PLANNING, PROJECT DEVELOPMENT, AND PROJECT IMPLEMENTATION

Environmental issues are considered by NJDOT from the earliest stages of transportation planning through project design and construction. To illustrate how this is accomplished, a description of environmental services will be described for each major stage of transportation planning, project development, and implementation. Figure 3 shows these functions.

Public involvement is recognized as an important aspect of NJDOT's environmental process. However, to keep the scope of this paper manageable, details are not provided on the public involvement process here.

PLANNING

NJDOT's planning process includes transportation needs assessments, corridor analyses, air quality planning, and development of the annual transportation improvement plan. Since at these stages the focus is on identifying specific capacity, safety, and operations problems with only conceptual

PROJECT STAGES	*ENVIRONMENTAL FUNCTION*
PLANNING	✓ SCREEN PROBLEM STATEMENTS
PROJECT DEVELOPMENT	✓ PROJECT SCOPING • Find best 'fit' • Establish project cost ✓ ENVIRONMENTAL APPROVALS • EIS • Env. Assessment/ FONSI • Categorical Exclusion
FINAL DESIGN & RIGHT OF WAY	✓ PLAN REVIEWS ✓ ENVIRON. RE-EVALUATION ✓ ENVIRON. PERMITS ✓ CONTAMINATION CLEAN UP SPECIFICATIONS ✓ FINAL NOISE STUDY ✓ ARCHAEOLOGICAL SALVAGE
CONSTRUCTION	✓ MONITOR COMPLIANCE WITH ENVIRON. COMMITMENTS
MAINTENANCE	✓ MONITOR EFFECTIVENESS OF ENVIRONMENTAL MITIGATION

FIGURE 3 Environmental functions during stages of project development and implementation.

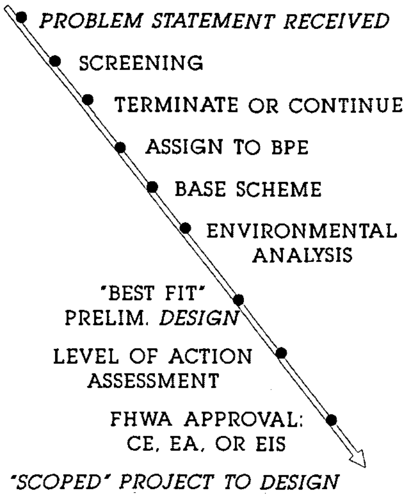

FIGURE 4 NJDOT's project scoping process.

recommendations for improvements, detailed environmental information, with the exception of air quality planning, is generally not required. At this stage, only broad-based screenings of environmentally sensitive areas are done to generate information for planning decisions. The culmination of the planning stage is problem statements, which articulate transportation deficiencies with conceptual recommendations for improvements.

PROJECT DEVELOPMENT AND PROJECT SCOPING

The concept of project scoping is the newest significant aspect of the NJDOT project development process. It is an organizational and procedural arrangement that integrates environmental analysis with preliminary engineering to produce environmentally feasible project proposals.

To address environmental issues at the earliest stage of project conception and development, BPE was created in 1990 and, working together with BEA, the process of project scoping was initiated. Figure 4 shows the process. A brief explanation follows.

Problem statements, which include detailed information on transportation needs, are submitted to the Division of Project Development from planning for a preliminary screening. BPE and BEA do a quick screening of broad engineering and environmental issues for obvious constraints that may affect feasibility. Environmental information is provided in a four-page preliminary environmental screening form and used, with input from other units, by senior management to decide whether the problem statement should be developed further into a capital project or the effort should be terminated.

If a decision is made to continue development of a project, BPE, staffed with civil engineers, develops the initial project footprint, which provides maximum transportation service, unconstrained by environmental factors. These conceptual engineering sketches, showing boundaries of potential land disturbance and property acquisition, along with field information, photographs, and video film are provided to BEA staff. At this point a detailed environmental analysis is done to identify all environmental constraints and opportunities for enhancement. Using this information, preliminary engineering staff and environmental staff develop an optimum project concept with minimal environmental impacts but providing acceptable transportation service. Alternatives analysis is done at this stage to the extent required to find the "best fit," and the results are documented in a level of action (LOA) assessment.

The LOA assessment is a key aspect of NJDOT's project scoping process. Codified in the department's policies and procedures, it is a minienvironmental assessment, which addresses the full range of potential environmental impacts. It includes input from not only BEA but also Right-of-Way, NJ Transit, external affairs, and design units and is used as supporting documentation by FHWA to classify projects into the categorical exclusion, environmental assessment, or EIS category. It also includes a comprehensive listing of all environmental approvals and permits needed to implement the project as well as any special commitments to address specific environmental issues in the final plans and specifications. Finally, it also includes a plan for implementing an appropriate community involvement program. To preserve the option for federal participation, all projects are subjected to LOA assessments and presented to FHWA for concurrence.

To obtain FHWA approvals on recommendations to classify project proposals as categorical exclusions, the LOA assessment must demonstrate compliance with Section 106 of the Historic Preservation Act of 1966 and Section 4(f) of the DOT Act of 1966. Reasonable assurance must also be provided that the project will comply with all other environmental statutes. FHWA approval of an LOA assessment for projects categorically excluded from NEPA constitutes NEPA signoff. If it is clear from the preliminary screening that the project proposal will need an EA or an EIS, considerably less detail is included in the LOA assessment, since the EA or EIS will comprehensively address all relevant environmental requirements as well as public involvement. The LOA in these cases is simply used as support for decisions on classifying projects into the EIS or EA categories.

The larger projects classified as EAs or EISs remain under the lead of BPE. Development of these documents, although an interesting and complex process, is not covered here. It is sufficient to point out, however, that the "NEPA process" involving iterative engineering and environmental effort is conducted within the same NJDOT division to find the best environmental fit for projects. All capital projects need an LOA assessment to get FHWA authorization for funding of final design and right-of-way acquisition. All projects must go through BEA for this assessment with the exception of a small group of categories that do not involve any additional ROW or significant disturbance of land. In these cases, although an LOA is still needed, the lead engineering units process it directly, without BEA input.

The products of the project scoping process are project proposals that have FHWA approval for compliance with the provisions of NEPA, Section 4(f), and Section 106; are likely to receive environmental permits; and have realistic cost estimates and predictable implementation schedules (*2,3*). In other words, scoping produces feasible project proposals ready for inclusion in a well-defined and "deliverable" annual capital program for final design, right-of-way, and construction.

As shown in Figure 3, the preliminary engineering plans of scoped project proposals are transferred to final design unit for 30 scale plan development, right-of-way acquisition, and specification development. A key element of this project handoff is the transfer of specific environmental commitments made during the categorical exclusion and NEPA document approval processes.

FINAL DESIGN PROCESS

Scoped project proposals are assigned to the appropriate final design unit and the development of 30 scale project plans and specifications begins. At this point, proposals are given project status and are included as line items in annual capital construction programs for final engineering, right-of-way, and construction funding. With this also comes a more acute focus on tracking project schedules and cost.

NJDOT has a four-phase plan development process, with the fourth phase being final plans and specifications used for bidding. During these stages, important environmental functions continue to be performed by BEA.

To ensure that commitments addressing environmental concerns identified during the scoping process are included in the final project plans and specifications, a checklist, known as the Environmental Commitments Report, is provided to the designer. This document also tracks the need for and status of all subsequent environmental permits and approvals required before advertisement. Examples include floodplain, wetlands, and water permits. This checklist is circulated with each phase of plan development and updated by design and environmental staff as new information develops. At each of four stages of plan development, procedures require reviews by BEA staff to keep track of design changes that may require additional environmental analysis and to suggest ways to enhance the environmental compatibility of the project.

Environmental permits are obtained by BEA staff during final design. The lead design units provide the required engineering information to BEA permits/ecology staff, who then add the required environmental data to complete permit applications. BEA staff are responsible for negotiating with permit agencies and are accountable for maintaining schedules. Permit conditions, including mitigation plans, special design features, and best management practices are added to the environmental commitments report for future tracking. The manager of BEA attends monthly meetings among senior NJDOT and New Jersey Department of Environmental Protection and Energy (DEPE) management to resolve problems involving policy interpretation, project priorities, and new initiatives.

Another significant function by BEA during the final design process is the environmental reevaluation, codified in NJDOT's official policy manual. It was developed in response to an initiative by the New Jersey division FHWA office to address the reevaluation provisions of 23 CFR, Part 662, Section 771.129. Since the property acquisition and completion of the final plans may occur several years after project scoping and NEPA approvals, the intent is to make sure significant changes in project design, right-of-way, public reaction, and environmental impact (including those resulting from new programs) are addressed before federal authorizations are given for right-of-way acquisition and project advertisement. The environmental reevaluation is performed on all projects by BEA staff and approved by the BEA manager. Federal authorization is not given without this sign-off. If significant changes are identified, appropriate steps are taken, including additional environmental assessment, to bring the project back into compliance. The reevaluation for advertisement must include copies of all necessary permits and approvals. The substantive issues addressed by the reevaluation form are shown in Figure 5.

During the final design process, environmental staff develop detailed DEPE-approved soil contamination remediation plans and specifications that are included in project plans and specifications. This information is also made available to right-of-way staff for use in property appraisals, negotiations, and, if necessary, condemnation proceedings. Environmental staff provide continuous technical assistance and expert testimony through the conclusion of the property acquisition process. Since the department policy is to try to get owners to remediate contamination before property acquisition or recover cleanup expenses from those unwilling to do so, the availability of environmental staff expertise is critical to success in these endeavors.

To ensure that right-of-way staff are aware of all environmental features on proposed ROW parcels that may affect appraisals, negotiations, settlements, and condemnations, BEA staff identify environmentally sensitive parcels on right-of-

ENVIRONMENTAL REEVALUATION

DONE AFTER "NEPA"...
FOR ROW AUTHORIZATION...
FOR CONSTR. AUTHORIZATION

1. HAVE ALL PERMITS?
2. PROJECT SCOPE CHANGE?
3. SIGNIFICANT LAND USE CHANGES?
4. NEW LAWS, REGULATIONS?
5. CHANGE IN PUBLIC SUPPORT?
6. NEPA ENVIRONMENTAL COMMITMENTS IN PLANS/ SPECS?
7. PERMIT CONDITIONS IN PLANS AND SPECS?
8. DOES ANY "ANSWER" CHANGE NEPA DOCUMENT CONCLUSION?

FIGURE 5 Environmental reevaluation checklist.

way plans that include wetlands, contamination, parkland, or other constraints that require special consideration or special procedures.

Other environmental activities that run concurrently with final design include archaeological salvage, historic structure mitigation (relocation, archival recording, etc.), wetland mitigation plan development and agency approval, and preliminary noise barrier design. Environmental staff make a significant effort to fit these functions in the design process at the appropriate time, to ensure a smooth process.

The final involvement by environmental staff during the design process (or beginning of the construction stage) is the handoff of environmental information to the resident construction engineer, construction's environmental support staff and contractor. The environmental commitments report is provided and discussed at a preconstruction conference. The intent is to carefully explain the significance of environmental protection and enhancement features and emphasize the need for resident engineers to ensure contractor compliance.

CONSTRUCTION AND MAINTENANCE

During construction, regular field checks are made by Environmental Support Services staff (see Figure 1 for relationship to BEA) and BEA during sensitive stages of construction to check for compliance with environmental requirements and provide assistance to construction staff. Day-to-day environmental field services are also provided by the Environmental Support Unit, including water quality sampling, erosion control, and technical assistance to resident engineers on implementing environmental specifications. Field information is supplied to BEA staff, who provide general oversight for environmental compliance and reporting to FHWA. BEA also obtains permit modifications as field conditions warrant and provides technical assistance in resolving violations of permit conditions by contractors.

After construction is complete, BEA is responsible for monitoring and reporting on the success of wetland mitigation projects to regulatory agencies for 3 to 5 years. Other environmental follow-up activities, such as groundwater monitoring of remediated contaminated sites and archaeology data recovery reports, are also performed by environmental staff during this late stage.

Occasionally, the long-term effectiveness and maintenance characteristics of environmental project features are also evaluated with assistance from environmental staff. Examples include oil/water separator devices and water quality treatment features of drainage systems.

ENVIRONMENTAL PROJECT MANAGER

A discussion of NJDOT's integrated environmental process is not complete without a description of the role of the environmental project manager. The environmental bureau is split into two generalized functions, specialists and project management. Specialists in a wide range of professional disciplines, many with advanced degrees, provide in-depth skills and knowledge needed to conduct and direct technical studies, which are the basis for environmental documents and project decisions. These professionals are located in the technical and permits/ecology sections of BEA.

Environmental project managers (who include environmental permit managers), organized into four regions, homogeneous with design, construction, and maintenance regions, serve as the "integrators" of specialist functions into the mainstream transportation development process. Although most of these professionals have environmental degrees, they serve as generalists. All projects requiring environmental service by BEA are assigned to project managers, who coordinate project scoping efforts; prepare LOA assessments, 4(f) documents, NEPA documents, and environmental reevaluations; review design plans, and audit compliance with environmental commitments during construction. These managers coordinate environmental services and track their assigned projects from the earliest scoping stages through construction and beyond. The most important functions of environmental project managers, however, involve a strong responsibility for project "ownership" manifested through environmental advocacy, accountability for compliance with environmental regulations, and environmental functions that are kept on schedule, within cost, and integrated with the efforts of other functional units in NJDOT from early planning through construction (see Figure 6). They coordinate bureau efforts with FHWA, lead engineering and support units in the department, attend virtually all program status meetings, and represent the bureau at public meetings and hearings. The environmental project managers also maintain a comprehensive and current computer data base on the status of environmental services on all projects. Used to generate regular status reports distributed to all concerned units, the data base is also extremely helpful in developing and evaluating project lists for annual capital construction programs and for diagnostic purposes.

This arrangement encourages environmental professionals to formulate a comprehensive and intimate view of the department's mission and operations and discourages the propensity for viewing environmental functions as an assembly line "add-on" exercise. It encourages staff to think in terms of physical projects and services, reinforcing the fact that good

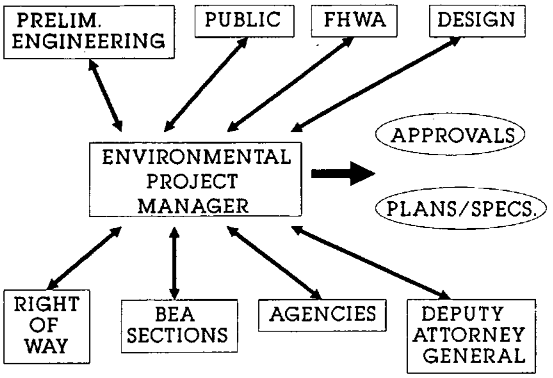

FIGURE 6 Environmental project managers integrate and coordinate efforts to obtain environmental approvals and ensure development of environmentally enhanced construction plans.

projects and good operational practices, not simply good environmental documents, are the ultimate goal of the environmental process.

CONCLUSION

NJDOT's environmental functions in 1993 are no longer limited to obtaining NEPA compliance for projects, as they were in 1973. All aspects of department operations must now be in compliance with the myriad of state and federal environmental statutes and the public's expectations. In 20 years, the role of NJDOT environmental staff has dramatically increased in significance, affecting virtually all aspects of department operations, especially capital program development and execution.

NJDOT's organizational structure, procedures, and staffing now provide continuous opportunities to incorporate contemporary environmental values at virtually all stages of transportation planning and implementation. The arrangement also provides excellent control over program compliance with environmental laws and regulations, resulting in consistent delivery of annual capital programs.

The newly created process of project scoping has already been effectively used to reevaluate several long-standing, environmentally infeasible projects, resulting in decisions to terminate them. It has also been used effectively in quickly determining feasibility of major controversial transportation proposals, which in years past would have languished as multiple iterations of feasibility studies lasting decades.

Since the project scoping process is only about 2 years old, the track record is still under development. It is anticipated that the next few years will produce evidence that scoped projects will proceed through the final design process and receive environmental permits on a faster, more predictable track and will be better accepted by the public and environmental agencies.

A significant challenge remains for NJDOT. The Intermodal Surface Transportation Efficiency Act provides unprecedented opportunities to make transportation part of the environmental solution. The department's organizational infrastructure is well established to fully incorporate environmental values in program development and execution. NJDOT environmental professionals, planners, and engineers must now learn to better recognize opportunities to enhance the environment and take full advantage of NJDOT's integrated process to act on them. The standard of environmental success should reach beyond good environmental documents and speedy environmental approvals. Good projects and well-run transportation operations that reflect contemporary environmental values will be the standard for success in the 21st century.

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PART 2

Air Quality

Analysis of Fine Particulate Matter near Urban Roadways

MORGAN BALOGH, TIMOTHY LARSON, AND FRED MANNERING

The emission and dispersion of particulate matter near urban roadways has become an issue of increasing concern because of the possible health risks to humans associated with the inhalation of small particulates. Despite the potential health risk, little is known about the concentration of particulates near urban roadways or the particulates emission rates of various vehicles. Particulate matter smaller than 2.5 micrometers (microns), typically denoted $PM_{2.5}$, was studied. Data were collected along paved roads on the University of Washington campus. The results of the data collection and subsequent statistical analysis indicated, as expected, that urban buses are by far the major source of particulate emissions and that buses with low exhaust pipes generate higher concentrations of roadside fine particulate matter than buses with elevated exhausts. The findings suggest that the Environmental Protection Agency's procedure AP-42 for calculating resuspended particulate matter near urban roads is grossly inaccurate, producing values that are 9 to 20 times higher than observed fine particulate levels.

Highway traffic has long been identified as a significant source of air pollution in urban areas. Of the numerous pollutants associated with highway vehicles, particulate matter has gained attention because of recent evidence of health impacts at levels below current federal standards (*1*). Near paved urban roadways there are numerous sources of airborne particulate matter, including emission of incomplete combustion products from the tailpipe and resuspension of material from the road surface. In general, combustion processes produce smaller particles—functionally defined for sampling purposes as $PM_{2.5}$ [i.e., particles with sizes less than or equal to 2.5 micrometers (μm)] in aerodynamic diameter (*2*). Particles larger than this are generally of mineral origin, including soil particles, tire and brake wear products, and ice control compounds (*3*).

Different types of fuels, engine control technologies, and vehicle types influence the characteristics of particulate emissions. For example, emission characteristics of diesel, leaded gasoline, and unleaded gasoline vehicles differ. Also, the gross vehicle weight and the available horsepower vary the emission of particulates. Table 1 summarizes the size distribution of particles emitted by vehicles, expressed as the cumulative fraction of particulate mass smaller than a given diameter.

Among the negative impacts associated with airborne particulate matter are impaired visibility, unsightly settlements on surrounding buildings and plant life, and diminishment of road sign reflectivity and the illumination of roadway lighting. A recent study in France produced evidence that 70 to 80 percent of the soiling of objects along roadways is due to transportation particulate matter (*4*). The health effects associated with particulate matter depend on particle size. Those particles $\leq$ 10 μm in diameter (PM_{10}) are small enough to penetrate the nose or mouth and thereby deposit in the respiratory tract. Therefore the sources of both $PM_{2.5}$ and PM_{10} are of interest, including sources associated with paved urban roadways.

Of all particulate sizes, $PM_{2.5}$ is arguably the least studied, primarily due to difficulties in finding equipment sensitive enough to measure such small particulates. The established standards for estimating $PM_{2.5}$ vehicle emission rates are contained in the Environmental Protection Agency's (EPA's) AP-42 document on particulate emissions (*3*). However, other studies [e.g., Black et al. (*5*)] suggest that the AP-42 standards grossly overestimate $PM_{2.5}$ vehicular emission. Given the potentially detrimental health effects associated with $PM_{2.5}$, the significance and consequences of such overestimation could have an undesirable and misguided effect on transportation pollution control policy. The object of this study is to provide additional evidence on the suitability of AP-42 for estimating $PM_{2.5}$ vehicle emission rates.

DETERMINATION OF FINE PARTICLE IMPACTS

Study Site

The site selected for the $PM_{2.5}$ analysis is Stevens Way, located on the Seattle campus of the University of Washington. This site was chosen because of its proximity to our research laboratory, its high ratio of buses to automobile traffic, and its representative urban terrain. Stevens Way is a two-lane, paved road that passes through the University of Washington campus in Seattle, Washington. It has a curb, gutter, and concrete sidewalk and is on about a 2 percent grade. Near the study area, the buildings on the upwind side of the road and the trees, shrubs, and sloped ground on the downwind side produced both canyon and line source effects.

The buildings in this area were approximately 13 m from the centerline, on the upwind, or west, side of the roadway. Trees and shrubs were 5 to 7 m from the centerline of the roadway. On the downwind, or east, side of the roadway was an incline at about 7 m from the roadway. This incline rose about 2 m above the road and leveled off. During peak periods automobile traffic volumes can exceed 500 vehicles per hour (vph), and transit and tour bus volumes can exceed 30 buses per hour. Traffic counts during this study indicated that approximately 97 percent of the buses traveled upgrade.

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TABLE 1 Particle Size Distribution by Type of Fuel (Proportion)

Diameter	0.2 *u*m	1.0 *u*m	1.0 *u*m	2.5 *u*m	10 *u*m
leaded	0.23	—	0.43	—	0.64
unleaded*	0.87	—	0.89	—	0.97
unleaded**	0.42	—	0.66	—	0.90
diesel	0.73	0.86	0.90	0.92	1.00

* with catalytic converter
** without catalytic converter

Measurement Equipment

The equipment used to measure $PM_{2.5}$ must be highly sensitive and accurate. An integrating nephelometer is an appropriate $PM_{2.5}$ measuring device. It uses the fact that particulate matter in air scatters light. Integrating nephelometers measure the optical scattering coefficient (defined by the variable b_{sp}) from light in a sensing volume, integrated over all scattering angles. Many studies have shown high correlations between the scattering coefficient (b_{sp}) and particulate matter with diameters less than or equal to 2.5 μm. Waggoner and Weiss (*6*) showed that these two measures are a constant ratio with a correlation coefficient greater than 0.95.

The integrating nephelometers used in this study were designed and built by Radiance Research, Seattle, Washington. Nephelometers measure b_{sp} in the ranges of 0 to $10^{-3}m^{-1}$ or from 0 to $10^{-2}m^{-1}$. They operate at a wavelength of 475 nanometers (nm) with a Type 1A filter or at 525 nm with a Type 59 filter. The nephelometers used in this research operated at 475 nm. This is a satisfactory wavelength for the measurement of b_{sp}. The b_{sp} can be used to calculate $PM_{2.5}$, with a lower particle size limit of 0.1 μm. Data can be stored internally in intervals of 5 min or read directly in ½- or 1/15-sec intervals. Portable computers were used to record real-time data from these nephelometers using ½-sec intervals.

To accompany $PM_{2.5}$ site measurements, wind speed and wind direction were collected on a Weather Pro Model TWR-3 portable weather station. The weather station anemometer is accurate from 3 to 120 mph in 1-mph increments, or 5 to 190 kph in 1-kph increments. Wind direction was reported in 10-degree increments. In addition, traffic volumes were closely monitored by an observer who recorded information on a laptop computer so that the effects of individual vehicle types on $PM_{2.5}$ concentration could be determined.

The collection of these related traffic data to accompany $PM_{2.5}$ concentrations allowed us to statistically isolate the determinants of $PM_{2.5}$ concentrations. This was achieved by regression analysis, as described later in this paper.

Data Collection

At this location data were collected on 2 days: July 11, 1991, from 3:50 to 5:05 p.m. and July 29, 1991, from 3:35 to 5:30 p.m. Site data included distance from the edge of pavement to the nephelometers (2 m) and distances to trees and shrubs. b_{sp} readings were taken in ½-sec intervals for 190 min, or approximately 23,000 ½-sec periods. b_{sp} data were also converted to 5-min averages to total 38 periods. Automobile counts were taken in 5-min periods. The precise times that buses passed the sampling site were recorded. Whether the exhaust was above or below the bus was also recorded. Wind speed and wind direction were recorded at the sampling location when a change was noted. In general, all testing was performed on partly cloudy days with temperatures of 75°F to 85°F, wind speeds of 1 to 2 kph, wind gusts to 5 kph, and barometric pressures of 760 to 766 mm Hg. The equipment setup is shown in Figure 1. Nephelometers were placed 2 m from the roadway, and upwind and downwind concentrations were estimated in approximately ½-sec intervals.

Summary of Measurements

On July 11, 1991, ½-sec concentrations were calculated only for the downwind location, whereas on July 29, 1991, ½-sec concentrations were calculated for both the downwind and upwind locations. These measurements (see Figure 2) indicate

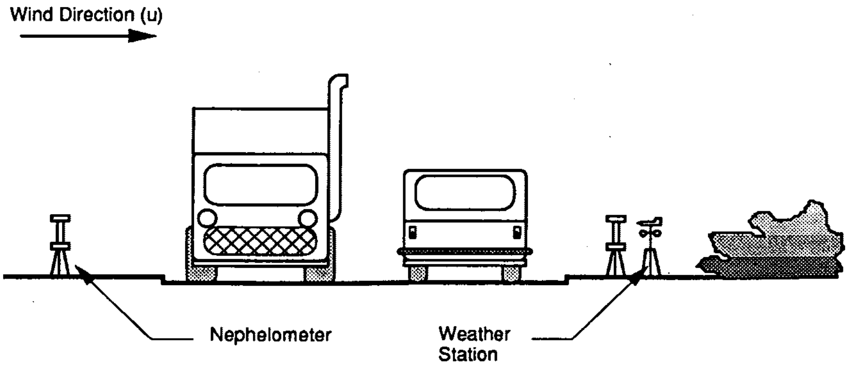
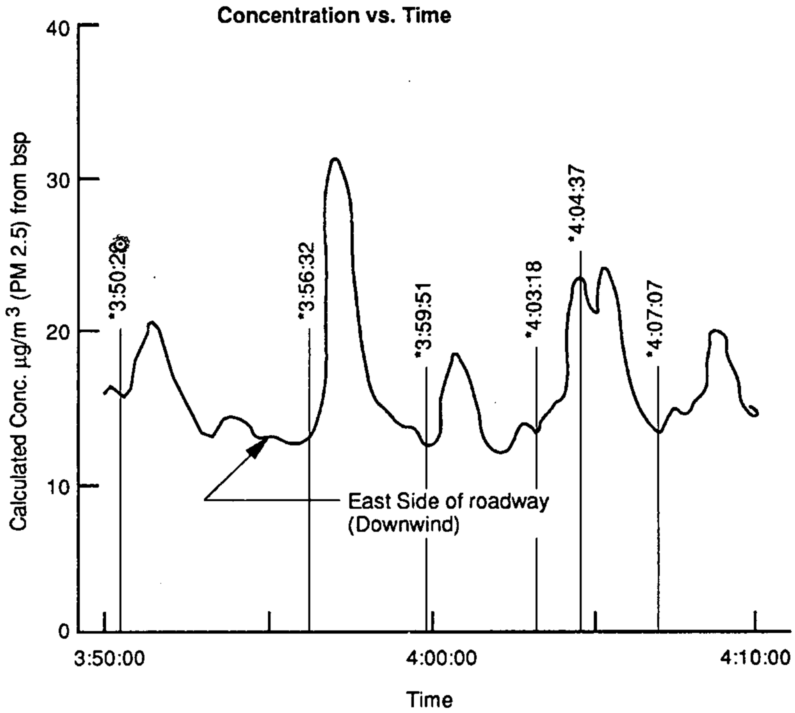


FIGURE 1 Equipment setup procedure.



* Time bus passed sampling location

FIGURE 2 **$PM_{2.5}$, July 11, 1991, 3:50 to 4:10 p.m.**

that each time a bus passed the sampling location, the downwind $PM_{2.5}$ concentration rose from approximately 5 to 15 g/m^3 and then returned to its initial level over a period of 1 to 1.5 min. The result was short-term, high concentrations in $PM_{2.5}$ each time a bus passed.

On the upwind side of the roadway on July 29th, three short-term spikes in concentrations were observed. These concentrations ranged between 35 and 65 g/m^3. Two of these spikes could be directly traced to tour buses with exhaust below the bus (see Figure 3).

Our data indicate that the effects of one bus were not always additive to that of a previous bus. Depending on the frequency of the buses, their emissions could be additive or their wakes could be mitigative. Automobiles tended to have very little effect on $PM_{2.5}$ concentrations. As the number of automobiles rose, the $PM_{2.5}$ concentrations also rose, but at a very low, consistent rate. When congestion occurred or the traffic speed became very low, the concentration rose and tended to stay at a high level for a longer period. Typically, congestion occurred only in one direction; therefore, while the vehicle turbulence effects were lost in the congested direction, the uncongested direction continued to cause turbulence. Also, a larger vehicle passing by slowly in the congested lane could still cause enough turbulence to lower the $PM_{2.5}$ concentration.

DATA ANALYSIS

Figure 4 shows the various analysis procedures used to compare our results with the AP-42 emission factors for $PM_{2.5}$ via resuspension and with previously reported direct measurements of vehicle tail pipe emissions. The typical approach for analyzing air pollution along roads is to estimate vehicle emission rates and put these rates in dispersion models to calculate air pollution concentration. The approach taken in this research is to measure air pollution concentrations and put these values in both a regression and a dispersion model to uncover the underlying vehicle emission rates for fine particles emitted by various vehicles.

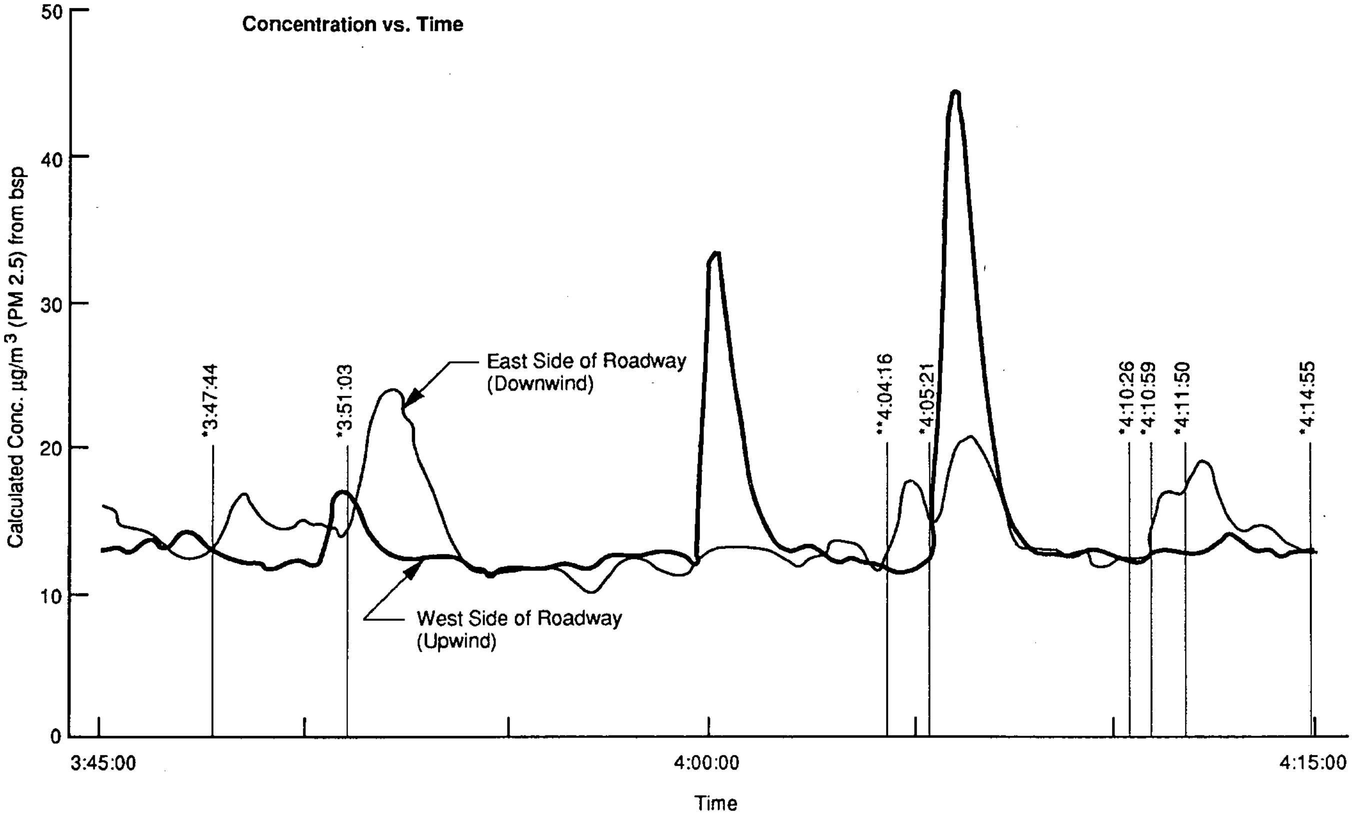
Emission Factors

The AP-42 emission factors predict the emission rate of fine particles via resuspension from the road surface due to passing vehicles as a function of road surface silt loading, SL (g/m^2). For $PM_{2.5}$ the functional relationship takes the following form:

$$e = 1.02(SL/0.5)^{0.6} \qquad (1)$$

where e is the $PM_{2.5}$ emission factor for resuspended particles (g/vehicle/km).

For paved urban roads, the emission factor for $PM_{2.5}$ ranges from 0.7 to 2.4 g/vehicle/km (*3*). We can compare these values with the emission factor for fine particles directly emitted from the tail pipe of various vehicles. Black et al. (*5*) give a value of 0.01 to 0.02 g/veh/km for automobiles and values of 0.9, 0.38, and 0.16 g/veh/km for pre-1987, 1987, and 1988–1991 vintage heavy-duty diesels. Therefore, according to EPA's AP-42 emission factor, the emission of resuspended $PM_{2.5}$ from any vehicle, including cars, is approximately 4 to 15 times



* Time bus passed sampling location

** Time diesel truck passed sampling location

FIGURE 3 $PM_{2.5}$, July 29, 1991, 3:45 to 4:15 p.m.

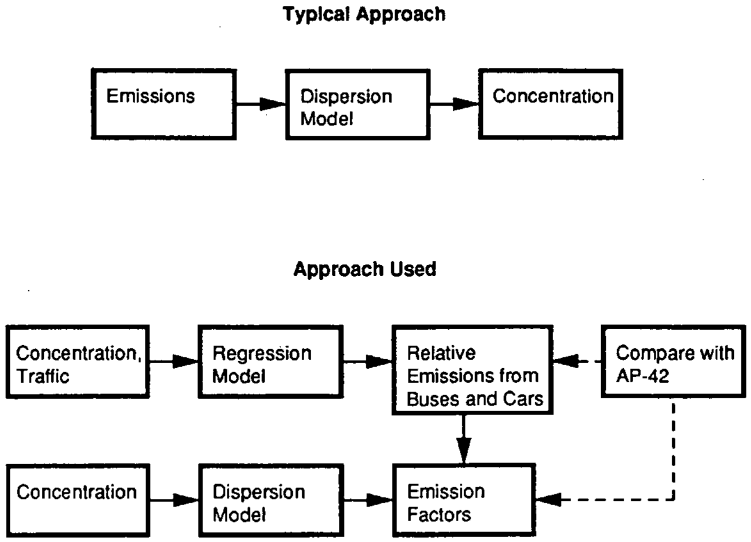


FIGURE 4 Modeling approaches.

greater than from the tail pipe of a heavy-duty diesel and 30 to 120 times greater than from the tail pipe of a car. If this were true, it would be very difficult to observe the effects of individual buses near a road. In fact, we have observed such effects and have also estimated the relative contributions from diesel buses versus automobiles using logistic regression models.

Regression Models

Five-min average $PM_{2.5}$ concentrations were calculated from the ½-sec b_{sp} readings. We then sought to statistically define the determinants of these 5-min average concentrations. To do so, two regression models were specified: one for downwind concentrations and one for upwind concentrations. The estimation of these regression coefficients allows us to determine separate $PM_{2.5}$ emission rates for cars and diesel buses, because we consider each of these two sources in the model.

The downwind 5-min average $PM_{2.5}$ concentration was regressed against the corresponding 5-min diesel bus and automobile volumes. With $PM_{2.5}$ measurements 2 m from the roadway, wind speeds of 1 to 5 kph, and dry conditions, 5-min average $PM_{2.5}$ concentrations ($\mu g/m^3$) are given by the following linear equation:

$$\begin{aligned} PM_{2.5} = {} & 10.65 \\ & + 2.74(\text{bottom exhaust bus volume, vph}) \\ & + 1.60(\text{top exhaust bus volume, vph}) \\ & + 0.05(\text{automobile volume, vph}) \end{aligned} \qquad (2)$$

The traffic volumes are expressed in units of vehicles per hour but are computed as 5-min averages. The regression results of this equation are presented in Table 2. We attempted to separate out the effects of wind speed and wind direction, but we had too few observations and too small of a variance in our data to arrive at statistically significant variable coefficients in a regression equation.

Table 2 indicates a significant difference in $PM_{2.5}$ emissions between buses with top exhausts (standard public transit buses) and buses with bottom exhausts (tour buses). This is expected since our nephelometers are set at near-pedestrian height levels, and lower exhausts can potentially provide a much more dramatic effect.

Equation 2 can be written in general form as

$$C = a_1 + a_2[\text{vph}]_2 + \dots + a_i[\text{vph}]_i + \dots \qquad (3)$$

where

$a_i = e_i/D_i$ for $i \neq 1$;
D_i = the atmospheric dilution factor, expressed in units of m^3/hr for a moving point source where mixing and dilution occurs in the crosswind direction (along the roadway) and in units of m^2/hr for an infinite line source where only the dilution occurs in the vertical direction; and
e_i = the emission factor for the ith source, expressed in units of g/vehicle when D_i has units of m^3/hr or in units of g/vehicle/meter when D_i has units of m^2/hr.

For $D_i = D_j$, $i \neq j \neq 1$, the dilution effect from each vehicle type is the same, and

$$a_i/a_j = (e_i/e_j)\,(D_j/D_i) = e_i/e_j \qquad (4)$$

From Equation 2, $a_2 = 2.74$ for bottom exhaust buses, and $a_4 = 0.05$ for automobiles. Assuming $D_2 \approx D_4$ [i.e., the dilution effects are the same for buses and automobiles (the tailpipe emissions are of equivalent height and the resuspension emissions are both at ground level)], we deduce that $e_2/e_4 \approx 50$. This implies that a diesel bus with bottom exhaust emits approximately 50 times more $PM_{2.5}$ from the road than an automobile. In contrast, AP-42 emission factors imply that resuspension from the road is the main source of $PM_{2.5}$ and that all vehicles should contribute approximately equally.

To explore wake effects, a regression model was also run to arrive at a predictive model of upwind effects. The upwind model was of the form

$$\begin{aligned} PM_{2.5} = {} & 16.08 + 3.98(\text{bottom exhaust bus volume, vph}) \\ & - 0.615(\text{top exhaust bus volume, vph}) \\ & - 0.614(1/\text{automobile volume, vph}) \end{aligned} \qquad (5)$$

The regression results of this equation are presented in Table 3.

In this model, buses with exhausts above the vehicle actually lowered the upwind concentration. This is because the wake

TABLE 2 Least Squares Regression of Measured Downwind 5-min Averaged $PM_{2.5}$ Concentration Calculated from b_{sp}

Independent Variable	Estimated Coefficient	Standard Error	t-Statistic
Bus volume with bottom exhaust	2.73747	0.45577	6.00629
Bus volume with top exhaust	1.60366	0.19854	8.07724
Automobile volume	0.049991	0.029113	1.71710
Constant	10.65253	1.22219	8.71596

Number of Observations	38
R-squared	0.80279

TABLE 3 Least Squares Regression of Measured Upwind $PM_{2.5}$ Concentration Calculated from b_{sp}

Independent Variable	Estimated Coefficient	Standard Error	t-Statistic
Bus volume with bottom exhausts	3.978	0.658	6.04
Bus volume with top exhausts	-0.615	0.287	-2.14
Inverse of automobile volume	-0.614	0.287	-2.140
Constant	16.08	1.589	10.11

Number of Observations	38
R-squared	0.52355

of the bus dispersed the pollution, lowering the $PM_{2.5}$ concentration, and its emissions were released high enough that they did not increase the $PM_{2.5}$ concentration. On the other hand, if the exhaust was below the bus, the emissions were carried by its wake, traveling along the ground and registering on the nephelometer, thus increasing the upwind $PM_{2.5}$ concentration. Aside from this, the findings were consistent with the downwind model.

Dispersion Models

In considering dispersion model alternatives (to arrive at vehicle emission rates), several model options are available. These include Gaussian line source, wake theory, box, street canyon, and intersection models. A summary of the characteristics of these models is presented in Table 4 [see Balogh and Mannering (*7*) for a complete review]. The primary dispersion model used in this research is the Gaussian line source model, although a comparison with the street canyon model (*8*) will also be made. Descriptions of the Gaussian line source and street canyon models are provided below.

The Gaussian model was developed by applying a Gaussian distribution to Fick's turbulent diffusion equation. Therefore, for the Gaussian model to hold true, the basic assumptions of the Fickian diffusion equation must be satisfied. These assumptions include spatial homogeneity (invariance in space), stationarity (invariance in time), and a large diffusion time (*9*).

Most models currently used in practice for assessing near-roadway effects are modified forms of the Gaussian model. What differentiates models are the formulation and choice of parameters. The finite line source model described below is the Gaussian dispersion model modified for highways (*10*).

$$\frac{C}{Q} = \frac{1}{\text{sigma}_z u} \times \left\{ \exp[-(z-h)^2]/2\text{sigma}_z^2 + \exp[-(z+h)^2]/2\text{sigma}_z^2 \right\} \qquad (6)$$

where

C = the concentration ($\mu g/m^3$);
Q = the emission rate ($\mu g/sec$);
h = the effective height of emission release (m);
u = wind speed (m/sec);
z = the height above the ground (m);
sigma_z = the standard deviation of the distribution C in the z axis (m), adjusted for on-road vehicle wake effects = $1.5 + t_R/10$; and
t_R = the residence time of air passing over the mixing zone (sec).

In the 1970s, several models based on the Gaussian equation were developed to predict concentrations of gaseous air pollutants. Evidence has shown that there are definite differences in the dispersion of particulate matter and gases, such as gravitational settlement and coagulation (*11*). However, because the models are used here on a microscale and the focus of our measurements is on particulate matter emissions less than 2 μm, these differences are not important. When the early models were tested with gaseous tracers, they proved accurate when the wind was perpendicular to the road and the atmospheric boundary layer was neutrally bouyant. However, when winds were nearly parallel to the roadway, the concentrations predicted by the models were higher than the actual measured concentrations (*12*).

A street canyon is any roadway sheltered on both sides by complex topographical features, such as buildings, walls, earth banks, and trees. In street canyons pollutants can be trapped and concentrations elevated. Exposure to pollutants is short term for pedestrians passing through the area and long term for people working or living in adjacent buildings.

Because of the many complex street canyons in urban areas, accurate modeling is necessary. Most successful street canyon models are based on a modification of the box model. The

TABLE 4 Dispersion Model Alternatives

Type of Model	Use	Relative Accuracy	Relative Difficulty
Gaussian line source	flat open highway	good	little difficulty
wake theory	flat open highway	excellent	difficult
box	highway network	low	little difficulty
street canyon	areas sheltered by trees, buildings, walls, etc.	good	little difficulty
intersection	highway intersections	good	some difficulty

model described below assumes circular air patterns over the street (*8*). The background $PM_{2.5}$ concentration, plus C_L or C_w, is the total concentration for that respective side of the roadway.

$$C_L = \frac{7 * 10^6 * Q'}{(u + 0.5)[(x^2 + z^2)\,0.5 + 2]} \qquad (7)$$

$$C_w = \frac{(7 * 10^6)\,Q'(Hb - z)}{W(u + 0.5)\,Hb} \qquad (8)$$

where

Q' = emission rate (g/m/sec),
C_L = concentration contributed by vehicle emissions for the downwind or leeward side ($\mu g/m^3$),
C_w = concentration contributed by vehicle emissions for the upwind or windward side ($\mu g/m^3$),
u = the average wind speed above the canyon (m/sec),
x = the horizontal distance to the receptor from the emissions source (m),
z = the vertical distance to the receptor (m),
Hb = the leeward side average building height, and
W = the width of the canyon (m).

As an adjustment factor for vehicle wake turbulence, 0.5 is added to the wind speed.

With the coefficients of Equation 2, the estimated sigma_z (2.5 m), the average wind speed (0.6 m/sec), and the Gaussian line source model (see earlier discussion), an emission factor could be calculated. We used 1-hr average fine particle concentrations in the calculation. This averaging time is more consistent with the assumption of the line source model than are the 5-min average values used in the regression analysis. The emission factors were estimated to be 0.02 g/veh/km for automobiles and 0.8 g/bus/km for buses.

Table 5 gives a comparison of our emission rates with those of Black et al. (*5*) as well as the EPA's AP-42 computation (*3*). The AP-42 computation for paved urban roads produces emission factors that range from 0.73 to 2.42 g/veh/km. Putting these factors into the Gaussian line source model with an average of 480 vehicles/hr resulted in $PM_{2.5}$ concentrations of 108 and 358 $\mu g/m^3$ for 0.73 and 2.42 g/veh/km, respectively. The range of observed hourly average $PM_{2.5}$ concentrations was 15 to 17 $\mu g/m^3$. Therefore, the paved urban road computations resulted in $PM_{2.5}$ concentrations from 6 to 24 times higher than those actually measured. Even if every vehicle on the road was a heavy-duty diesel bus (i.e., our calculated value of 0.8 g/bus/km), the maximum concentration would not have exceeded concentrations calculated with the AP-42 recommended factor of 0.73 g/veh/km.

The regression models combined with the Gaussian line source model produced emission factors close to those used in the studies of Black et al. but much lower than those that resulted from the AP-42 study. Table 5 compares the emission factors calculated in this study with those of Black et al. (*5*) and EPA's AP-42 (*3*).

Finally, to compare the prediction of the Gaussian line source model, emission factors of 0.012 g/veh/hr and 0.51 g/bus/hr were put into the street canyon model [described by Dabbert and Sandys (*8*)]. The resulting downwind concentrations were from 0.95 to 1 times those calculated by the Gaussian line source model and from 0.9 to 1.15 times those actually measured. The resulting upwind concentrations ranged from 0.40 to 0.95 times those actually measured. This difference probably occurred because the street canyon model does not take into account the exhaust release location, which was shown to have a strong correlation with measured concentration.

STUDY LIMITATIONS

The critical limitation of this study is that $PM_{2.5}$ measurements were only taken at a single elevation on each side of the road. The Gaussian line source model used to uncover vehicle emission rates suggests that $PM_{2.5}$ concentrations should be taken at a number of points (heights above the ground surface) so the particulate plume profile can be accurately determined. This may affect our conclusions about release height as a determinant of downwind concentrations. However, the potential error introduced into our dispersion model calculations by our single point measurement is at most a factor of 2 or 3, which is not sufficient to nullify our primary finding. That is, the confidence intervals of our vehicle $PM_{2.5}$ emission estimates do not cross the AP-42 estimates, and, consequently, AP-42 clearly overestimates $PM_{2.5}$ emissions. In addition, our estimates of the relative emission rates derived from the regression model are not as sensitive to this limitation.

The other concern is our data limitations, both in terms of quantity and variability defined by meteorology, traffic volume, engine type, fuel types, exhaust controls, and different road types. There is clearly a need for an elaborate and extensive study that will precisely establish $PM_{2.5}$ emission rates. Such a study could use the same approach adopted in this study, but emphasis should be placed on extensive data collection with high variability in road and meteorological conditions. Particle size distributions should be measured in real time as a function of height above the ground, and these measurements should be correlated with short-term fluctuations in wind speed as an additional measure of mass flux from the road surface.

TABLE 5 Emission Factor Comparison by Study (g/veh/km)

Type of Vehicle	Black et al. (5)	EPA's AP-42 (3)	This Report
Automobiles	0.01 - 0.02	None	0.02
Heavy Duty Diesels/Buses	0.9 (before 87) 0.38 (1987) 0.16 (88-91)	None	0.8
Entire Roadway	0.06	0.73 - 2.42	0.08

CONCLUSIONS

Integrating nephelometers are excellent tools for examining particulate matter along the roadway. The nephelometers used in this study took b_{sp} measurements that resulted in the accurate calculation of particle concentrations with diameters between 2.5 and 0.1 μm. The measurements' accuracy and sensitivity allowed the measurement of subtle canyon effects.

Although the equipment used in this study could not measure particles smaller than 0.1 μm, such particles exist and may be significant. Near highways, nuclei-mode-sized aerosols, particles between 0.1 and 0.01 μm, can contribute an additional particulate mass equal to 30 to 50 percent of that measured between 2.5 and 0.1 μm (*13*). These particles are created by the rapid cooling of many hot, supersaturated vapors. Nuclei-mode-sized aerosols are typically created by catalyst-equipped cars. These particles tend to coagulate quickly, approximately 1 to 2 min, into and onto particles larger than 0.1 μm (*13*). Placing integrating nephelometers close to the road may cause the effects of nuclei-mode-sized aerosols to be overlooked. This problem could indicate that integrating nephelometers placed next to roads are better for application to diesel than gasoline vehicles. Nonetheless, this does not negate the fact that essentially all of the $PM_{2.5}$ we observed comes from tail pipe emissions, not resuspension. Using EPA's AP-42 emission factors for $PM_{2.5}$ results in the opposite, erroneous conclusion.

The health risks associated with $PM_{2.5}$ make it the greatest concern of particulate matter. For example, in the Puget Sound area, the Washington State Department of Ecology claims that motor vehicles annually emit 3,000 tons of combustion particles into the air and are responsible for another 177,000 tons of fine particulates from road dust. Particles resulting from combustion are clearly on the order of $PM_{2.5}$. However, when $PM_{2.5}$ is measured along paved urban roads, there is little or no contribution from road dust. Therefore, when the health effects associated with particulate matter near roads are discussed, combustion particles, not road dust, are of primary concern.

Because of the high, short-term rises in particulate matter concentrations that result from passing diesels, more real-time studies are necessary. Since major particulate matter polluters usually pass at varying intervals, modeling them as continuous sources can be erroneous.

Bus exhausts are sometimes put under the vehicle to reduce the noise associated with the bus. However, they tend to increase the particulate matter concentrations close to the roadway. In fact, our regression model results suggest that buses with exhausts below the vehicle can have nearly twice the effect on $PM_{2.5}$ that buses with exhausts above the vehicle have.

The procedure in AP-42 for calculating particulate matter concentrations along paved urban roadways is inappropriate for calculating $PM_{2.5}$. It produces values that are from 6 to 24 times higher than those actually observed.

The use of emission standards as emission factors in line source models seems to be a valid approach for determining PM concentrations near roadways. However, adjustments must be made to account for poorly maintained vehicles. The determination of emission factors necessary for calculating $PM_{2.5}$ concentrations close to those measured in the field resulted in factors close to those reported by Black et al. (*5*) as well as recent tail pipe emission standards.

Highways with complex terrain can have both line source and street canyon characteristics. Whereas buildings are predominantly responsible for canyon characteristics, gaps between buildings and perpendicular roads can produce line source characteristics. These effects were seen during our study. The buildings on the upwind side of the road and the trees, shrubs, and sloped ground on the downwind side produced both canyon and line source effects.

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Magnitude and Value of Electric Vehicle Emissions Reductions for Six Driving Cycles in Four U.S. Cities with Varying Air Quality Problems

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The emissions of logically competing mid-1990 gasoline vehicles (GVs) and electric vehicles (EVs) are estimated as if the vehicles were driven in the same pattern (driving cycle). Six driving cycles are evaluated, ranging in speed from 7 to 49 mph. These cycles are repeated using specific fuel composition, electric power mix, and environmental conditions applicable to Chicago, Denver, Los Angeles, and New York. The emissions differences for 2000 are estimated for each of five pollutants: hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), and carbon dioxide (CO_2). With use of EVs, HC and CO emissions are consistently lowered by 98 percent or more. Across metropolitan areas, CO_2 emissions reductions are uniformly large at low speed but variable at high speed. Initially introduced EVs could achieve 100 percent emission reductions in Chicago by using off-peak power from nuclear power plants for recharging EVs. Emissions reductions occur for all combinations in Los Angeles and for most combinations in New York, except for SO_x. NO_x emissions are reduced in all four cities. An "avoided cost" value in dollars per ton of emissions reductions for each of the five pollutants is estimated for each of the four cities. The values for each city depend on severity of air quality standard violations. Dollar value of EV emissions reductions is calculated with dollars per ton of emissions reductions and estimated emissions reductions by EVs over the vehicle lifetime. The emissions reduction value is estimated as if a mid-1990s EV were substituted for a GV for each driving cycle in each city. Depending on driving conditions assumed, the emissions reduction value for EVs driven an average of 1.6 hr/day ranges from $12,600 to $19,200 in Los Angeles, $8,500 to $12,200 in New York, $3,200 to $9,400 in Chicago, and $6,000 to $9,000 in Denver (in 1989 dollars).

Use of electric vehicles (EVs) is considered to be an effective strategy to reduce vehicular air pollutant emissions. Since 1989, several studies have been conducted to compare air pollutant emissions of EVs and gasoline-powered vehicles (GVs) (*1–6*). Accounting for power-plant emissions increases due to EV use, these studies show large reductions in per-mile vehicle emissions of hydrocarbons (HC) and carbon monoxide (CO) by EVs relative to GV emissions. EV use could decrease or increase emissions of nitrogen oxides (NO_x), depending on the type of power plants that provide electricity for recharging EVs and the intensity of NO_x emission control in the power plants. EV use usually increases emissions of sulfur oxides (SO_x) and particulate matter (PM), primarily because SO_x and PM emissions from GVs are small. To bring about the emissions reduction benefits of EVs, the California Air Resources Board has mandated the sale of EVs by vehicle manufacturers after 1997 (*7*). States in the Northeast region of the United States are likely to follow California's mandate of EV sales.

In analyzing EV emission impacts, all previous EV studies used the GV emissions that were estimated with the driving conditions specified in the U.S. federal urban driving schedule (FUDS). In reality, because of the limited range of EVs and traffic congestion in the major urban areas where EVs are most likely to be used, most early model EVs are likely to be driven at speeds lower on average than those simulated by FUDS-specified conditions. The per-mile GV emissions that are to be eliminated by use of such EVs tend to increase significantly as average driving speed decreases. For example, the U.S. Environmental Protection Agency's (EPA's) Mobile5A model estimates that GV emissions at 5 mph are 2 or 3 times more than those at the FUDS average speed (19.6 mph) (*8*).

Although EV electricity consumption rates (kilowatt-hours per mile) and emission rates (grams per mile) also differ under different driving conditions, they are far more stable than for GVs. To analyze the effects of driving conditions on EV emissions, this study estimated GV emissions and EV electricity consumption (therefore EV emissions) under six driving cycles ranging in average speed from 7 to 49 mph and compared EV emissions with GV emissions under each of the six cycles (Table 1).

Estimated emissions of GVs can differ from state to state, since federal or state legislation and regulation allow different measures to control motor vehicle emissions. Currently, California has different emissions certification standards from the rest of the nation and uses its own emissions model, called EMFAC. In the future, the Northeast states may adopt California's certification standards. On-road emissions rates, as estimated by models, also vary because of different ambient environmental factors. For EVs, the mix of power-plant types providing electricity differs in different regions, and so do the emission control efforts in power plants. In summary, EV emissions at any given speed show far more geographical variation than do emissions of GVs, whereas GV emissions in any given metropolitan area show far more variation in per-mile emissions rates as a function of driving speed than do EVs.

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TABLE 1 Average Speed, GV Fuel Economy, and EV Electricity Consumption Under Six Driving Cycles

Driving Cycle[a]	Average Speed (mph)	GV Fuel Economy (MPG)	EV Electricity Consump. (Kwh/mi.)
NYCC	7.1	9.5	0.40
ECE-15	11.7	16.9	0.32
SAE C	15.4	21.3	0.35
SFUDS	18.5	26.1	0.37
SAE D	28.4	35.1	0.41
HWY	48.6	36.1	0.39

[a] For specifications of most of the driving cycles, see Reference 10. NYCC--New York city cycle; ECE-15--Economic Community of Europe Cycle 15; SAE C--SAE C cycle; SFUDS--simplified federal urban driving schedule; SAE D--SAE D cycle; HWY--highway cycle.

Previous EV studies have focused on the significant regional variation in EV emissions but have ignored the significant speed variation of EV and GV emissions. Although two studies (*2,4*) have compared EV emission impacts in different U.S. regions, they analyzed regional EV emissions for large regions (for example, Wang et al.'s study analyzed EV impacts in California and in the United States, and ICF's study divided the U.S. into 10 regions and analyzed EV emission impacts for each region). This study selected four major U.S. metropolitan areas—Chicago, Denver, Los Angeles, and New York—and analyzed EV emission impacts for each area.

A recent study by Ford that examined emissions reduction potential in the Los Angeles basin estimated a dollar value for the predicted emissions reductions by EVs (*9*). For the Los Angeles area, Ford estimated a cumulative value of nearly $9,000 for avoided emissions control costs made possible by introduction of an average household EV. Our estimates are more comprehensive than Ford's. We estimate EV emissions reduction values for four cities under various driving speeds. We use Mobile5A to estimate on-road GV emissions, whereas Ford used GV emissions standards. Because of this, we estimate larger dollar values for Los Angeles than did Ford and larger values for Los Angeles than elsewhere. The costs paid for emission control in the Los Angeles basin are the highest in the United States. The value of EV emissions reductions in Los Angeles should be greater because of both the severity of violations of individual air quality standards and the number of the pollutants for which standards are violated. Since the mechanism driving emitters to pay to reduce emissions is the violation of ambient air quality standards, payments for further control can only be expected for those pollutants contributing to violations (although payments for further control of emissions where pollutant concentrations marginally meet the standard can also be expected). Thus, the locations that can be expected to pay most for EVs or be most likely to force EV introduction through regulations will have violations of ambient air quality standards (e.g., ozone or CO standards).

METHODOLOGY

This study compared EV emissions with GV emissions. The comparison was conducted under each of the six driving cycles (Table 1) and in four metropolitan areas (Chicago, Denver, Los Angeles, and New York). Chicago violates the federal ozone standard; Denver violates the federal CO standard; Los Angeles violates the federal ozone, CO, and NO_x standards; and New York violates the federal ozone and CO standards. The analysis was targeted at a base year of 2000, although the substitute EVs and GVs were assumed to be 1996 models. Emissions of HC, CO, NO_x, SO_x, and CO_2 were analyzed. Emissions of other pollutants, such as particulate matter and toxic air pollutants, were not included in this study.

Calculation of GV Emission Rates

On-road per-mile GV emissions of HC, CO, and NO_x were calculated with Mobile5A, the most recent version of EPA's Mobile model for estimating on-road vehicle emissions. To account for emission deterioration effects, GVs were assumed to have about 50,000 mi accumulated. This implies that a GV with 50,000 mi accumulated in 2000 is actually produced around 1996. Mobile5A was run to generate GV emissions for the average speed of each of the six driving cycles and with ambient temperature, gasoline Reid vapor pressure (RVP), and inspection and maintenance (I/M) program applicable for each metropolitan area. The Stage II technology to control vehicle refueling emissions at gasoline service stations was assumed to be implemented in Chicago, Los Angeles, and New York, where the federal ozone standard is violated. When calculating emissions of HC and NO_x, we used summertime (July) temperature, but when calculating emissions of CO, we used wintertime (January) temperature. This is because HC and NO_x emissions contribute to formation of ozone, whose concentrations peak on hot summer days, whereas CO emissions and ambient concentrations peak on cold winter days. This approach is recommended by EPA for estimating motor vehicle emissions inventories.

GV emissions of SO_x and CO_2 were calculated for different driving cycles with the following two formulas:

$$SO_x = 2{,}798 \times 0.03\% \times 64/32/\text{MPG} \tag{1}$$

and

$$CO_2 = (2{,}798 \times 86.6\%/\text{MPG} - CO \times 12/28) \times 44/12 \tag{2}$$

where

SO_x = SO_x (mainly SO_2) emissions (g/mi),
CO_2 = CO_2 emissions (g/mi),
2,798 = gasoline density (g/gal),
0.03% = sulfur content of gasoline by weight (*2*),
86.6% = carbon content of gasoline,
MPG = vehicle fuel economy (mi/gal; the estimation will be shown below),
CO = CO emissions (g/mi) (calculated with Mobile5A);
64 = molecular weight of SO_2,
32 = molecular weight of sulfur,
12 = molecular weight of carbon,
28 = molecular weight of CO, and
44 = molecular weight of CO_2.

GV fuel economy under each of the six cycles was calculated by use of an on-road fuel economy profile versus speed developed by Toyota (*11*). The base SFUDS fuel economy is about 26 mpg, an on-road value representative of published city values of manual transmission-equipped 1993 subcompact cars (*12*). Estimated MPG (and therefore SO_x and CO_2 emissions) varies with different driving cycles but is the same for the four cities. Table 1 presents estimated GV MPG for each cycle.

Emissions from refining the crude to gasoline were included in estimates of GV emissions. DeLuchi et al. (*13*) estimate refinery emissions of 0.85, 1.26, 1.46, and 1.99 g/gal of gasoline produced for HC, CO, NO_x, and SO_x, respectively. DeLuchi (*14*) estimates refinery emissions of 1,461 g/gal of gasoline produced for CO_2. Grams-per-gallon refinery emissions were assumed to be the same in the four cities. Grams-per-mile refinery emissions were calculated by dividing the grams-per-gallon emissions by GV fuel economy.

Calculation of EV Emissions

Unless augmented with fuel-using auxiliary heat or power sources, EVs themselves do not produce emissions, but power plants that provide electricity for EVs do. The emissions comparison between EVs and GVs here is the comparison between the power plant emissions attributable to EV use and the vehicle and refinery emissions attributable to GV use. No auxiliary EV power sources are included, nor are estimates of electricity demand for heating and cooling of the EV. Emissions of EV battery recycling could be a potential concern. However, we estimated that NO_x emissions of EV lead-acid battery recycling are between 0.0017 and 0.0034 g/mi, or less than 1 percent of per-mile GV NO_x emissions.

The value of the gram-per-mile EV emissions is equal to the power plant emission rate in grams per kilowatt-hour of electricity generated times the EV electricity consumption rate in kilowatt-hours per mile. The average power plant emission rates for EV recharging were calculated from the emission rates and the percentage of EV electricity generated by power plant types.

The effect of driving cycle on EV electricity consumption was estimated using a computer model. Marr and Walsh of Argonne National Laboratory have established a microcomputer software package called MARVEL to model EV electricity consumption rates under different driving cycles (*15*). Taking into account vehicle rolling resistance, drag resistance, EV power train efficiency, battery and charger efficiency, and other factors, MARVEL simulates the dynamics of vehicle movement and generates per-mile electricity consumption of EVs. Marr has run MARVEL for this study to generate EV electricity consumption rates for each of the six driving cycles. Input values were characteristic of a projected two- to four-passenger EV equipped with a sodium-sulfur battery and with weight and battery-pack size/weight characteristics similar to those of of the Ford Ecostar EV.

Integration of Emissions with Estimates of Dollar Values per Ton

Finally, per-mile GV emissions were compared with per-mile EV emissions to estimate total emissions reductions per EV in tons. This estimate was based on an assumed average daily period of operation (1.6 hr/day) held constant for each of the six driving cycles in each of the four cities. Dollar values per ton of emissions reductions (avoided costs that would otherwise have been incurred by other sources) were approximated using California Energy Commission's (CEC's) dollars-per-ton emissions values and EPA information on status of air quality standard violations (*16,17*). The reduced emissions in tons per vehicle and the dollar value estimates per ton were multiplied together for each pollutant in each metropolitan area and for each driving cycle. Total values of emissions reduction per EV were developed for each metropolitan area and under each driving cycle by adding the individual pollutant values.

RESULTS

GV Emission Rates

Per-mile GV emissions for HC, CO, NO_x, SO_x, and CO_2 calculated with the methodology described are presented in Table 2. Grams-per-mile refinery emissions of HC, CO, NO_x, SO_x, and CO_2 are a function of driving cycle (i.e., gallons per mile) but do not vary by metropolitan area. For example, under the SFUDS, refinery emissions are 0.033, 0.048, 0.056, 0.076, and 56 g/mi for HC, CO, NO_x, SO_x, and CO_2, respectively.

EV Emission Rates

Power Plant Emission Rates for EV Recharging

A given mix of power plants generates electricity to meet electricity demand in an individual region. When EVs are introduced, the EV electricity demand will be met by those types of power plants available to provide additional power. It is these so-called marginal plants that need to be considered in estimating EV emissions. The marginal plant mix for each of the four cities is presented in Table 3. Using the marginal mix and the emission rates of power plant types (coal-, gas-, and oil-fired power plants), the average emission rates for EV recharging in each of the four cities were calculated and are presented in Table 4.

TABLE 2 GV Emissions by Driving Cycle (g/mi)[a]

Pollutant	Chicago	Denver	Los Angeles	New York
NYCC:				
HC[b]	2.18	2.17	1.75	2.37
CO[c]	33.35	32.38	22.41	31.97
NO_x[c]	0.94	0.93	0.92	0.95
SO_x[c]	0.39	0.39	0.39	0.39
CO_2[c]	1030	1038	1054	1040
ECE-15:				
HC[b]	1.56	1.60	1.06	1.70
CO[c]	25.31	23.18	16.04	21.89
NO_x[c]	0.82	0.81	0.80	0.82
SO_x[c]	0.22	0.22	0.22	0.22
CO_2[c]	573	576	587	578
SAE C:				
HC[b]	1.29	1.35	1.07	1.39
CO[c]	21.59	22.90	13.68	19.52
NO_x[c]	0.78	0.77	0.76	0.78
SO_x[c]	0.17	0.17	0.17	0.17
CO_2[c]	452	450	464	455
SFUDS:				
HC[b]	1.11	1.20	0.95	1.19
CO[c]	19.62	17.97	12.44	17.74
NO_x[c]	0.76	0.75	0.74	0.76
SO_x[c]	0.14	0.14	0.14	0.14
CO_2[c]	366	368	377	369
SAE D:				
HC[b]	0.80	0.89	0.68	0.85
CO[c]	12.00	10.98	7.60	10.85
NO_x[c]	0.77	0.76	0.75	0.77
SO_x[c]	0.11	0.11	0.11	0.11
CO_2[c]	276	278	283	278
HWY:				
HC[b]	0.52	0.63	0.45	0.55
CO[c]	5.63	5.15	3.57	5.09
NO_x[c]	0.81	0.80	0.79	0.81
SO_x[c]	0.10	0.10	0.10	0.10
CO_2[c]	278	279	281	279

[a] These are emission rates for a 1996 model-year passenger car in year 2000.

[b] HC emissions include exhaust, evaporative (hot soak and diurnal), refueling, running losses, resting losses, and refinery emissions.

[c] Emissions of CO, NO_x, SO_x, and CO_2 include vehicular exhaust emissions and gasoline refinery emissions.

TABLE 3 Marginal Power Plant Mix for EV Recharging (percent)

Fuel Type	Chicago	Denver	Los Angeles	New York
Coal	0.0	52.6	7.5	24.0
Gas	0.0	35.2	85.0	28.0
Oil	0.0	3.3	0.0	48.0
Others[a]	100.0	8.9	7.5	0.0

[a] Including nuclear, hydropower, and other sources. It is assumed here that power plants fueled by these sources have zero air emissions.

TABLE 4 Average Emission Rates for EV Recharging (g/kw-hr)

Pollutant	Chicago[a]	Denver[a]	Los Angeles[b]	New York[c]
HC	0.0	0.013	0.067	0.013
CO	0.0	0.123	0.087	0.150
NO_x	0.0	1.484	0.156	0.400
SO_x	0.0	0.714	0.029	3.900
CO_2	0.0	687	623	643

[a] Average emission rates were calculated from the rates of coal-, gas-, and oil-fired plants weighted by their mix. The marginal power-plant mix is presented in Table 3.

[b] The average emission rates for Los Angeles were calculated from the emission rates of coal- and gas-fired plants weighted by their mix. The marginal power-plant mix is presented in Table 3.

[c] The average emission rates for New York were calculated by Tennis (6) from the emission rates of power-plant types and their mix.

EV Emission Rates in Grams per Mile

To allocate power plant emission rates in grams per kilowatt-hour of electricity to EV emission rates in grams per mile, EV electricity consumption in kilowatt-hours per mile is needed. Marr's MARVEL computer model was run for this project to generate EV electricity consumption for each of the six driving cycles. The estimated EV electricity consumption rates are presented in Table 1. Marr's estimates are for a 2,750-lb inertia weight EV assumed to be capable of carrying four passengers and using a projected sodium-sulfur (or equivalent) battery pack. To run MARVEL, the following energy efficiencies were assumed: 85 percent for drivetrain efficiency, 85 percent for electric motor efficiency, 80 percent for battery efficiency, and 90 percent for battery charger efficiency.

The EV electricity consumption presented in Table 1 is at the wall outlet. To calculate EV emission rates using power plant emission rates, the electric distribution and transmission loss, which amounts to about 8 percent, needs to be considered (*18*).

EV Emission Impacts

The changes in per-mile passenger car emissions due to EV use are shown in Figure 1. EV emissions reductions are shown on a percentage basis for each pollutant, under each driving cycle, in each of the four cities. Since it was assumed that nuclear-power plants will supply electricity for EVs in the Chicago area, EV emissions reductions are 100 percent in the Chicago area for each individual pollutant under each cycle (secondary uranium mining and processing emissions were not included in this study). Emissions reductions in the other three metropolitan areas are summarized below.

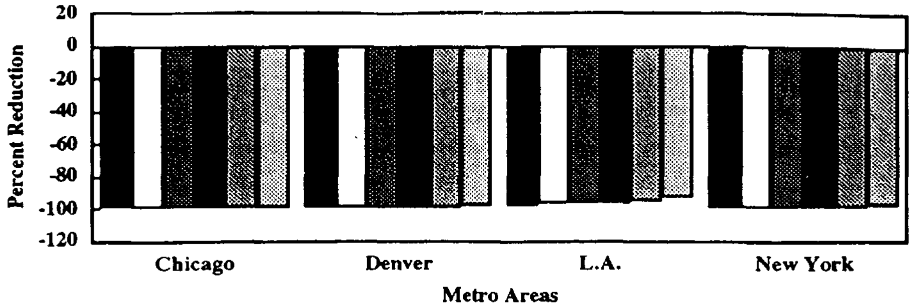
EV use reduces HC and CO emissions by more than 98 percent, regardless of driving cycle or metropolitan area. Use of EVs appears to be a technically effective strategy to help solve the CO air pollution problem in Denver, Los Angeles, and New York and to help reduce the ozone air pollution problem in the areas where HC control will help reduce ozone formation.

The power plant mix in Los Angeles results in emissions reductions for all pollutants under the six driving cycles. Thus, in the area where across-the-board emissions reductions are most necessary—Los Angeles—the estimated reductions are consistent and significant. Los Angeles is in an airshed that may be described as VOC/NO_x lean (smaller ratio of volatile organic compounds [VOCs] to NO_x) (*19*). In the VOC/NO_x-lean areas, where control of HC (the predominant class of VOC) helps reduce ozone formation, use of EVs alleviates the ozone pollution problem. New York City is an area where HC reduction is predicted to be effective in reducing ozone, whereas NO_x reduction is not. However, NO_x reduction within the city should reduce downwind metropolitan area ozone formation (*19*). Thus, theory suggests that the Los Angeles and New York metropolitan areas can benefit from simultaneous reductions of HC and NO_x. Houston is a city where HC reduction would not be very effective.

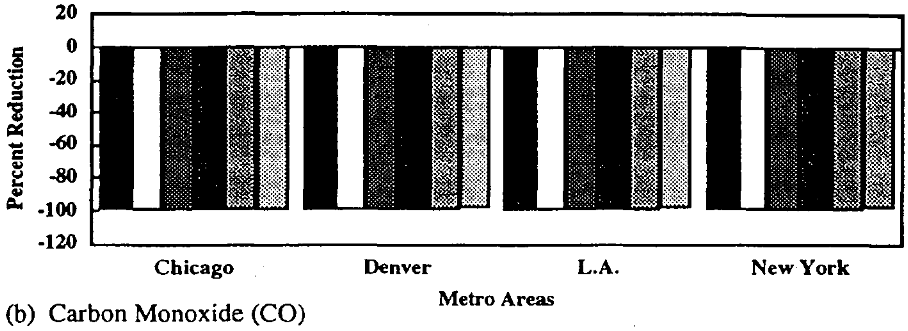
NO_x emissions in Denver, Los Angeles, and New York are reduced under each driving cycle. NO_x emissions reductions are 10 to 40 percent in Denver, more than 90 percent in Los Angeles, and about 80 percent in New York. In all three cities, the largest percentage NO_x emission reductions occur at the lowest speed, and emissions reductions decrease from the NYCC to the SAE D but increase again under the HWY. Overall, the reductions in both HC and NO_x attributable to EVs will help solve the ozone air pollution problem in Los Angeles and New York. NO_x emission reductions will also help Los Angeles meet the federal ambient NO_2 standard.

For SO_x emissions, we have estimated that increases would occur in the absence of additional control. However, national SO_x emissions are capped, and increases caused by EVs would have to be offset. SO_x emissions in Denver increase when using EVs under all driving cycles except the NYCC and increase in New York under all six cycles. This is primarily because a large portion of EV electricity in these two cities is provided by coal- and oil-fired power plants. SO_x increases in New York are much larger than in Denver. Though the percentage increases in SO_x emissions are large, the absolute amount of SO_x increase by EVs will be small compared with overall SO_x emissions because of the very tiny amount of SO_x emissions attributable to GVs. The dollar value computations in the next section show that SO_x emissions are relatively unimportant. In Los Angeles, EVs reduce SO_x emissions by more than 85 percent.

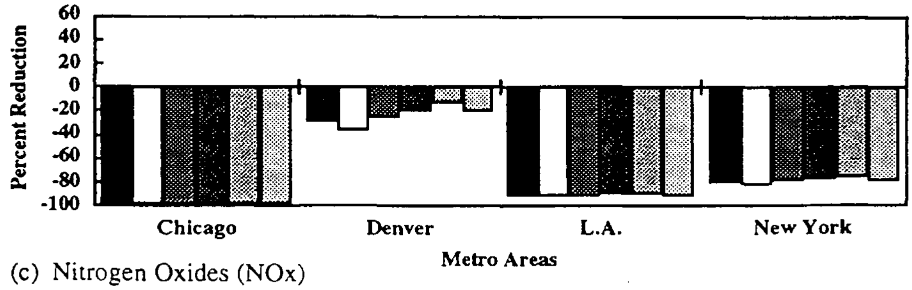
CO_2 emissions are decreased in Los Angeles and New York under each of the six cycles. The CO_2 percent changes in these two cities are from a reduction of 70 percent for the



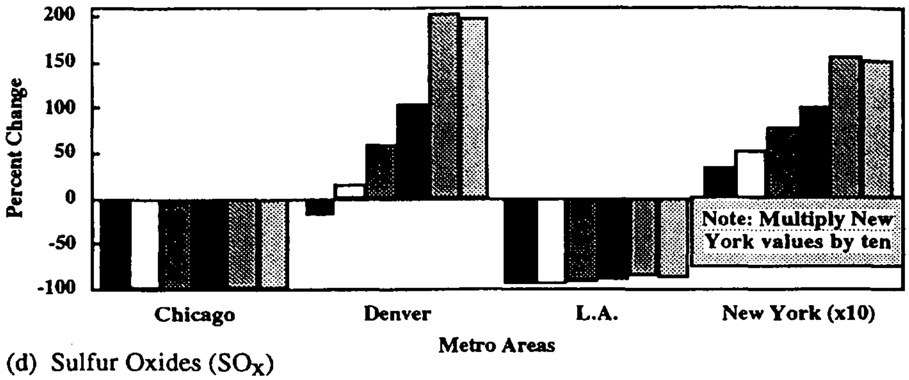
(a) Hydrocarbons (HC)



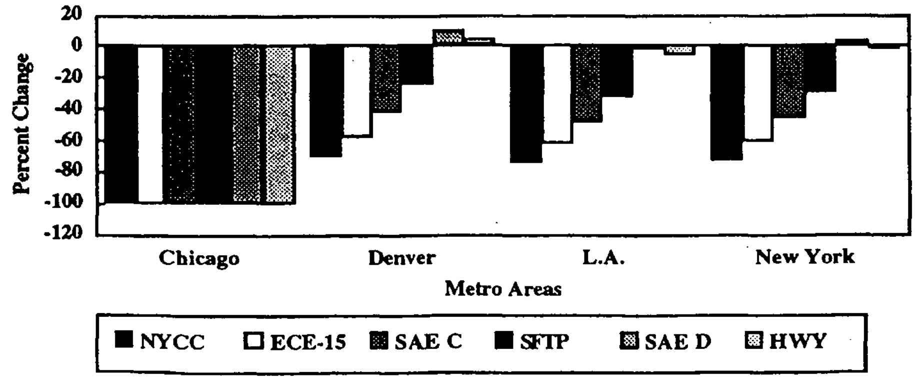
(b) Carbon Monoxide (CO)



(c) Nitrogen Oxides (NOx)



(d) Sulfur Oxides (SO_X)



(e) Carbon Dioxide (CO_2)

FIGURE 1 EV percent change emissions impacts: Mobile5 speed correction factors.

NYCC to approximately no change at the two highest speeds. In Denver, CO_2 emissions are reduced from 70 to 30 percent from the NYCC to the SFUDS but increased by about 5 percent under the SAE D and the HWY. At higher average driving speeds, it appears that the effect of substituting EVs or GVs could be positive or negative depending on the estimate of relative fuel economy of the vehicles. For lower speeds, however, the estimation of a benefit for EVs is definite.

In the preceding analysis, the calculated EV emissions include the emissions of power plants located in and outside of each of the metropolitan areas. The estimated refinery emissions of GVs may be in or outside of the metropolitan areas. Since emissions of out-of-area power plants do not contribute to the emissions in each of the areas, actual air quality benefits of using EVs in each of the areas are likely to be larger than when the same emissions reductions are obtained by substituting low-emission internal combustion engine vehicles for GVs. This is especially true for HC, CO, and NO_x, which cause area-confined air pollution problems. Since SO_x and CO_2 cause acid rain and global warming, which are regional or global pollution problems, the location of power plants is less critical to SO_x and CO_2 emissions.

Value of Emissions Reductions

A prior study by Ford for Southern California Edison of the dollar value of emissions reductions of EVs in Los Angeles driven according to the FUDS emissions test procedure arrived at an estimate of value per vehicle of about $9,000 in 1989 dollars (*9*). In this study, we have assumed that one EV replaces one GV with exactly the same driving pattern over time. The vehicles last 13 years and are driven an average of 1.6 hr/day, which is equivalent to 10,500 mi/year for the 18.5-mph SFUDS driving cycle. The annual mileage (and hours per day) are greater early in the vehicle's lifetime, tapering off in later years. Consistent with the CEC methods of converting future costs into present value dollars, we convert our tons saved per year estimates to "present value" tons using a real discount rate of 4.0 percent (*20*).

The value of the emissions reductions on a dollars per ton basis for Los Angeles was directly from CEC (*16*). The value for the metropolitan areas outside California was estimated by relating the avoided cost of emissions in various areas of California to the severity of the air quality violation there (see Table 5). If one of our non-California cities had the same level of air quality violation as a location in California, a dollars per ton value comparable with the California value was used. In the case of CO, the severity of violations in Denver and New York were intermediate between values in Los Angeles and the two other major California cities (i.e., San Diego and San Francisco). Thus, an intermediate dollars per ton value was selected. When no violation of a standard occurred, the corresponding emissions reductions were valued at zero. This is consistent with CEC's control cost estimates (*20*, Table 2).

The treatment of SO_x was different, primarily because we were attempting to make conservative assumptions that would not overstate the emissions reduction value of an EV. In the case of SO_x, it was assumed that costs would be incurred to offset emissions that would otherwise occur because of added electricity output caused by EVs. These costs would allow utilities to stay within the required SO_x cap.

It could be argued that the pollutants to which we have assigned a zero emissions reduction value should be given a positive value in an area if maintenance of air quality related

TABLE 5 Estimated Avoided Costs of Emissions Reduction (1989$/Ton) and Selected Emission Violation Status

Pollutant	Chicago[a]	Denver[a]	New York[a]	Los Angeles[b]	San Diego[b]	San Francisco[b]
Ozone Violation Status	Extreme or Severe	In Attainment	Extreme or Severe	Extreme or Severe	Extreme or Severe	Moderate
HC	18,200	0	18,200	18,900	17,500	10,200
NO_x	22,350	0	22,350	26,400	18,300	10,400
CO Violation Status	In Attainment	High Moderate > 12.7 ppm	High Moderate > 12.7 ppm	Serious	Low Moderate ≤12.7 ppm	Low Moderate ≤12.7 ppm
CO	0	3,925	3,925	9,300	1,100	2,200
SO_x[c]	3,000	3,000	3,000	19,800	3,600	8,900
CO_2[d]	8.50	8.50	8.50	8.50	8.50	8.50

[a] These HC, NO_x, and CO values are ad hoc estimates judgmentally correlating CEC estimates (16) with the seriousness of violation (17) in the three California cities. CEC presented avoided costs in emission reductions in dollars/ton/year (20). By checking original data sources from which CEC derived its cost estimates, CEC's adjustment on cost estimates, and CEC's application of its cost estimates, we determine that CEC's estimates are actually in dollars/ton.

[b] Estimates based on CEC data (Reference 16, Table 4-1).

[c] Outside California, the lowest in-state control costs of CEC's estimates (16) are used (i.e., $3000 per ton).

[d] CEC proposes use of $28 per ton of carbon, which is equivalent to $8.50 per ton of CO_2.

to that pollutant is marginal. For Chicago, whose ozone violations fall in the "extreme or severe" category, the average of the $2/ton values from the California "extreme or severe" cases was selected. The dollars-per-ton estimates for Chicago, Denver, and New York are obviously approximations, but they provide reasonably logical benchmarks.

Although emissions estimates have been presented in terms of grams per mile of driving, some reflection caused us to switch to a computation of dollar value of emissions reductions benefits based on typical hours of driving at the assumed average speed. A distance of 30 mi/day (equivalent to 11,000 mi/year) takes more than 4 hr if the average speed is at the NYCC speed of 7.1 mph. It seemed highly unlikely that private owners would spend that many hours in a vehicle for commuting, shopping, and entertainment. Since 30 mi/day would take about 1.6 hr at the SFUDS speed, we assumed that the car would be on the road about 1.6 hr/day on the average.

The emission value estimates (Table 6) are not fully comparable with Ford's estimates because Ford did not include emissions from power plants providing EV power. If it had been estimated that some power plants are outside of the

TABLE 6 Estimated Value of EV Emissions Reductions (Dollars per Vehicle)[a]

Driving Cycle Pollutant	Chicago	Denver	Los Angeles	New York
NYCC:				
HC	1,800	0	1,475	1,952
CO	0	5,756	9,439	5,681
NO_x	953	0	1,020	787
SO_x	53	10	336	-178
CO_2	399	285	302	293
Sum	**3,205**	**6,051**	**12,572**	**8,535**
ECE-15:				
HC	2,122	0	1,465	2,307
CO	0	6,789	11,131	6,408
NO_x	1,370	0	1,472	1,138
SO_x	49	-7	306	-256
CO_2	364	214	235	225
Sum	**3,905**	**6,996**	**14,607**	**9,822**
SAE C:				
HC	2,310	0	1,943	2,481
CO	0	8,826	12,488	7,517
NO_x	1,715	0	1,820	1,381
SO_x	51	-29	314	-387
CO_2	378	158	190	176
Sum	**4,455**	**8,955**	**16,755**	**11,098**
SFUDS:				
HC	2,383	0	2,062	2,549
CO	0	8,314	13,637	8,203
NO_x	2,008	0	2,113	1,582
SO_x	50	-52	303	-506
CO_2	368	92	127	111
Sum	**4,814**	**8,354**	**18,242**	**11,939**
SAE D:				
HC	2,642	0	2,230	2,788
CO	0	7,781	12,760	7,680
NO_x	3,123	0	3,260	2,400
SO_x	57	-116	331	-889
CO_2	426	-43	8	-13
Sum	**6,248**	**7,622**	**18,589**	**11,967**
HWY:				
HC	2,939	0	2,475	3,078
CO	0	6,213	10,203	6,126
NO_x	5,622	0	5,935	4,444
SO_x	95	-187	551	-1,445
CO_2	734	-32	44	17
Sum	**9,390**	**5,994**	**19,208**	**12,220**

[a] EV driven 1.6 hours per day on the specified driving cycle, lasting 13 years, and experiencing greatest rate of use early in the vehicle life. These lead to different lifetime VMT (vehicle miles traveled) for different driving cycles. Specifically, EV lifetime VMT is 52,463 for the NYCC, 86,454 for the ECE-15, 113,794 for the SAE C, 136,700 for the SFUDS, 209,853 for the SAE D, and 359,115 for the HWY.

airshed, higher emissions reductions estimates would have resulted (except for Chicago). The GV emission estimates used in our study are consistently higher than those used by Ford, because we estimated on-road emissions and included refinery, evaporative, refueling, resting, and running loss emissions. The emissions reduction benefit estimate for Los Angeles with the SFUDS cycle, at about $18,200 per vehicle, is about twice Ford's estimate. The highest values for 1.6 hr/day of driving occur at the highest speeds for Chicago, Los Angeles, and New York and at the SAE C speed in Denver. In general, HC and NO_x values peak at the HWY cycle—the highest speed, whereas CO values peak at the SAE C or SFUDS cycle—an intermediate speed.

The estimates for New York and Los Angeles provide an indication of the relative value of EVs in altering the emissions of motor vehicles. The value of reducing CO is estimated to be far greater than the value of reducing ozone precursors (HC and NO_x). Generally, the changes in SO_x and CO_2 emissions have a relatively small effect on the total avoided costs of emissions changes.

In summary, depending on driving conditions assumed, it is estimated that the emissions reduction value of EVs driven an average of 1.6 hr/day ranges from $12,600 to $19,200 in Los Angeles, $8,500 to $12,200 in New York, $3,200 to $9,400 in Chicago, and $6,000 to $9,000 in Denver (1989 dollars).

In closing this section, we note that the method of avoided cost results in a much larger value of emissions reduction than would use of estimated avoided damage arising from the emissions reductions [based on California damage values recommended by National Economic Research Associates (*21*) and estimated by CEC (*16,22*). The intention in this paper has been to get an idea what EVs are worth in terms of reduction of administratively imposed costs of complying with emissions standards. For those whose preferred method of valuation is damage estimates, we note that the CEC-recommended dollars per ton damage estimates (*16*, Table 4.1) would result in an estimate that the emissions reduction value of EVs driven an average of 1.6 hr/day in Los Angeles ranges from $720 to $3,500. However, for administrators in agencies charged with meeting the air quality goals that have been chosen through a national political process rather than an economic process, it is probably necessary to use control cost estimates to determine least-cost methods of meeting these goals.

CONCLUSIONS

This study indicates that use of EVs reduces per-mile vehicle emissions of HC and CO by more than 98 percent in four cities and under six driving cycles. The impacts of EV use on NO_x emissions depend on the stringency of NO_x emission control in power plants and types of power plants that provide electricity for EVs. In Chicago, Los Angeles, and New York, EV use helps significantly reduce NO_x emissions, with the greatest reduction occurring in Chicago. EV use causes moderate NO_x emissions reductions in Denver. The computation in this study illustrates that changes in SO_x emissions are large in percentage terms but are relatively unimportant in dollar value. EV use reduces CO_2 emissions sharply for trips with lower speeds (e.g., 20 mph or less) in cities other than Chicago and reduces it at all speeds in Chicago. However, the CO_2 emissions reductions are relatively unimportant in dollar value.

The results of this study imply that use of EVs would be most valuable in addressing the CO air pollution problem in metropolitan areas such as Denver, Los Angeles, and New York. The use of EVs helps alleviate the ozone pollution problem, but the estimates indicate that the emissions control costs that can be avoided when EVs are used for this purpose are generally far smaller than for CO reduction. Costs of SO_x control should have little effect on the desirability of using EVs either for CO or ozone reduction. Relative to probable initial vehicle cost, the estimated values of emissions reductions are large if one assumes that the EVs are used by private owners driving about 1.6 hr/day.

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Roadway Electrification: Regional Impacts Assessment

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Roadway electrification has been proposed to address urban air pollution. The impacts on fossil fuel use and the electric utility industry are investigated, and the regional economic effects of this technology are assessed. The analysis initially involved the development of a roadway electrification network scenario selected from several alternatives on the basis of sensitivity analyses that allowed for variability in network location, network lane kilometers (miles), and market penetration of roadway-powered electric vehicles. A comparative analysis of emissions and fossil fuel usage between the roadway electrification scenario and a baseline (no roadway electrification) was performed. Emissions investigated were reactive organic gases, carbon monoxide, nitrogen oxides, sulfur oxides, and particulate matter. Petroleum and natural gas were the fossil fuels considered. Findings indicated that overall moderate reductions in emissions for all pollutants and petroleum usage may be obtained, but a sizable increase in natural gas consumption was likely. A small increase in generating capacity for the electric utilities was projected. The cost analysis of the system included construction and operating expenses of the electrified roadway and life cycle costs to facility users. The technology may offer economic advantage to users over the life of the vehicle if roadway infrastructure costs are subsidized like conventional nonpowered highway developments.

Urban traffic congestion and air pollution are issues in many metropolitan areas but are more acute in Southern California than in most other North American cities. The California Partners for Advanced Transit and Highways (PATH) Program at the Institute of Transportation Studies, University of California, Berkeley, and the Southern California Association of Governments (SCAG) have recently completed a 3-year investigation of the regional impacts that could result from implementation of advanced highway technologies in the Greater Los Angeles area (*1–3*). This paper summarizes the study's findings of a projected application of roadway electrification to portions of the SCAG region highway network (the nondesert portions of Los Angeles, Riverside and San Bernardino counties, and Orange and Ventura counties) for 2025. That year was chosen for the analysis to allow sufficient time for this technology to reach maturity and large-scale implementation.

Mitigation of mobile source emissions was expected to be the principal benefit derived from electrifying selected portions of the highway system. Reactive organic gases (ROG), carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM) were assumed to decline as roadway-powered electric vehicles (RPEVs) replaced conventional vehicles. Fossil fuel usage and utility and regional economic impacts were also estimated.

Designing an electrified highway system for 2025 was the initial step in the roadway electrification assessment. The scenario development process included a sensitivity analysis that varied the location, number of lanes, and number of lane kilometers (miles) for the powered roadway. Additional network considerations, such as lane separation, access and egress opportunities, and lane capacity were investigated for electrified and mixed-flow facilities. The methodology that produced the electrified system configuration is documented elsewhere (*2*).

The impacts analysis contrasted 2025 baseline (no roadway electrification) emissions and fossil fuel and utility usage projections with comparable roadway electrification estimates. Baseline population, employment, transportation demand, and vehicle emissions were compiled using projected SCAG regional transportation and emission model updates. The 2025 regional transportation network consisted of the existing highway network, currently funded new highway construction, reconstruction specified in SCAG's Regional Mobility Plan for 2010, and long-range corridors identified to assist future transportation needs (*4*).

In addition to mobile source emissions, other environmental issues, such as electromagnetic fields produced by the powered lanes and acoustic noise in vehicles traveling on the powered roadway, should be addressed as part of a complete investigation of the technology's impacts. These issues are evaluated in another recently completed PATH project, conducted by Systems Control Technology, Inc. (SCT) (*5*), and summarized elsewhere (*3*).

ROADWAY ELECTRIFICATION SCENARIO DESCRIPTION

The objective of roadway electrification is to provide all-electric vehicles (EVs) that have the same characteristics as internal combustion engine vehicles (ICEVs), such as range, acceleration, and life cycle costs, by providing an external energy source for long trips augmenting the on-board battery. External energy can be transferred to RPEVs while they operate on powered roadways (e.g., freeways where long trips typically occur). This technology could increase the market penetration of EVs, especially with the proper incentives.

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Battery size for RPEVs can be considerably smaller than for pure battery EVs because energy is available from the powered roadway for long trips. The size reduction results in improved payload and acceleration and reduced battery costs. Short RPEV trips on battery power only were ignored in the analysis, resulting in conservative estimates for emissions reductions, user costs, and utility power demand profile.

To help select the 2025 roadway electrification scenario configuration, combinations of alternative electrified vehicle kilometers traveled (VKT) [vehicle miles traveled (VMT)] market penetration and network size were simulated with the SCAG transportation model for the a.m. peak period. Market penetrations of 5, 15, and 30 percent were each modeled on networks of 377, 694, and 1,058 center-lane km (234, 431, and 657 center-lane mi). This sensitivity analysis incorporated battery range and RPEV market potential considerations. A full description of the scenario development process is given elsewhere (*2*).

A key consideration in the scenario development was an appropriate battery range for the RPEV. Since only unlinked vehicle trips were reported in the modeling process, derated autonomous battery ranges were studied. For example, a derated battery range of 64 km (40 mi) with a derating factor of 2 would correspond to a total battery range of 129 km (80 mi) without recharging. Derated battery ranges of 32, 48, 64, 81, and 97 km (20, 30, 40, 50, and 60 mi) were studied with respect to 2025 a.m. peak trip length distribution data for distance traveled on and off all three networks (*2*). This analysis estimated the number of trips [and VKT (VMT)] that could be performed by battery only, RPEV, and conventional vehicles, or market potential, and indicated a direct relationship among the market potential number of trips [and VKT (VMT)], battery range, and network size (*2*). The selection of a 64-km (40-mi) derated battery range enabled at least 97 percent of a.m. peak trips and more than 78 percent of a.m. peak VKT (VMT) to be completed by RPEVs.

Separation of RPEV and mixed-flow lanes was not required for the technology. Two roadway-powered systems were designed, however, to address practical implementation issues. A nonexclusive design permitted all vehicles to use the RPEV lanes. An exclusive system allowed only RPEV vehicles on the electrified lanes to ease collection of user costs and ensure accommodation of RPEVs requiring recharge. Exclusive access and egress facilities were not specified, thus requiring RPEVs to cross mixed-flow lanes to enter or leave the RPEV facility and use conventional on- and off-ramps. RPEV facility merge points were specified at 8-km (5-mi) intervals or less, depending on the number of ramp connectors, traffic volume, and modeling limitations. Modeling restrictions resulted in all vehicles experiencing some increased delay (*3*).

Lane capacity limitations were not required, although an RPEV network was designated with volume/capacity ratios representative of the baseline scenario.

An analysis of 2025 trip length distribution was performed next, which grouped the system's origin-destination travel pairs by on- and off-freeway network length, enabling comparison of total trip lengths with alternative battery ranges. The potential number of trips requiring the RPEV technology for trip completion was identified given the 64-km (40-mi) derated battery range selection for the impacts analysis. Of this set of trips, the number of RPEV trips designated for the RPEV scenario's trip assignment was based on a random selection of trips within the origin-destination pairs identified for RPEV use. In general, the longer the trip length, the greater the likelihood the trip would be chosen as an RPEV trip. For the RPEV scenario, 3.3 percent of the potential RPEV trips [or 15 percent of the VKT (VMT)] were selected. These trips were assigned first, since modeling restrictions precluded simultaneous loading of conventional and RPEV trips, and alternative model runs yielded negligible differences between the two trip assignment arrangements (*3*).

The roadway electrification scenario had the following characteristics: network size, 1666 lane-km (1,035 lane-mi); market penetration, 15 percent a.m. peak VKT (VMT) [10.6 million VKT (6.6 million VMT)] and 3.3 percent a.m. peak trips (170,000 trips); derated battery range of 64 km (40 mi); lane separation designated but not required; no special access or egress facilities required; and no lane-capacity restriction. Figure 1 shows the 2025 roadway electrification network.

Trip assignment results indicated that 4.7 million VKT (2.9 million VMT) was associated with RPEV travel on the RPEV facility, or 46.5 percent of all RPEV vehicle kilometers (miles) traveled. The impacts assessment of electricity demand, fossil fuel use, and powered-roadway operating costs required dividing VKT (VMT) into on and off powered-roadway components. The emissions impact was calculated for total RPEV VKT (VMT), since RPEVs are zero-emission vehicles. A comparison of the exclusive and nonexclusive RPEV system impacts produced negligible differences. Exclusive RPEV scenario impacts are reported in the following sections.

FOSSIL FUEL ENERGY CONSUMPTION

Comparisons of 2025 petroleum and natural gas usage for the RPEV and baseline scenarios were performed. Petroleum consumption was important due to this fuel's extensive use in the U.S. transportation sector and U.S. dependence on foreign oil. Natural gas consumption was significant since it was forecast to fuel approximately 81 percent of 2025 SCAG regional generated electricity (*3*).

The methodology used to estimate the fossil fuel energy consumption modified research by Wang et al. (*6*) for RPEV application and assessed each stage of the energy production process. All downstream energy sources were included to derive the primary energy consumption associated with the electricity-generating process, including trace amounts of nonfossil fuels such as biomass.

The impacts analyses were calculated for a.m. peak and daily time periods, light-duty automobile (LDA) and light-duty truck (LDT) vehicle types, and the extent of RPEV travel (*3*). LDAs and LDTs represented approximately 94 percent of the vehicle fleet in the SCAG region. Medium- and heavy-duty trucks and motorcycles, making up the remaining 6 percent of the fleet, were not included because of data limitations.

Petroleum Consumption

The baseline scenario vehicle fleet was assumed to consist entirely of gasoline ICEVs. Their petroleum consumption was

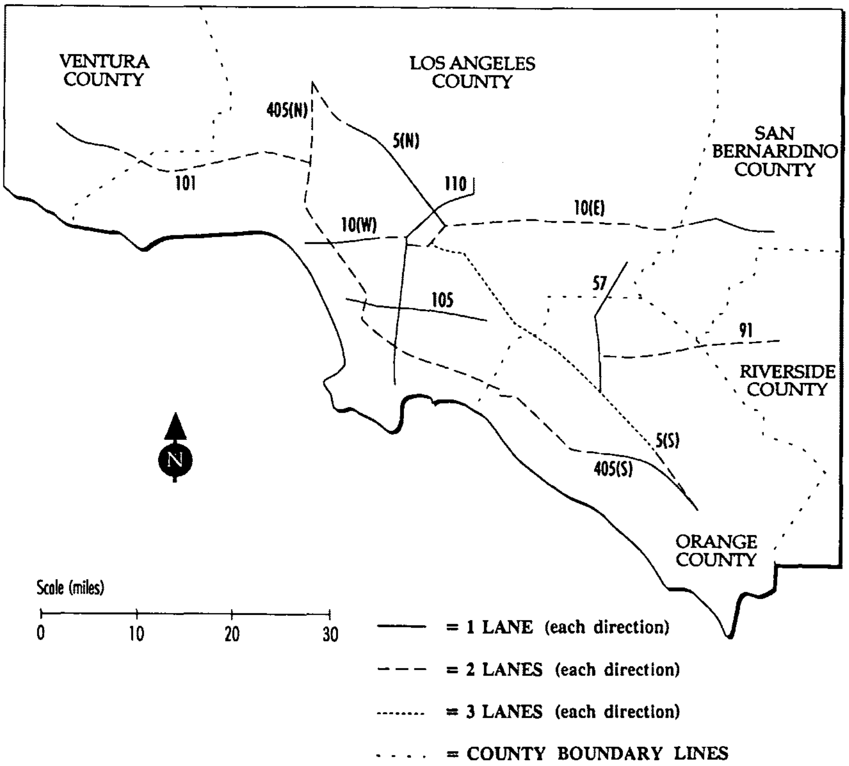

FIGURE 1 RPEV scenario, 2025 regional highway network.

derived from gasoline use and the use of petroleum-derived fuels in the initial phases of the gasoline production cycle. RPEV petroleum consumption was derived from petroleum use for electricity generation and processing other fuels such as natural gas.

The findings indicated a 15 percent daily petroleum consumption savings across vehicle types for both total and on-network RPEV travel as expected given the 15 percent decrease in ICEV vehicle kilometers (miles) traveled in the RPEV scenario. This savings meant a gasoline reduction of approximately 8.3 million L (2.2 million gal).

The percentage petroleum consumption reduction was derived relative to all LDAs, all LDTs, and their total. Relative to the fleet of vehicles replaced by RPEVs, the percentage petroleum consumption reduction ranged from 99 to 100 percent across all vehicle types.

Natural Gas Consumption

Total daily natural gas consumption for LDAs, LDTs, and the combination of the two was approximately 53.3, 18.8, and 72.4 thousand megawatt-hr (mwh) [0.182, 0.064, and 0.247 trillion Btu (tBtu)], respectively, in the baseline scenario. Corresponding estimates for the exclusive RPEV scenario were 80.3, 35.2, and 115.4 thousand mwh (0.274, 0.120, and 0.394 tBtu), representing increases in natural gas consumption of 50.5, 87.5, and 59.5 percent.

Large increases were expected since natural gas was projected to fuel 81 percent of electricity generated in 2025. Whereas the forecast petroleum consumption percentage decrease (15 percent) was considerably smaller than the natural gas percentage increase (59.5 percent), petroleum usage decreased approximately 81.5 thousand mwh (0.278 tBtu), whereas natural gas consumption increased approximately 43.1 thousand mwh (0.147 tBtu).

Baseline annual end use demand for natural gas in California was projected to be approximately 440 million mwh (1,500 tBtu) (*7*). Approximately half was expected for the SCAG region on the basis of population estimates, yielding an average daily amount of 602 thousand mwh (2.055 tBtu). The increase in daily natural gas consumption for the RPEV scenario for LDAs and LDTs relative to the baseline was estimated to be approximately 43.1 thousand mwh (0.147 tBtu), or a 7.2 percent increase.

The projected average daily percentage increase in natural gas demand for the SCAG region between 1990, 577 thousand mwh (1.97 tBtu) (*8*), and the 2025 baseline, 602 thousand mwh (2.055 tBtu), is 4.3 percent. Daily natural gas supply for the SCAG region in 2025 was forecast to be approximately 966 thousand mwh (3.297 tBtu). Thus, whereas the increase in natural gas usage for the RPEV scenario was significant relative to the period from 1990 to 2025, plentiful supplies of natural gas were projected for 2025.

EMISSIONS ANALYSIS

Emissions impacts of roadway electrification were derived and compared with 2025 baseline emissions. Daily results were compiled for ROG, CO, NOx, SOx, and PM for LDAs and LDTs and both vehicle types combined. Baseline mobile source emissions were composed of cold and hot start, evaporative, and running emissions and were derived from the California Air Resources Board's emissions impact rate models (EMFAC7E), SCAG's direct travel impact model, and Caltrans's travel data (*9*). Two stationary source emissions, refueling (evaporative emissions at fuel stations and bulk plants) and petroleum refinery emissions, also contributed to baseline emissions. The methodology used to estimate these stationary source emissions was based on research by Wang et al. (*10*).

Total emissions for the RPEV scenario consisted of mobile source emissions generated by ICEVs, stationary source emissions attributed to ICEVs, and power plant emissions produced during the electricity generation process. The ICEV mobile and stationary source emissions were derived by the methodology used to compute analogous baseline emissions. Total regional power plant emissions (grams per kilowatt-hour) were calculated by pollutant and power plant type. Data required for this derivation included (*a*) the percentage breakdown of fuel feedstock sources for regional electricity-generating power plants, (*b*) power plant mix by type for each fuel feedstock source, (*c*) future emission reduction technologies used in each power plant type coupled with the percentage emission reduction for each pollutant, and (*d*) the percentage of power plants by type using these emission reduction technologies (*1,3,11*).

Natural gas was the only regional fuel source used to derive power plant emissions. Gas power plants were further divided into steam, turbine, combined cycle, and advanced combined cycle types. Wind and solar fuel sources were excluded from the analysis because of negligible emissions. Oil-fired power plants were excluded given their negligible contribution to regional electricity production. Biomass-fired power plants were excluded given their small contribution to electricity production, lack of sufficient data to describe biomass emissions, and the assumption that biomass would not be part of the marginal power plant mix to produce electricity for RPEV usage (*12*). Coal-fired power plants were not projected for the region in 2025 and were excluded from the analysis since the study's focus was on regional air quality. Approximately 4 percent of the 2025 electricity supply was expected to be imported to the region from coal and hydroelectric power sources (*1*), with coal accounting for approximately two-thirds of the imports and all hydroelectric power imported from the Pacific Northwest. The data were insufficient to estimate the in- and out-of-state mix for coal imports. The entire amount of daily emissions from coal-fired power plants will range from approximately 9 kg (20 lb) for PM to 91 kg (200 lb) for SOx. These additional emissions increase the precoal power plant emission levels by at most 4 percent across all pollutants except SOx. Additional SOx emissions increased corresponding emission levels by 500 percent. However, precoal power plant emissions were sufficiently small that these added coal-generated emissions have no effect on the percentage change in emission levels from the baseline to the RPEV scenario for all pollutants. Thus excluding all coal-fired power plants from the analysis displaces a small amount of emissions attributed to usage in the SCAG region to other regions.

The power plant mix used in the analysis was representative of the average rather than the marginal fuel mix needed to satisfy incremental electricity demand created by RPEVs. No forecasts have been made of such fuel combinations for the SCAG region for 2025. Related research was done for the Southern California region for battery-powered EV use for 2010 (*12*) focusing on the Southern California Edison Company (one of two major regional electricity service providers) service area. This work showed that most energy needed for EVs (70 to 90 percent) will come from natural gas-fired power plants. This result agrees with the fuel mix used in our research, since natural gas was forecast to fuel 81 percent of 2025 generated electricity.

Power plant emissions (grams/kwh) were converted to grams per kilometer (mile) for each vehicle type after accounting for distribution losses between the power plant and the vehicle. Vehicle energy consumption for LDAs and LDTs was estimated to be 0.15 kwh/km (0.24 kwh/mi) and 0.34 kwh/km (0.55 kwh/mi) (*3,13*), respectively, representing averages over several driving cycles. Emissions were aggregated across power plant types, for each vehicle type, power source (electrified roadway or overnight battery recharging), and pollutant. For total RPEV travel, a weighted average of emissions was derived to reflect the on-network/off-network mix of RPEV usage. Total emissions were calculated by summing power plant and ICEV-related emissions.

Table 1 gives the emission reductions for RPEV travel relative to the baseline. Decreases varied between 7.1 and 14.9 percent, given the relatively modest market penetration for the roadway electrification scenario. The variation in emissions across pollutants for a given vehicle type was due to the strength of the relationship between pollutant and VKT (VMT). For example, SOx emissions depended primarily on distance driven, yielding a 15 percent emissions reduction for RPEVs. The number of daily trips rather than distance driven was the determining factor for CO emissions, thus producing an 8 percent emission decrease for RPEVs. Emission reductions ranged from 92 to 100 percent over all pollutants and vehicle types compared with the fleet of vehicles replaced by RPEVs. Substantial emission reductions occurred because of the small contribution of power plant emissions to total daily RPEV scenario emissions, which varied between 0.1 and 0.8 percent. The resulting trade-off between increased RPEV market penetration and associated power plant emissions and reduced ICEV emissions should be favorable for the RPEV technology, since the decrease in ICEV emissions should more than offset increased RPEV-related emissions.

TABLE 1 Roadway Electrification Total Daily Emissions, 2025 (Metric Tons)[a]

	Baseline		Exclusive RPEV			
Pollutant	LDA[b]	LDT[c]	LDA	(%)[d]	LDT	(%)[d]
ROG	199.8	55.8	185.6	(-7.1)	51.6	(-7.5)
CO	1,116.4	296.6	1,026.6	(-8.0)	272.6	(-8.1)
NOx	226.1	60.5	202.5	(-10.4)	54.3	(-10.2)
SOx	54.3	17.2	46.3	(-14.9)	14.7	(-14.7)
PM	70.2	18.6	60.5	(-13.8)	16.1	(-13.2)

[a] 1 Metric Ton = 1.1 short tons
[b] LDA = Light Duty Auto
[c] LDT = Light Duty Truck
[d] Numbers in parentheses represent percentage changes relative to the baseline for each vehicle type respectively

UTILITY DEMAND

The impact of roadway electrification on electricity use was derived for a.m. peak, p.m. peak, and daily time periods. Total energy use was calculated as the product of vehicle energy consumption per kilometer (mile) and RPEV vehicle kilometers (miles) traveled. Because vehicle energy consumption and VKT (VMT) differed by vehicle type, estimates were made for each vehicle type before aggregation. LDAs and LDTs are driven approximately the same average distance per vehicle type (*14*), and it is assumed for each time period that total VKT (VMT) is distributed uniformly across each vehicle by type. Thus, the VKT (VMT) percentage split of LDAs and LDTs mirrors their actual split (74.1 percent/19.6 percent) in the vehicle fleet. All distribution, vehicle, and roadway energy losses were included in the calculation of vehicle energy consumption. Results were derived for total and on-network RPEV travel.

Table 2 gives total electricity use for the RPEV scenarios. Electricity use for roadway power during a given time period refers to on-network travel. Overnight recharging in a particular time period is referred to as off-network travel. The time-of-day electricity demand profile was derived to provide a peak use day for analysis and planning purposes on the basis of historical daily use patterns. Travel distribution patterns were also required to develop an accurate impact assessment of roadway electrification on electricity service providers. The daily peak travel periods [a.m. peak (6 to 8 a.m.) and p.m. peak (3:30 to 6:30 p.m.)] overlap with electricity demand peaks in the late afternoon and seasonal peaks during the summer months (*15*).

TABLE 2 Roadway Electrification Electricity Demand, 2025 (mwh)

Time Period	RPEV Usage Roadway Power	 Overnight Charging	Total
AM-PEAK	866	1,015	1,881
PM-PEAK	2,595	5,374	5,633
DAILY	8,879	10,385	19,264

The SCAG region's 2025 baseline time-of-day electricity demand profile was projected from current usage estimates and the 2025 baseline peak hour demand estimate. The time-of-day electricity usage profile for on-RPEV network travel was derived from the daily on-RPEV network electricity demand (Table 2), the hourly traffic distribution on SCAG regional freeways, and the assumption that hourly energy demand for transportation was proportional to hourly traffic volume.

The time-of-day electricity usage profile for off-RPEV network travel was derived from data in Table 2, assuming that all battery recharging occurred overnight, all vehicles were fully recharged in the morning, and all roadway power was used to drive the vehicle rather than charge the battery. Whereas the first and third assumptions are rather strong and optimistic, they enable a time-of-day impact analysis to be derived. Overnight recharging was assumed to occur uniformly between 10 p.m. and 6 a.m., and all households were assigned the same average recharge over those 8 hr. Thus there was an average hourly demand for approximately 1,298 megawatts (mw) for overnight recharging (10 p.m. to 6 a.m.) (see Table 2) (*12*).

Total regional electricity demand by time of day was calculated as the sum of baseline and RPEV electricity use (see Figure 2). The time-of-day electricity demand profile was dominated by baseline use, since the additional amount of RPEV-demanded electricity was relatively small. Peak-hour demand shifted slightly from 2 to 3 p.m. to 3 to 4 p.m. Additional RPEV electricity demand represented an increase of 1 percent over the baseline peak. Although not entirely negligible, this increase must be compared with the 93 percent capacity increase the utilities must supply between the present and the baseline for 2025.

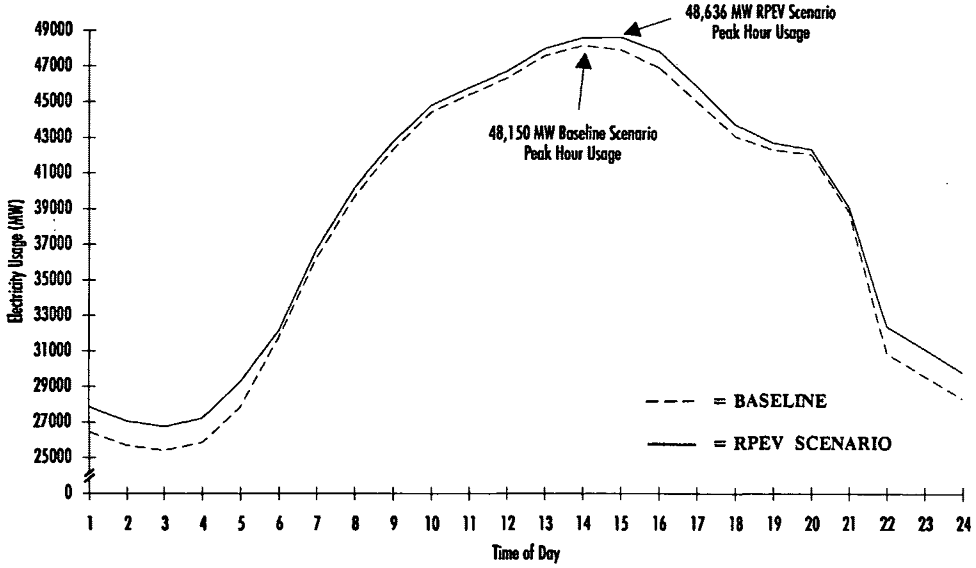

FIGURE 2 Electricity usage comparison, baseline versus RPEV scenario.

With a larger RPEV market penetration, the demand for electricity will increase. The estimate for total daily RPEV vehicle kilometers (miles) traveled was approximately 103 million (64 million), representing 15 percent of total daily VKT (VMT). A sensitivity analysis of RPEV market penetration increases was performed and indicated changes in peak-hour electricity demand. A 5 percent increase in peak-hour demand, for example, would be required if RPEV market penetration grew to 55 percent of total daily VKT (VMT). On the basis of the RPEV scenario development analysis (*2*), a more likely conservative upper limit on market penetration would be about 40 percent, corresponding to a 3.4 percent increase in peak-hour electricity demand.

ECONOMIC ASSESSMENT OF ROADWAY ELECTRIFICATION

This section presents the RPEV economic model (REM) system development and operation costs results and an assessment of regional economic impacts. Construction and operating expenses of the electrified roadway were examined as well as life cycle costs to users. The complete RPEV economic analysis contained elsewhere (*3*) reviews supportive cost model analyses used to cross check the REM results (*16*) and life cycle expenses associated with owning and operating an RPEV and gasoline vehicle (*3,17*).

System Costs

The REM was developed by SCT with input from SCAG and PATH to portray the relationship between costs and revenues associated with powered-roadway operation (*3,16*). The analysis determined the cost to build and operate the electrified roadway with revenue derived from power purchased by system users. It used estimates of roadway construction, energy, and operation costs and calculated interest charges to offset deficits that accrued during the early stages of roadway development and use. The REM incorporated a market-penetration growth profile consistent with RPEV use, financing considerations for system development and use, and a construction schedule for network design. Table 3 summarizes the REM model inputs used for the baseline cost and revenue analysis.

The REM assumed that loans were used to finance roadway construction costs. Wholesale energy cost was calculated by multiplying the amount of energy sold by the wholesale energy rate and adding system distribution losses. Operating expenses were assumed to be related to construction activity and number of users.

TABLE 3 Regional Economic Model Inputs for Baseline Scenario

Parameter Values	Description (units)
Market Penetration:	
4,000	Number of RPEV users in the initial year of market growth
6,000	Number of additional users per year until market saturation
3	Start year
28,737	Volume limit (vehicles/lane/day or vehicle kilometers/lane-kilometer/day)
Revenue:	
0.294	Cumulative breakeven electricity rate[a] ($/kwh)
Cost:	
1.55 million	Cost per lane-kilometer[b] of roadway ($/lane-kilometer)
1.04 million	Replacement cost ($/lane-kilometer)
2.5	Administrative (% of debt + energy)
2.5	O & M (% of cumulative new roadway capital cost)
0.07	Wholesale cost of energy ($/kwh)
Vehicle:	
0.13	Energy consumption of vehicle (kwh/kilometers)
75	System efficiency (%)
53.8	Average vehicle-kilometers per day on the system per vehicle
Debt Service:	
3.3%	Interest rate (real %/year)
25	Life of loan and life of roadway (years)
Miscellaneous:	
25	Designated year for cumulative breakeven rate
9.95	Number of years for roadway construction
84	New system-kilometers constructed per year (168 lane-kilometers)

[a] Output of model

[b] 1 kilometer = 0.62 mile

The REM produced an estimate of the cumulative breakeven rate, or retail energy price, necessary to break even by Year 25. This cumulative cost and revenue analysis immersed the complete cost profile into electricity rate determination so that all previous roadway construction deficits would be zero by Year 25 and thereafter become cumulatively profitable. As indicated by the baseline results in Table 4 (see asterisk output values) and Figure 3, the cumulative breakeven of all system revenues and costs by Year 25 required a retail energy price of $0.294/kwh, or a 3.83 cents per km (6.17 cents per mi) user charge. At this rate, cumulative system revenues in Year 25 equaled costs of $7,552.8 million, including the full cost to build the 1666 lane-km (1,035 lane-mi) of roadway with a scenario specified market penetration of 28,737 vehicles per lane per day.

Important annual cost and revenue patterns embedded in the cumulative cost results were rapid annual cost increases during the 10 years of initial roadway construction; lower annual costs after Year 25 due to roadway replacement costs, assumed to be two-thirds of initial roadway construction expenses, and removal of the deficit interest charges associated with initial roadway construction; and increased annual revenue until market penetration was completed.

The wholesale energy price was approximately one-third the retail energy price in the breakeven year, with debt service and cumulative interest on the cumulative deficit representing

TABLE 4 Regional Economic Model Output Results: Sensitivity Results

	Year 25		Year 40, $M		
Sensitivity Measures	Cumulative Breakeven Rate ($/kwh)	Cumulative Revenue & Costs ($M)	Cumulative Revenue	Cumulative Costs	Cumulative Profit
Roadway Cost ($M)					
0.0	0.156	3,998.0	9,326.4	8,317.3	1,009.1
1.5	0.241	6,182.1	14,421.5	11,518.6	2,842.9
2.5[a]	0.294	7,552.8	17,618.8	13,602.6	4,016.3
4.0	0.376	9,646.3	22,502.5	16,725.8	5,776.7
6.0	0.492	12,613.3	29,424.0	21,197.6	8,226.4
Wholesale Energy Cost ($)					
0.05	0.267	6,851.9	15,984.0	11,967.6	4,016.3
0.07[a]	0.294	7,552.8	17,618.8	13,602.6	4,016.3
0.09	0.322	8,253.7	19,254.0	15,237.6	4,016.3
Operating Expenses (%)					
1.0	0.256	6,573.0	15,333.2	11,966.3	3,366.8
2.5[a]	0.294	7,552.8	17,615.8	13,602.6	4,016.3
5.0	0.358	9,185.9	21,428.6	16,329.7	5,099.0
Interest Rate (%)					
3.3[a]	0.294	7,552.8	17,615.8	13,602.6	4,016.3
6.6	0.377	9,675.7	22,571.2	16,438.4	6,132.8
9.9	0.481	12,340.8	28,788.3	19,914.0	8,874.2
Energy Consumption (kwh/kilometer)					
0.10	0.357	6,968.7	16,256.4	12,240.1	4,016.3
0.13[a]	0.294	7,552.8	17,615.8	13,602.6	4,016.3
0.16	0.256	8,136.9	18,981.4	14,965.1	4,016.3
System Efficiency (%)					
65	0.309	7,930.2	18,499.3	14,483.0	4,016.3
75[a]	0.294	7,552.8	17,618.8	13,602.6	4,016.3
85	0.283	7,264.2	16,945.7	12,929.3	4,016.3
Average Vehicle-kilometers per day on system					
53.8[a]	0.294	7,552.8	17,619.8	13,602.6	4,016.3
64.4	0.262	8,037.6	18,749.8	14,733.4	4,016.3
80.51	0.229	8,772.0	20,463.0	16,446.7	4,016.3

[a] Baseline values

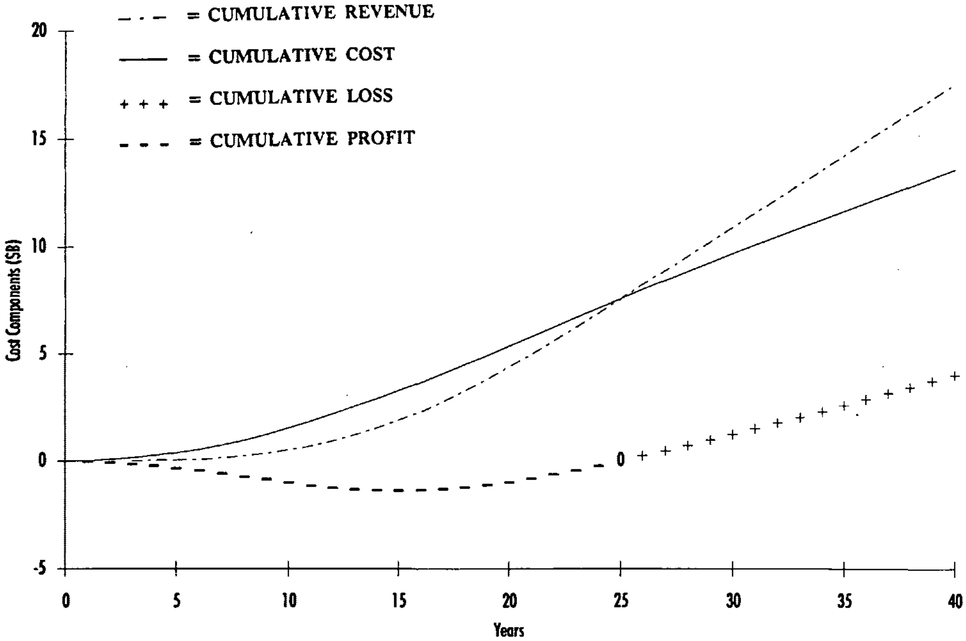

FIGURE 3 RPEV economic model cumulative revenues and costs.

nearly half the retail energy price. The wholesale energy cost represented an increasing proportion of the retail energy price over time, whereas all other cost components' percentage contributions declined since all system costs other than energy were spread over more users with time.

Sensitivity analyses were completed with respect to changes in roadway capital cost, wholesale energy cost, operating expenses, interest rates, energy consumption, system efficiency, and average vehicle-kilometers (vehicle-miles) per day on the system. The results, presented in Table 4, were based on the requirement that cumulative costs and revenues balance in Year 25 and demonstrate that the cumulative breakeven retail electricity rate generally increased with expense category sensitivity values and decreased as system performance and usage sensitivity measures improved. Greater system efficiency, however, reduced cumulative costs. Cumulative costs, revenues, and profits were found to be especially sensitive to alternative roadway costs and interest rate measures.

Regional Economic Impacts

Air quality improvement associated with reduced mobile source emissions is the most significant regional economic impact of roadway electrification. Its quantification requires calculating the associated primary health benefits (*3,18,19*). In addition to health benefits, increased crop yields for produce sensitive to ozone damage, visibility improvements and the associated increased property values, reduced damage to livestock, and decreased material deterioration would be further regional air quality improvements (*18*). Benefits associated with improved air quality may also exist in the labor market, since areas that provide amenities are often migration attractors (*20,21*).

Attempts to measure benefits associated with reduced emissions are often imperfect. The California Energy Commission (CEC) calculated dollar values per metric ton for yearly residual emissions in the South Coast Air Basin (*22*). Using its estimates to quantify emissions changes relative to the 2025 baseline and RPEV scenarios produced the following annual benefits: $424 million from daily CO decreases of 113.4 metric tons (125 tons), $177 million to $318 million for daily NOx reductions of 2.7 metric tons (3 tons), $37 million to $87 million from decreased daily SOx of 10.9 metric tons (12 tons), and $3 million to $138 million for daily ROG reductions. CEC did not report a residual emission value for PM emissions. Thus, this partial emissions assessment indicates annual benefits of $641 million to $967 million for the study's application of roadway electrification.

The benefit of reduced reliance on petroleum consumption to fuel the transportation system would be another primary economic impact of RPEV technology (*23*). Decreased production of greenhouse gases associated with petroleum-fueled vehicles could also be experienced globally. At the regional level, it is likely that reduced petroleum consumption could provide secondary environmental quality gains through decreased water pollution. Losses to regional economic sectors providing petroleum would occur.

Roadway electrification-related electricity demand would increase utilities' revenues. The utility sector would experience income and job growth, although there would probably be corresponding job and income losses in gasoline production and distribution.

Employment and income changes in the construction, maintenance, and vehicle service sectors are unclear. Although maintenance and vehicle servicing are expected to be substantially reduced by the RPEV technology, workers may gain skills necessary to provide assistance to RPEV users and acquire different positions as part of a newly created RPEV industry.

Another potential benefit would be associated with successful efforts to manufacture and commercialize RPEVs [and

EVs (*24*)] in the SCAG region. Such developments would necessitate provision of complete production systems to integrate local industries, service centers, and training and research facilities toward building an industrial base for this technology. Localization economies could be fostered by clustering firms regionally within the RPEV industry to capture scale economies in the production of intermediate inputs, labor market economies, and communication economies. Regional RPEV production and service could generate local multiplied impacts for the regional economy if market demand spread to other areas.

The ability of the Southern California region to attract federal funding and private capital for RPEV system development would play an important role in capturing many of the significant regional income and employment impacts and fostering regional economic growth. The ability to fashion proper incentives to stimulate increased RPEV (and EV) market penetration, to provide supportive public and industrial policies to assist technology development, and to build an integrated support structure for maintaining and servicing these technologies is important in the overall determination of regional economic impacts.

Implementing an RPEV system requires coordinated planning and management efforts addressing market penetration, continued technology development, and support service dimensions of system implementation simultaneously to capture maximum regional benefits. Mobilization of local industry, government, universities, and other institutional participants should be a first step toward system development.

CONCLUSIONS

Roadway electrification was modeled and evaluated on a portion of the Greater Los Angeles area highway system with respect to motor vehicle emissions, fossil fuel use, electricity demand, system costs, and other regional economic impacts. Results demonstrated the potential for air quality improvement and reduced petroleum use. Emission decreases varied between 7 and 15 percent, depending on pollutant and vehicle type. Reduction in petroleum consumption resulted in savings of approximately 8.3 million L (2.2 million gal) of gasoline. Natural gas consumption for transportation use was estimated to increase by 50 to 85 percent, yet forecast 2025 regional natural gas supplies would be plentiful. Increased RPEV electricity demand was 1 percent higher than peak-hour baseline usage and could be fulfilled by planned power plant capacity.

An economic model examined the magnitude and pattern of costs and revenues corresponding to electrified roadway development and use. The model incorporated a market-penetration growth profile, financing considerations, a construction schedule, and sensitivity to alternative model inputs. All revenues were derived from power purchases, and costs included roadway construction, energy, operation, and interest on development loans.

The cumulative breakeven of all system revenues and costs specified for Year 25 required a retail energy price of $0.294/kwh for system users. The cumulative breakeven rate generally increased with roadway expenses and decreased as system performance and usage increased. Increased system efficiency, however, reduced cumulative costs. Cumulative costs, revenues, and profits were found to be most sensitive to alternative roadway cost and interest rate measures.

Health benefits corresponding to emission decreases and reduced reliance on petroleum consumption were expected to be the most significant regional economic benefits. Additional RPEV-related electricity demand provided increased revenues to the utilities. Employment and income changes in the construction, maintenance, and vehicle servicing sectors are unclear. A potential benefit for roadway electrification exists with successful efforts in regional manufacturing and commercializing of RPEVs and EVs.

Implementing a powered roadway system requires coordinated planning and management addressing market penetration, continued technological progress, and support services for system implementation to capture maximum regional benefits. Mobilization of local industry, government, universities, and other institutional participants should be a first step toward system development.

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Remote Sensing, Means, Medians, and Extreme Values: Some Implications for Reducing Automobile Emissions

BABAK NAGHAVI AND PETER R. STOPHER

A remote sensing unit that measures exhaust percentages of carbon monoxide (CO) and hydrocarbons (HC) from vehicles passing through a single lane of roadway was used in this study. During a 4-day period, more than 24,000 valid motor vehicle CO and HC emission measurements were made in the Baton Rouge area. The results indicated that more than half of the CO was emitted by 6.9 percent of the vehicles—the "gross polluters." About half of the HC was emitted by 20 percent of the vehicles measured. The average emission for the measured fleet was 0.72 percent CO, which corresponds to approximately 70 grams CO per liter of gasoline consumed. The average emission was 0.09 percent HC, or 14 grams HC per liter of gasoline. Usually the impact of transportation control measures (TCMs) is estimated from the mean emissions levels. However, it is most likely that TCMs based on voluntary compliance will achieve reductions primarily by individuals best represented by the median emissions. On the other hand, if TCMs were aimed specifically at vehicles with extreme levels of CO and HC emissions (gross polluters), more significant emissions reductions may be achieved.

Passage of the Clean Air Act Amendments of 1990 (CAAA) has given transportation agencies new challenges to improve air quality in many urban areas that do not meet the federal air quality standards. The CAAA has also initiated a round of state implementation plans and the need for establishing emission inventories (*1*). Carbon monoxide (CO) standards are primarily violated as a result of direct automobile emissions. Violations of the ozone standard arise from photochemical transformation of oxides of nitrogen (NO_x) and hydrocarbons (HC). In this paper we will only discuss CO and HC since NO_x measurements by remote sensing were not possible at the time of this study.

Mobile sources are believed to contribute significantly to emissions of CO, HC, and NO_x. Various sources of CO, HC, and NO_x in the Baton Rouge nonattainment area (six parishes) are given in Table 1. Air pollution control measures taken to mitigate mobile source emissions in nonattainment areas include inspection and maintenance (I/M) programs, oxygenated fuel mandates, and transportation control measures (TCMs). Despite two decades of air pollution control efforts, 84 million Americans continue to live in areas where the air is unhealthful (*2*). On a national basis, vehicle miles traveled (VMT) increased an average of 4.4 percent annually during the 1980s while the population increased 2.5 percent (*3*). Cars and trucks in the United States now travel 2 trillion mi every year compared with 1 trillion mi in 1970. The car and truck VMT is expected to increase to 3.8 trillion by 2020 (*4*).

Usually the impact of TCMs is estimated from the mean emissions levels. However, it is most likely that TCMs based on voluntary compliance will achieve reductions primarily by individuals best represented by the median emissions. On the other hand, if TCMs were aimed specifically at vehicles with extreme levels of CO and HC emissions, referred to as gross polluters, more significant emissions reductions may be achieved. Such an approach is currently feasible through the use of remote sensing to obtain on-road measurements of vehicular pollutants.

The remote sensing instrument used in this study [Fuel Efficiency Automobile Test (FEAT)] was developed by the University of Denver. This instrument measures the CO and HC in the exhaust of any vehicle passing through an infrared (IR) light beam, which is transmitted across a single-lane of roadway. Figure 1 shows the instrument.

THE INSTRUMENT

FEAT was designed to emulate the results obtained using a conventional exhaust gas analyzer, for example, a tail pipe probe. FEAT can measure the CO and HC emissions in all vehicles, including gasoline- and diesel-powered vehicles, as long as the exhaust plume exits the vehicle within 1 m of the ground. Because of the current height of the sensing beam, FEAT will not register emissions from exhausts that exit from the top of vehicles, as in heavy-duty diesel vehicles. The CO and HC emissions from diesel vehicles are, in any case, relatively unimportant. FEAT analyzes the exhaust from a car that drives between an IR source and the detector. Each time the IR beam is blocked, an analysis for vehicle exhaust is initiated. The IR source sends a horizontal beam across a single traffic lane approximately 25 cm above the road surface. The beam is picked up by the detector on the opposite side and split into four wavelength channels: CO, CO_2, HC, and reference. Placed in front of the detector is an optical filter that transmits the IR light of a wavelength known to be uniquely absorbed by the molecule of interest. The absorption of light by the molecules of interest reduces the signal, causing a reduction in the output voltage. FEAT is effective across traffic lanes up to 12 m wide. However, it can only operate across a single lane of traffic if one wishes to identify positively and video-record each vehicle with its exhaust.

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TABLE 1 Sources of CO, HC, and NO_x in the Baton Rouge Nonattainment Area (Six Parishes) (Source: Baton Rouge Ozone Advisory Committee)

	Carbon Monoxide (Tonnes/Day)	Hydrocarbons (Tonnes/Day)	Nitrogen Oxides (Tonnes/Day)
Industry	244	65	209
Mobile	510	80	55
Biogenic	0	909	0
Miscellaneous	127	47	43
Total	881	1101	307

Although not used for the Baton Rouge area study, a radar system has also been developed that is capable of determining both the speed and acceleration of passing vehicles during the same fraction of a second in which the emissions are measured. The radar readings are stored in the data base with the emissions information.

The mechanism by which FEAT measures the exhaust percentages of CO and HC is explained by Bishop et al. (*5*). The system works by sampling in front of and behind the vehicle and registering the difference. Hence, the ambient air quality conditions do not affect the measurements. Also, there is no effect on measurements from the pollution plume left by a previous vehicle. For every vehicle that passes through the IR beam, the computer freezes a videotaped picture of the rear end of the vehicle showing the license plate number and a readout of the percentage of CO, CO_2 , and HC in the exhaust plume. The results are stored on a digital computer data base as well as on S-VHS videotapes. The computer writes the date, time, and the calculated exhaust CO, HC, and CO_2 percentage concentrations at the bottom of the image.

The measurements are independent of wind, temperature, and turbulence. FEAT operates most effectively on dry pavement. Rain, snow, and very wet pavement cause scattering of the IR beam. These interferences cause the frequency of invalid readings to increase, ultimately to the point that all data are contaminated by too much "noise." Error-checking routines in the FEAT computer eliminate invalid data caused by oversized vehicles, pedestrians, or other nonexhaust obstacles; when errors are detected, the measurement is rejected, and an invalid data flag is set in the data base. Two major criteria for rejection are not observing sufficient signal change to measure exhaust components accurately and observing too much scatter in the HC or CO to CO_2 correlations to derive the ratio from the slope of the best fit straight line. The calibration gases (mixtures of CO, propane, and CO_2) are used as a daily quality assurance check on the system. FEAT has been shown to give correct readings for CO and HC by means of double-blind studies of vehicles (*6–8*).

On the basis of combustion chemistry, the percentages of CO and HC can be used to determine many parameters of the vehicle's operating characteristics, including the instan-

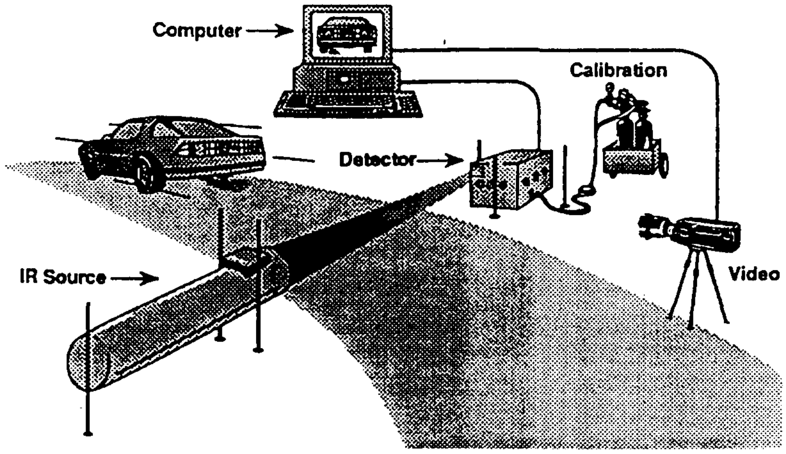

FIGURE 1 On-road emissions monitor used in the Baton Rouge study.

taneous air/fuel ratio, grams of CO emitted per liter of gasoline (gCO/L), and the percentage of CO. The measured emissions in percentages of CO and HC can be converted to mass emissions in grams per liter of gasoline burned using the following equations (*7*):

$$gCO/L = 4{,}180 * \%CO/(42 + 1.07 * \%CO) \qquad (1)$$

and

$$gHC/L = 1.57 * gCO/L * (\%HC/\%CO) \qquad (2)$$

CO AND HC EMISSIONS FROM AUTOMOBILES

The automobile CO and HC emissions in the exhaust manifold are a function of the air-to-fuel ratio at which the engine is operating. Figure 2 shows approximate engine-out emissions as a function of air-to-fuel ratio where 7.09 (14.7 percent air to fuel by weight) is the ratio at which there is exactly enough air to fully burn the fuel to CO_2 and water.

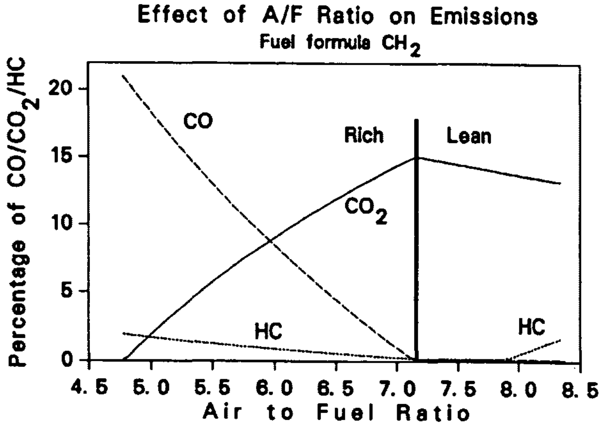

FIGURE 2 Approximate relative concentrations of CO and HC produced by a spark-ignited engine as a function of air/fuel ratio by moles.

CO emissions are caused solely by the lack of adequate air for complete combustion (*9*). Therefore, CO is likely to be produced if the mix is too rich or under stop-start conditions where the engine load keeps changing. Although a fuel-lean air/fuel ratio impairs driveability, it does not produce CO in the engine.

For HC the situation is more complex. In the main part of the combustion chamber away from the walls, essentially all the HC is burned. However, the flame front initiated by the spark plug cannot continue to propagate within about 1 mm of the relatively cold cylinder walls. This phenomenon causes a "quench layer" next to the walls made up of a thin layer of air/fuel mix against the cylinder wall. The opening exhaust valve and the rising piston scrape this layer off the walls and send it out of the exhaust manifold. As the mixture becomes richer, the quench layer contains more HC; thus, more HC is emitted when the vehicle is operating with rich mixtures. This production of HC is likely to be correlated with emission of CO.

A second peak in HC emissions is indicated on the right-hand (fuel-lean) side of the diagram. This phenomenon is known as "lean burn misfire" or "lean miss" and is the cause of the hesitation experienced at idle before a cold vehicle has fully warmed up. When this misfiring occurs, a whole cylinder full of unburned air/fuel mix is emitted into the exhaust manifold. Misfiring also occurs if a spark plug lead is missing or the ignition system to one cylinder is otherwise not working. Thus, the second peak HC emission occurs under conditions in which CO is not produced and is not correlated with CO emissions.

The "engine-out" emissions are further altered by any tail pipe emission controls that may be present. The catalytic converters are placed in the exhaust line to remove excess HC. Therefore, if the catalytic converter is present and functioning at correct operating temperature, most of the HC produced under the above conditions will be partially or totally converted to CO and CO_2. Thus, under the condition of lean miss, a high CO reading with low HC would be observed. If the catalytic converter is absent or nonfunctional, high HC will be observed in the exhaust without the presence of high CO. Table 2 gives a summary of various levels of CO and HC that may be expected under various engine operating conditions. In summary, this shows that a high HC reading cannot be obtained when the catalytic converter is fully func-

TABLE 2 Expected Levels of CO and HC Emissions from Automobiles

Engine Operating Condition	Working Catalytic Converter		Non-Working Catalytic Converter	
	CO	HC	CO	HC
Fuel-lean or Misfire	High	Low	Low	High
Normal	Low	Low	Low	Low
Fuel-rich	High	Low	High	High

tional, although an incorrect air/fuel ratio will generate high CO readings. If the catalytic converter is absent, faulty, or nonfunctioning, the state of operation of the vehicle engine is clearly defined by the exhaust composition. In addition, an absent, faulty, or nonfunctioning catalytic converter will result in emissions readings from an incorrect air/fuel ratio that are distinct from those produced when the catalytic converter is functional.

RESULTS AND DISCUSSION

In March 1992, 4 days of measurement were carried out, 2 days at the eastbound on-ramp to Interstate Route 10 in Baton Rouge at College Drive and 2 days at the southbound on-ramp to Interstate 110 in Baton Rouge at Harding Boulevard. The measurement sites are shown in Figure 3. There was no precipitation during the data collection period, and the average

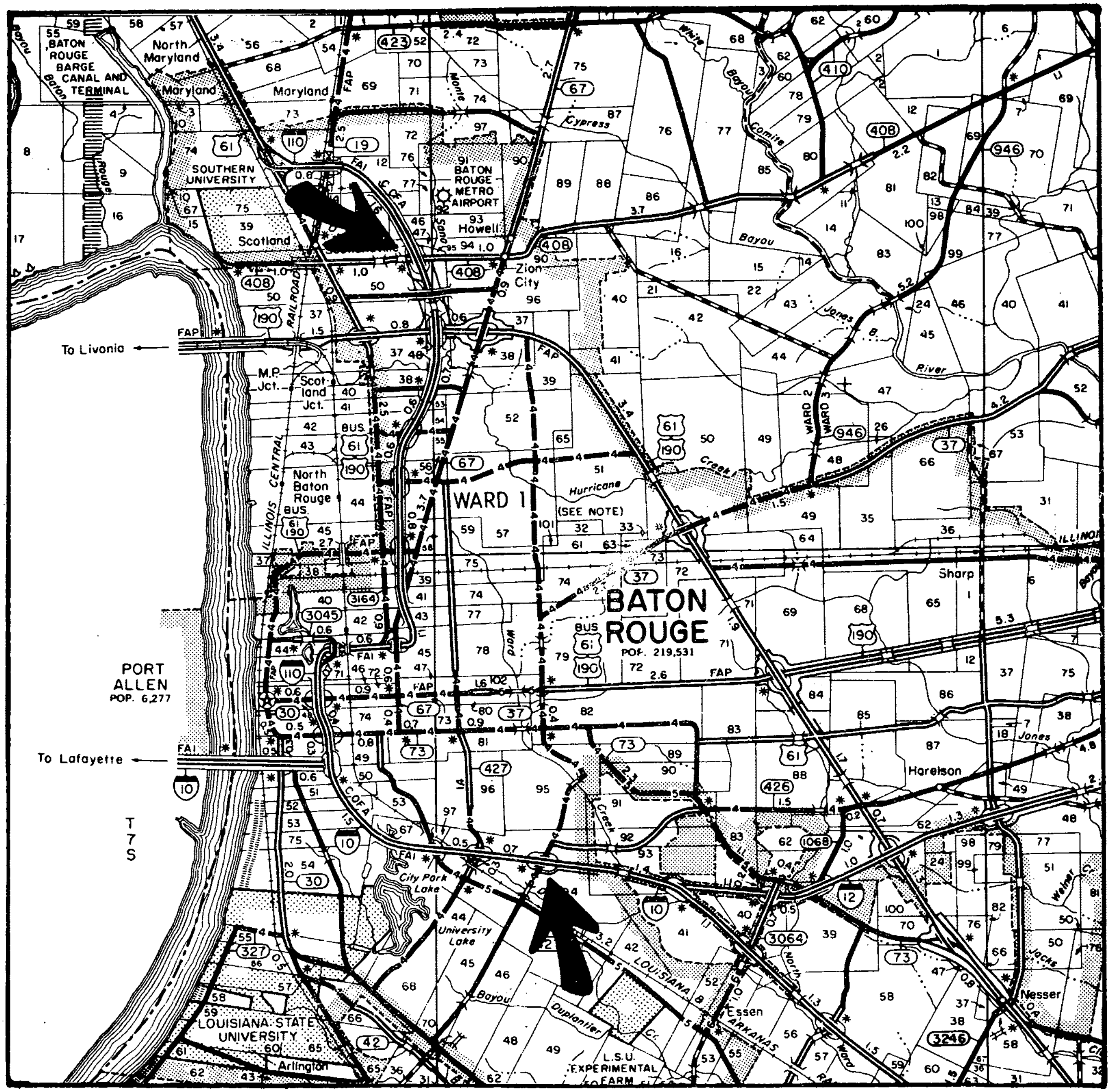

FIGURE 3 Location of remote sensing sites.

daily maximum temperature was 24°C. At the Harding Boulevard location, the vehicles were accelerating up a moderate slope and around a reverse loop to I-110. The vehicles at the College Drive location were accelerating on a relatively flat and straight approach ramp. The videotapes were read for license plate identification at both locations. A total of 24,133 vehicles with valid CO and HC readings were recorded. Of that total, 12,127 measurements were taken at College Drive and 12,006 at Harding Boulevard. The College Drive site is located in the southern part of Baton Rouge and is a mixed socioeconomic area, although it is fairly close to one of the high-income areas of Baton Rouge. On the average, we expected to get a large number of newer models in the vehicle fleet. Neighborhoods around Harding Boulevard are predominantly low income. This site is located between Southern University and some of the major refineries in the Baton Rouge area, and the interchange is also used heavily by airport traffic. As a result, it was expected that the fleet would more likely consist of older vehicles with the exception of the airport traffic. However, no analysis has been performed to correlate the emissions with the age of the vehicle fleet. Also, the data were not expanded and weighted; therefore, they may not be fully representative of the vehicle fleet in the Baton Rouge area. To develop reliable emissions inventories based on the collected data, we are currently conducting a study to expand and weight the data and to correlate the emissions with the age and make of the entire fleet in the Baton Rouge area.

The results are presented in Figures 4 through 8. Figure 4 shows the distribution of CO emissions by percent CO category for the 24,133 vehicles measured in Baton Rouge. The mean percent CO is 0.72, with a standard deviation of 1.429, whereas the median is only 0.18. The average emissions of 0.72 percent CO translates into 70 gCO/L. If mass emissions in grams per kilometer are required, then grams per liter must be converted to grams per kilometer by means of data on kilometers traveled per liter of gasoline. For the purpose of obtaining emissions inventories, it is likely that accurate data on liters of gasoline sold are more easily obtainable than accurate VMT data. The distribution of the data is such that more than half of the emissions come from 6.9 percent of the vehicles with emissions greater than 3.0 percent CO or 277 gCO/L of gasoline. Vehicles in this 6.9 percent category are referred to as gross CO polluters.

To convert these emission figures to total daily emissions, the daily gasoline use in the parish of East Baton Rouge is needed. Because this figure is not readily available, it was estimated by calculating an average per vehicle consumption of gasoline for Louisiana (2345 L/year/vehicle, or 6.42 L/vehicle/day) and multiplying this figure by the number of registered vehicles in the parish. This yields an estimate of 2.16 million L of gasoline used per day in the parish. Applying this figure to the mean CO emissions shows a total vehicular production of 152 tonnes (metric) of CO per day. Of that total, assuming that they consume gasoline at the average rate, the top 10 percent of polluters account for 85 tonnes, leaving 67 tonnes produced by the remaining 90 percent of vehicles. Whereas evidence suggests that a number of gross polluting vehicles are driven fewer miles than the clean vehicles, the gasoline consumption of these vehicles is usually above the average. Therefore, average gasoline figures are probably a good approximation.

Figure 5 shows the distribution of HC emissions by percent HC category for the Baton Rouge data. The average percent HC in propane equivalent is 0.09 with a median value of 0.06. The mean percent HC of 0.09 converts to 14 gHC/L. As with the CO emissions, the distribution is skewed such that more than half the emissions come from 20 percent of the vehicles with emissions greater than 0.16 percent HC or 14 gHC/L of gasoline (the HC gross polluters).

To convert HC emissions to total daily values, the same procedure can be used as was used to estimate CO emissions from the estimated daily gasoline consumption in the parish of East Baton Rouge (2.16 million L). Applying this figure to the mean HC emissions shows a total vehicular production of 29 tonnes of HC per day. Of that total, assuming that all vehicles consume gasoline at the average rate, the top 10

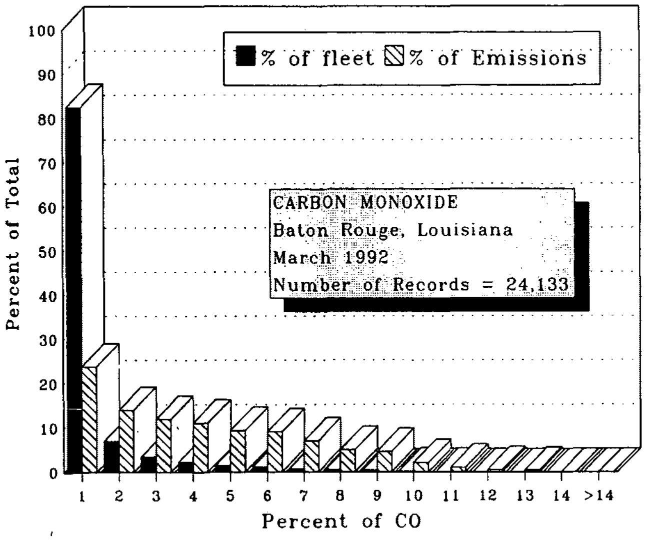

FIGURE 4 Distribution of CO emissions in Baton Rouge.

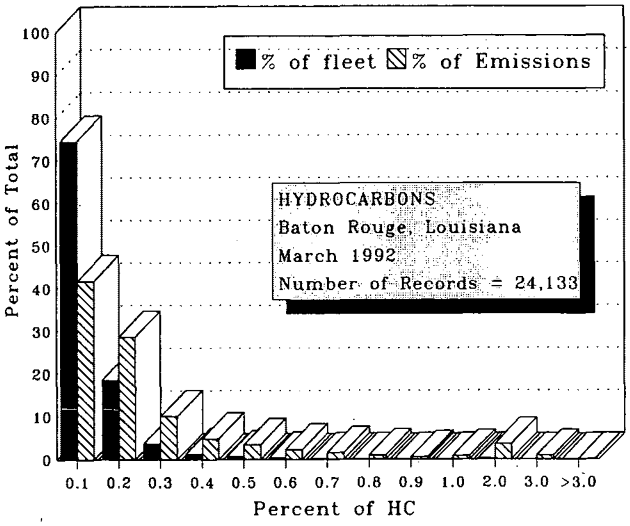

FIGURE 5 Distribution of HC emissions in Baton Rouge.

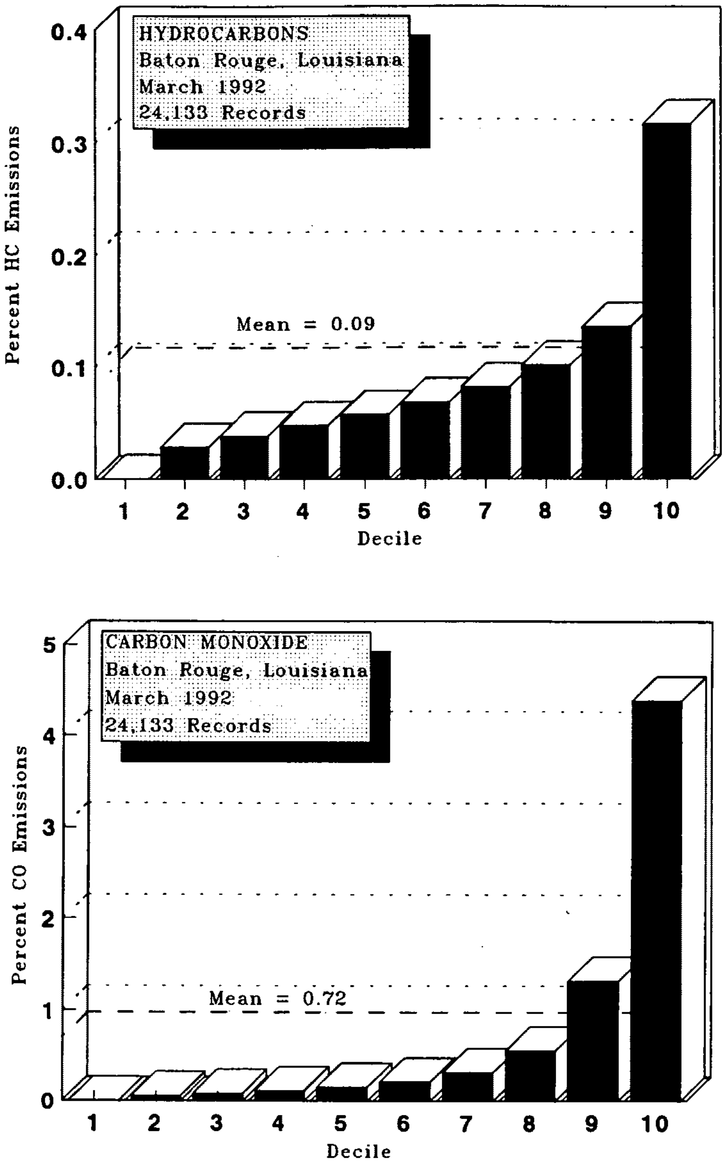

FIGURE 6 Percent CO and HC emissions in Baton Rouge organized into deciles.

percent of polluters account for 10 tonnes, leaving 19 tonnes produced by the remaining 90 percent of vehicles.

The estimated total vehicular production of each of CO and HC are based on on-road measurements that represent normal driving conditions. These figures, in reality, are expected to be higher because of higher emissions during other modes of engine operation, such as a typically fuel-rich acceleration mode. The estimated figures, however, seem to be in accordance with the modeled estimates of an analysis of air quality for the Baton Rouge urban area that was conducted jointly by the Louisiana Department of Transportation, Department of Environmental Quality, and the Capital Region Planning Commission, which is the metropolitan planning organization (*10*). Since the Baton Rouge area has been designated as a serious nonattainment area for ozone, this study only pertains to HC and NO_x. Using TRANPLAN estimates of VMT and MOBILE 4 emission factors, an estimate of total 1988 base year emissions for the Baton Rouge metropolitan area, which includes parts of the West Baton Rouge and Livingston parishes, are 31 tonnes per day of HC and 21 tonnes per day of NO_x. The 31 tonnes per day of HC compares very favorably with our estimate of 29 tonnes per day for almost the same geographical area.

Figure 6 shows, in a different way, the overall sample fleet shown in Figures 4 and 5. The sample has been subdivided into tenths, and the height of each bar represents the average emissions for that tenth of the sample fleet. The graphs show even more clearly the impact of the gross polluters representing the dirtiest 10 and 20 percent of vehicles. Clearly, vehicles in the two highest deciles (9 and 10) produce by far the largest

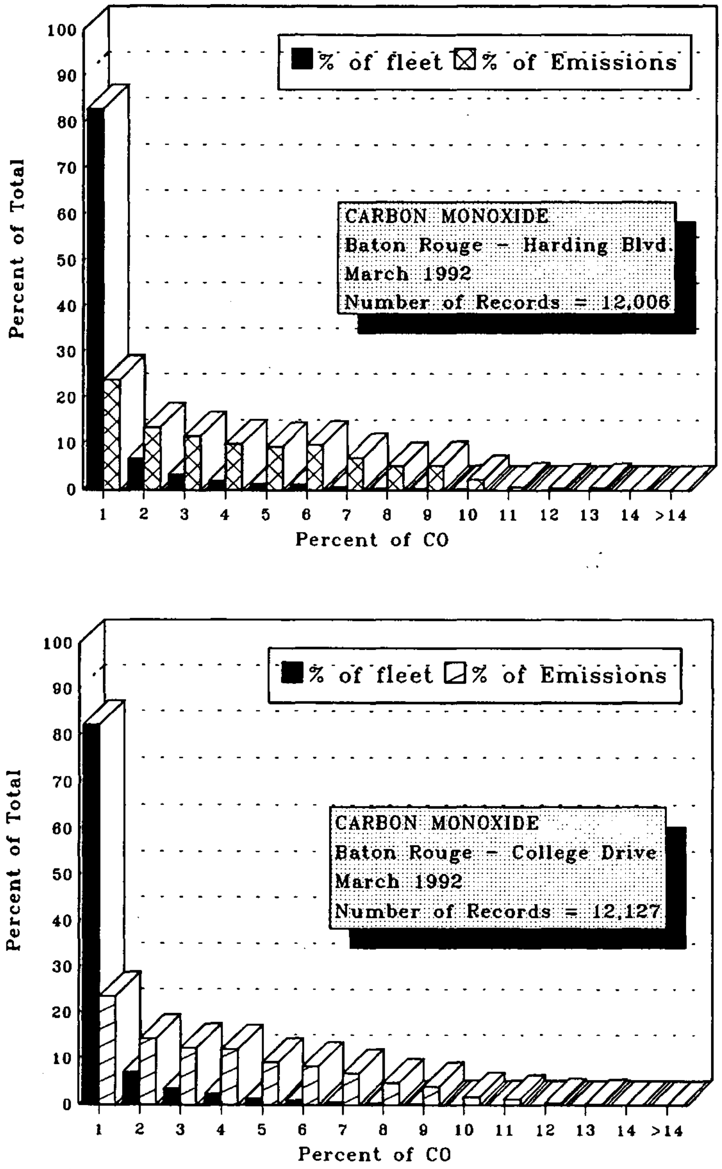

FIGURE 7 Percent CO emissions for Harding Boulevard and College Drive.

contribution to emissions. Removal or remediation of these vehicles would clearly provide considerable reductions in mobile emissions.

A comparison of the College Drive and Harding Boulevard data is shown in Figures 7 and 8. Figure 7 shows the percentage of vehicles in each CO category and the percentage of the total CO emissions for the College Drive and Harding Boulevard data. Most noteworthy are the similarities between the two sites; more than 80 percent of the vehicles are quite clean, emitting less than 1 percent CO and contributing only 24 percent of total emissions. The CO gross polluter cut-point (50 percent of emissions) is about 3 percent CO for both locations. However, for HC, the results are slightly different, as shown in Figure 8. The HC gross polluter cut-points are 0.10 and 0.15 percent for the College Drive and Harding Boulevard locations, respectively. These findings show that even though these two locations are from two demographically different areas, the CO and HC emissions are practically identical.

The impact on the effectiveness of any type of TCM because of the skew in both the HC and CO emissions frequency distributions is important. Usually, it is assumed that the impact of a TCM can be estimated from the mean. However, few vehicles are actually at the mean. In the case of CO emissions more than 80 percent of vehicles emit less than the mean, and in the case of HC emissions more than 70 percent of vehicles emit less than the mean. The effects of this can be illustrated best by the following scenarios. These scenarios are based on the estimated daily emissions for the parish of East Baton Rouge (152 tonnes of CO and 29 tonnes of HC).

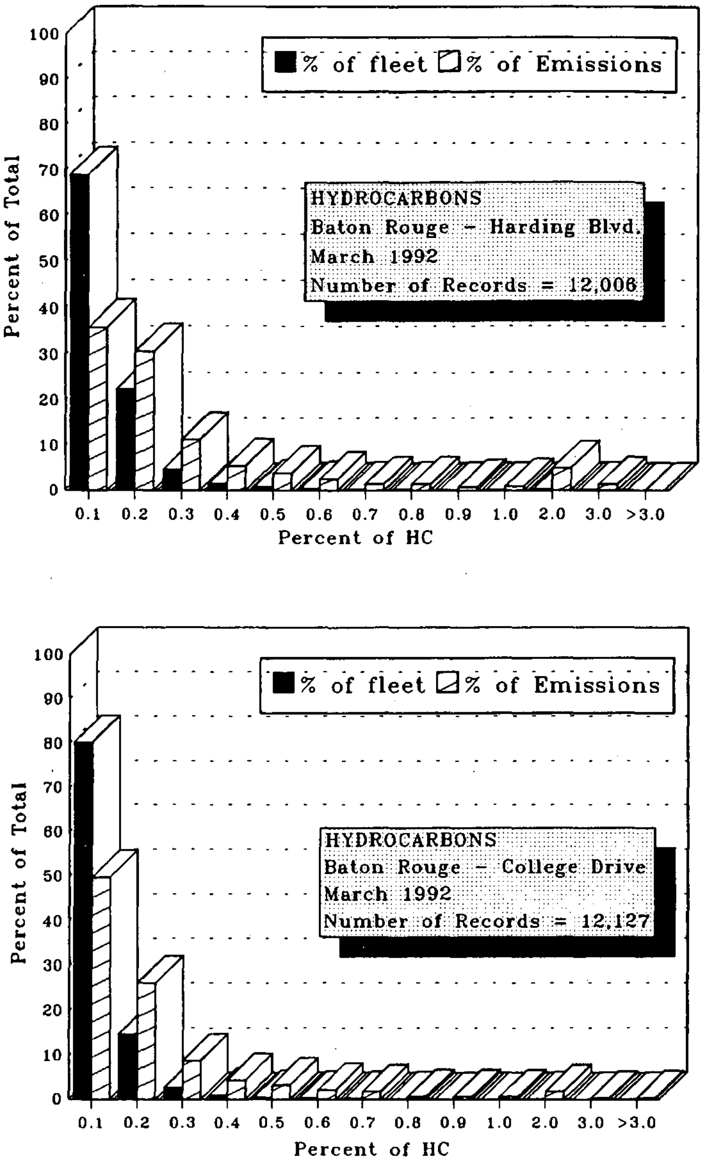

FIGURE 8 Percent HC emissions for Harding Boulevard and College Drive.

Suppose a TCM package were implemented in Baton Rouge that resulted in a 10 percent reduction in fuel use. If the strategies achieved a uniform reduction in fuel use across the entire vehicle fleet, the reductions in emissions would be 15 tonnes of CO per day and 3 tonnes of HC per day. This is a highly optimistic scenario, however, as has been shown by Fleet and DeCorla-Souza (*11*). It is most likely that TCMs based on voluntary compliance will achieve reductions primarily for those individuals who already maintain their vehicles, own newer, cleaner vehicles, and are best represented by the median emissions. In this case, the emissions reductions are more likely to be on the order of 4 tonnes of CO per day and 2 tonnes of HC per day (assuming that the 10 percent fuel reduction is achieved from 80 percent of the vehicles). On the other hand, if the TCMs were aimed at the gross polluters representing the dirtiest 10 percent of vehicles and these vehicles were brought down to the median emissions level, the emissions reductions would be 81 tonnes of CO and 8 tonnes of HC. These results are given in Table 3.

Each scenario results in impacts on 10 percent of the vehicle fleet. Scenario 2 is the most likely result of applying voluntary TCMs, whereas Scenario 1 is most likely to be the claimed result for voluntary TCMs before they are applied. Scenario 3 is clearly far more desirable than either the reality of Scenario 2 or the expectation of Scenario 1. However, Scenario 3 is possible only when remote sensing is used to identify the gross polluters and it is used in association with a follow-up to correct emissions problems of these vehicles. Such a strat-

TABLE 3 Summary of Emissions Reduction Scenarios

Scenario	CO (Tonnes/day)		HC (Tonnes/day)	
	Total Remained	Reduction Achieved	Total Remained	Reduction Achieved
1. Uniform Reduction	137	15 (10%)	26	3 (10%)
2. Reduction on Clean Vehicles Only	148	4 (3%)	27	2 (7%)
3. Targeted to 10% Dirtiest Vehicles	71	81 (53%)	21	8 (28%)

egy has the advantage of not inconveniencing vehicle owners who keep their vehicles in good condition and avoids wasting time on needless inspections of these vehicles.

CONCLUSIONS

The measurements of the 24,133 on-road vehicle emissions show that only a small percentage of vehicles contribute to more than half of the pollution from CO and HC. The average CO emissions for the measured fleet was 0.72 percent CO, which corresponds to approximately 70 g CO per liter of gasoline consumed. The average emission of hydrocarbons was 0.09 percent HC, or 14 g HC per liter of gasoline.

The results imply that on-road identification of gross polluters in conjunction with targeted repair programs may be the only strategy available currently that can have significant impacts on vehicle emissions. Remote sensing has the advantage of inconveniencing only a small fraction of the vehicle owners affected by routine I/M programs while producing potentially large reductions in emissions.

ACKNOWLEDGMENTS

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PART 3

Noise

Reference Energy Mean Noise Emission Levels for Riyadh, Saudi Arabia

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In the oil-rich countries of the Persian Gulf, traffic noise pollution in rapidly developing urban areas has become a major source of concern for the public and for policy makers. The FHWA traffic noise model (STAMINA), because of its flexibility and adaptability to a changing environment, provides an effective tool for the analysis of traffic noise impact. However, no study has been undertaken to examine the applicability of the FHWA models to urban areas in the Persian Gulf region. In this study, noise emission data were collected for cars, medium trucks, and heavy vehicles. Using the data, reference energy mean noise emission levels were developed as a function of vehicle class and speed. These functions were used to predict traffic noise levels for two roadway locations in Riyadh. A comparison of model-predicted noise levels with field measurements indicated a significantly closer agreement between the Riyadh and the original FHWA models.

This paper reports the development of reference energy mean noise emission levels (REMNEL) for vehicles in Riyadh, Saudi Arabia. In rapidly developing urban areas of the oil-rich countries of the Persian Gulf, the problem of traffic noise pollution becomes complex. The complexity arises from a continuous migration of population from rural to urban areas, construction of hundreds of kilometers of urban expressways, and an intense rate of growth in household socioeconomic activities. Studies have shown that a major portion of the urban population in Saudi Arabia is annoyed with traffic noise (*1–3*).

A commonly used model for detailed noise impact analysis and forecasts is the Federal Highway Administration model FHWA/STAMINA (*4*). The model can easily be calibrated for new conditions since the REMNEL for various classes of vehicles are used as independent inputs to the model. FHWA has also published reference energy mean emission levels as a function of vehicle class and vehicle speed (*5*).

Several research studies in North America have shown that the use of the original REMNEL curves published by FHWA may result in a significant overestimation of noise levels in the vicinity of roadways where the studies were performed (*6–8*). However, no study has been performed to examine and evaluate the transferability of the FHWA traffic noise models to urban areas of the Persian Gulf region. A number of related factors in the region vary from those of the North American environment: poor vehicle maintenance practices, overloading of vehicles, and rough pavement surfaces caused by poor material characteristics and a lack of systematic and timely pavement maintenance.

The specific objectives of the study were (*a*) to develop REMNEL curves for Riyadh and (*b*) to compare the Riyadh and FHWA noise emission curves.

DATA AND METHOD

The sampling plan was designed in accordance with the requirements established by FHWA (*9*). Five sites were chosen for field measurements. All sites were level (less than 2 percent grade) open spaces and were free of large reflective surfaces. The microphone was placed 15 m from the centerline of the near traffic lane and was mounted on a tripod at a height of 1.5 m.

The study instrumentation included a Bruel and Kjaer noise level analyzer, Type 4427; a sound level meter, Type 2209; a calibrator (pistonphone), Type 4220; a ½-in. microphone, Type 4165; an extension cable, Type A00029; a microphone windscreen; a tripod; and a radar vehicle speed detection unit.

Vehicles were classified into three groups in accordance with the FHWA procedure. The noise emission data were collected from vehicles moving at a constant speed under cruise conditions. Samples were grouped into speed ranges of ±5 km/hr and covered a range from 50 to 100 km/hr.

Statistical Analysis of the Sample Data

The required number of sample vehicles for each class and speed group was determined using the procedure recommended by FHWA (*10*). The number of sample vehicles for each class (automobiles, medium trucks, and heavy trucks) were 75, 108, and 94, respectively (error interval ±0.5 dBA and $\alpha = 0.05$, a 5 percent significance level). The number of vehicles actually monitored for noise emission data at each speed group was slightly higher: 80 for automobiles and light trucks, 110 for medium trucks, and 100 for the heavy vehicle group. Using the final sample size and the sample standard deviation, the actual confidence interval at the 95 percent confidence level was computed for each vehicle class and each speed group according to the Student's *t* distribution (since the true variance is unknown), shown by Equation 1:

$$\bar{x} - t_{\alpha/2,n-1}\frac{S}{\sqrt{N}} \leq \mu_{1-\alpha} \leq \bar{x} + t_{\alpha/2,n-1}\frac{S}{\sqrt{N}} \quad (1)$$

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where

$\bar{x}$ = mean sample emission level,
$t_{\alpha/2,n-1}$ = the percentile value of the t distribution with $(n-1)$ degrees of freedom (*10*),
S = sample standard deviation,
μ = true mean emission level,
N = sample size for each vehicle class and speed group, and
α = significance level.

Table 1 presents the results of the statistical analysis of the sample emission data. Figure 1 shows variations in the mean ± one standard deviation for each speed group for automobiles, medium trucks, and heavy vehicles.

Computation of REMNEL

The following steps were taken to compute REMNEL:

1. The arithmetic mean emission level for the ith vehicle class, $(\overline{L}_o)_i$, was computed according to Equation 2:

$$(\overline{L}_o)_i = \left(\frac{1}{N}\right) \sum_{K=1}^{N} (L_o)_{Ki} \tag{2}$$

where $(\overline{L}_o)_{Ki}$ is the Kth measured emission level for the ith class of vehicles at a given speed group and N is the number of measured emission levels for the ith vehicle class at a given speed group.

2. The sample standard deviation of the ith vehicle class, $(S)_i$, was computed using Equation 3:

$$(S)_i = \sqrt{\left[\frac{1}{(N-1)}\right] \sum_{K=1}^{N} [(L_o)_{Ki} - (\overline{L}_o)_i]^2} \tag{3}$$

3. The REMNEL for each vehicle class and speed group, $(\overline{L}_o)_{Ei}$, was computed in accordance with the following equation:

$$(\overline{L}_o)_{Ei} = (\overline{L}_o)_i + 0.115(S)_i^2 \tag{4}$$

Equations 2 through 4 were used with the sample data to compute the REMNEL for the three vehicle classes and each speed group. Results are presented in Table 2. The data in Table 2 clearly indicate that the REMNEL values increase with increases in vehicle speed and vehicle size.

Using the REMNEL values from Table 2 and the midpoint of each speed group, a least squares regression analysis was performed to develop the equation for the reference mean emission levels for each vehicle class in Riyadh. The equations are as follows for automobiles, medium trucks, and heavy vehicles, respectively:

$$(\overline{L}_o)_E = 9.84 + 33.21\log(V) \qquad R^2 = 0.8779 \tag{5}$$

$$(\overline{L}_o)_E = 15.54 + 35.68\log(V) \qquad R^2 = 0.9765 \tag{6}$$

$$(\overline{L}_o)_E = 44.39 + 22.46\log(V) \qquad R^2 = 0.9433 \tag{7}$$

where V is vehicle speed in km/hr.

The high values of coefficients of determination (R^2) are in accordance with expectations. Since the sample observation values for both the dependent and independent variables are the mean values of emission levels and speed groups, respectively, the models only explain the in-between group variations of emission levels. The within-group variations are not explained by the models because of the use of the mean values.

A comparison of FHWA's regression curves and those developed for Riyadh indicated higher REMNEL values for all vehicles and all speed groups predicted by the Riyadh models. Important factors contributing to higher noise levels produced

TABLE 1 Statistical Analysis of Sample Data

Vehicle Class	Speed Class (km/h)	Mean Noise Emission Level (dBA)	Standard Deviation of Emission Level (dBA)	Sample Size	Confidence Interval 95% level (α=005) ± dBA
	50	65.4	2.05	80	0.46
	60	66.8	0.83	80	0.28
Automobiles	70	69.2	0.60	80	0.13
	80	70.8	1.71	80	0.38
	90	73.1	0.83	80	0.18
	100	75.0	2.20	80	0.49
				Σ=480	
	50	74.5	1.22	110	0.23
	60	77.0	1.16	110	0.22
Medium Trucks	70	79.4	1.04	110	0.19
	80	81.5	1.05	110	0.20
	90	83.5	0.86	110	0.16
	100	85.0	0.87	110	0.16
				Σ=660	
	50	81.6	0.86	100	0.18
	60	83.6	0.85	100	0.17
Heavy Trucks	70	85.6	0.78	100	0.15
	80	86.6	0.80	100	0.16
	90	87.4	0.69	100	0.14
	100	88.0	0.89	100	0.18
				Σ=600	

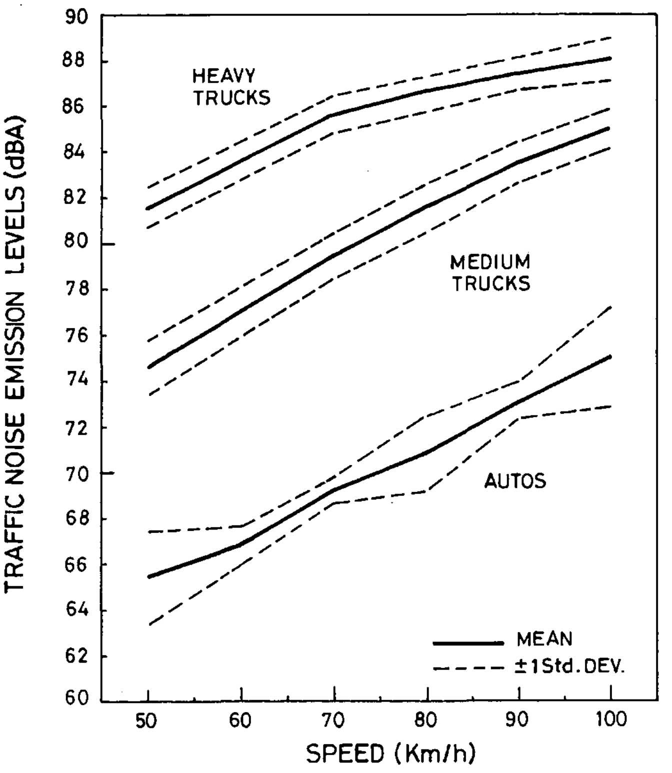

FIGURE 1 Mean and standard deviation of emission levels by vehicle class and speed group.

by vehicles in Riyadh were the generally poor level of vehicle maintenance, overloading of vehicles, and the rough pavement surface of urban roadways (due to the nonexistence of high-quality pavement materials in most parts of Saudi Arabia).

Model Validation

The Riyadh and FHWA emission level curves were used to compute reference energy mean noise emissions $(\bar{L}_o)_{Ei}$, and, subsequently, the equivalent noise levels, L_{eq}, for two roadway sites in Riyadh. Actual measurements of traffic volumes, speeds, and noise levels were made during five periods, covering the morning (7:00 to 9:00 a.m.), afternoon (4:30 to 8:30 p.m.), and night (9:30 to 11:00 p.m.).

Table 3 presents the measured and model-predicted hourly equivalent noise levels by monitoring period and vehicle class for the two study sites. The data in these tables clearly indicate that the use of FHWA-recommended curves consistently underestimated traffic noise at both sites.

The Student's *t* test for paired data was used to determine whether the difference between measured traffic noise levels and those predicted by the two models was statistically significant (*9*). A mean difference of 0.37 dBA was obtained by using the Riyadh noise emission data, and −2.02 dBA resulted from using the FHWA emission levels. The difference between the model-predicted $L_{eq}S$, using the FHWA emission data, and measured noise levels was significant at the 95 percent significance level ($\alpha = 0.05$). No significant difference, however, was found to exist between the model result using Riyadh emission levels and the measured noise levels.

CONCLUSION

This study indicates that the traffic noise emission data originally recommended by FHWA models are not representative of those measured from vehicles in Riyadh. The FHWA emission curves consistently underestimated traffic noise levels in Riyadh.

The Riyadh model, on the other hand, accurately predicted traffic noise levels at two independently monitored roadway locations in Riyadh.

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TABLE 2 REMNEL by Vehicle Class and Speed Group

Speed Group[a] (km/h)	Vehicle Class, i								
	Autos			Medium Trucks			Heavy Trucks		
	$(\bar{L}_o)_i$	$(S)_i$	$(\bar{L}_o)_{Ei}$	$(\bar{L}_o)_i$	$(S)_i$	$(\bar{L}_o)_{Ei}$	$(\bar{L}_o)_i$	$(S)_i$	$(\bar{L}_o)_{Ei}$
50	64.4	2.05	64.9	74.5	1.22	74.7	81.6	0.86	81.7
60	66.8	0.83	66.9	77.0	1.16	77.2	83.6	0.85	83.7
70	69.2	0.60	69.2	79.4	1.04	79.5	85.6	0.78	85.7
80	70.8	1.71	71.1	81.5	1.05	81.6	86.6	0.80	86.7
90	73.1	0.83	73.2	83.5	0.86	83.6	87.4	0.69	87.5
100	75.0	2.20	75.6	85.0	0.87	85.1	88.0	0.89	88.1

[a] Each speed group includes observations within ±5 km/h.

TABLE 3 Measured and Model-Predicted Hourly Equivalent Noise Levels—Ulayyah Arterial and Maccah Freeway

Variable Name	L_{eq} by monitoring Period and Vehicle Class								
	Morning			Afternoon			Night		
	Autos	Medium Trucks	Heavy Trucks	Autos	Medium Trucks	Heavy Trucks	Autos	Medium Trucks	Heavy Trucks
				(a) ULLAYYAH ARTERIAL					
Riyadh Model	69.1	66.6	66.5	68.5	69.0	68.1	68.6	64.2	64.1
FHWA Model	65.4	64.3	64.4	64.8	66.7	66.0	64.9	61.9	62.0
All Vehicles:									
Riyadh Model		72.4			72.0			71.0	
FHWA Model		69.5			69.1			67.9	
Measured		73.0			72.0			71.0	
				(b) MACCAH FREEWAY					
Riyadh Model	79.5	77.8	72.1	79.1	74.6	74.8	77.8	78.6	68.1
FHWA Model	76.7	75.2	70.4	76.3	72.0	73.1	75.0	76.0	66.5
All Vehicles:									
Riyadh Model		82.2			81.5			81.4	
FHWA Model		80.9			79.0			78.8	
Measured		81.7			79.9			80.7	

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Special Noise Barrier Applications

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The technical, aesthetic, and economic feasibilities of incorporating special noise barrier applications into a highway noise control program are investigated. The starting point is taken as the thin, vertical, reflective barrier now used in most applications. Special barrier applications are those beyond the thin vertical reflective barrier. The investigation of technical feasibility relates to the mathematical formulation of the effects of absorptive treatments, slanted tops, T tops, and other special applications. The economic and aesthetic feasibility investigations examine the value of using these special applications in lieu of thin, vertical, reflective barriers. The research was performed on behalf of the Washington State Department of Transportation. The research was intended for background studies of the effects of special barrier treatments so the department could implement pilot projects at a later date.

More than 1150 linear m of noise barriers have been constructed in the United States during the last 20 years by state highway agencies. Most of these barriers have been vertical, reflective walls made of concrete, wood, or steel. The standard barrier top for these walls is a "knife-edge," providing a single diffraction edge with a reflective diffraction zone.

Clearly, there are many other options for noise barrier shapes. In addition to earth berms, there are options to make barriers absorptive or partially absorptive, to displace the diffraction zone horizontally through the use of a slanted section on top, or to provide for a double-diffraction zone through the use of a T-top or Y-top section on the top of the wall.

SHAPED BARRIER TOPS

The effective width of the barrier may be increased by either increasing the width of the top by various means or by making the entire barrier thicker. In either case, the result is double diffraction. The following is a review of three promising barrier top modifications: the T-top, Y-top, and slanted-top barriers.

T-Top Barriers

The concept of T-top barriers has been studied extensively in Canada, mainly through scale modeling (*1*). T-tops of varying widths were tested for a single barrier configuration with a protected receiver (i.e., a receiver behind the barrier). Results indicate an increase in insertion loss of about 2 dB for a cap width of 16 in. due to double diffraction by the T-top. If the 16-in.-wide T-top were stood on its end, thus adding height to the barrier, insertion loss would be increased by about 0.7 dB, based on the rule of thumb that insertion loss increases 1 dB for every 0.61 m height beyond the line-of-sight break.

May and Osman also studied the possibility of an absorptive treatment on the top of a reflective T-top barrier (*1*). In this study, two frequency bands (500 and 1000 Hz) were considered as well as the A-weighted spectrum. Three levels of absorption were used: noise reduction coefficient (NRC) values of 0.52, 0.57, and 0.74. (NRC is the arithmetic average of the absorption coefficients at 250, 500, 1000, and 2000 Hz.) A direct comparison is made between the insertion loss of the reflective and absorptive T-tops in Figure 1, which shows that the absorptive treatment increased insertion loss. For the realistic cap width of 0.61 m, the absorptive top produced an additional 1.9 dB of attenuation compared with the same width reflective T-top. The absorptive top functions better at higher frequency sound levels because the shorter sound wavelengths have more opportunity to be affected while diffracting across the barrier top.

In addition to their scale model testing, May and Osman conducted a full-scale test on an existing highway noise barrier built in Toronto in 1978 (*2*). The 3.96-m-high barrier was tested first with an absorptive side, second with a reflective side, and finally with a 30-in. T-top. Although they found no statistically significant difference between the noise reductions produced by the absorptive and reflective barriers, sound measurements in the residential community behind the barrier indicated that the T-top barrier produced a 1 to 1.5 dB greater noise reduction than the other two configurations. This is less than would be expected from adding 30 in. of height to the barrier; however, May and Osman noted that high background noise in the area likely reduced insertion loss measurements. Consequently, they believed that their measurements understated the T-top effects.

Other scale modeling experiments were conducted in Canada in 1983 at the Technical University of Nova Scotia (*3*). Hutchins et al. conducted the experiments, which investigated the frequency dependence of barrier insertion loss for various noise barrier designs. The effects of ground surfaces were studied, treating both grass-covered ground and asphaltic surfaces. In both cases, the T-top barrier produced larger insertion losses than did a standard thin barrier.

The potential of T-top barriers is evident. In general, past studies have shown that T-top barriers achieve a significant increase in insertion loss over a conventional barrier of the same height. This is primarily due to the opportunity for double diffraction to occur on the continuous flat surface of the top of the barrier. There are currently two mathematical

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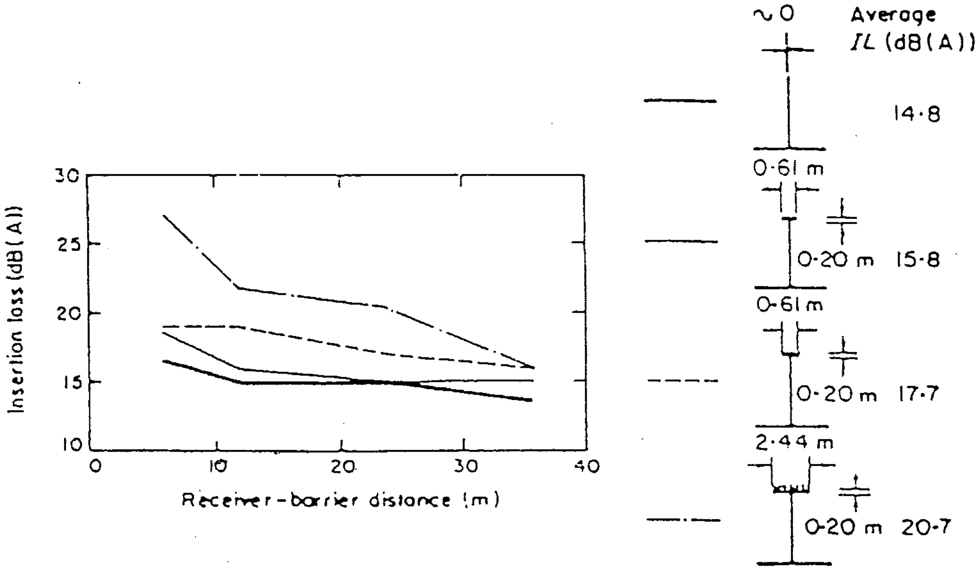

FIGURE 1 Insertion loss of T-top absorptive and T-top reflective barriers, of the same cap thickness, compared with a conventional knife-edge top barrier (*1*).

methods of describing the phenomenon of double diffraction: geometrical theory of diffraction (GTD) (*4*) and the boundary element method. These methods are discussed elsewhere (*4*–*8*). There is, however, currently no exact solution for the double diffraction problem.

In a scale model study, Hothersall et al. (*7*) reported that the spectrum for a T-top barrier of the dimensions shown in Figure 2, but with a reflecting upper surface, followed a similar trend to that shown for the vertical wall, but with an increase in insertion loss of approximately 0.5 dB. The absorptive T-top performed substantially better at higher frequencies. This performance can be attributed to the increased opportunity for sound absorption due to the shorter wavelengths of sound at high frequencies. Although the insertion

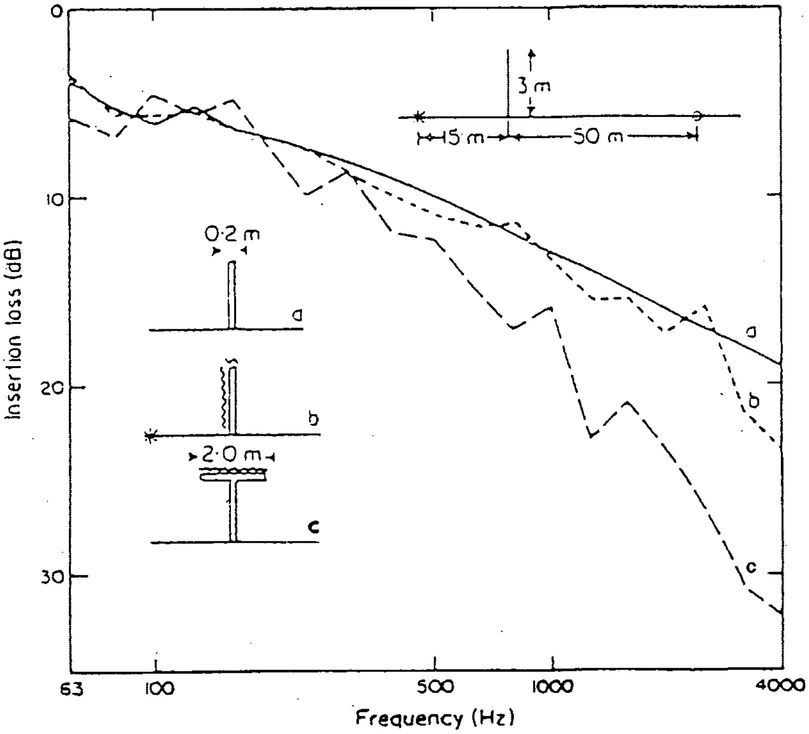

FIGURE 2 Insertion loss spectra for three barrier types: (*a*) vertical reflective, (*b*) vertical absorptive, and (*c*) absorptive T-top.

loss values in Figure 2 are reported in dB, the A-weighted L_{eq} for the values can be calculated. In that case, the absorptive T-top barrier provides approximately 3.5 dBA more insertion loss than the conventional reflective barrier. This excellent performance has been observed in model experiments but has not been tested in full-scale trials.

Two contrasting ways to model double diffraction have been referenced and briefly discussed, and both have proven that excess attenuation can be obtained through the use of T-top barriers. It is clear that the good performance of the T-top barrier depends on the interaction of its flat top and the grazing sound wave. This performance is significantly improved when the T-top includes an absorptive treatment. In summary, T-top barrier performance can currently be approximated as follows: the improvement in performance resulting from the absorptive T-top is at least equivalent to that which would result if the T-top section were stood on its end and added to the height of the vertical section of the barrier.

Y-Top Barriers

Y-top barriers were also studied by both Hutchins and May and Osman to determine whether, for an equivalent height and overall width, they had an insertion loss equal to that of the T-top barrier. Such a finding would have suggested that the good performance of the T-barrier is independent of the interaction of its flat top and the grazing wave. This would open the way to considering barriers similar in their diffractive effects to the Y-top barriers, but which present fewer snow clearance and drainage problems.

In their scale model study, May and Osman found that the Y-top barrier gave a 3.5-dB higher insertion loss than a conventional knife-edge barrier (*1*). However, the insertion loss was 0.7 dB lower than that of the T-top barrier with an equivalent 2.44-m span. Figure 3 shows the insertion loss of the Y-top reflective barrier.

Slanted-Top Barriers

Slanted-top noise barriers are used extensively in Japan. In a 1982 article, their possible advantages were discussed (*9*). These advantages were observed during research conducted on barrier materials and shapes in the Laboratory of the Japan Highway Public Corporation.

It is common to see noise walls in Japan with the upper one-third of height slanted toward the traffic at a 30- to 45-degree angle. The result is that the slanted tops displace the location of the diffraction edge and can contribute to slightly increased barrier attenuation.

A slanted barrier top has the effect of moving the diffraction edge slightly closer to the receiver or source (depending on the direction of the slope). This movement of the diffraction edge is equivalent to the construction of a vertical, knife-edge reflective barrier located at the same distance from the source as the horizontal distance between the source and the apex of the sloped top. Since Fresnel diffraction governs slanted-top barriers, there is no significant additional insertion loss.

Single-Wall Absorptive Barriers

Absorptive noise barriers have been extensively studied for many years. However, a review of the literature on this subject shows that there are still many uncertainties about the usefulness of covering barriers with absorptive material. For example, Maekawa carried out experiments on the diffraction of an absorptive barrier, but he discarded his experimental results because of their significant deviations from theory (*10*). Later, however, Butler noted that those experimental results were probably accurate (*11*).

Jonasson (*12*) proposed combining the propagation theory of Ingard (*13*) with the diffraction solution of Bowman et al. (*14*) to calculate and compare the insertion loss provided by a depressed road and an absorptive barrier. At about the same time, Rawlins published theoretical studies on the diffraction of sound by an absorptive wedge (*15*). He showed that a strip, one wavelength wide, of an absorptive material at the top edge of a barrier led to the same diffracted field as that provided by a totally covered barrier. However, Rawlins did not consider the effect of placing this absorptive strip only on the source side or on the receiver side or on both sides of the barrier.

In 1977, Fujiwara presented a study that specifically dealt with the excess attenuation provided by an absorptive material placed on the surfaces of a barrier (*16*). His results suggest that an absorptive cover can increase the free-field attenuation

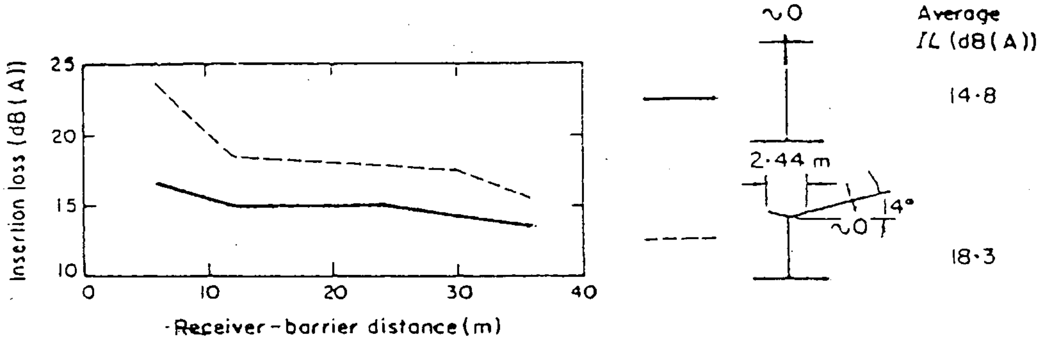

FIGURE 3 **Insertion loss of the Y-top reflective barrier compared with a conventional knife-edge barrier (*1*).**

of a barrier by more than 6 dB. Later, Isei presented a method for calculating the insertion loss of an absorptive barrier on a finite impedance ground using a diffraction solution (*17*). In contradiction to Fujiwara, the theoretical and experimental results obtained by Isei showed that the absorptive properties of the barrier do not significantly change its insertion loss.

Koers recently suggested a solution for calculating the diffracted field over an absorptive barrier (*18*). This solution is derived from the diffraction solution of Pierce and Hadden (*19*); additional terms are introduced to take into account the specific impedance of each side of the wedge. Unlike the other diffraction model, this solution has the advantage of respecting the reciprocity condition. Unfortunately, Koers did not extend his solution to the calculation of the insertion loss provided by an absorptive barrier, as he did not study the real benefit of covering the barrier with an absorptive material.

In 1989, Nicolas et al. published a method for calculating the insertion loss of a thin barrier covered with absorptive material, on the source side, the receiver side, or both sides (*20*). The method used combined a classical theory for the propagation of sound over ground with the approximate solution for diffraction over an absorptive wedge proposed by Koers, which can take into account the specific impedance of each side of the barrier. The validity of the method was confirmed by comparing theoretical results with experimental measurements for various geometrical configurations and barrier boundary conditions. The results showed that, when the angles of diffraction are significant, the insertion loss of a hard barrier can be substantially increased by covering one of its surfaces with an absorptive material. This absorptive layer must be placed on the surface of the barrier associated with the greatest angle of the diffracted rays' paths (source top-edge or receiver top-edge). When these angles are about the same on each side of the barrier, the increase will be the same if the absorptive material is placed on the source or on the receiver side. In this case, it was found that by covering both sides of the barrier, the increase of the insertion loss due to the absorptive material will double compared with a single covering.

In a 1988 study, the Federal Highway Administration, in conjunction with the Maryland Department of Transportation State Highway Administration, conducted an experiment to determine the resistance of absorptive sound barriers to repeated cycles of freezing and thawing (*21*). The experiment was intended to help determine the acceptability of the sound barrier samples; it was not intended to provide a quantitative measure of the service life of a particular product. Testing was performed on two absorptive sound barrier samples, each 0.61 by 0.92 m. The 4-in.-thick samples consisted of 2-in.-thick porous concrete on one side of the panel and 2-in.-thick normal concrete on the other side of the panel. Embedded in the surface of the porous concrete were 1-in. smooth aggregate pieces. The two concretes differed in such properties as strength, mix proportions, and density.

The testing conformed to procedures described in the Interim Method of Test for Resistance of Porous Concrete to Freezing and Thawing, which was developed internally by FHWA. The samples were exposed to regular cycles of freezing and thawing. Thawing took place for 4 to 6 hr during the day; samples were then stored in a freezer each night. During the testing, the specimens were situated randomly in both the freezer and the moist room to negate any location-specific effects. The initial saturated weights and the condition of the specimen were recorded. Both specimens were weighed and evaluated after 50, 95, 158, and 200 cycles. The normal concrete showed no signs of deterioration; however, the porous concrete surface of both specimens was severely deteriorated, with both losing approximately 60 percent of the surface. Therefore, these porous concrete samples were determined to be unsuitable as absorptive sound barriers in situations where they will be subjected to repeated freeze/thaw cycles.

The mathematics involved in the phenomenon of diffraction over absorptive barriers is quite complex and has not yet been fully defined in the literature. Laboratory scale model measurements, however, have shown that up to 2 dB additional insertion loss can be gained in certain situations when using absorptive treatments on single barriers. These unpublished results were obtained by Cohn as part of a parallel barrier study using the laboratory of the Japan Highway Public Corporation in 1982. This maximum of 2 dB is obtainable when the barrier protrudes well past the line-of-sight break and the diffraction angle is large (i.e., deep in the shadow zone). The requirement of steep diffraction angles was confirmed in a study by Nicolas et al. (*20*), which combined an approximate diffraction solution with a well-known theory for sound propagation over the ground (*22*) to calculate the insertion loss of a thin absorptive barrier.

In summary, absorptive barriers offer potential for enhancement of insertion loss performance over reflective knife-edge barriers, even for single-wall systems. The upper limit of this enhancement is likely to be on the order of 2 dB.

AESTHETIC AND ECONOMIC FEASIBILITY

Absorptive T-Top Barriers

The performance characteristics of T-top barriers were discussed previously. Absorptive T-top barriers have performed well in past acoustical scale modeling studies. However, full-scale modeling and direct field measurements from absorptive T-tops have been extremely limited in past studies. Nevertheless, the possibility of enhanced performance from this barrier top is evident.

The greater complexity of a T-top barrier compared with a conventional barrier of equal performance may be offset by a lower wind loading for its lesser height. Wind loads often dictate the strength requirements of the posts used in most barrier designs, which are a major component of barrier costs. A situation has also been discussed by Hajek and Blaney where foundation design did not favor a further increase in height, thus necessitating the use of a T-top, or similar design, to increase insertion loss (*23*). The T-top design clearly has an economic advantage in these two areas (wind loading and foundation requirements) compared with increasing the height of a conventional noise barrier.

The aesthetics of a barrier are also an important factor for nearby residents. A shorter T-top barrier may be received better by citizens than a higher conventional barrier. Knauer has reported a situation where the demands of residents to retain a full view of their coastal surroundings led to the erection of barriers having insufficient height to meet target noise levels (*24*). This appears to be an ideal situation in which to make use of a T-top design. Intuitively, if predicted conventional barrier insertion losses are small, the increase that may be provided by a T-top barrier may help justify the barrier in the first place.

Experimental studies have shown that absorptive T-top barriers perform well in the laboratory. However, the durability of this absorptive treatment when exposed to seasonal weather conditions has yet to be proven. The question of durability of absorptive side treatments has been discussed earlier. The placement of absorptive treatment on the flat top of a T-shaped barrier will undoubtedly increase the opportunity for liquid infiltration into the absorptive material. Whether this chance for increased exposure proves detrimental to the success of absorptive T-top barriers is also yet to be proven by adequate exposure time of full-scale prototype models.

In summary, absorptive T-top barrier feasibility can be approximated as follows: Absorptive T-top barriers have both positive economic and aesthetic qualities, and performance is at least equivalent to that which would result if the T-top section were stood on its end and added to the height of the vertical section of the barrier.

Slanted-Top Barriers

Slanted-top barriers have been used extensively in Japan (*9*). However, the findings of the mathematical formulation indicate that only a slight potential for additional insertion loss (compared with a conventional barrier) exists. Still, the slanted-top barrier has a better aesthetic appearance.

In a situation requiring a relatively tall barrier, a slanted top may be advantageous. Slanting the upper part of a tall reflective barrier toward the source can yield a diminishing appearance from the receivers. This appearance would definitely be more aesthetically pleasing to the residents while providing the same insertion loss as a vertical barrier of equivalent height. The slanted top may actually appear shorter and could provide better light and less screening of view for the receivers.

A slight increase in cost due to structural requirements and increased construction times could arise from the selection of a slanted-top barrier. However, the benefits gained from a better public acceptance of this special barrier top may justify its selection.

TABLE 1 Design Matrix for Special Noise Barrier Applications

Barrier Type	T-Top	Y-Top	Slanted Top	Absorptive Single	Absorptive Parallel
Height	> 13'	> 13'	> 13'	All	> 10'
Approx. Increased I.L. (dB)	1.5-2.0	1.0-1.5	0.0-0.5	0.0-2.0	2.0-3.0
Approx. Increased Cost (%)	10%	10-20%	10%	25%	20%
ADVANTAGES					
Reduced Height	✓	✓		✓	✓
Reduced Windloads	✓	✓		✓	
Smaller Foundation Requirements	✓	✓		✓	
Aesthetic Appearance	✓		✓		
DISADVANTAGES					
Debris Accumulation	✓	✓			
Drainage Problems	✓	✓			
Increased Foundation Requirements			✓		
Questionable Durability of Material				✓	
Periodic Maintenance	✓	✓		✓	✓

Y-Top Barriers

Y-top barriers were initially studied to compare with T-top barriers. Although they have consistently performed slightly worse (about 1 dB) than an equivalent reflective T-top barrier, the Y-top is still superior in performance to conventional barriers of the same height.

The benefits of Y-top barriers are very similar to those of the absorptive T-top barrier. Lower wind loading and lesser foundation requirements due to the decreased height of the Y-top compared with a conventional barrier are benefits. The decreased height could also prove to be more aesthetically pleasing to the public.

On the negative side for Y-top barriers is the potential drainage problem produced by the trough created at the top of the barrier. Although installation of drains along the barrier top may alleviate this problem, it could also increase costs. Drains would also require periodic maintenance to ensure a debris-free path. The drainage question may render the Y-top less economically feasible than the absorptive T-top barrier.

Single-Wall Absorptive Barriers

The performance of thin perfectly reflective barriers may be improved with the use of absorptive material. Many studies have been performed to show improved effectiveness by the addition of absorptive materials to the surface of barriers.

The improvements in aesthetics from the use of absorptive materials consist of reducing the potential for vandalism by roughening the surface texture and reducing required height.

CONCLUSIONS

This research produced a design summary matrix (*25*) (Table 1) summarizing the qualities of the five special noise barrier applications. Each barrier possesses unique characteristics that may prove beneficial to the designer in certain scenarios. The Washington Department of Transportation plans continued research into these special applications and may implement them in pilot projects.

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Determination of Traffic Noise Barrier Effectiveness: An Evaluation of Noise Abatement Measures Used on I-440

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The noise abatement efforts used on I-440 were studied to evaluate their effectiveness. The results of tests confirmed that the FHWA abatement criterion for land use Category B receivers had not been exceeded at any of 40 representative sites. The Tennessee Department of Transportation criterion for substantial increase in levels at receivers due to new highway sources was exceeded at only 2 of 40 sites. Noise level reductions of as much as 9.5 dB at the receiver locations were attributed to depressing the roadway (cut) with the average being 2.8 dB. Of the sites tested, 75 percent realized at least a 5 dB reduction because of barriers alone (in addition to effect of cut, if any). The results of 24-hr measurement periods show the variation in traffic noise levels as well as background influences on levels and insertion loss determination. Comparison tests of absorptive and reflective barriers at two sites indicated that benefits were realized by the use of absorptive barriers on fill sections where barriers were installed close to shoulders. An evaluation of the FHWA STAMINA 2.0 model for highway traffic noise indicated that the model tended to predict levels higher than those measured. Insertion loss results were obtained using the ANSI S12.8 indirect predicted method of insertion loss determination. This method's dependence on the accuracy of the prediction model was seen as a limitation on its usefulness.

The highway traffic noise mitigation effort by the Tennessee Department of Transportation (TDOT) for I-440 has entailed one of the more ambitious abatement plans undertaken by a department of transportation. Large-scale excavation of limestone rock at considerable cost was required to depress most of the 7.2-mi roadway to provide the first step in noise reduction. This step was followed by the construction of a variety of noise barrier types [with a total length of 17.9 km (11.1 mi)] at an additional cost of $13.2 million. A total of 718 first-row residences along the 11.6-km (7.2-mi) project were protected at an average cost of $18,000 per residence for barriers alone.

The design of the noise barriers, which required modeling the entire length of I-440, was marked by both the complexity of the terrain and the multiplicity of abatement types. Furthermore, it included one of the largest analyses in this country of multiple reflections, both between noise barriers on opposite sides of the highway and between vertical rock faces in deep cut sections. The analysis resulted in the use of absorptive barriers for certain sections and modifications of barrier heights at other locations.

In the light of the extensive commitment that TDOT has made to noise mitigation for I-440, the decision was made to evaluate the effectiveness of the various abatement methods to determine the benefits realized. The evaluation was to be comprehensive in its treatment of all types of abatement used on I-440. The variety in types of terrain and the abatement methods used make the evaluation particularly useful for future projects in terms of the effectiveness of the various noise reduction measures and the accuracy of the design methods.

BACKGROUND

As early as 1957, the Tennessee Bureau of Highways held a public hearing on the location of the Interstate system in Nashville, which included the proposed I-440. This portion of the network was planned as an outer loop to improve crosstown transportation in the southern portion of Nashville. The proposed I-440 was planned to connect three legs of Nashville's urban Interstate system: I-40 West, I-65 South, and I-24 East. In 1964, FHWA approved a six-lane section of I-440 from I-40 West to I-65 South. Between 1968 and 1973 public hearings were held, and most of the right-of-way acquisition and relocation had taken place.

During this period the National Environmental Protection Act was enacted, but FHWA believed that because of the advanced stage of I-440, an environmental impact statement (EIS) was not required. However, as a result of a class action suit filed by the National Wildlife Federation against FHWA, the courts determined that an EIS was necessary for projects in which a substantial federal action remained. Further concerns from neighborhood groups were beginning to be expressed regarding the I-440 project. Many environmental concerns were expressed, especially about noise.

A protracted court battle over environmental issues was finally resolved in 1981 when the courts ruled that the project be built with a commitment from TDOT to minimize impacts. Two major revisions were (*a*) to reduce the number of lanes from six to four and (*b*) to change the basic profile from mostly at-grade or on-fill to mostly in-cut to reduce both noise levels and visual intrusion in neighboring communities. A major commitment was made to construct noise barriers wherever needed and feasible, and TDOT entered into an agreement with Vanderbilt University for analysis and design.

By early 1984, all of the I-440 project was under construction, with noise barriers included in the design along much of the project. The project opened to traffic in 1987.

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RESEARCH OBJECTIVES

The evaluation process for the project included investigation of four issues: noise barrier effectiveness, changes in community noise levels due to I-440, effectiveness of sound absorptive walls, and differences between predictions and measurements.

Noise Barrier Effectiveness

Noise barrier insertion loss is the reduction in noise levels achieved by the insertion of a noise barrier between the noise source and a receiver of the noise. The insertion loss of a barrier is best determined by a direct before/after study: an existing, constant noise source is measured at a receiver position; the noise barrier is then built, and the noise level is measured at the same receiver position. If all conditions remain constant, the insertion loss would be the difference between the before- and after-construction noise levels. However, in highway applications, both the noise source and the surrounding conditions are changing. In the case of I-440, the highway noise source did not exist before construction of the noise barriers. Therefore, other methods of insertion loss determination must be used, such as measuring at equivalent "before" sites or predicting the before levels.

Whereas barrier performance is typically described in terms of insertion loss, the insertion loss of a barrier is a varying value. The insertion loss of a barrier varies depending on the distance of the receiver from the barrier, the distance of the barrier from the source, the height of the source, traffic flow, weather conditions, and so forth. Unlike a physical characteristic of a noise barrier, such as the density of its material, the insertion loss is not an intrinsic property. Therefore, the objective was to determine insertion losses for the barriers under typical conditions for the 40 receivers studied, which represented a subset of all possible receivers.

Once the determination of noise barrier insertion loss was made, the results were to be considered from the four following viewpoints:

- Determine the range of effectiveness for each noise abatement type. A number of noise abatement methods were used on I-440, including reflective and absorptive noise walls, natural barriers, berms, and retaining walls. In addition, the various abatement types were constructed in varying terrain, involving cuts, fills, and at-grade conditions. Whereas these methods were not used in equal amounts, they were to be categorized for comparison to determine the relative effectiveness of each type. TDOT could then use this information on future projects. All noise abatement methods used on I-440 were placed in one of the following four categories: noise wall at grade, noise wall on fill, depressed section (cut) plus noise wall, and depressed section (cut) plus berm.
- Compare noise barrier performance with design goals (predicted performance). The comparison was designed to determine how closely the performance of the noise abatement method matched the predictions of the model in the original acoustical design of the barriers and the general TDOT goal of a 5- to 10-dB noise reduction.
- Determine the overall amount of noise reduction achieved for residences. Using the insertion loss information, the amount of noise reduction that was experienced at the residences distributed along I-440 was to be characterized.
- Compare the performance of FHWA STAMINA 2.0 (*1*,*2*), which was used in the barrier design, with field measurements. By measuring the actual barrier performance, the ability of STAMINA to accurately predict the results could be evaluated. The purpose of the evaluation was to provide input for future noise barrier performance predictions for TDOT.

Changes in Community Noise Levels due to I-440

Despite the various methods of noise abatement used to reduce the highway traffic noise, I-440 represents a new noise source to its neighbors. Thus, even though attenuated, the I-440 noise is heard and may be thought undesirable by some people. The changes in community noise levels due to the construction of I-440 were to be quantified using two methods:

1 Before construction of I-440, TDOT had made extensive measurements to determine the sound levels in the community around the proposed location. These levels, without the highway, were used in this study for comparison with the levels measured behind the barriers at the 40 sites being studied to determine the increase in community levels at the current time. As a further step, the measured existing noise levels were to be compared with established FHWA noise impact and abatement criteria to gain insight as to how the community is being affected.

2. A second concern relates to possible changes in barrier effectiveness or community noise levels over time with future growth of traffic on I-440. A site was to be selected for monitoring long-term effects. The measurements at this site would be made for 24-hr periods and would be repeated in the future, perhaps annually. The 24-hr measurement would provide information relating to both the actual levels and insertion loss changes occurring for day and night periods. In addition, the repeated annual measurements would provide insight into changes occurring in the long term. The objective for this study included both the site selection and the first in a series of 24-hr data collection periods.

Effectiveness of Sound Absorptive Walls

Sound absorptive walls were installed along certain sections of I-440 to overcome multiple sound reflection problems between parallel reflective walls. The materials used represented an innovative application for traffic noise control; however, no data are available on their actual performance. This objective included not only a study of the insertion loss at residential sites in the sections using absorptive barriers, but also a more detailed comparison of the change in insertion loss in each sound frequency band as a result of using absorptive materials and reflective materials.

Differences Between Predictions and Measurements

Differences between the predicted barrier performance and the measured results were anticipated. To provide insight for future designs, an analysis of these differences was to be undertaken. An investigation of each site where a discrepancy might occur was to be made. The reasons for the discrepancy were to be categorized under three major areas: acoustical analysis concerns, physical design issues, and construction problems. The reasons for the differences between the predicted and measured barrier performance were to be studied and a series of recommendations developed to improve the noise barrier analysis design and construction process for future TDOT projects.

RESEARCH AND RESULTS

To accomplish the preceding objectives, 40 representative sites were selected for noise measurements. Before noise measurements were made, an emissions testing program was undertaken for the traffic and roadway conditions specific to I-440. The amount of noise emitted by a particular class of vehicle for the road surface on which it is operating was described statistically. The results of this testing shown in Figure 1 indicated that two of three vehicle classes, automobiles and heavy trucks, were different from those previously determined by FHWA on a national basis (automobiles about 4 dB higher than national average and heavy trucks 1 dB lower). These new values were used in the noise model predictions that were principal elements in the evaluation of the noise abatement methods. The information taken at each study site included the sound levels typically experienced by a given residence as well as the traffic conditions occurring at the time of the measurements. The combined data from site testing, vehicle noise emissions testing, and computer prediction modeling were analyzed to produce the following results.

The effect of depressing the roadways (cut sections) was to reduce the 1-hr average sound levels L_{eq} for residences by as much as 9.5 dB with an average of 2.8 dB. The amount experienced at a given site was generally proportional to the amount that the roadway was depressed. In addition to the depressed roadway section method of noise abatement, noise walls or berms were also effective in further reducing the sound levels. The results are shown in Figure 2. The determination of the insertion loss for the walls or berms alone was based on the difference between the measured after levels with the barriers in place and the predicted before levels. The predicted before levels included the effect of any natural barriers such as the side slopes of depressed sections. As shown in Figure 3, at least a 5-dB reduction (L_{eq}) due to the noise barriers alone was realized by 75 percent of all the sites tested, including those not depressed. The overall noise reduction achieved by the combination of depressing the roadways and constructing barriers reduced the levels by an average of 11.5 dB (see Figure 2).

Whereas the preceding results are indicative of the performance of the noise abatement measures tested, the overall results of these measures were judged by two other methods. The first method of determining the impact of a new noise source was to quantify the change in sound levels experienced at a given residence (i.e., from before construction to after construction with the new source) and compare the changes with established criteria. The TDOT criteria for impact are as follows: 0 to 5 dB, no impact; 6 to 15 dB, moderate impact; and greater than 15 dB, substantial impact. A design goal for all residences on I-440 was to limit impact to the moderate category. As shown in Figure 4, only two sites increased in levels enough to be considered substantially affected. These

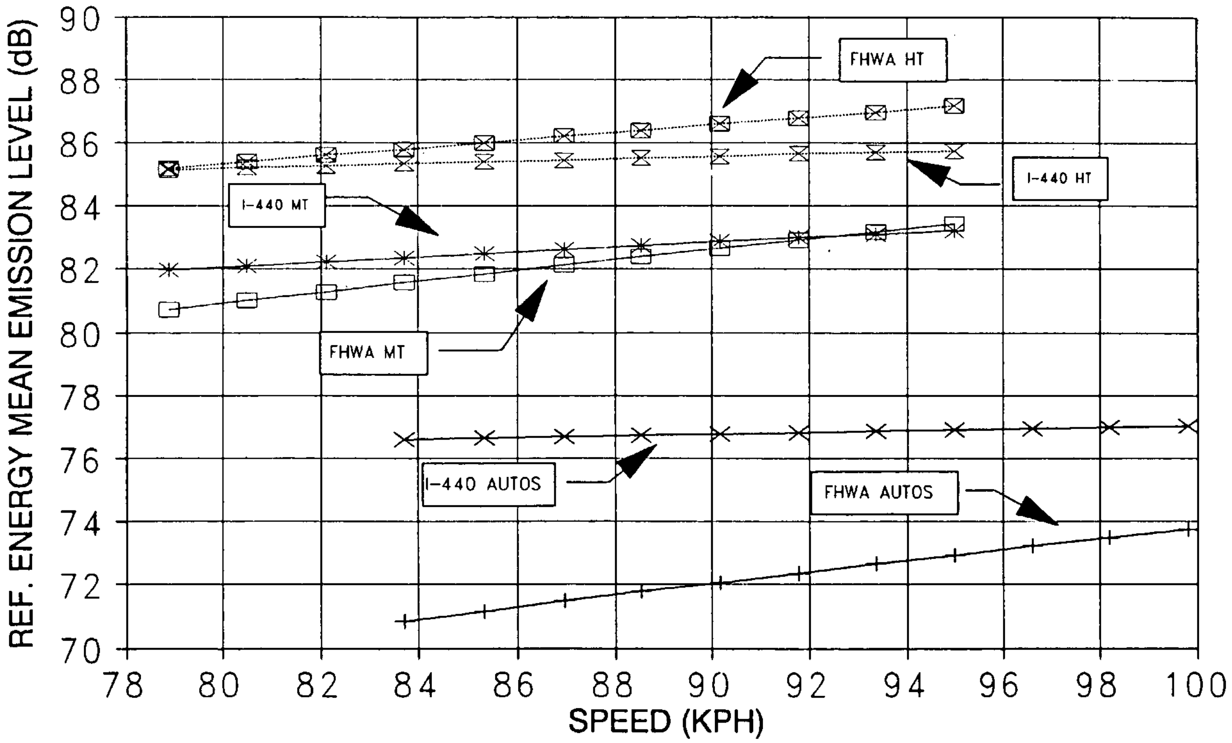

FIGURE 1 Comparison of I-440 and FHWA reference energy mean emission levels.

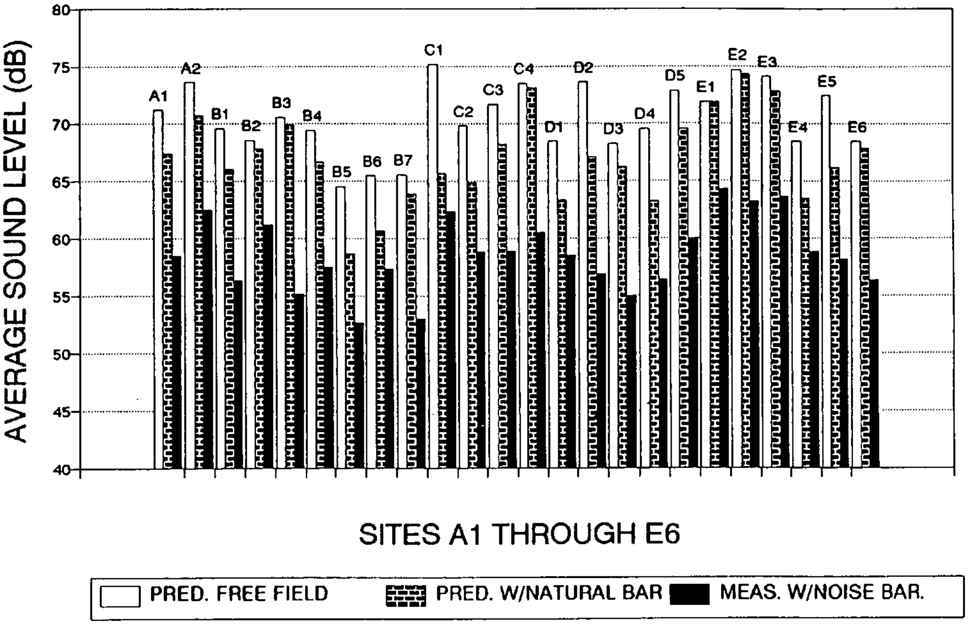

FIGURE 2 Overall insertion loss (depressed roadway and barriers), Sites A1 through E6.

two sites, however, began with the some of the lowest preproject levels recorded (see levels shown in Figure 5). These levels were so low that the addition of the new highway noise source had a greater effect than at other sites with higher preproject levels. Furthermore, site E1, which experienced a level of 64 dB, was located on a knoll, thus reducing the effectiveness of the barrier compared with adjacent residences. This comparison was based on the L_{10} descriptor (the level exceeded for 10 percent of the measurement period, which was used by TDOT in its preproject measurements).

The second method used to judge the overall effectiveness of the noise abatement measures was to compare the noise levels at the measurement sites with a benchmark or reference level. The benchmark chosen for this project was the FHWA abatement criteria. These criteria are not design goals. However, if predicted project levels without abatement had been below the criteria, the impact of the project would not have been judged serious enough (by these criteria alone) to warrant consideration of abatement. The FHWA criterion for Activity Category B receivers, the relevant category for the sites studied, is an L_{10} of 70 dB (or an L_{eq} of 67 dB). The FHWA noise standards state that abatement must be considered for those receivers in Category B in which levels "approach or exceed" an L_{10} of 70 dB or an L_{eq} of 67 dB.

The comparison of the levels at the individual sites with the FHWA criterion shown in Figure 5 supports the success of the abatement efforts. Regardless of the specific abatement measure or combination of measures used for a particular

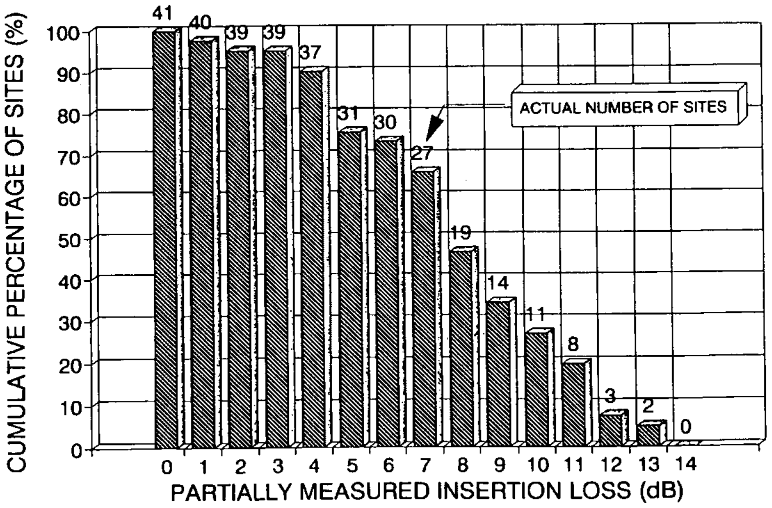

FIGURE 3 Percentage of sites equaling or exceeding a given partially measured insertion loss.

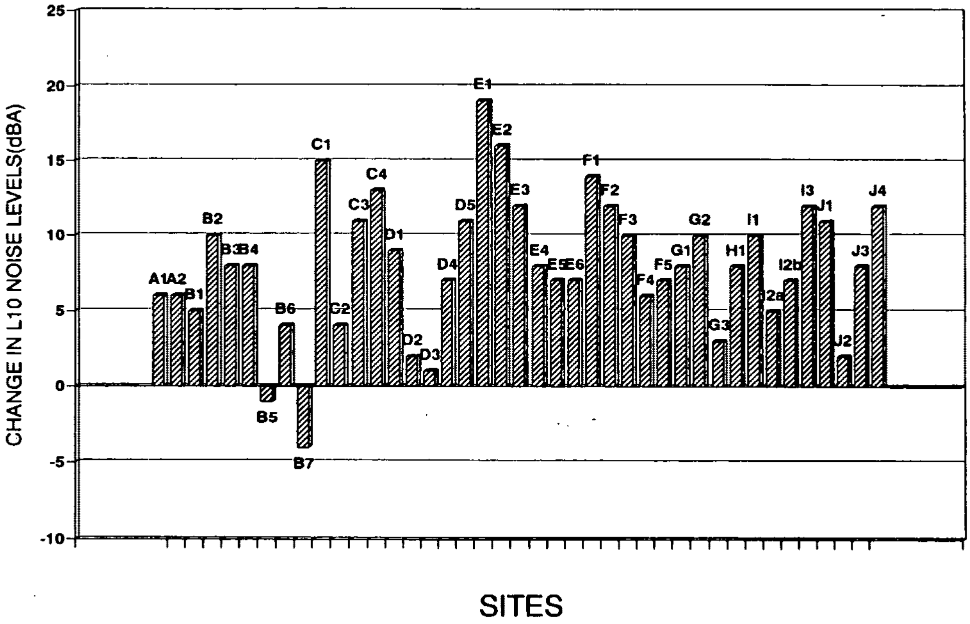

FIGURE 4 **Change in community noise levels due to I-440 construction.**

site, the net result is that not one of the sites measured "approached or exceeded" the FHWA criterion (all were 4 dB or more below the L_{10} of 70 dBA and 2 dB or more below the L_{eq} of 67 dBA). In other words, the levels for every site tested were below this reference level.

Noise barriers that reduce reflected noise through the use of sound-absorbing materials had been constructed on certain fill sections of I-440. A detailed investigation of the effectiveness of these barriers was accomplished by comparing the levels behind the absorptive barriers with those at the adjacent reflective barriers used on bridge overpasses. Because of the number of interrelated factors affecting the measured levels, however, the effect of the absorptive barriers could not be completely isolated. The measured levels at the absorptive barrier sections were lower than the levels at the adjacent reflective metal walls. Whereas several other influences were present in these levels, as detailed in the project report, the absorptive barriers were found to be effective in reducing wall

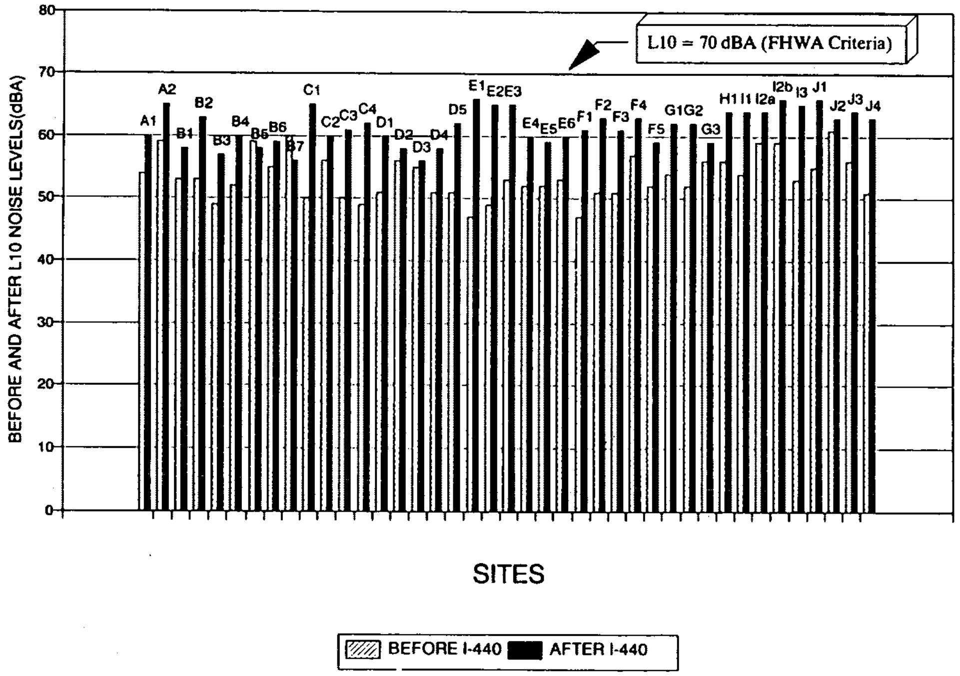

FIGURE 5 **Change in community noise levels and comparison with FHWA criteria.**

heights for situations where the barriers are located close to roadway shoulders and sound reflections are likely to occur.

Measurement periods of 24 hr were conducted at one site to determine the changes in levels and insertion loss experienced throughout the day. The change in levels for the four microphones (two reference, two study) is shown in Figure 6. The two sites included in this comparison involved a section with a noise barrier and a section without a noise barrier. The sites were adjacent at a depressed section of the roadway. They were judged to be very close in terms of terrain equivalence. Whereas only the second 24-hr period is shown in Figure 6, the hour-by-hour levels for the first 24-hr period were remarkably close to the second period, indicating consistent day-to-day traffic patterns on I-440. The insertion loss produced by the barrier is represented by the difference in levels between the study microphones (adjusted for differences in the levels at the reference microphones). The measurements were made simultaneously; therefore, the reference microphone levels essentially canceled for the standard insertion loss calculation.

The large variation in "with barrier" and "no barrier" levels, centered on 3:00 a.m. in Figure 6, was studied subsequent to the initial measurements and data reduction. The tape-recorded samples indicated that the levels at the "no barrier" study microphone site were elevated by insect noise. In effect, the insertion loss computed from these data is a lower bound, since the traffic noise level at the "no barrier" study microphone is masked. This observation emphasizes the importance of background considerations for true insertion loss determination.

A detailed investigation of the FHWA STAMINA 2.0 prediction model was undertaken. It was concluded that the model tends to predict sound levels somewhat higher than those actually measured, as shown in Figure 7.

In addition to the inaccuracies introduced by the prediction model, construction differences were considered. Barrier heights that were measured at every site tested proved to be consistent with design specifications. The results of these measurements indicate that the wall heights were indeed as planned. However, a median berm was added to the project after the acoustical planning stage. The median berm was calculated to have reduced sound levels by approximately 0.5 dB for the unshielded reference microphone location at the barrier, depending on the overall cross-sectional configuration. An even greater reduction would be projected for residential receivers.

CONCLUSIONS

Among the conclusions of the study of the I-440 noise abatement methods were the following:

- The noise abatement efforts used on I-440 were successful considered in light of both the FHWA criteria for noise abatement and the TDOT criteria for substantial increases in noise levels over levels before highway construction.
- The FHWA STAMINA 2.0 model could benefit by enhancements to more accurately predict noise levels. It is recommended that the research be supported and actively followed for an upcoming FHWA project that will develop a STAMINA 3.0 model. A statewide survey of the reference energy mean emission levels of its vehicles with attention to the full range of travel speeds and pavement types should be performed.
- To monitor long-term changes in sound levels due to traffic noise as well as the corresponding performance of noise abatement methods, the 24-hr measurements should be continued with annual measurements at the same site.
- When noise is anticipated to be a problem, depressing future highways and using median berms should be considered where possible. Whereas the single or combined effects of

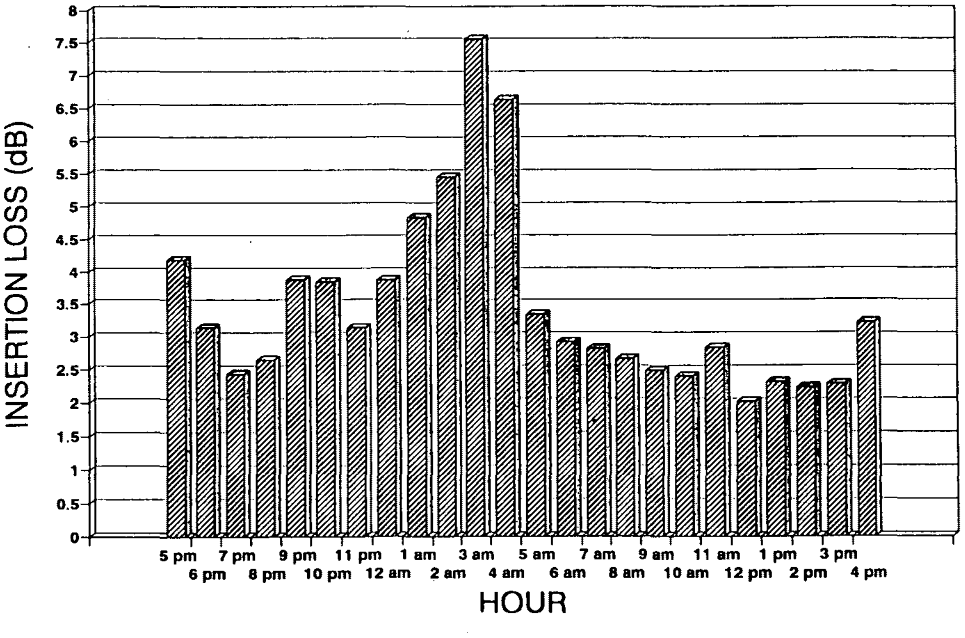

FIGURE 6 Hourly average insertion loss, 24-hr site, second 24-hr period, August 14–15, 1991.

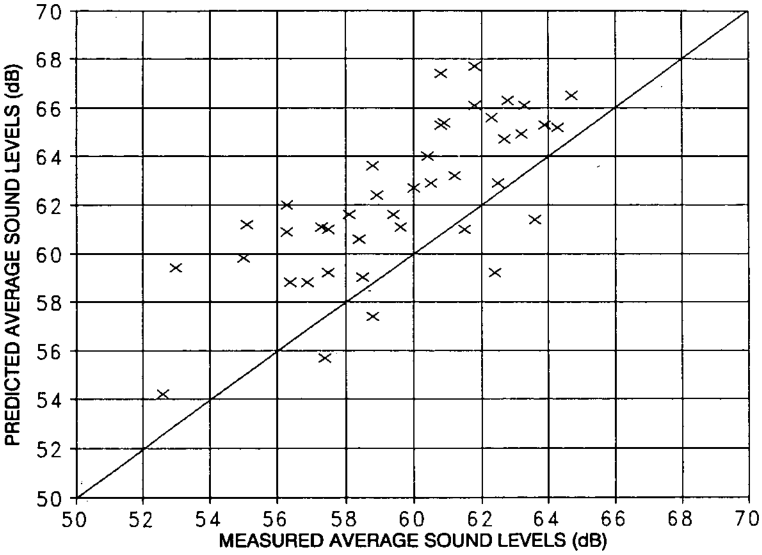

FIGURE 7 Comparison of measured and predicted levels: study microphone.

either of these methods alone will generally not be adequate, they contribute to the overall noise reduction when coupled with the construction of noise walls or berms.

- Noise abatement committees should be established for each abatement project. The committees should include representatives from planning, design, structures, construction, maintenance, and landscape architecture. This team concept, which is used effectively in other states, helps to ensure continuity in the abatement project development process and to identify and resolve concerns or problems early in the process.

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Development of Reference Energy Mean Emission Levels for Highway Traffic Noise in Florida

ROGER L. WAYSON, TIMOTHY W. A. OGLE, AND WIN LINDEMAN

Reference energy mean emission levels (REMELs) specific to Florida were developed. This became necessary because of an increase in the national speed limit from 55 to 65 mph on Interstate highways, changes in vehicle technology, and differences between emission levels measured in Florida and national averages. Past data bases specific to Florida were reviewed, data were collected and analyzed in the higher speed range of 55 to 70 mph (88 to 113 kph), and the final combined results of two Florida data bases were included in the computer program STAMINA 2.0. The work effort and results of developing and implementing the Florida-specific REMELs into the STAMINA 2.0 model are documented.

Noise prediction models help determine whether existing or planned roadways meet or will meet applicable noise criteria. The models are also used to design abatement measures. At the heart of these models, such as STAMINA 2.0 (*1*), are the reference energy mean emission levels (REMELs) for various vehicle types. These emission levels function as the basic building block of the model, representing the maximum, energy-averaged, A-weighted sound level of a specific vehicle type passing a location. Adjustments to this level can be made for other than reference conditions (e.g., at varying distances) and for multiple vehicle pass-bys (*2*). Accordingly, the accuracy of the reference level determines the accuracy of the model and the entire analysis. REMELs represent the maximum vehicle pass-by level, are a function of vehicle type and speed, and are fixed in space by defined distances and height during measurement. Updates are necessary to maintain or improve the accuracy of the mathematical model.

Two previously gathered data bases were determined to be directly relevant to Florida: a 1978 DOT report by Rickley et al. (*3*), which included four states, one being Florida, and a 1986 report by Dunn and Smart (*4*). The report by Rickley et al. was prepared under the authority of FHWA and will be referred as the FHWA report. The report by Dunn and Smart was similar to the FHWA report, and both determined speed-dependent equations using linear regression techniques to predict the REMELs. The equations as implemented from the FHWA report are as follows for automobiles, medium trucks, and heavy trucks, respectively (*2*), where S_{mph} is speed (mph):

$$(L_o)_{EA} = 38.1\log S_{\text{mph}} + 5.47 \quad (1)$$

$$(L_o)_{EMT} = 33.9\log S_{\text{mph}} + 24.40 \quad (2)$$

$$(L_o)_{EHT} = 24.6\log S_{\text{mph}} + 46.58 \quad (3)$$

L_o represents vehicle-specific REMELs (dB). Subscripts A, MT, and HT refer to automobiles, medium trucks, and heavy trucks, respectively.

The data base collected by Dunn and Smart (*4*) is more recent, and REMEL values are specific to Florida roadways. The equations derived and reported from this later study for speeds (kph) are as follows for automobiles, medium trucks, and heavy trucks, respectively:

$$(L_o)_{EA} = 32.283\log S + 10.803 \quad (4)$$

$$(L_o)_{EMT} = 23.221\log S + 36.129 \quad (5)$$

$$(L_o)_{EHT} = 14.058\log S + 56.234 \quad (6)$$

where S is speed in kph.

A comparison of the FHWA and Dunn and Smart prediction equations is shown in Figure 1. As can be seen in the figure, automobiles tend to follow the same slope but are offset by roughly 2 to 3 dB (A-weighted). A review of medium truck data shows a fair agreement between the two linear regressions (see Figure 1). However, the two regression lines tend to diverge at the low and high speed ranges with the Dunn and Smart curve predicting lower sound levels at the higher speeds. Heavy trucks again show pronounced differences with somewhat good agreement at low speeds, but a strong divergence in the higher speed range is indicated.

These comparisons indicate either that changes in vehicle technology have occurred since the FHWA study or that regional trends make the Florida REMELs somewhat different. Accordingly, whereas the three vehicle types may be approximately characterized by the national reference levels, errors in prediction appear to occur.

Because the data base by Dunn and Smart lacked measurements in the higher speed ranges (greater than 55 mph), measurements of highway noise were taken at sites along the four Interstate highways in Florida to validate and extend the Florida data base. The actual data collection and subsequent data reduction were performed by the University of Central Florida (UCF) Civil and Environmental Engineering Department using the FHWA mobile noise laboratory. The measurements included individual pass-bys of highway vehicles divided into

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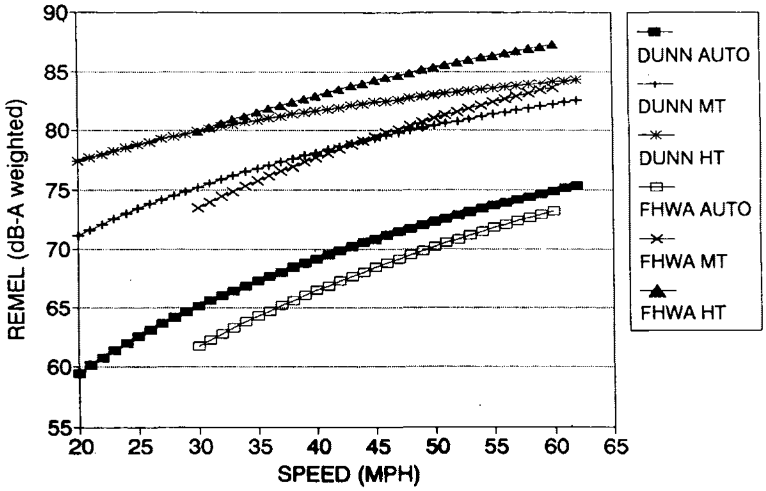


FIGURE 1 Comparison of REMELs by vehicle type.

the three standard categories depending on size, number of tires, and number of axles: automobiles, medium trucks, and heavy trucks. Concurrent measurements of vehicle speed and weather parameters were also performed.

METHODOLOGY AND RESULTS

Prescribed methodologies regarding equipment, site selection, measurement procedures, and analysis were carefully followed. The methodology used is described in this section.

Test Sites

To decrease the chance of site bias, one site along each Interstate highway within the state was selected for evaluation. Since 65 mph is only permitted outside urban areas, each site was away from many urban influences. Measurements were made between November 3, 1990, and April 2, 1991, and for safety considerations all measurements were made during daylight hours. Test site requirements were as follows:

- Only asphalt surfaces were used because of Florida's trend of using overlay asphalt exclusively on the Interstate highways, where the higher speed will occur.
- Only level, open sites were selected, free of large reflecting surfaces located near either the vehicle path or the microphones.
- Ground covering at all sites included a paved shoulder with predominantly low grass away from the highway.
- Only smooth, dry, level highway surfaces free of extraneous material such as gravel were selected.
- Ambient sound levels at least 10 dB (A-wt) lower than the level of the vehicle being measured were required.
- Freely flowing traffic was measured, operating under typical Interstate cruise conditions.
- A clear line of sight in either direction with an arc of 170 degrees was required to avoid possible errors.
- Microphones were located 50 ft from the centerline of the near lane of traffic, 5 ft above the pavement surface, and at multiple locations along the roadway to evaluate existing sound levels.

Three of the sites were weigh-in-motion stations, and the other was an unused weigh station. Each site had two lanes of traffic in each direction, separated by a median. At two sites no line power was available, so two portable power generators were required to provide electricity. Care was taken to shield the noise of the generators from the measurement area.

Instrumentation

Working closely with the Florida Department of Transportation (FDOT), UCF was able to obtain the FHWA mobile noise laboratory. The mobile laboratory included eight systems with ½-in. microphones and analyzers that permitted measurement of octave band data. Microphone cables (from 150 to 500 ft each) provided the capability to support microphone arrays. The output of the analyzers was fed through a specially designed interface to an IBM PC for data collection.

A portable meteorological station was also supplied by FDOT, and a system was available with the mobile laboratory. These systems provided a strip chart readout of ambient temperature, wind speed, and wind direction. FDOT also supplied a radar unit so that vehicle speeds could be determined. The vehicle speeds were measured just after the vehicle passed the microphone array to avoid influencing the speed of drivers who were using radar detectors. In addition, since only a single vehicle was passing, the research team was sure that the speed measurements were unbiased.

All measurement system specifications met or exceeded the recommendations outlined in the FHWA document *Sound Procedures for Measuring Highway Noise* (*5*).

Although only maximum sound levels were needed to develop REMELs, the equipment provided the capability to record the frequency spectra of each pass-by event in real time. These data provided a means to establish a very strict quality control methodology.

Operational Procedure

Instrumentation was deployed at each site according to methods outlined elsewhere (*5,6*). In addition to multiple microphones being used at the reference distance and height, other microphones were used at various locations along the roadway to permit further evaluation of the site characteristics and background sound levels. During data collection, the following criteria were strictly adhered to:

- Only individual vehicle pass-bys with sufficient separation between vehicles were measured to avoid unwanted vehicle noise.
- Test events included only vehicles traveling in the near lane, 50 ft from the reference microphones.
- No events were measured if the far lanes had truck traffic or perceptible automobile noise at the time of measurement.

The result of each sample was a histogram of the sound levels of individual vehicle pass-bys per time and frequency. The plots allowed determination of the maximum A-weighted sound level during any ⅛ sec as well as the change in frequency and amplitude for further considerations.

To ensure accurate data, calibrations (upscale and downscale) were performed at the beginning and end of each sample day.

Data Analysis

Data reduction was performed at the UCF campus using software developed by the Transportation System Center (TSC) especially for use with the mobile laboratory (*7*) and standard statistical software packages.

Before analysis, the data were carefully reviewed. The weather station's strip chart data were tabulated and searched for conditions that violated the defined meteorological criteria of excessive wind turbulence or wind gusts greater than 12 mph (*8*). Only one site was influenced in this way, and all suspect data were deleted from the data base. Any vehicles with greatly defective exhaust controls were noted during data collection, and data from these events (there were three) were discarded during data formatting. The data included loud or somewhat defective exhausts systems; data discarded were from vehicles that apparently had no exhaust controls and would be ticketed and removed from the fleet.

A "clean" vehicle pass-by was defined as a measured rise and fall of the sound level by 7 dB (A-wt) during passage of the vehicle in front of the microphones without being influenced by other noises. Several parameters could be identified and checked by plotting each pass-by using the TSC software.

As each pass-by was plotted, background levels were compared with the maximum pass-by sound level. Background levels were required to be at a minimum 10 dB down (A-weighted) from measured vehicle pass-by levels. This ensured that the maximum sound level was not biased by ambient events because of the logarithmic nature of decibels. This helped to ensure that the maximum level recorded was uninfluenced by other area sources as reported by the octave band analyzer.

To check that the upper limit of the octave band analyzers was not exceeded, any event that recorded an overload of any frequency (output parameter of analyzer) was further reviewed. If the event did indeed equal or surpass the upper limit of the equipment, the event was deleted.

To ensure that no data were included that may have been influenced by other vehicles, individual pass-by data plots were examined to ensure that no overlapping of peaks (in time) occurred.

After all criteria had been examined, each data point that passed all screening criteria was included in the final data base.

Calculation of REMELs

After quality control, the maximum pass-by sound levels per vehicle type (L_{oi}) were tabulated, and average pass-by levels for the multiple microphone array were calculated. The standard deviation (σ_o) of the sample distribution was also calculated.

As outlined elsewhere (*3*), $(L_o)_{Ei}$, or REMELs for prediction of L_{eq} values, are calculated from the relationship of the Gaussian probability density function and the acoustic pressure ratio. Mathematically this relationship may be reduced to

$$(L_o)_{Ei} = L_{oi} + 0.115\sigma_o^2 \tag{7}$$

Terms are as previously defined.

Use of linear regression techniques for speed band data lead to

$$(L_o)_i = A_i + B_i \log_{10} S \tag{8}$$

(S_{mph} may be used in Equation 8.) And for the overall distribution (aggregate data over all speeds of consideration),

$$(L_o)_{Ei} = A_i + B_i \log_{10} S + 0.115\sigma_o^2 \tag{9}$$

Here, $(L_o)_{Ei}$ is the developed REMEL over the entire applicable speed range used to predict L_{eq} values.

For this project, REMELs were computed in various ways to allow multiple reviews of the data.

Individual Site Analysis

During any in situ research, site bias must be considered. In an effort to avoid such bias, each of the four measurement sites was evaluated. First, average values and standard deviations were computed, and then linear regression analysis was used to determine predictive equations for maximum pass-by levels and REMELs for each site. By comparing the mean and variance for each site, it was determined that no site was significantly biased, although some differences occurred.

Speed Band Analysis

One way to approach building an equation for REMELs is to analyze the data by speed bands as previously stated. In other words, the data are grouped according to a user-defined speed range, an average value is calculated from all data in that speed range, and then linear regression techniques are applied. This analysis separates the data into smaller groups and provides another review of the data for uncharacteristic values. For this project, data were grouped in 2-mph ranges or speed bands for analysis. Average values for each speed band were then used to develop REMELs as previously described.

The speed band analysis showed good results with the exception of medium trucks. The large variation in this vehicle type's noise emission characteristics appear to be the cause of this scatter.

Aggregate Analysis

Data may also be analyzed using linear regression techniques for the data as a whole. This approach represents all measurements over the speed range of concern and was also used for this project. The advantage of this approach is that the linear regression analysis results more accurately reflect measurements at all speeds. Of course, average values of all reference microphones were still used to compute REMELs to avoid any bias that may have occurred from various analyzers.

A review of the automobile data indicated substantial scatter as expected, but a definite trend was apparent. This scatter is common for this type of data base. Some outliers exist [such as a measured level of greater than 84 dB (A-weighted)], but these values passed all quality control criteria and could not simply be discarded. Accordingly, some pass-by events may not be typical, but the overall averages are considered appropriate.

The overall measurements for medium trucks show much more scatter than do those for automobiles. The large degree of scatter for motor homes (considered medium trucks) is shown in Figure 2 and compared with the FHWA REMEL curve. Note that motor homes do not seem to fit in the medium truck or automobile classification. This scatter is as expected from a review of past research and the broad definition of medium trucks.

The heavy truck data analysis results showed that outliers still existed, but the trend was again quite obvious. Accordingly, the data collection effort was successful.

COMPARISON OF THE ANALYSIS RESULTS AND PAST DATA BASES

After all data were evaluated for sites, speed bands, and in the aggregate, a comparison of the data was necessary for validation and extension of the defined REMELs to be used in Florida. Comparisons were begun by plotting the derived REMEL data from the previous reports (FHWA and Dunn and Smart) and this project (Wayson et al.) for each vehicle type versus speed and reviewing the differences of the data.

The comparison for automobiles is shown in Figure 3. Medium and heavy trucks are shown in Figures 4 and 5, respectively. For this comparison, as well as for trucks, the lower speed ranges have been omitted in the graphs for clarity. The reason is that the project data were primarily to supplement Dunn and Smart's data for the higher speed ranges, and measurements during this project were made on Interstate highways where speeds seldom dropped below 55 mph. The Dunn and Smart and FHWA REMELs extend to the lower speed ranges and so are shown down to 45 mph for comparative purposes. The project data are listed as WAYSON1 for the aggregate analysis and WAYSON2 for the speed band analysis. The plot for WAYSON2 was derived for 2-mph bands but is plotted in 1-mph increments to allow a smooth curve in the figure.

The data were statistically tested, using a 95 per cent confidence limit, to determine whether they could be considered to belong to the same distribution as the Dunn and Smart or FHWA data. It would have been desirable to include the FHWA and Dunn and Smart data error bands, but this was not practical due to the specific data requirements of these past data bases. Figure 3 shows the automobile data with error bands included, whereas Figures 4 and 5 show the same analysis for medium and heavy trucks. The statistical testing veri-

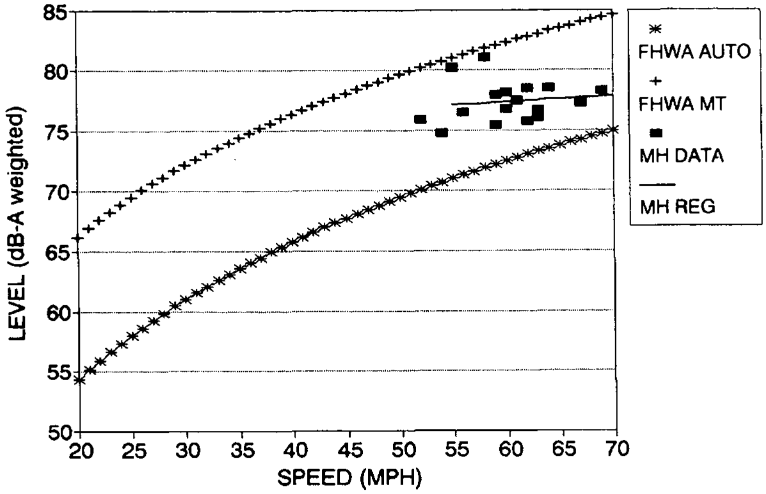


FIGURE 2 L_{max} **comparison, FHWA automobile and medium trucks with measured levels for motor homes.**

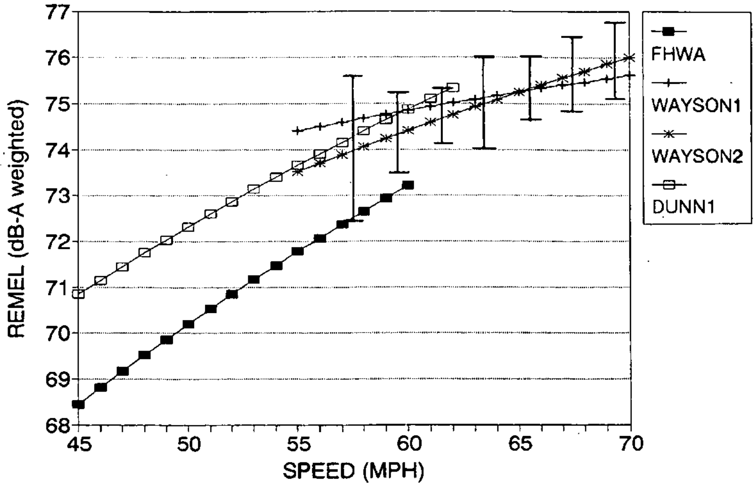


FIGURE 3 Comparison of REMEL models—automobiles.

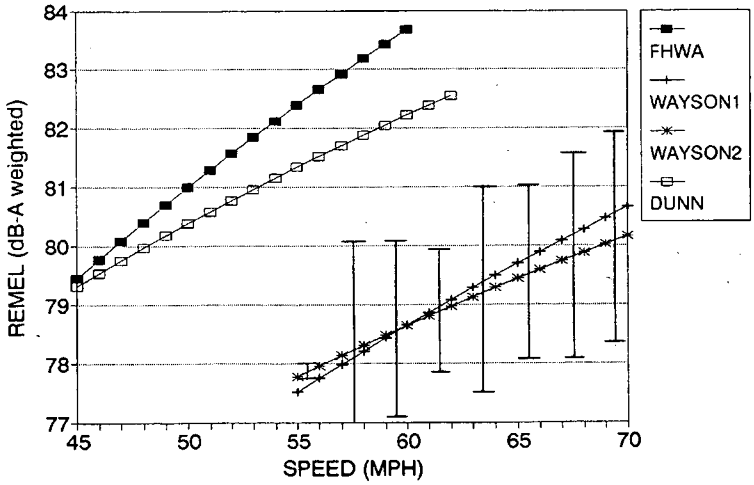


FIGURE 4 Comparison of REMEL models—medium trucks.

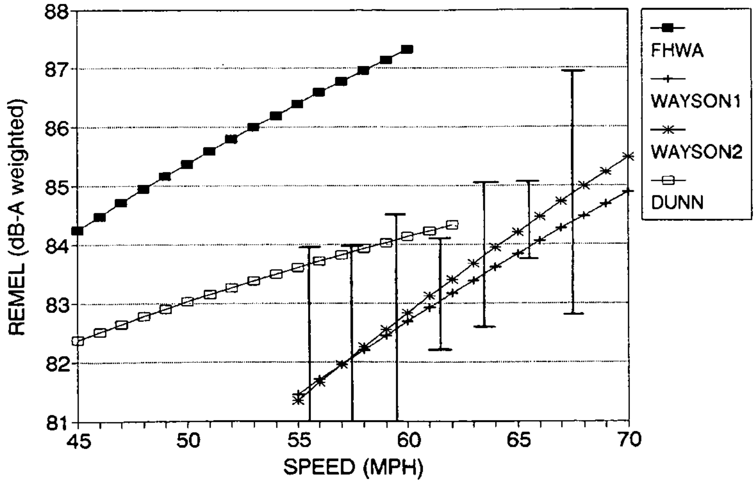


FIGURE 5 Comparison of REMEL models—heavy trucks.

fies that the Dunn and Smart and the measured data are compatible for cars and heavy trucks, as shown by the error limit bars in Figures 3 and 5. The very good agreement for automobiles is notable. For these two vehicle types, extension of the Dunn and Smart data base to 70 mph is considered statistically valid.

Figures 3 and 5 also show that the FHWA REMELs may be statistically different, and the previous opinion that the REMELs should be updated for Florida appears to be justified.

A review of the comparison for medium trucks does not show such close agreement (see Figure 4). Whereas the slopes are similar, the linear regression lines are offset by approximately 3 dB from Dunn and Smart. A difference of approximately 4 dB occurs between the project data and FHWA. When the 95 percent confidence limit was evaluated, statistical differences between the measured data, Dunn and Smart, and FHWA are apparent, as shown in Figure 4. Many hours were spent searching for errors in the project data base because of this comparison. After considerable effort, one reason is apparent. For the medium truck category, considerable leeway in the interpretation of the vehicle type occurs, as previously discussed. A review of the FHWA data shows that medium trucks are only specified as two-axle vehicles with six tires. Motor homes were not as prevalent in the early 1970s as they are today, and they most likely were included in very small numbers, if at all, in the FHWA data base. Dunn and Smart specifically point out that such vehicles were not included. Accordingly, since a significant portion of the project data base included such vehicles as motor homes, the sound levels tend to be lower.

As a check of this hypothesis, the project data base was searched and motor homes were deleted, which reduced the data base for medium trucks from 67 to 42 events. Figure 6 shows the relationship determined from this analysis. Figure 6 shows that the slope remains relatively unchanged, but the offset from the Dunn and Smart and FHWA curves is decreased by about 1 dB, resulting in a closer agreement of the data bases. With this change, Dunn and Smart's data base could be considered statistically the same as shown by the 95 percent confidence limits. Again, the FHWA data base does not appear to be statistically the same.

However, there is still roughly a 2-dB difference that cannot be explained unless other considerations such as pavement type are included. The lower speed data presented by Dunn and Smart included concrete pavements. Measurements for this project were done for the higher speed ranges on Interstate highways (>55 mph), which are all going to asphalt overlay in Florida, and concrete was not considered.

This analysis led to two possible conclusions: (*a*) medium trucks should be separated into at least two vehicle classes as discussed before or (*b*) pavement types influenced the data collection effort. The difference is not quantifiable without further extensive research. It is debatable which is the proper approach. One thought is to include mobile homes, since they are such a large percentage of the medium truck fleet in Florida (more than 37 percent of the random sample base). Another is to take the conservative approach and use the higher medium truck REMELs that do not include motor homes. For this project it was decided motor homes would be eliminated from the medium truck category. In this way, abatement may be slightly overdesigned, but not inadequate. Also, medium trucks represent the smallest category in terms of vehicle counts, which tends to lessen any expected error in predictions. This permitted the extension of Dunn and Smart's REMEL curve (it was realized that there might be a slight overprediction.

The comparison for heavy trucks is presented in Figure 5. As pointed out before, the data from Dunn and Smart show a much flatter curve than the FHWA REMEL linear regression curve. Whereas the project data have a much steeper slope, due to the small speed range used during data collection, the levels validate the Dunn and Smart study when the error limits are evaluated. It appears that a citation in the FHWA four-state study suggesting that overprediction may occur using the DOT four-state data in Florida may be correct. The FHWA text indicates that the prediction model (*2*) performed better for Florida when Florida-specific REMELs were used.

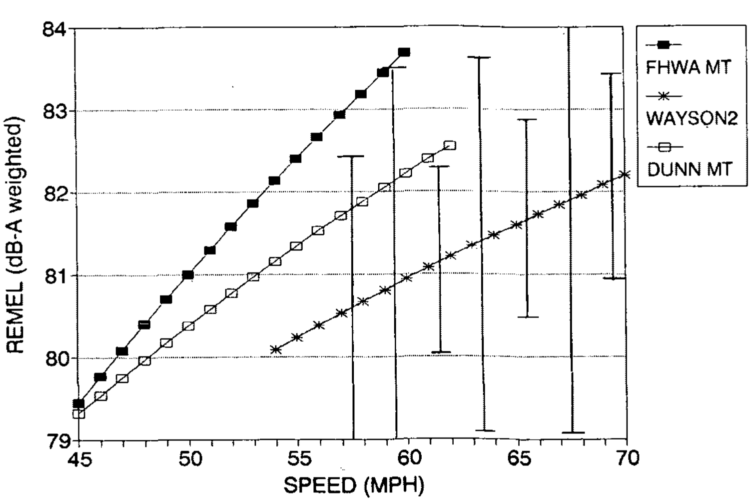


FIGURE 6 Comparison of REMEL models—medium trucks excluding motor homes.

IMPLEMENTATION

To derive the appropriate REMEL regression parameters, slope and y-intercept, linear regression analysis using the mean values of both data bases (Dunn and Smart and WAYSON2) was used. The solid lines in Figure 7 show the results of the best fit curve for automobiles, medium trucks, and heavy trucks, respectively. Figure 7b is shown with all medium truck data included.

Figure 7a (the results for automobiles) shows a good relationship for the final REMEL curve when the Dunn and Smart data base and the project speed band data (WAYSON2) are combined. The speed band data (WAYSON2) were used because it is the first method presented in *Determination of Reference Energy Mean Emission Levels* (*6*) and as such was considered to be the preferred method. Use of either the aggregate or speed band measured project data would have provided very similar results, so either could have been selected. The developed linear regression line shown for automobiles is

$$(L_o)_{EA} = 31.130\log(S) + 12.777 \qquad (10)$$

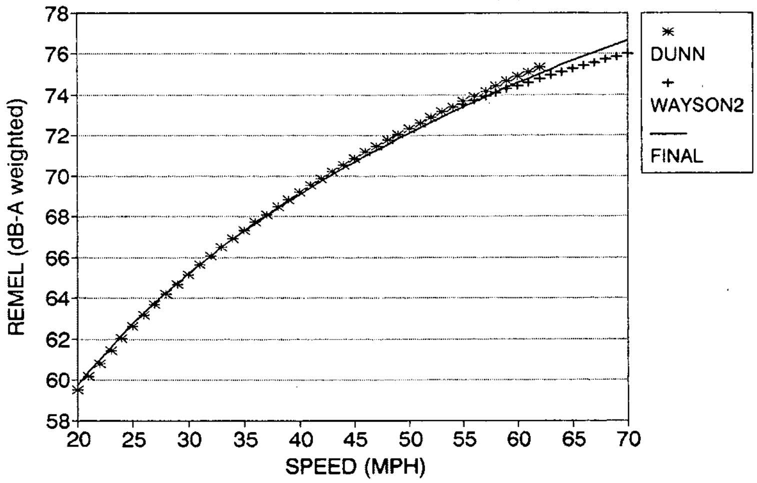
The best fit for medium trucks, using the same method as for automobiles and all medium truck data, is shown in Figure 7b. This fit corresponds to

$$(L_o)_{EMT} = 16.951\log(S) + 46.775 \qquad (11)$$

The same problem exists as described previously: noncompatibility of the two data bases leading to a large error at the higher speed. On the basis of the conservative approach previously discussed (elimination of motor homes), the following linear regression equation was derived and is plotted in Figure 7c:

$$(L_o)_{EMT} = 18.765\log(S) + 43.697 \qquad (12)$$

(a)



(b)

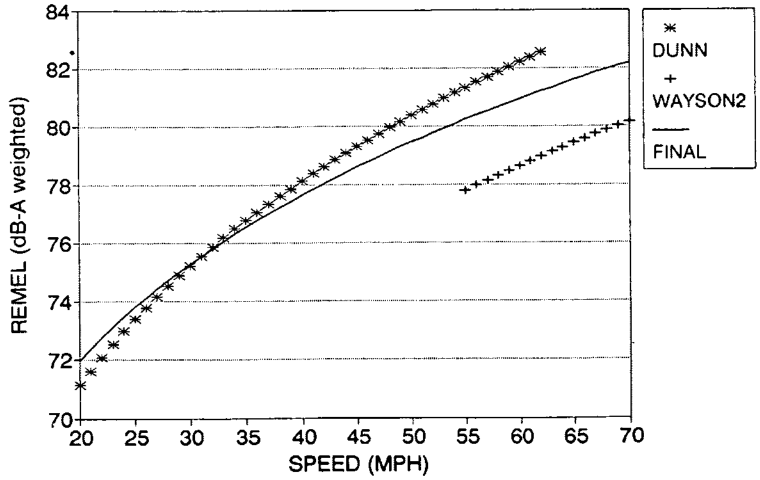


FIGURE 7 Derived REMELs: (*a*) automobiles, (*b*) medium trucks, (*c*) medium trucks excluding motor homes, and (*d*) heavy trucks. (*Continued on next page*)

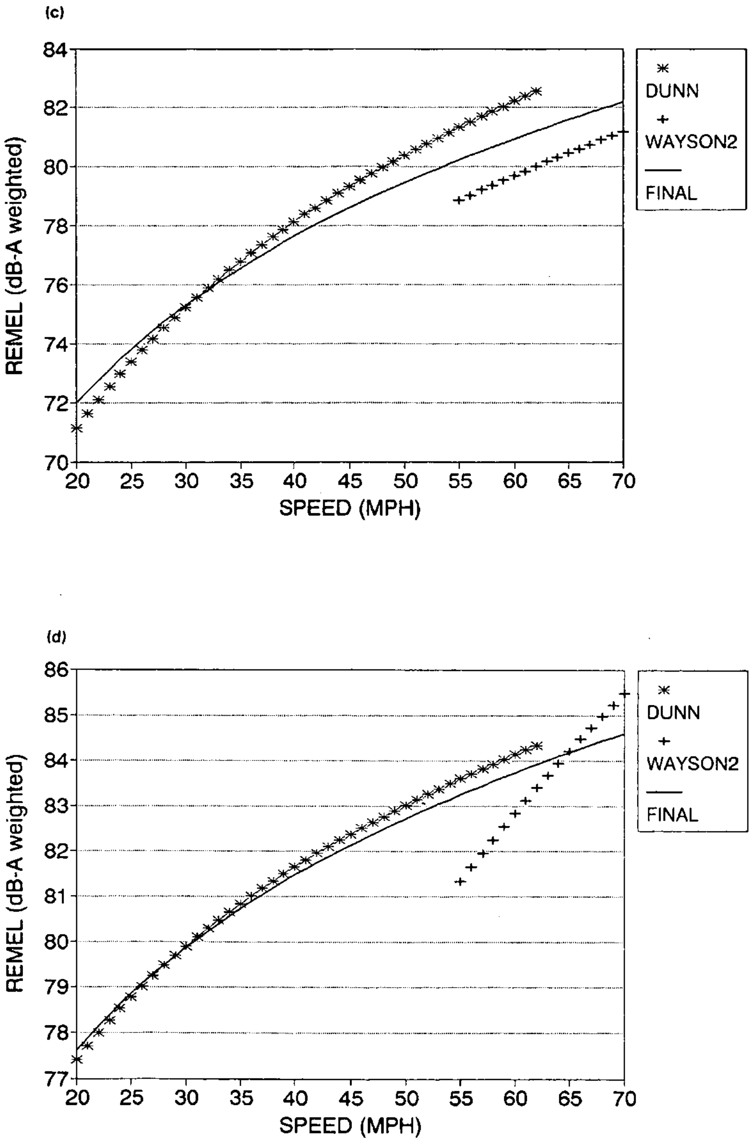


FIGURE 7 (*continued*)

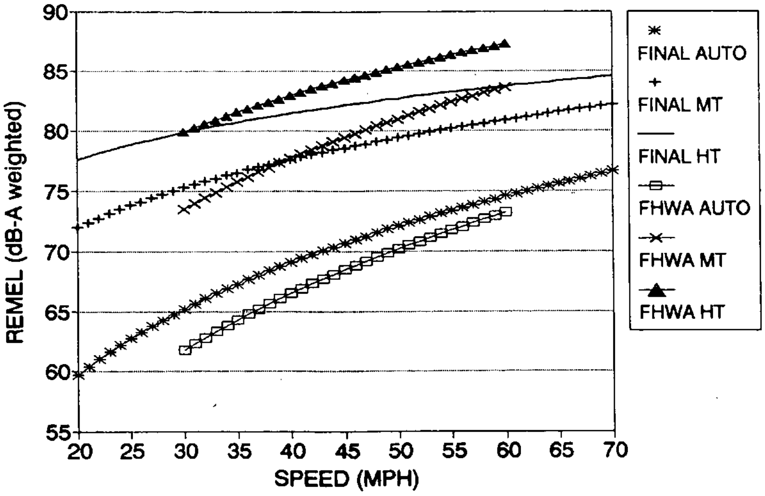


FIGURE 8 Comparison of FHWA with final REMELs.

This led to a much better fit of the data for the final derived curve.

Figure 7d is a graph of the heavy truck results for best fit. Although the slope of the project data appears to be too steep, probably because of the smaller data base only taken at the higher speeds, the regression analysis still verifies the Dunn and Smart data, and the derived curve appears to fit the two data bases well. The equation for this linear regression is

$$(L_o)_{EHT} = 12.831\log(S) + 58.270 \qquad (13)$$

For the three vehicle types, then, Equations 10, 12, and 13 are recommended for implementation. The final recommended speed range to be used is 20 to 70 mph. These curves, compared with the FHWA curves they are intended to replace, are plotted in Figure 8.

The preceding results have been incorporated into STAMINA 2.0, and testing has been accomplished. Several lines of the FORTRAN program were changed to implement the results of the newly developed REMELs and the increased speed range.

OTHER FINDINGS

Work to study the changes in vehicle frequency spectra observed with changes in speed has begun. This is important since STAMINA now uses a frequency of 500 Hz during barrier analysis. A comparison of A-weighted ⅓ octave band frequency spectra of measured vehicle pass-bys for automobiles, medium trucks, and heavy trucks is shown in Figure 9. This small sampling indicates that the dominant frequency does not correlate well with a value of 500 Hz. Also, the spectra tend to shift to the higher frequency ranges as tire noise frequency increases with speed.

Analysis of these specific examples indicates that vehicle speed can have a visible effect on higher frequency sound levels. However, the changes in the lower frequency sound levels due to differences in vehicle speed are not as obvious and will require further analysis. Ongoing research is being performed at UCF to determine whether any trend in spectral changes exists, and, if so, to what extent the trend occurs and how it can be predicted.

Another important finding came out of this research. It appears that the three basic vehicle types should be expanded to at least four types. This is necessary because, whereas automobiles and heavy trucks tend to validate past studies, the medium truck category has a large variance attributable to the definition of the vehicle type. Since multiple vehicle types are needed for air pollution studies and are available, consideration should be given to expanding vehicle types.

CONCLUSIONS

Several conclusions can be drawn from this research. First and most important, the primary goal of the research, to validate and extend the range of the REMELs, has been accomplished. Using the lower speed range data reported by Dunn and Smart (*4*) and the project data collection effort, equations were derived from 20 to 70 mph. Equations 10, 12,

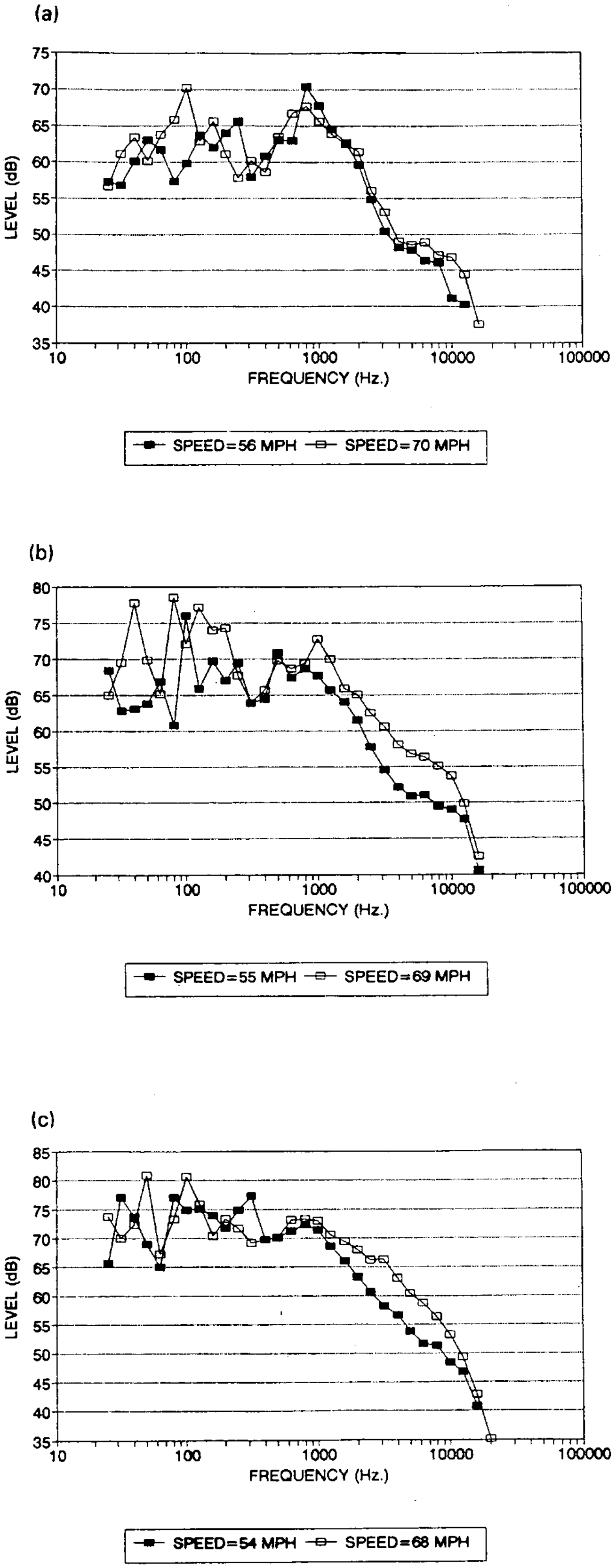


FIGURE 9 Comparison of frequency spectra for vehicles traveling at two speeds: (*a*) automobiles, (*b*) medium trucks, and (*c*) heavy trucks.

and 13 are considered to be the best fit of the Florida data bases using a linear regression analysis approach. These equations have been implemented in the computer program STAMINA 2.0 and tested.

The results of the measurements and developed emission levels show that the national reference levels (*2*) tend to underpredict for cars, overpredict for medium trucks in the higher speed ranges, and overpredict for heavy trucks. This could lead to significant errors in predictions and abatement considerations.

Another finding is that the three basic vehicle types may need to be expanded to at least four types. This appears necessary because, although automobiles and heavy trucks tend to validate past studies, the medium truck category has shown a large variance, most likely due to the very broad definition of the vehicle type. Multiple vehicle types are needed for air pollution studies and are available. More work is needed to determine the true return in accuracy for the increased effort.

The vehicle frequency spectra observed did not compare well with the basic frequency of 500 Hz used in STAMINA 2.0 during barrier analysis. Since frequency is a primary factor in wall height, additional considerations, such as multiple frequency analysis during barrier design, may be warranted.

ACKNOWLEDGMENT

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PART 4

Energy and Alternative Fuels

Cost-Effectiveness Analysis of Texas Department of Transportation Compressed Natural Gas Fleet Conversion

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Increased emphasis on energy efficiency and air quality has resulted in a number of state and federal initiatives examining the use of alternative fuels in motor vehicles. Texas's program for alternative fuels includes compressed natural gas. On the basis of an analysis of 30-year life cycle costs, development of a natural gas vehicle program for the Texas Department of Transportation (TxDOT) would cost about $47 million (in 1991 dollars). These costs include savings from lower-priced natural gas, infrastructure costs for a fast-fueling station, vehicle costs, and operating costs. The 30-year life cycle costs translate into an average annual vehicle cost increase of $596, or about 4.9 cents per vehicle mile of travel, compared with gasoline and diesel. Sensitivity analyses are performed on the discount rate, price of natural gas, maintenance savings, vehicle use, diesel vehicles, extended vehicle life, original equipment manufacturer vehicles, and operating and infrastructure costs. The best results are obtained when not converting diesel vehicles, converting only large fleets, and extending the period the vehicle is kept in service. Combining these factors yields results that are most cost-effective for TxDOT.

Texas, a state rich in natural gas, adopted alternative fuels legislation in 1989. In general, the legislation requires state agencies with more than 15 vehicles and school districts with more than 50 school buses to restrict new vehicle purchases to vehicles capable of operating on an alternative fuel. Alternative fuels, as currently defined, include natural gas, propane, electricity, and methanol. The principal objective of the legislation was to stimulate the development of an alternative fuels market in Texas. Greater use of alternative fuels would assist the state in (*a*) improving air quality; (*b*) promoting economic development, particularly in the natural gas and propane industries; and (*c*) supporting national energy security objectives through reduced dependence on imported oil. An important argument in the development and adoption of the legislation was that use of alternative fuels would save costs for state agencies. Accordingly, the legislation provides for a waiver if affected agencies demonstrate that operation of an alternative-fueled fleet is more expensive than that of a gasoline or diesel fleet over its useful life, alternative fuels are not available in sufficient supply, or the agencies are unable to acquire alternative-fueled vehicles or equipment necessary for their conversion.

Previous work examining the cost-effectiveness of compressed natural gas (CNG) as an alternative fuel is useful in placing this paper in perspective. A brief review of other published works that attempt cost-effectiveness analyses for CNG vehicles relative to gasoline/diesel vehicles is presented in the remainder of this section.

The California Energy Commission performed what is basically a user cost/benefit analysis, considering several classes of users: individual, small private fleet, large private fleet, and government fleet. The study did not attempt to account for societal impacts (*1*).

Several studies attempted to analyze both economic and environmental factors. First, the American Gas Association (AGA) accounted for the wellhead, distribution, and public filling station costs influencing the price of CNG to individual users (*2*). By including vehicle costs to the user, it computed the difference in costs between operation of vehicles on gasoline/diesel and CNG. By estimating the difference in emissions of reactive hydrocarbons and carbon monoxide between CNG and gasoline/diesel vehicles, it computed the cost (or savings) to remove a ton of each via conversion to CNG.

With a methodology similar to that of AGA, Radian performed two studies in 1990 analyzing CNG as a replacement fuel. It used scenarios from several proposed federal alternative fuel legislative efforts of that time. The study differs from the AGA's study in that it targeted converted fleets, whereas AGA's study targeted individual vehicles (*3,4*).

Sperling performed a very thorough multiobjective study, which addressed most of the factors (both economic and societal) generally considered to be important. The study uses quantitative and qualitative measures to determine preferred near-term fuel choices in various geographic regions of the world, in addition to discussing five possible future vehicular-fuel pathways (*5*).

A recent study by the authors differs from the previous literature in an important way. A comprehensive model that accounts for virtually all possible incremental cost components and relevant factors was developed to analyze the cost-effectiveness of CNG (*6,7*). The current analysis uses a net present value (NPV) model developed in the authors' previous work to analyze vehicle fleets. This entails the use of actual fleet characteristics (vehicle miles traveled, fuel efficiencies, etc.) for the Texas Department of Transportation (TxDOT). A detailed discussion of the model's operation and assumptions is available elsewhere (*6,7*). Some of the more important assumptions of the NPV model are discussed in the next section.

BASIC ASSUMPTIONS

A monetary cost/benefit fleet analysis based on the NPV of all future incremental costs and benefits over a 30-year life cycle time horizon is used. The NPV model is designed to

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provide a level of service to the fleet manager and users comparable with that of existing gasoline/diesel fill stations. Consequently, slow-fill is not included in the analysis. The model assumes continuous fast-filling of all near-empty vehicles on a daily basis. Moreover, social benefits, such as cleaner air, energy security, economic growth, although important, are not incorporated into the model analysis. However, if the NPV in the model is negative, this can be identified as the minimum value that social benefits must attain for the alternative to be cost-effective. The decision on the value of social benefits is highly debatable and will be left to policy makers. Finally, cleanup costs and tank removal for existing gasoline stations are not included, since they are a sunk cost; these costs will be incurred regardless of any future fuel selected. But to the extent that future inspection and maintenance costs of tanks are identified, they should be taken into account in a comparative analysis of fuels. This cost factor is not included in the model.

Some of the basic assumptions used in the model are as follows:

1. Dedicated (and optimized) original equipment manufacturer (OEM) natural gas vehicles (NGVs) are available in Year 11.
2. Diesel vehicle conversions begin in Year 6. In addition, all diesel conversions and OEM diesels are dedicated and not dual-fuel engines.
3. Vehicle conversion costs, based on a fairly mature NGV market, are given in Table 1.
4. Conversion kits and tanks are transferred between vehicles at the labor costs given in Table 1 when a converted vehicle is retired from the fleet. When replaced with an OEM, the kit and tanks remain on the retired vehicle with a $200 and $500 increase in the salvage value of gasoline-converted and diesel-converted vehicles, respectively.
5. For gasoline dual-fuel vehicles, the fuel economy is assumed to be only 95 percent of what it is for a gasoline-only vehicle. For OEMs dedicated to CNG, the fuel economy is increased by 15 percent. Diesel converted vehicles have only 74 percent of the economy of a comparable diesel-only vehicle. Finally, for dedicated OEM diesels the fuel economy is 80 percent of a diesel-only vehicle.
6. Tank recertification costs are $55 per tank, including labor. Tank recertification costs are discontinued as a separate cost for OEM vehicles.
7. Fuel prices are as follows: natural gas, $0.076/m^3 ($2.50/mcf); gasoline, $0.235/L ($0.89/gal); diesel, $0.225/L ($0.85/gal). The fuel prices do not include federal fuel taxes.
8. Capital fueling infrastructure costs are as follows: dispenser, $25,000; dryer, $10,000. Compressor and storage are sized to meet continuous fast-filling of all vehicles requiring fueling in a day; setup cost is computed at 25 percent of the combined compressor, storage, and dispenser costs. These dispenser and dryer costs may be too high for small fleet refueling stations. The fueling station has an estimated 30-year life. Sensitivity tests on these values are reviewed in a later section.

NPV SUMMARY ANALYSIS

TxDOT Fleet Summary

There are 314 locations around the state that currently serve as fill stations for the 8,377 vehicles used in this analysis. The vehicles are classified into four groups: automobiles, light trucks (pickup trucks), heavy-duty gasoline trucks, and heavy-duty diesel trucks. Automobiles and light trucks are gasoline fueled, with the exception of a few diesels included in the light truck group. The average fleet size is biased upwards because of the existence of several large fleets. More than 75 percent of the locations have 30 or fewer vehicles in their fleet, as shown in Figure 1, but 73 percent of the vehicles are in fleets with more than 20 vehicles.

Whereas the locations are analyzed individually, representative fleets are used for the sensitivity analyses performed on important variables. On the basis of an analysis of the 314 fleets, five representative sizes were chosen and are given in Table 2. The values for the variables from the representative fleets, given in Table 3, are calculated from all the fleets of that particular size grouping. These data are used as the baseline for the sensitivity analyses discussed later.

Thirty-Year Life Cycle Analysis

The fleets stationed at the 314 TxDOT locations were evaluated by the NPV model. The basic input data included the number of vehicles of each type in the fleet, fuel consumption, and annual miles traveled. The results of the NPV analysis are summarized in Table 4. Overall, implementation of a natural gas fleet for TxDOT would cost $47.1 million over a 30-year period, or $5 million per year annualized. This amounts to an average increase in annual cost per vehicle of $596, or about 4.9 cents per vehicle mile traveled.

TABLE 1 Natural Gas Vehicle Costs (1991 Dollars)

	Automobiles	Light Trucks	Heavy-Duty Gasoline Trucks	Heavy-Duty Diesel Trucks
Conversion Costs:				
Kit	$700	$700	$700	$2,000
Labor	$800	$600	$600	$2,350
Tank(s)	$450	$900	$2,000	$2,000
Total	$1,950	$2,200	$3,300	$6,350
OEM differential	$900	$900	$900	$2,800

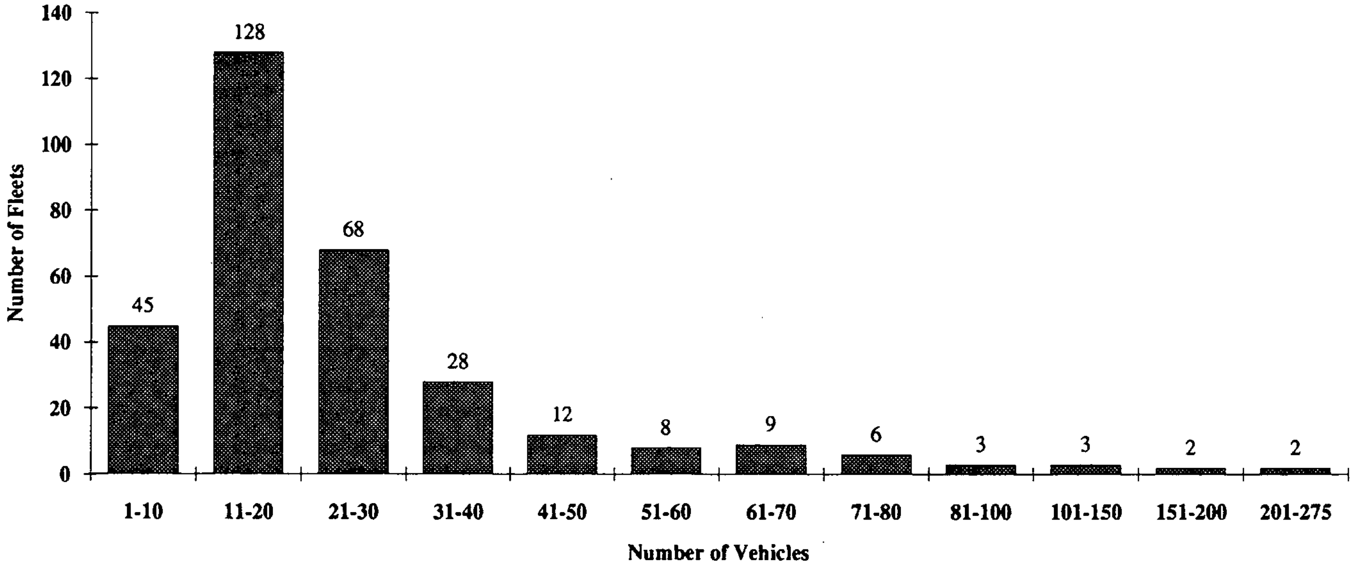


FIGURE 1 Fleet size distribution.

The 30-year NPV costs range from a low of −$73,656 in District 29, Garza County, to a high of −$688,548 in District 29, Travis County. The overall distribution for all locations is shown in Figure 2. More than 72 percent of the locations have a 30-year NPV between −$100,000 and −$160,000 [More detailed information on all fleets is given elsewhere (*8*).]

Because of the fixed fueling infrastructure costs required for each of the fleets, the NPV results are highly dependent on the number of vehicles in the fleet. On a cost per vehicle basis, the larger fleets are much cheaper to operate on CNG than are smaller fleets. The District 12, Houston District Office location, with 257 vehicles, ranks 313 in the 30-year NPV analysis but first in the lowest annual cost increase per vehicle (−$229). On the other hand, District 29, Garza County, although ranking first in NPV, ranks 314 on an annual cost increase per vehicle basis. There is a high negative correlation between the number of vehicles in a fleet and the average annual cost increase per vehicle, as shown in Figure 3. The exponential relationship between fleet size and annual cost increase per vehicle can be empirically calibrated as follows:

$$y = 973.31(0.9899^{f}) \qquad (1)$$

where y is the average annual cost increase per vehicle and f is the fleet size.

TABLE 2 Representative Fleet Groups

Fleet Group	Number of Vehicles	Percentage of Vehicles
1-10 vehicles	385	4.6
11-20 vehicles	1,847	22.0
21-30 vehicles	1,707	20.4
31-50 vehicles	1,480	17.7
51 or more vehicles	2,958	35.3
TOTAL	8,377	100.0

SENSITIVITY ANALYSES

The NPV model has a number of assumptions affecting the cost-effectiveness of CNG fleet conversion and operation. Extensive sensitivity analysis has been performed to examine the robustness of the conclusion vis-à-vis the underlying assumptions and to help identify the fleet operating characteristics and economic scenarios under which CNG adoption is likely to become cost-effective. Another important role of this analysis is to determine the principal directions along which policy actions might be directed to encourage CNG adoption. The focus of the analysis is on a systematic assessment of the model's sensitivity to each of its principal elements, taken individually. This assessment will highlight the range of applicability of the model and its results and provide the building blocks for various policy scenarios. Because the effects of the various elements appear to be largely additive with limited interactions, single-factor sensitivity analyses allow reasonable estimation of the direction and general magnitude of changes in results due to changes in several factors simultaneously. Nevertheless, we consider explicitly several scenarios involving the combined effects of changes in several factors; these have been selected for their inherent substantive interest, as an illustration of the proposed approach, and for their clear policy significance. (The various sensitivity tests are summarized on an NPV basis in Table 5 and on an annual cost increase per vehicle basis in Table 6.)

Base Case

On the basis of the information contained in Table 3, analyses were performed on the five representative TxDOT fleets. The results are summarized in Table 7. The net present value worsens as the fleet size increases, but the cost increase per

TABLE 3 Summary Fleet Data for Sensitivity Analyses[a]

Fleet Group	Autos	Light-Trucks	Heavy-Duty Gasoline	Heavy-Duty Diesel	All Vehicles[b]
(1-10)					
Number of Vehicles	1	2	1	5	9
Annual Travel					
kilometers	36,239	29,506	20,817	21,753	26,032
miles	22,509	18,327	12,930	13,511	16,169
Annual Fuel Consumed					
liters	4,190	5,409	7,169	6,306	6,154
gallons	1,107	1,429	1,894	1,666	1,626
Annual Repair Costs	$989	$923	$1,490	$1,776	$1,437
(11-20)					
Number of Vehicles	1	5	2	7	15
Annual Travel					
kilometers	36,806	25,910	19,908	19,652	22,981
miles	22,861	16,093	12,365	12,206	14,274
Annual Fuel Consumed					
liters	4,553	4,674	7,676	5,481	5,394
gallons	1,203	1,235	2,028	1,448	1,425
Annual Repair Costs	$880	$753	$1,628	$1,592	$1,253
(21-30)					
Number of Vehicles	2	13	3	8	26
Annual Travel					
kilometers	26,807	22,490	17,056	18,702	20,999
miles	16,650	13,969	10,594	11,616	13,043
Annual Fuel Consumed					
liters	3,248	3,944	7,104	5,443	4,735
gallons	858	1,042	1,877	1,438	1,251
Annual Repair Costs	$628	$653	$1,659	$1,638	$1,072
(31-50)					
Number of Vehicles	3	20	4	10	37
Annual Travel					
kilometers	24,150	21,405	15,282	19,719	20,565
miles	15,000	13,295	9,492	12,248	12,773
Annual Fuel Consumed					
liters	2,960	3,777	6,529	5,908	4,576
gallons	782	998	1,725	1,561	1,209
Annual Repair Costs	$636	$623	$1,530	$1,597	$986
(51 or more)					
Number of Vehicles	19	54	4	11	88
Annual Travel					
kilometers	17,985	18,636	16,139	17,834	18,291
miles	11,171	11,575	10,024	11,077	11,361
Annual Fuel Consumed					
liters	2,033	3,289	6,575	5,587	3,433
gallons	537	869	1,737	1,476	907
Annual Repair Costs	$527	$675	$1,560	$1,790	$815

[a] All annual figures are per vehicle.
[b] Totals may not add up due to rounding.

TABLE 4 Summary CNG NPV Analysis for 314 TxDOT Locations

	30-Year NPV	Percent of Subtotal
Savings Differential:		
Gasoline	$34,582,695	81.8
Diesel	$7,702,222	18.2
Subtotal	$42,284,918	100.0
Costs Differential:		
Infrastructure	-$36,950,573	41.4
Vehicle	-$26,424,427	29.6
Operating	-$25,967,923	29.1
Subtotal	-$89,342,924	100.0
TOTAL	$-47,058,006	

vehicle and the cost increase per vehicle-mile improve as the fleet size increases.

The model categorizes costs into three groups—infrastructure, vehicle, and operating. Basically, infrastructure consists of the fill-station equipment and setup, vehicle costs are the conversion or OEM purchase costs, and operating costs reflect the operating elements for both the station and the vehicle. The importance of these cost components changes with the size of the fleet (Figure 4). The infrastructure costs are somewhat fixed, whereas vehicle and operating are variable, primarily dependent on the number of vehicles in the fleet and their annual mileage. The relatively high infrastructure cost for small fleets translates into very high annual vehicle cost increases and incremental costs per vehicle mile.

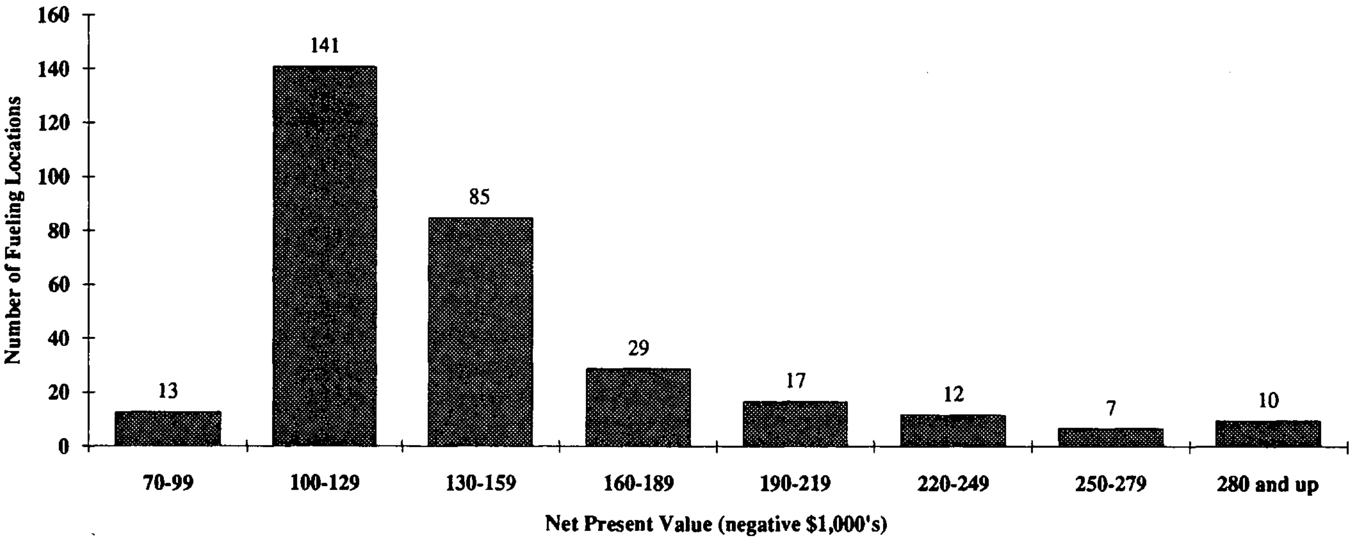


FIGURE 2 Number of fueling locations by 30-year NPV (all locations have negative NPVs).

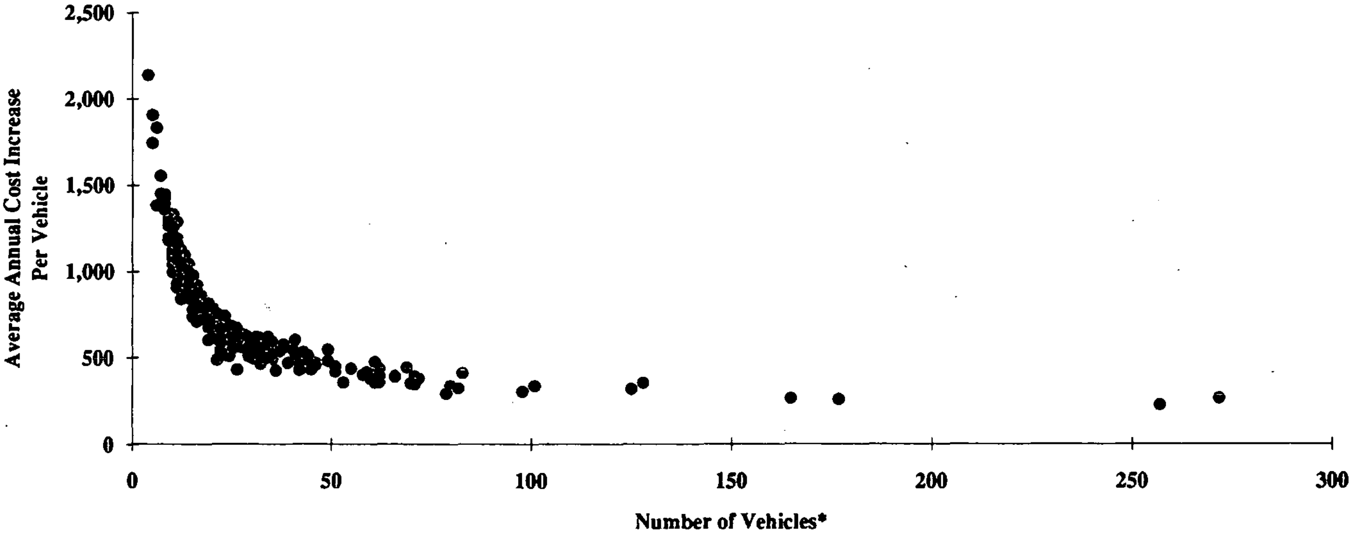
Discount Rate

A 10 percent discount rate is used for the base case analysis, although the model allows any rate to be selected. Two other rates—5 percent and zero—were used for the five fleets to determine whether the discount rate significantly affects the conclusions. Tables 5 and 6 indicate that the effects of altering the discount rate are mixed. With respect to the three largest fleet groups, the NPV improves as the discount rate decreases, as expected. On the other hand, the NPV for the smallest fleet actually gets worse as the discount rate decreases. This is a result of the magnitude and timing of the annual benefits and costs. Annual costs exceed annual benefits for the small fleet; therefore, discounting reduces the net cost for each period. Consequently, as the discount rate increases, the NPV, being negative, improves. The timing of costs and benefits also is a factor behind the unusual change in the NPV for fleets of 11 to 20 vehicles. As the discount rate increases from zero to 5 percent, the NPV decreases, but as the discount rate increases from 5 to 10 percent, the NPV increases slightly.

Overall, regardless of the discount rate selected, the NPV and the annual cost increase per vehicle are negative for the five fleet sizes.

Fuel Prices

The major benefit of natural gas as an alternative fuel is that it is less expensive on an energy basis than gasoline and diesel. A price of $0.076/m³ ($2.50/mcf) was selected for the base case analysis. Initially, two alternative prices of $0.030/m³



*Includes only fleets of more than 3 vehicles

FIGURE 3 Relationship of fleet size to vehicle cost.

TABLE 5 Sensitivity Analyses, 30-Year NPV (Dollars)

	Fleet Size				
	1-10	11-20	21-30	31-50	51 & up
Discount Rate					
10%	-109,264	-125,735	-150,013	-177,842	-298,171
5%	-117,221	-125,761	-137,188	-152,977	-239,988
Zero	-118,769	-96,155	-69,406	-44,432	-25,110
Natural Gas Price					
\$0.076/m³ (\$2.50/mcf)	-109,264	-125,735	-150,013	-177,842	-298,171
\$0.030/m³ (\$1.00/mcf)	-86,151	-89,930	-95,363	-102,528	-159,443
Free	-70,744	-66,059	-58,930	-52,319	-66,958
Maintenance Savings					
Zero Savings	-109,264	-125,735	-150,013	-177,842	-298,171
10% Savings	-100,182	-112,006	-128,749	-149,528	-237,391
25% Savings	-86,559	-91,413	-96,853	-107,056	-146,220
50% Savings	-63,854	-57,090	-43,693	-36,269	+5,730
Vehicle Miles of Travel					
No Increase	-109,264	-125,735	-150,013	-177,842	-298,171
25% Increase	-110,713	-125,870	-145,952	-179,534	-273,118
50% Increase	-110,518	-123,856	-142,121	-168,890	-266,253
100% Increase	-110,757	-120,608	-130,623	-153,655	-226,155
Effects of Diesel					
Diesel Included	-109,264	-125,735	-150,013	-177,842	-298,171
No Diesel	-77,941	-83,831	-102,480	-117,837	-234,104
Diesel to Gasoline	-82,619	-90,036	-107,787	-124,255	-243,599
Extended Vehicle Life					
No Added Life	-109,264	-125,735	-150,013	-177,842	-298,171
10% Added Life	-84,247	-100,982	-113,628	-126,631	-211,013
25% Added Life	-75,462	-90,903	-82,397	-83,063	-80,572
50% Added Life	-59,405	-64,007	-45,123	-15,819	+40,162
Effects of Dedicated Natural Gas OEM					
Purchased at Year 11	-109,264	-125,735	-150,013	-177,842	-298,171
Purchased At Year 1	-82,654	-80,510	-75,537	-76,025	-80,866
Year 1 Without Diesel	-65,334	-58,036	-50,059	-43,988	-47,147
Operating and Infrastructure Effects					
Base Case - No Changes	-109,264	-125,735	-150,013	-177,842	-298,171
Various Adjustments	-70,066	-77,877	-88,298	-102,924	-169,511
10% Extend Life, OEM at Year 1, No Replacement of Diesel Vehicles					
Base Case - No Changes	-109,264	-125,735	-150,013	-177,842	-298,171
Combined Effects	-49,893	-35,448	-19,963	+5,351	+36,436

(\$1.00/mcf) and free natural gas were used, as indicated in Tables 5 and 6.

Since the NPV results remained negative for all fleets with both scenarios, the break-even price for each of the fleets was estimated. Table 8 gives the break-even price for gasoline and diesel, assuming a natural gas price of \$0.076/m³ (\$2.50/mcf) and a constant 1.1 cents/L (4 cents/gal) price differential between gasoline and diesel. The gasoline/diesel prices include state taxes but not federal taxes.

Maintenance Savings

Anecdotal and theoretical evidence suggests that there may be maintenance savings associated with natural gas vehicles compared with gasoline/diesel vehicles. The range in savings is most likely from 10 to 20 percent. However, because of a lack of empirical support, the base case does not assume any savings in maintenance costs. The effects of maintenance savings for the sensitivity tests presented here are based on the actual average maintenance costs for the existing fleets reported in Table 3. Three savings rates (10, 25, and 50 percent) were selected. The results of these analyses are summarized in Tables 5 and 6. Significant maintenance savings are required to change the bottom line. Maintenance savings improve the results most dramatically for larger fleets. A 25 percent savings in maintenance costs for the smallest fleet would yield only a 21 percent reduction in the annual cost increase per vehicle but would result in a 51 percent reduction in the annual cost increase per vehicle for the largest fleet. More empirical support is needed to accurately account for reductions in maintenance costs.

Vehicle Use

The mileage estimates for each of the vehicle groups are based on current operations. If annual mileage were to increase, there would be improvements in the NPV in most cases. Three scenarios—25, 50, and 100 percent increase—were constructed to illustrate the effect of vehicle miles of travel on the model output. The results are summarized in Tables 5 and 6. The NPVs for the smallest fleet are counterintuitive and are a result of the timing of cash flows and the change in the number of years the vehicle is kept. Gasoline and diesel vehicles are assumed to operate for 90,000 and 150,000 mi, respectively. The ideal scenario is to replace a vehicle as close to the availability of OEM as possible, because of the beneficial effects of OEM vehicles, as described later. In general, the increased mileage per vehicle generates greater benefit than cost. Because of the various factors influencing the NPV (i.e., timing of introduction of OEM vehicles, fuel price, etc.),

TABLE 6 Sensitivity Analyses, Annual Cost Increase per Vehicle (Dollars)

	Fleet Size				
	1-10	11-20	21-30	31-50	51 & up
Discount Rate					
10%	-1,288	-889	-612	-510	-359
5%	-847	-545	-343	-269	-177
Zero	-440	-214	-89	-40	-10
Natural Gas Price					
\$0.076/m³ (\$2.50/mcf)	-1,288	-889	-612	-510	-359
\$0.030/m³ (\$1.00/mcf)	-1,015	-636	-389	-294	-192
Free	-834	-467	-240	-150	-81
Maintenance Savings					
Zero Savings	-1,288	-889	-612	-510	-359
10% Savings	-1,181	-792	-525	-429	-286
25% Savings	-1,020	-646	-395	-307	-176
50% Savings	-753	-404	-178	-104	+7
Vehicle Miles of Travel					
No Increase	-1,288	-889	-612	-510	-359
25% Increase	-1,305	-890	-595	-515	-329
50% Increase	-1,303	-876	-580	-484	-321
100% Increase	-1,305	-853	-533	-441	-273
Effects of Diesel					
Diesel Included	-1,288	-889	-612	-510	-359
No Diesel	-2,067	-1,112	-604	-463	-323
Diesel to Gasoline	-974	-637	-440	-356	-294
Extended Vehicle Life					
No Added Life	-1,288	-889	-612	-510	-359
10% Added Life	-993	-714	-464	-363	-254
25% Added Life	-889	-643	-336	-238	-97
50% Added Life	-700	-453	-184	-45	+48
Effects of Dedicated Natural Gas OEM					
Purchased at Year 11	-1,288	-889	-612	-510	-359
Purchased At Year 1	-974	-569	-308	-218	-97
Year 1 Without Diesel	-1,733	-770	-295	-173	-65
Operating and Infrastructure Effects					
Base Case - No Changes	-1,288	-889	-612	-510	-359
Various Adjustments	-826	-551	-360	-295	-204
10% Extend Life, OEM at Year 1, No Replacement of Diesel Vehicles					
Base Case-No Changes	-1,288	-889	-612	-510	-359
Combined Effects	-1,323	-470	-118	+21	+50

average miles traveled per vehicle may not be as significant as reported in the previous TRB paper (*6*).

Diesel Vehicles

Conversion of diesel vehicles to natural gas is much more complicated than is conversion of gasoline vehicles to natural gas. (During the model development, there was not a widely accepted conversion kit available for diesel vehicles.) In addition, because of the efficiencies of the diesel engine, there are important losses in fuel economy when converting from diesel to natural gas. Two analyses were performed on diesel vehicles to determine their effect on NPV. The first scenario removes diesel vehicles from the fleet analysis. The second treats existing diesel vehicles like heavy-duty gasoline vehicles and converts them to natural gas along with the other gasoline vehicles. The results of these scenarios are given in Tables 5 and 6. Conversion of diesel vehicles has a negative effect on NPV. On an annual cost increase per vehicle basis, the costs for the removal of diesel vehicles improve for the three largest fleet groups and decrease for the two smallest fleet groups, again because of the nature of fixed refueling facility costs on a small number of vehicles. Not surprisingly, replacing diesel with gasoline (spark ignition) vehicles before converting to CNG use decreases the annual cost increase per vehicle. Overall, converting diesel vehicles, as they currently exist, has a negative effect on cost-effectiveness. There is more to gain in converting gasoline vehicles than diesel vehicles.

Extended Vehicle Life

Some natural gas proponents argue that because natural gas burns cleaner than gasoline and diesel, vehicles using natural gas should have a longer operating life. Although this contention is not fully supported by operating data to date (because of less experience with CNG vehicles and converted rather than dedicated OEM vehicles), the model can be adjusted to evaluate the impact of extending the life of vehicles. Three scenarios (10, 25, and 50 percent extended life) were analyzed and the results summarized in Tables 5 and 6. The model results were adjusted to accommodate the differences in the number and timing of vehicle purchases. For example, the fleet group of 1 to 10 vehicles requires the purchase of one automobile every 4 years, or eight automobiles over the 30-year life cycle. Extending the life by 50 percent, however, requires the purchase of one natural gas automobile every 6 years, or five vehicles over the 30-year life cycle. Each of the fleet size groups was adjusted to reflect the additional savings

TABLE 7 Savings and Costs—Summary of Base Case

	Fleet Size				
	1-10	11-20	21 - 30	31 - 50	51 and up
SAVINGS					
Gasoline Price Difference	$32,193	$62,402	$113,695	$159,615	$346,548
Automobiles	$6,069	$6,586	$9,395	$12,829	$54,998
Light Trucks	$15,782	$33,879	$73,711	$108,741	$254,291
Heavy Duty Trucks	$10,342	$21,936	$30,588	$38,045	$37,259
Diesel Price Difference	$18,346	$22,327	$25,183	$34,468	$35,568
Maintenance	$0	$0	$0	$0	$0
Total Savings	**$50,540**	**$84,729**	**$138,878**	**$194,083**	**$382,116**
COSTS					
Infrastructure					
Land	$0	$0	$0	$0	$0
Station setup	-$15,880	-$18,585	-$22,556	-$26,920	-$39,499
Compressor	-$21,193	-$22,609	-$24,666	-$26,983	-$34,169
Storage Vessels	-$15,876	-$24,915	-$38,245	-$52,759	-$94,415
Dispenser	-$24,857	-$24,857	-$24,857	-$24,857	-$24,857
Dryer	-$9,943	-$9,943	-$9,943	-$9,943	-$9,943
Subtotal	-$87,747	-$100,908	-$120,267	-$141,462	-$202,882
Vehicle					
Conversion Kit	-$7,749	-$12,504	-$20,141	-$27,960	-$62,612
Tanks	-$9,895	-$16,853	-$27,632	-$38,639	-$77,568
Labor	-$11,026	-$17,170	-$26,966	-$36,895	-$85,118
OEM	-$5,178	-$6,199	-$9,186	-$13,853	-$20,986
Subtotal	-$33,848	-$52,725	-$83,925	-$117,348	-$246,284
Operating					
Station Maintenance	-$5,650	-$8,753	-$13,359	-$18,411	-$33,913
Cylinder Recert.	-$1,927	-$3,666	-$6,274	-$8,326	-$19,242
Power	-$13,846	-$17,473	-$22,902	-$28,825	-$46,907
Labor - fuel time loss	-$7,976	-$11,756	-$18,306	-$25,457	-$54,767
NG Fuel Tax	-$8,809	-$15,184	-$23,857	-$32,098	-$76,292
Additional Training	$0	$0	$0	$0	$0
Subtotal	-$38,208	-$56,831	-$84,699	-$113,117	-$231,120
Total Costs	**-$159,803**	**-$210,464**	**-$288,890**	**-$371,926**	**-$680,287**
Savings - Cost	**-$109,264**	**-$125,735**	**-$150,013**	**-$177,842**	**-$298,171**
Annual Cost Increase per Vehicle	-$1,288	-$889	-$612	-$510	-$359
Incremental Cost/mile	-$0.0903	-$0.0669	-$0.0491	-$0.0418	-$0.0323

from fewer and later vehicle purchases. The effect of extending vehicle life can be significant. For example, in the largest vehicle group a 25 percent increase in vehicle life results in a 75 percent increase in the 30-year NPV. Again, these improvements may be somewhat offset by increased maintenance costs on components not affected by fuel type (such as drivetrain, brakes, transmission, etc.). Only close monitoring and evaluation of NGVs over time will validate the overall effect of extended vehicle life.

OEM Vehicles

The base case analysis provides for the availability of OEM vehicles in Year 11. Actual purchase of OEM vehicles is dependent on vehicle replacement for each fleet. Two scenarios were analyzed with respect to the introduction of OEMs. The first assumes OEM vehicles are available in Year 1 for spark ignition (gasoline) vehicles and in Year 6 for diesel vehicles. The second converts only gasoline vehicles in Year 1 (i.e., there are no diesel conversions). The results of the two scenarios are summarized in Tables 5 and 6. Improvements in the NPVs for OEM are driven by three factors. First, and most significant, the OEM cost differential is $900 for spark ignition vehicles ($2,800 for diesel) compared with $1,950, $2,200, and $3,300 for gasoline-converted CNG automobiles, light trucks, and heavy-duty trucks, respectively ($6,350 for diesel). (The OEM price estimates are based on a mature market, which in the base case is estimated to occur at about Year 11. Current OEM prices, based on a limited supply of vehicles, are much higher.) For all fleet sizes, this OEM/conversion cost differential accounts for at least 55 percent of the improvement in the NPV. The second factor relates to the improvement in fuel efficiency of an OEM vehicle versus a converted vehicle.

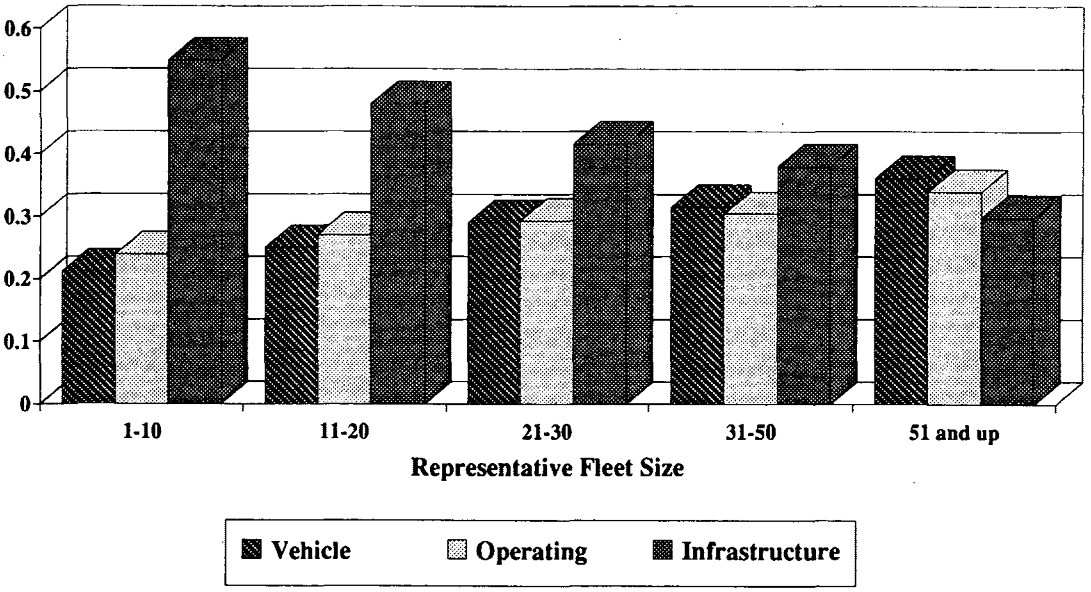


FIGURE 4 Cost component distributions for vehicle fleets.

The model incorporates a 5 percent reduction in fuel economy for converted gasoline vehicles versus a 15 percent improvement in fuel economy for an optimized OEM vehicle. Similarly, the model uses a 26 percent reduction for converted diesels versus a 20 percent reduction for optimized OEMs replacing diesels. The improvements in fuel efficiency translate into lower infrastructure costs and operating costs, in addition to increased fuel savings. The final factor relates to recertification. The model assumes that recertification costs will be factored into vehicle inspection costs for OEM vehicles and that the current requirements for tank removal on converted vehicles will not be necessary. Consequently, OEMs have no incremental costs associated with cylinder recertification. This also translates into additional natural gas consumption, which increases the savings differential, since the model assumes that converted vehicles must operate on gasoline during recertification of their pressurized storage vessels.

The results indicate that, for smaller fleets, replacement of diesel vehicles with OEM vehicles reduces the annual cost increase per vehicle. For larger fleets, replacement of diesel vehicles increases the annual cost increase per vehicle. The larger fleets are more indicative of the effects of introducing OEM vehicles to replace diesels. The improvement in the annual cost increase per vehicle for the smaller fleets is driven by the fixed infrastructure costs. However, as fleet size increases, these fixed costs become less significant and variable costs become more important. Arguably (considering only fleet economics, and not air quality benefits, etc.), replacement of vehicles, regardless of fleet size, should focus on gasoline and not diesel vehicles. This strategy could change as improvements in natural gas engines are made for diesel vehicles.

TABLE 8 NPV Break-Even Price for Gasoline and Diesel

	Gasoline		Diesel	
Fleet Group	($/liter)	($/gallon)	($/liter)	($/gallon)
1-10	0.52	1.96	0.51	1.92
11-20	0.44	1.65	0.43	1.61
21-30	0.39	1.46	0.38	1.42
31-50	0.36	1.38	0.35	1.34
51 & up	0.35	1.32	0.34	1.28

Operating and Infrastructure Costs

The previous sensitivity tests focused, principally, on vehicle parameters; this subsection examines some of the basic assumptions regarding operating and infrastructure costs. Taken individually, these various cost items are not significant. Therefore, several of the cost items will be analyzed in combination to determine their collective effect on NPV.

On the basis of a literature review, our research found that station maintenance cost estimates range from 3 to 10 cents per gallon equivalent of CNG. The base case for the model assumes a maintenance cost of 4.5 cents per CNG gallon equivalent. Three cents per gallon equivalent is used in this sensitivity test.

With respect to power costs, the model assumes that the maximum possible energy is used by the compressor (i.e., the motor draws full power whenever operating). The actual energy usage should be less, since the motor only draws full power when the back pressure of the storage vessels is near maximum. The base case rate of 6.3 cents/kW-hr of electricity is reduced to 2 cents/kW-hr for sensitivity purposes.

Cylinder recertification costs, although not significant relative to the other operating costs, affect savings and other infrastructure costs. For sensitivity purposes, recertification requirements and costs of CNG pressure vessels are eliminated.

Finally, in estimating the labor costs associated with additional refueling, $15/hr is used for the base case. The sensitivity tests use $7.50/hr. Likewise, two infrastructure cost items—dispenser and dryer—are reduced by 50 percent. The base case for the model assumes $25,000 and $10,000 for the dispenser and dryer, respectively.

The results of these changes in operating and infrastructure costs are summarized in Tables 5 and 6. Collectively, the changes in the operating and infrastructure cost assumptions reduce the average annual cost increase per vehicle by about one-third for each of the fleet groups. There are no changes in the conclusions for any of the fleet groups.

Selected Combined Effects

The next area of sensitivity examines the effects of combining some of the previous factors. The three most logical factors to combine are extended vehicle life, replacement with OEM vehicles, and nonconversion of diesel vehicles. Although there is a strong case for including maintenance savings, it is unlikely that there would be net maintenance savings for a vehicle with an extended life. Traditionally, maintenance costs for vehicles increase exponentially over time. In fact, there may be a stronger case for arguing that total maintenance costs will increase if a vehicle is kept for a longer time. In this analysis, we assume that maintenance savings are offset by the increased life of the vehicle. The results of the combined analysis are given in Tables 5 and 6.

As noted previously in the discussion of diesel vehicles, fixed costs are the most significant costs affecting the annual cost increase per vehicle for the two smallest fleets. These fixed costs are significant enough that introduction of diesel vehicles improves the overall cost-effectiveness, which is not the case for the larger fleets. The same is true for the combined analysis. Unlike the larger fleets, introduction of diesel vehicles actually reduces the annual cost increase per vehicle for the two smallest fleets—from −$1,323 to −$674 and from −$470 to −$390 for fleets of 1 to 10 and 11 to 20 vehicles, respectively.

CONCLUSIONS

On the basis of the operating assumptions of the model, introduction of natural gas vehicles into the TxDOT fleet will cost an estimated $47 million over the next 30 years, or $5 million annually. On the basis of the sensitivity analyses, costs could be held to a minimum by focusing on conversion of the larger fleets, utilization of OEM vehicles whenever practicable, and the delay of diesel conversions. TxDOT should continue to closely monitor its vehicles to determine the effects of natural gas on maintenance costs and resulting opportunities for holding the vehicles for a longer period of time. Extending the operating life of vehicles can have a pronounced effect on vehicle costs by reducing the number of vehicle purchases over time.

The sensitivity tests provide insight into the significance of various model parameters. By focusing on the larger fleets (i.e., fleets with more than 30 vehicles), TxDOT could realize some cost savings, if the combined effects presented in the previous section hold true. Assuming a more mature OEM market (i.e., CNG vehicles for gasoline replacements cost only $900 more per vehicle), a 10 percent extended life with no additional maintenance costs, and no diesel conversions, TxDOT could save about $180,000 annually. Moreover, this group of fleets accounts for about 53 percent of the vehicles listed in Table 2. Increasing the range to include vehicles in smaller fleets and diesel vehicles means that TxDOT will require additional outlays to support a CNG-vehicle program.

ACKNOWLEDGMENT

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Model of Fuel Economy with Applications to Driving Cycles and Traffic Management

FENG AN AND MARC ROSS

Fuel consumption by a vehicle is expressed in terms of a few vehicle characteristics and summary characteristics of any trip. This simple physical model can readily be adapted to any vehicle or combination of vehicles. The needed data for U.S. vehicles are in the public domain. Numerical results in the applications discussed are for an average U.S. car. One potential application is in modifying driving cycles to more accurately reflect actual driving behavior. The model shows that instead of a second-by-second velocity pattern being needed, fuel consumption depends on a small number of speed characteristics that summarize a trip: average speed, an average peak speed, braking time, stop time, and number of stops per unit distance. A second application concerns traffic management and fuel consumption. Average speed is the main determinant of fuel use. Attempted top speed of free-flow velocity is also an important determinant. Together, these driving characteristics enable a reasonable estimate of fuel consumption for planning purposes. For example, measures that increase traffic speed (up to about 50 mph) while decreasing maximum speed improve fuel economy. In these applications and others that are discussed, the coefficients are fundamental characteristics of the vehicles involved.

In two previous papers we developed a simple analytic approximation for fuel use by an automobile in terms of a small number of fundamental engine and vehicle characteristics and a few characteristics of driving over the course of a trip (*1*,*2*). We call this a simple physical model, distinguishing it from simulation models, which are also physical but much more detailed, and regression models, where the coefficients are estimated statistically rather than being directly measured physically. In this paper, we first explore some model capabilities, determining the effects on fuel use of changing the gear shift schedule, varying cruise speed, and driving to maximize fuel economy. We then analyze some common driving cycles to enable us to reexpress the fuel use model in terms of independent trip characteristics: average speed, target maximum speed, vehicle stop time, and, perhaps, number of stops. In this form, the model is a practical tool to help modify driving cycles so they reflect changes in driving behavior, estimate the effect of traffic management measures on fuel use, and analyze metropolitan area fuel use for planning purposes. Related work has also been done by Roumégoux (*3*).

The first paper in this series describes the simple (approximate) dependence of fuel use by engines based on systematic measurements made in the late 1970s (*4*):

$$\frac{P_f}{N} = a + \frac{1}{\eta}\frac{P_b}{N} \qquad (1)$$

where

P_f = rate of fuel energy use (kW),
P_b = rate of power output (kW), and
N = engine speed (revolutions per second).

The parameters are the engine's friction characteristic, *a* (fuel-energy rate at zero power output), which is approximately proportional to engine displacement, and a thermal efficiency characteristic, η, which is typically about 40 percent.

On the basis of this linear behavior, we showed in the second paper that fuel use in a trip can be approximately calculated in terms of certain additional vehicle characteristics and certain trip characteristics. The total trip time, *T*, has been divided into T_A, T_B, T_C, and T_D, where *A* incorporates periods of acceleration, *B* cruising and deceleration without brakes, *C* braking, and *D* vehicle stop. Thus $t_D = T_D/T$, for example.

The fuel use per unit distance, such as a kilometer or mile, is then

$$\begin{aligned}\varepsilon_{\mathrm{fuel}} = {} & [\alpha_{\mathrm{f\cdot pwr}}(1 - t_C - t_D)(v_{\mathrm{gear}}/\bar{v}) + \alpha_{\mathrm{f\cdot idle}}(t_C + t_D)/\bar{v}] \\ & + (\alpha_{\mathrm{tire}} + \alpha_{\mathrm{air}}\lambda v_{\mathrm{r}}^2 + \alpha_{\mathrm{brake}}\beta v_{\mathrm{p}}^2 n + \alpha_{\mathrm{acc}}/\bar{v}) \qquad (2)\end{aligned}$$

The α's are vehicle-dependent coefficients defined in the appendix. (Units are also presented in the appendix.) The principal trip-dependent variables are as follows:

$\bar{v}$ = overall average speed, D/T;
v_{r} = average running speed, $D/(T - T_D)$;
v_{p} = average peak speed (root-mean-square of subcycle peak speeds);
n = number of stops per mile (or major slowdowns); and
t_C, t_D = fraction of time braking and stopped, respectively.

Note that $v_{\mathrm{r}}(1 - t_D) = \bar{v}$.

Subsidiary trip variables that can be adequately estimated a priori are as follows:

v_{gear} = average vehicle speed in gear used in neighborhood of v_{r} times the gear ratio relative to that in top gear (discussed below);
λ = average of cubed running speed divided by the cube of the average, $\overline{v_{\mathrm{r}}^3}/\bar{v}_{\mathrm{r}}^3$, where, in this expression, only, v_{r} is the instantaneous running speed; and
β = fraction of vehicle kinetic energy absorbed by brakes (in regime *C*).

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One finds that (*a*) using the Federal Test Procedure (FTP) gear-shifting schedule, $v_{gear} \approx 24.6$ m/sec (55 mph) for an M5 transmission; (*b*) $\lambda \approx 2.0$ for urban driving and $\lambda \approx 1.0$ for highway driving (1.90 and 1.09 in the EPA urban and highway cycles, respectively); and (*c*) $\beta \approx 0.9$ in urban driving and $\beta \approx 1.0$ in highway driving. If ε is in kJ fuel energy per kilometer (mile), then the fuel economy *FE*, in kilometers per liter (miles per gallon) is

$$FE = 31{,}850/\varepsilon \qquad (120{,}600/\varepsilon) \tag{3}$$

where the energy content (lower heating value) of the common test fuel is 31.85 MJ/L (120.6 MJ/gal).

The form of Equation 2 is closely related to that of Equation 1, with, in the first brackets, a generalized engine friction term proportional to *a* and to the total number of revolutions through which the engine turns during the trip, and, in the second brackets, a load term proportional to $1/\eta$. The latter is the incremental fuel use to provide for the four loads: tire loss, air drag loss, braking loss, and operation of vehicle accessories. Equation 2 is an approximation that enables determination of the fuel economy of a vehicle, from nonproprietary information, to an accuracy of about 5 percent (standard deviation). [In particular, the fuel economies of a large sample of 1991 cars with M5 transmissions have been fit using a simplified version of Equation 2, depending only on three variable vehicle characteristics, weight, engine displacement, and N/v (engine speed to vehicle speed in top gear), with a standard deviation of 4 percent (*2*).] In Equation 2, the engine friction term is about 60 to 70 percent of the total fuel use in typical urban driving and about 50 percent in highway driving. Thus the parameters in that term must be determined relatively accurately. The individual load terms are less important and so can be determined more roughly.

The allocation of fuel use to the different terms of Equation 2 is based on a certain set of energy sinks: generalized engine friction (pumping air into the cylinders and exhaust out, rubbing friction, and operating the engine accessories) and four loads on the engine (the three drive-wheel loads of tire, air, and brakes, including transmission losses, plus operating the vehicle accessories). This is a different allocation from that often made. For example, one could allocate the engine friction term during vehicle running proportionately to the four loads. Since the engine friction term is large, this dramatically alters the picture. An argument for our approach is that the generalized engine friction term depends on a basic attribute of driving, the number of revolutions of the engine in a trip. Thus the fuel use associated with the generalized engine friction is closely related to trip velocities but roughly independent of the loads.

Whereas the model and applications in this paper apply to a wide range of driving patterns, they do not apply to all driving. Engine speed, air drag, and braking have been approximated for convenience. Because of this, and because the driving characteristics v_r, n, v_p, t_C, and t_D may be strongly correlated, scenarios of the kinds of driving to be analyzed need to be developed.

We consider the following scenarios, and they provide the structure for the paper:

1. A driver follows a pattern of travel defined in detail. (However, if any of three kinds of driving—extremely high acceleration, extremely high speeds, or long coastdown—occur, engine speed, air drag, and braking energy, respectively, have to be estimated with special care.)

2a. An arbitrary trip is made about which only four or five characteristics are specified. (The same qualifications on unusual driving apply.)

2b. This scenario is the same as Item 2a except that the trip has qualities relating to slowing down and stopping shared by many existing driving cycles. At a minimum, only two trip characteristics need to be specified.

APPLICATIONS TO SPECIAL KINDS OF DRIVING

Effect of Gear Shifting on Fuel Economy

Aggressive drivers tend to accelerate and decelerate the vehicle more quickly than the average. Aggressive acceleration usually results in much higher engine speed, because with manual transmission the driver tends to shift later (at higher *N*), and with automatic transmission, the system delays shifting up. This results in increased use of fuel. (Aggressive deceleration causes excessive fuel use as well.) By the same token, in driving designed to reduce fuel use, a major aim is reduced engine speed.

First a technical point: the first term in Equation 2 is proportional to the number of engine revolutions in a trip. Let the vehicle be moving at speed v and in a gear with ratio g. We define v_{gear} so that if the vehicle were in top gear it would have to move at speed v_{gear} to have the same engine speed. There are two cases. In the first, the vehicle moves at constant speed v:

$$v_{gear} = (g/g_{top})v \tag{4a}$$

In the second, the vehicle moves at a variety of speeds. While in the gear with ratio g,

$$v_{gear} \approx (g/g_{top})v_{w.a.} \tag{4b}$$

where $v_{w.a.}$ is the average speed in that gear. Using the gear shift schedule of the FTP, a good approximation to v_{gear} in the form of Equation 4b is 24.6 m/sec (55 mph) for M5 (manual five-speed) transmissions.

Starting with the EPA urban driving cycle (UDC) as the base case, consider that, with aggressive driving, gears are shifted at 125 percent of the velocities designated in the FTP. In the latter, gears are shifted up or down at 6.7, 11.2, 17.9, and 22.3 m/sec (15, 25, 40, and 50 mph), with an M5 transmission. According to Equation 2 this results in a 10 percent increase in fuel use (modeled with AVPWR).

Correspondingly, a shift indicator light (installed as original equipment in some cars) encourages shifting at about 80 percent of the FTP shift-schedule velocities. According to Equation 2, this results in a 9 percent fuel savings in the UDC (modeled with AVPWR). This savings is typical of that observed in tests (*5*). This kind of gear shifting is not feasible during rapid acceleration.

The savings from following a shift indicator light in the EPA highway cycle are less. In top gear, v_{gear} is roughly 23 m/sec (51 mph), and the corresponding fuel savings in the model are 3 percent. This estimate is in rough agreement with test results, but the latter are highly variable (*5*).

Cruise Fuel Economy

In constant speed, or cruise, driving, $v_p = \bar{v} = \bar{v}_r \equiv v$, the α_{brake} term is zero, and $t_C = t_D = 0$. Thus Equation 2 becomes

$$\varepsilon_{\text{cruise}} = \alpha_{\text{f.pwr}} v_{\text{gear}}/v + \alpha_{\text{tire}} + \alpha_{\text{air}} v^2 + \alpha_{\text{acc}}/v \qquad (5)$$

where Equation 4b is used for v_{gear}. (The use of Equation 4b smears the velocities with respect to gear shifting and so eliminates irregularities associated with the actual gear-shift velocities.) The fuel economies in cruise driving are shown in Figure 1 for the vehicle AVPWR (appendix). For today's streamlined cars, the maximum fuel economy at constant speed, v_{opt}, is near 23 m/sec (50 mph). The fuel economy falls off rapidly at low speeds. In particular, today's powerful engines are very inefficient at low power output. To illustrate this mismatch, the engine power required for the car AVPWR in cruise driving is also shown. The power requirement in urban cruise speeds is well under 10 kW, but the engine has power capability over 100 kW.

A more explicit view of the poor fuel economy at low speed is given in Figure 2. The source of inefficiency is the generalized engine friction, the $1/\bar{v}$ term, in Equation 2. This inefficiency is due to the large rate of fuel use at zero power output just to run a large engine.

Fuel Economy at High Speed

When the average speed is much higher than the optimal speed of about 22 m/sec (50 mph), the fuel economy decreases dramatically as the speed increases. This is what happens in driving on open highways, where the average speed has far surpassed 25 m/sec (55 mph). From Equation 5 we see that, since $v_{\text{gear}} = v$ (Equation 4a), the fuel consumption per mile is linear in v^2, except for the relatively small accessories term.

For AVPWR, the reductions in fuel economy from increasing the highway speed from 24.6 m/sec (55 mph) to 29.0, 33.5, and 44.7 m/sec (65, 75, and 100 mph) are 10, 20, and 40 percent, respectively.

Maximum Fuel Economy

What is the maximum fuel economy a given car can achieve? More specifically, in what kind of driving pattern does a car achieve maximum fuel economy? Consider a driving pattern with a lot of slow deceleration, with the brake seldom used. Call this pattern coastdown driving and the FE coastdown FE. An investigation of this issue (*6*, p. 117 ff) reveals that to achieve maximum fuel economy, you should first accelerate the car quickly, but not too quickly, to perhaps 33 m/sec (75

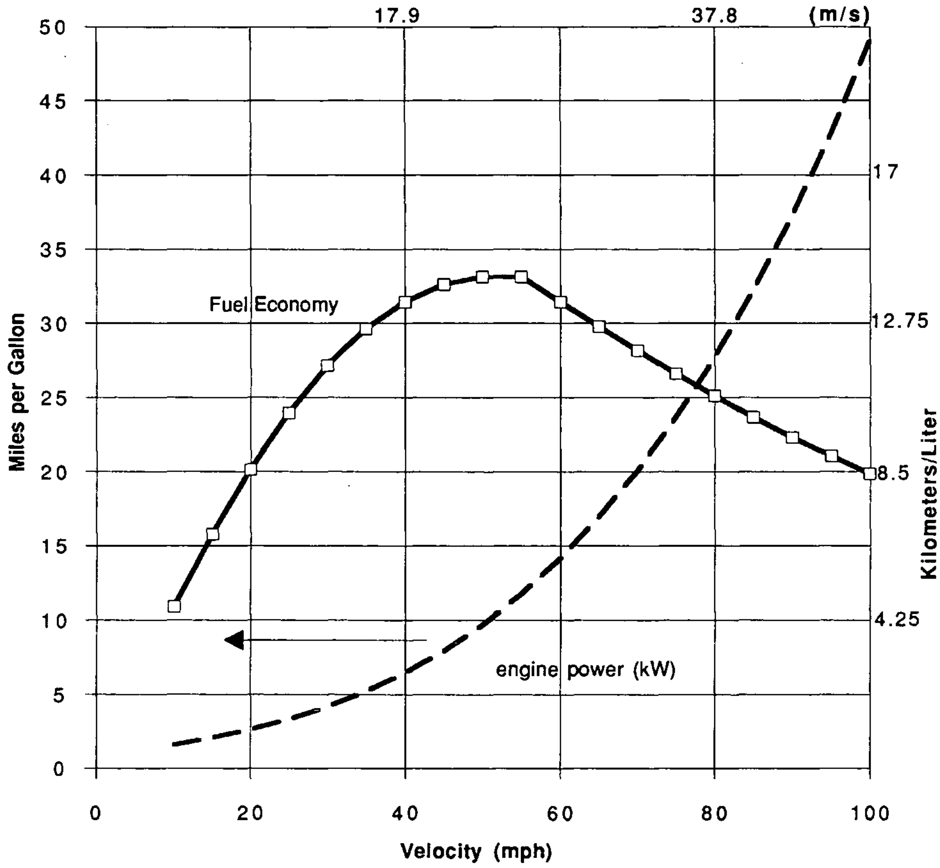

FIGURE 1 Fuel economy and power in cruise driving (car: AVPWR).

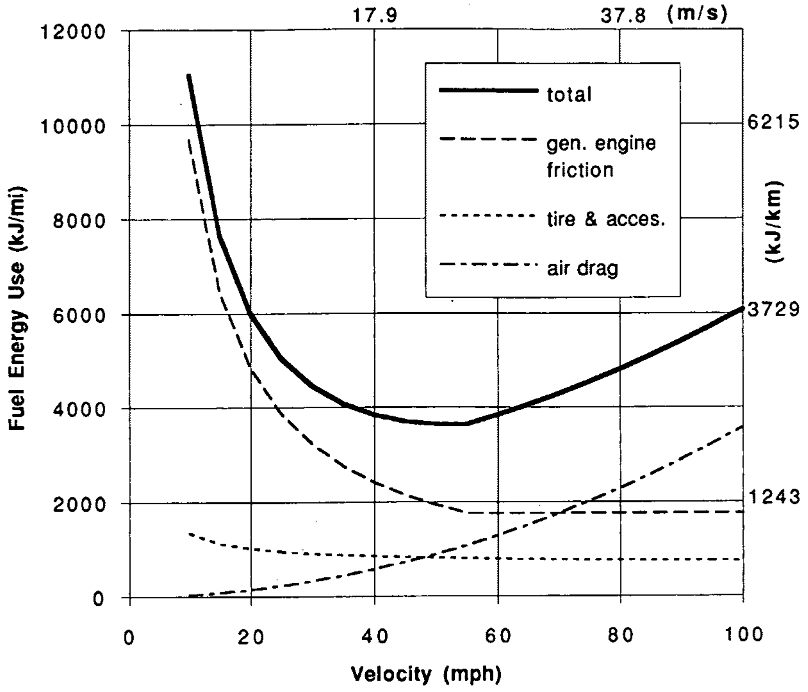

FIGURE 2 Specific fuel use in cruise driving (car: AVPWR).

mph), then let it coast to a stop. [The model does not account for rich operation of engines at high power (i.e., the use of high fuel-air ratios), which is a common design feature. This means that if one accelerates very rapidly or drives at very high speeds, the rate of fuel use is substantially higher, about 30 percent, than shown by Equation 2.] With repeated driving subcycles like this, you can improve the FE by 52 percent with average speed equal to that of the UDC, 8.8 m/sec (19.6 mph).

If you increase $\bar{v}$, the coastdown FE also increases until $\bar{v}$ reaches the cruise optimal speed v_{opt} (see Figure 3, fine-dashed line). For AVPWR, v_{opt} = 22 m/sec (49 mph), and the cruise optimal FE = 16.3 km/L (38.3 mpg).

Is coastdown driving with coastdown the most fuel-efficient driving? The answer is a surprising no. "Idle-off" driving with coastdown is more efficient. The definition of idle-off driving is that you turn off the engine and declutch when the vehicle coasts down. Thus $\alpha_{f,idle}$ = 0 (appendix). We get, for AVPWR,

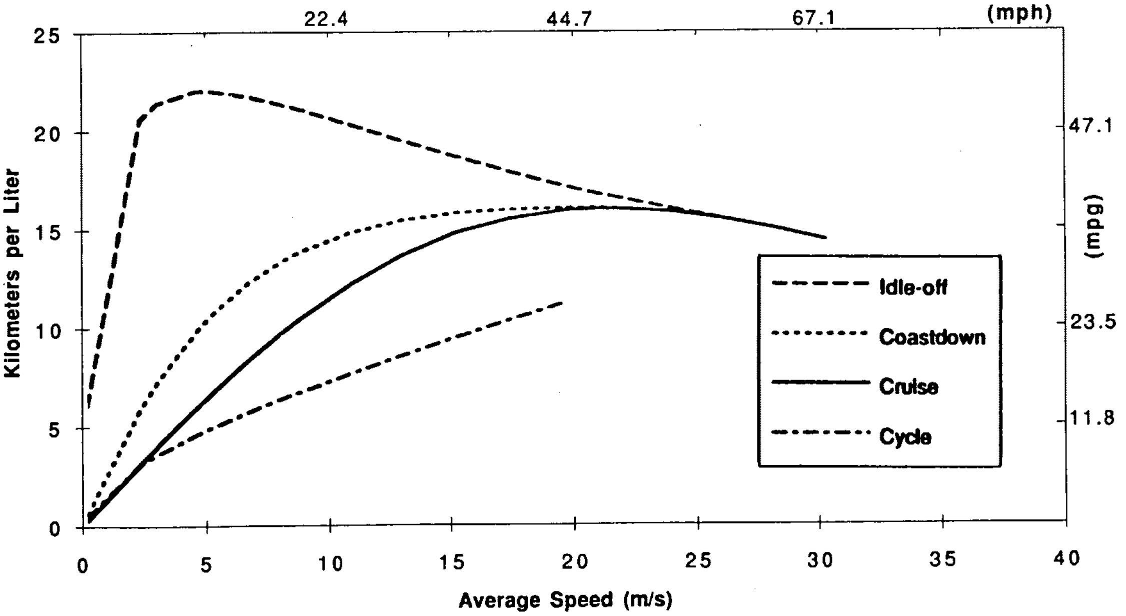

FIGURE 3 Maximum fuel economy.

with $\bar{v} = 8.8$ m/sec (19.6 mph), about 2.4 times better fuel economy than the driving cycle FE. (Here we again limit the maximum speed to 75 mph.) Unlike the other FEs, the idle-off FE peaks at very low average velocity [around 4.5 m/sec (10 mph)]. The long-dashed line in Figure 3 shows how the idle-off FE changes with the average speed. Table 1 gives the comparisons among the various FEs for AVPWR at $\bar{v} = 8.8$ m/sec (19.6 mph) except for cruise optimal driving, where $v = 22$ m/sec (49.0 mph).

In real driving conditions, the fuel economy can be dramatically improved by using the idle-off technique, even though the extreme coastdown driving discussed above is not involved. This has been discussed by several authors (*7–9*).

DRIVING-CYCLE MODEL

The model represented by Equation 2, although expressed in terms of macrocharacteristics of a trip, is still unwieldy for many purposes. In particular it involves five principal trip variables, two of which may be difficult to estimate (v_p and t_C) and are correlated with the others. By examining seven driving cycles, EPA urban and highway, Melbourne Peak, Beijing, ECE 15, Japan 10, and New York (*2*, Table 8), we find we can reduce the number of principal variables to three convenient trip characteristics.

It is often convenient to express fuel consumption as a function of overall average speed. L. Evans and others have shown how $\bar{v}$ alone enables a fairly good approximation of the effects of driving patterns on fuel economy (*10–14*). Our purpose here is to include the effects of other driving variables as well as to continue to express all the relationships in terms of fundamental engine and vehicle characteristics.

From study of the seven driving cycles we obtain the Driving-Cycle Model [adapted from Feng (*6*)]:

$$\varepsilon_{\text{fuel}} = \varepsilon_{\text{cruise}}(\bar{v}) - (\alpha_{\text{f.pwr}} v_{\text{gear}} - \alpha_{\text{f.idle}})(1 - \gamma^{-1} + t_C)/\bar{v} + \alpha_{\text{air}}\bar{v}^2(\lambda\gamma^2 - 1) + \alpha_{\text{brake}}\beta\gamma\bar{v}v_{\text{ff}}n \tag{6}$$

where $\gamma \equiv 1/(1 - t_D)$, and we suggest the following approximations:

$$t_C \approx (1.4\lambda - 1)s \tag{7}$$

$$n \approx \frac{1}{2\tau_{\text{stop}}} s/\bar{v} \tag{8}$$

where

$$s \equiv (1 - \sqrt{\gamma\bar{v}/v_{\text{ff}}})/\gamma \tag{9}$$

Here the principal trip-dependent variables are

$\bar{v}$ = overall average speed (or one can use $v_r \equiv \gamma\bar{v}$)
v_{ff} = free-flow velocity (discussed below), and
γ = vehicle stop factor (or one can use $t_D \equiv 1 - \gamma^{-1}$).

Although the principal variables are essentially independent, there is a bound imposed by v_{ff}:

$$v_r = \gamma\bar{v} \leq v_{\text{ff}} \tag{10}$$

Subsidiary variables that can be adequately estimated a priori are v_{gear}, λ, and β, as before, and τ_{stop}, the average braking time per stop, 6.7 sec in the EPA urban cycle and about 5 sec in the other urban cycles. τ_{stop} is about 1 min in the EPA highway cycle.

The Driving-Cycle Model, Equation 6, with the approximations given in Equations 7 and 8, is less accurate than Equation 2. The advantages are the smaller number of principal variables, their greater independence, and their easy interpretation. The new variable v_{ff} is defined in the driving cycles as follows:

$$v_{\text{ff}} = v_p^2/v_r$$

However, we find it can be estimated roughly as the speed limit plus 6.7 m/sec (15 mph) on freeways and speed limit plus 2.2 m/sec (5 mph) on urban roads. The column v_{limit} in Table 2 is the authors' estimate. The beauty of the variable v_{ff} in this form is that it is independent of $\bar{v}$ in that it depends on road and speed limit characteristics and not on any particular trip.

The variables $\bar{v}$ and v_{ff} are powerful predictors of fuel use in the context of the seven driving cycles. Is more detail needed for the kinds of applications to be made? To consider the important class of travel in which the fraction of vehicle stop time, t_D, is high, more detailed description of the travel, as provided by t_D, or γ, and perhaps n, may be needed.

Determination of Modified Driving Cycles

Driving patterns have changed since the specification of the regulatory driving cycles now in use. In the early 1980s, the discrepancy in FE between the FTP and actual driving was estimated to be 15 percent (*15*). It has been roughly estimated that this will rise to 30 percent by 2010 (*16*), and we estimate that it has already increased to between 20 and 25 percent. Some of the difference between test and actual conditions is associated with inaccuracies in testing (like tire slip on the dynamometer) and the poorer conditions, or maintenance, of actual vehicles in use than the new vehicles being tested. The

TABLE 1 Maximum Fuel Economy for AVPWR

	Cycle	Cruise	Coastdown	Cruise (opt)	Idle-off
$\bar{v}$ m/s (mph)	8.8 (19.6)	8.8 (19.6)	8.8 (19.6)	21.9 (49.0)	8.8 (19.6)
v_p m/s (mph)	13.8 (30.9)	8.8 (19.6)	33.5 (75.0)	21.9 (49.0)	33.5 (75.0)
FE km/ℓ(mpg)	9.1 (21.4)	10.2 (24.1)	13.8 (32.5)	16.3 (38.3)	21.5 (50.7)

TABLE 2 v_{ff} **in Seven Driving Cycles (m/sec, mph)**

Driving Cycle	v_{ff}	v_{limit}
EPA Highway	32.8, 73.5	24.6, 55*
EPA Urban	17.7, 39.6	15.6, 35
Melbourne	17.9, 40.1	15.6, 35
Beijing	11.2, 25.0	11.2, 25
Europe	12.4, 27.8	11.2, 25
Japan	12.0, 26.8	11.2, 25
New York City	14.7, 33.0	13.4, 30

* The EPA Highway Cycle involves a mix of four rural road types: principal arterial, minor arterial, collector, and local.

main reasons for the increase in the discrepancy are, presumably, increased congestion, increased open highway speeds, and perhaps, more urban-type driving. Both to reduce the differences between test and actual driving and to identify the sources of change, EPA is carrying out a program of observation on typical driving.

The model, Equation 2, suggests that cycle modifications be created on the basis of measurement of a few macrocharacteristics of driving instead of repeating the data-intensive process associated with the definition of the present cycles, which are second-by-second velocity patterns. Equation 2 depends on five principal summary variables for a trip. Equation 6 reorganizes some of these variables and suggests that three or four may be enough to define a trip for purposes of fuel consumption. Average speed, free-flow velocity, fraction of time vehicle stopped and, perhaps, stops per mile should be measured, and fuel-use weighted averages created. Another variable is implicit in the engine friction characteristic and needs to be incorporated in specification of a driving cycle for fuel economy: cold start. Whereas a revised cold start characterization may be needed, we have not studied what it should be.

In addition, certain driving characteristics are critical to emissions but not important for fuel use. Outstanding among those in an acceleration characteristic, for example, the distribution of the variable velocity times acceleration. Engine power output is closely related to the latter, and emissions are very sensitive to power output. Careful study is needed to define cycles for regulation of emissions; we do not suggest that our work relating to driving cycles for fuel economy implies the contrary.

We illustrate the effects on fuel economy of changing the three principal variables one at a time. [v_{gear} = 24.6 m/sec (55 mph) (given by Equation 4b) is used in all the remaining calculations.] Fuel economy is most sensitive to overall average speed, $\bar{v}$ (see Figure 4). For example, vary $\bar{v}$ 10 percent up (or down) from its UDC value of 8.8 m/sec (19.6 mph) while fixing v_{ff} at its UDC value and the fuel economy is increased (or decreased) 5 percent. At the relatively low speeds of the urban cycle, the dominant cause of fuel use is generalized engine friction, which is proportional to the number of engine revolutions in the trip. If the running speed is increased while engine speeds remain about the same, the trip time decreases and the total number of engine revolutions is decreased.

Fuel economy is also sensitive to free-flow velocity, v_{ff} (Figure 5). Decreasing v_{ff} by 25 percent from its UDC value of 17.7 m/sec (39.6 mph) while fixing $\bar{v}$ at its UDC value increases

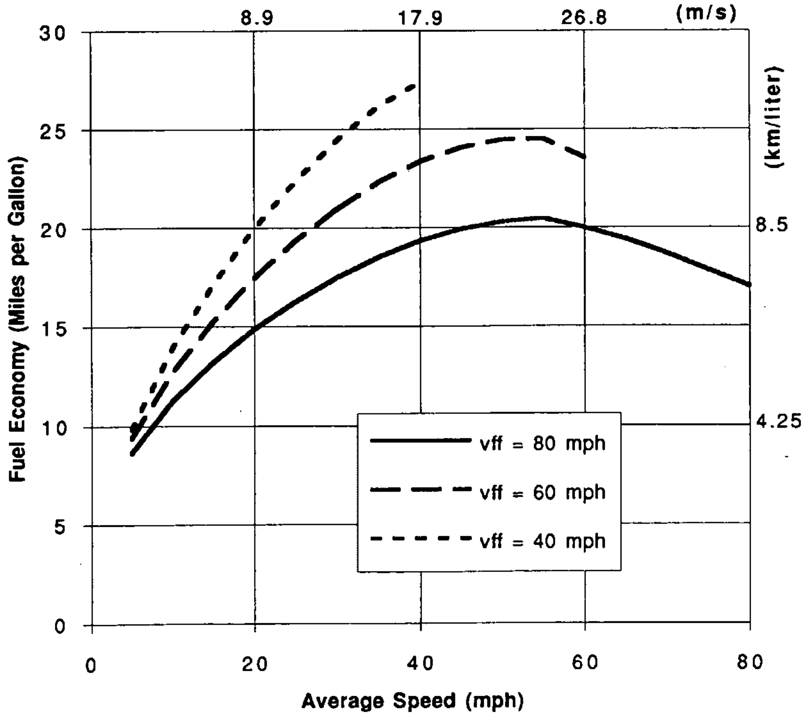

FIGURE 4 Fuel economy and average speed (stop time = 0.00; car: AVPWR).

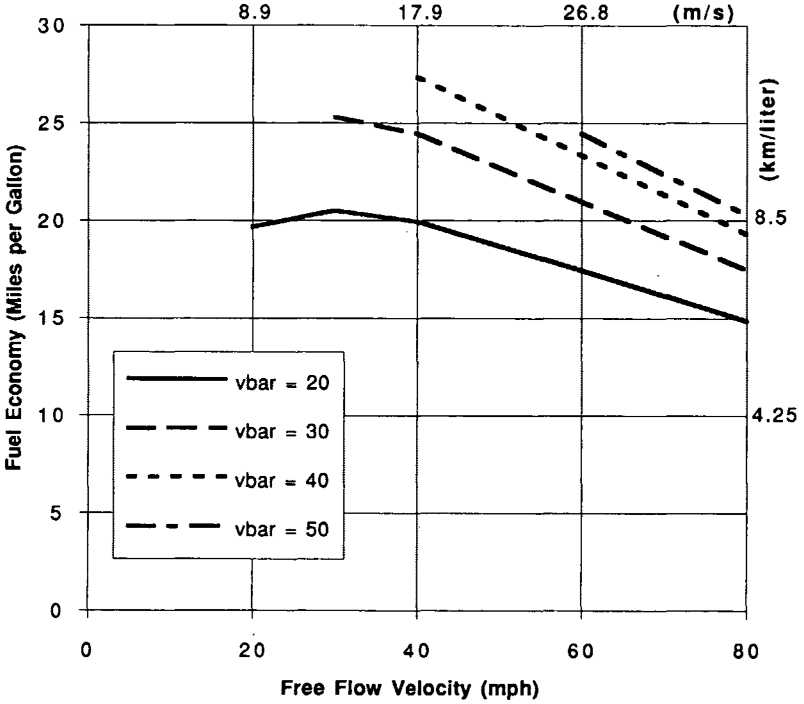

FIGURE 5 **Fuel economy and free-flow velocity (stop time = 0.0; car: AVPWR).**

the fuel economy by 5 percent. Fuel economy is less sensitive to vehicle stop time, although it improves slightly with increased stop time under most conditions (Figure 6).

Effect of Traffic Smoothness on Fuel Economy

From Equation 6, we see that fuel economy is determined by three factors: average speed $\bar{v}$, free-flow speed v_{ff}, and vehicle stop time. In this section, we will use Equation 6 to answer the question, How does traffic smoothness affect fuel economy?

There are two issues. The first is, If the average speed of total trip time is fixed, how can the traffic pattern be changed to improve fuel economy? From Equation 6, the answer is by reducing the free-flow speed v_{ff} and perhaps by increasing total vehicle stop time.

Assuming crowded roads such that the average travel speed cannot be increased, the answer is to reduce v_{ff}. While the primary determinant of fuel economy is average speed, Equation 6 shows that a road characteristic, the free-flow speed, is also important. In Figure 5 one finds, for example, that if $\bar{v}$ is fixed at 13.4 m/sec (30 mph), when v_{ff} is reduced from 26.8 to 17.9 m/sec (60 to 40 mph) the fuel economy of AVPWR increases 16 percent. The dependence of the fuel economy on roadway types has been discussed previously by Levinsohn and McQueen (*17,18*). They say, "In free flowing traffic conditions, the road type does not have an effect upon fuel consumption at a given speed; however, if there is congestion, vehicle fuel consumption will vary with road type." Their studies show that the speed that is important when related to traffic volume is the attempted speed of the automobile.

If the $v_{ff}/\bar{v}$ ratio is high, there is a lot of rapid acceleration and deceleration, with increased braking and air drag. The maximum attempted speed can be reduced by reducing the speed limit at times when traffic congestion is heavy, as long as overall average speed is not reduced, and by using traffic light control techniques, such as signal green wave, ramp control, and so on (*19*).

The second answer, to increase vehicle stop time t_D, is obscure at first glance. When you increase t_D but keep $\bar{v}$ and v_{ff} unchanged, you are decreasing the amount of low-speed driving with its high fuel use associated with generalized engine friction (Figure 2). The overall balance of effects is such that there is a small benefit from increased vehicle stop time (Figure 6). This means that, in principle, metering of traffic flow, as in the westbound approach to the San Francisco Bay bridge, is in itself helpful.

The above two measures not only increase the vehicle fuel economy but also can increase road capacities (*20*). Smoother traffic can reduce spacing or headway between cars, thus increasing capacity.

The second issue is, Can the average speed be increased? Among other benefits, fuel economy will usually improve. We discuss only this latter point: the main issue is whether v_{ff} is increased as part of the strategy to increase $\bar{v}$. If so, the increase in fuel economy is less. In Figure 5 we see that if one increases $\bar{v}$, the fuel economy is increased the most if v_{ff} can be kept fixed or, even better, decreased. Meanwhile if v_{ff} is greatly increased as part of the strategy to increase $\bar{v}$, the fuel economy may not be improved.

Traffic Management Analysis

The Driving Cycle Model is converted into numerical form using the definitions of vehicle factors α in the appendix and

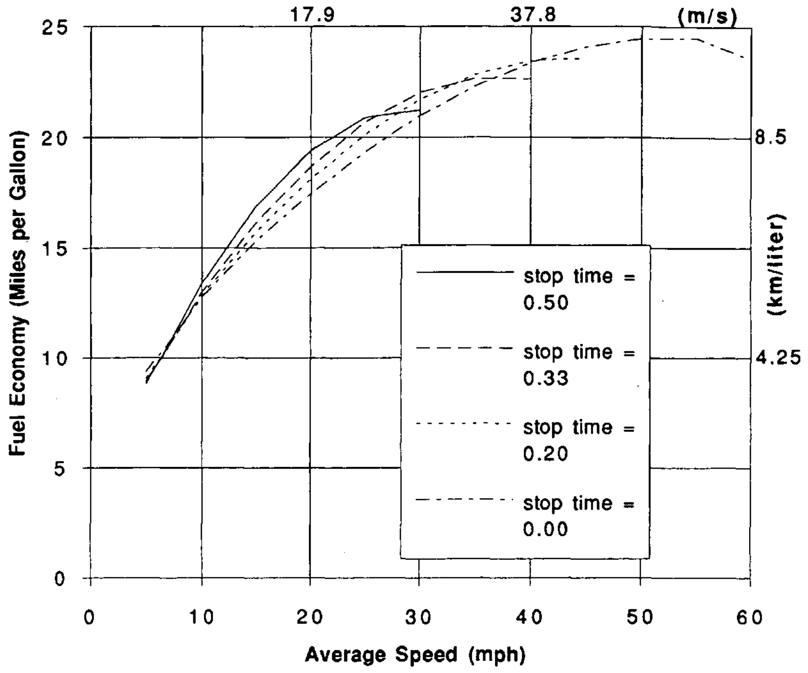

FIGURE 6 Fuel economy, fixed free-flow velocity, and various relative stop times (free-flow velocity 60 mph; car: AVPWR).

expressing all the dependence on vehicles in terms of two characteristics: inertial weight, W, and the product of engine displacement and (N/v), where N/v is rpm/mph in top gear. This procedure is analogous to that used to obtain Equations 32 and 33 of An and Ross (*2*). For convenience, the vehicle characteristics are related to the AVPWR base case:

$$M_0 = 1588 \text{ kg} \qquad (W_0 = 3500 \text{ lb})$$

and

$$V_0(N/v)_0 = 3.1\text{L} \times 1.306 \frac{\text{rps}}{\text{m/sec}} \left(3.1\text{L} \times 35 \frac{\text{rpm}}{\text{mph}}\right)$$

As suggested by Equations 6, 7, and 8, only three driving characteristics will be represented: $\overline{v}$, v_{ff}, and γ. We also express these variables in terms of ratios to a base case, the EPA urban driving cycle: $\overline{v}_0$ = 8.8 m/sec (19.6 mph), v_{ffo} = 17.7 m/sec (39.6 mph), and $\gamma_0 = 1/0.81$. We find the following for urban driving (in kJ/mi):

$$\varepsilon_{\text{fuel}} = \frac{[5{,}263 - 3{,}106\,(t_C + t_D)]}{(\overline{v}/\overline{v}_0)} \frac{V(N/v)}{V_0(N/v)_0} + \left[682 + \left(239\frac{W_0}{W} + 159\right)\frac{\gamma^2\overline{v}^2}{\gamma_0^2\overline{v}_0^2} + 925\frac{\gamma v_{\text{ff}} s}{\gamma_0 v_{\text{ffo}} s_0}\right]\frac{W}{W_0} \tag{11}$$

where

$$t_C + t_D = 1 - 0.81\gamma/\gamma_0 + 0.30\, s/s_0 \text{ and}$$

$$s = 0.81\left(1 - 0.7817\sqrt{\frac{\gamma\overline{v}\; v_{\text{ffo}}}{\gamma_0\overline{v}_0\; v_{\text{ff}}}}\right)\frac{\gamma_0}{\gamma}.$$

The first term in Equation 11 incorporates the generalized engine friction and the small vehicle-accessories term. The second term incorporates the tire, air drag, and braking terms, in that order. The coefficients are derived from measured physical quantities in essentially all cases; they are not regression coefficients. To convert Equation 11 to grams of fuel per mile, if needed, one multiplies every term on the right-hand side by the factor 0.227 (g/kJ).

Equation 11 is in a form to be used to calculate fuel use as an adjunct to traffic flow analysis. One first needs to decide what parameters characterize the vehicles in question. (The numbers in Equation 11 apply to M5 cars of recent vintage.) Then one can apply the equation to vehicle miles of travel on segments of roadway where specific values of average speed and free-flow speed apply, keeping in mind that average speed and free-flow speed are the critical parameters; accuracy in other parameters is less important.

CONCLUSIONS

The relatively simple equations presented in this paper enable accurate determination of fuel consumption in a trip in terms of basic characteristics of the vehicle and trip. The principal variables are easily interpreted physical quantities rather than regression coefficients, and the equation is the final result, not an input to a computer simulation program. These models combine trip and vehicle characteristics and can readily be expressed to yield fuel use for any mix of vehicles for which a few fundamental attributes can be estimated. We have suggested several applications; we believe there are many others.

TABLE A-1 Characteristics of AVPWR

V	engine displacement	3.1 liters (189 CID)
W	inertial weight	1588 kg mass (3500 lbs.)
N/v	engine/vehicle speed ratio (in top gear)	1.036 rps/(m/s) (35 rpm/mph)
C_DA	air drag factor	0.68 m^2

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APPENDIX
VEHICLE PARAMETERS

The vehicle-dependent coefficients in Equation 2 are as follows:

1. Generalized engine friction in powered operation:

$$\alpha_{f.pwr} = kV(N/v) = 60kV(N/v) \quad \text{(kJ/mi)} \qquad \text{(A-1)}$$

where

V = engine displacement (L),
(N/v) = (engine speed/vehicle speed) in top gear (rpm/mph),
k = V/a, and
a = the engine friction characteristic.

For current vehicles, we use the estimates $k = 0.27$ kJ/lit. rev. for the EPA urban driving cycle, where the engine starts cold, and $k = 0.25$ kJ/lit. rev. when it is hot (*1,2*).

2. Generalized engine friction in idle operation:

$$\alpha_{f.idle} = kVN_{idle} = 60kVN_{idle} \quad \text{(kJ/hr)} \qquad \text{(A-2)}$$

where N_{idle} is idle engine speed in rpm and k can be taken from Equation A-1. A convenient approximation that we use is $N_{idle} = 900(1 - V/14.8)$ rpm. For Equation 11 we use $N_{idle} \approx 21\ (N/v)$.

3. Tire rolling resistance:

$$\alpha_{tire} = C_RW/\eta\varepsilon = 4.45 \times 1.609C_RW/\eta\varepsilon \quad \text{(kJ/mi)} \qquad \text{(A-3)}$$

where

C_R = coefficient of rolling resistance (dimensionless, which we take to be 0.010),
W = inertial (loaded) vehicle weight (lb), and
ε = efficiency of the transmission system (taken to be 0.90, dimensionless).

η is defined by Equation 1 and is taken to be 2.45 (dimensionless). The numerical factors are the ratio of Newtons to lb and km to miles, respectively.

4. Air resistance:

$$\begin{aligned}\alpha_{air} &= \rho C_DA/2\varepsilon\eta \\ &= 0.5 \times 1.20(0.447)^2\ 1.609C_DA/\varepsilon\eta \\ &\quad \text{(kJ/mi)(mph)}^{-2}\end{aligned} \qquad \text{(A-4)}$$

where

ρ = 1.20 kg/m^3 is the density of air,
C_D = coefficient of drag of the vehicle (typically about 0.35 for 1992 cars), and
A = frontal area of the vehicle in (m^2) (about 2.0 for an average car). The factor 0.447^2 is to convert the v_r^2 in Equation 2, which is in mph, to m/sec.

5. Brakes:

$$\begin{aligned}\alpha_{brake} &= M^*/2\varepsilon\eta \\ &= \frac{1.035 \times 0.454 \times 0.447^2}{2{,}000}\ \frac{W}{\varepsilon\eta} \quad \text{(kJ)(mph)}^{-2}\end{aligned} \qquad \text{(A-5)}$$

where M^* is the vehicle mass including the effects of rotational inertia (a factor of 1.035). The factor 0.454 converts pounds to kilograms. The v_p and n factors in Equation 2 should then be in mph and mi^{-1}, respectively, to obtain kJ/mi.

6. Vehicle accessories:

$$\alpha_{acc} = P_{acc}/\eta = 3{,}600\ P_{acc}/\eta \quad \text{kJ/hr} \qquad \text{(A-6)}$$

where the power to operate the vehicle accessories, such as air conditioning, power brakes and steering, lights, and audio system is in kW (which we take to total 0.75).

In this paper we consider an average new U.S. car, denoted AVPWR, to have the characteristics given in Table A-1.

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Improving Fuel Economy: A Case Study of the 1992 Honda Civic Hatchbacks

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Since the early 1980s, U.S. automobile makers and policy makers have resisted policies to increase automobile fuel economy, arguing in part that such increases were neither technically feasible nor economically justified. Such assertions for the 1992 Honda Civic hatchbacks are analyzed. With the 1992 Honda Civic model line, an automobile maker has, for the first time, produced cars that are virtually identical to the previous year's models in size, vehicle amenity, engine power, and performance, but that offer substantially increased fuel economy and improved safety. The cost of improving fuel economy is assessed using actual retail prices, after correcting for differences in cosmetic features. Calculations indicate that the efficiency of the 1991 Civic DX was improved by 56 percent from 1991 to 1992 at a cost per conserved liter of gasoline that is \$0.20/L (\$0.77/gal), or 30 percent less than the levelized gasoline price without externalities or taxes. In addition, a comparison of two other Civic models indicates that fuel economy was improved in the 1992 versions at no additional cost. Virtually all of the efficiency increases described here were achieved through measures that do not affect safety or vehicle size, such as engine modifications, transmission alterations, and drag reduction.

Since the early 1980s, U.S. automobile makers and some analysts (*1*) have argued that policies to increase automobile fuel economy were neither technically feasible nor economically justified. This paper applies Kenneth Boulding's first law ("anything that exists is possible") to analyze such assertions in the case of the 1992 Honda Civic hatchbacks. With the new Hondas, an automobile maker has, for the first time, produced cars that are virtually identical to the previous year's models in size, vehicle amenity, engine power, and performance, but that offer substantially increased fuel economy and improved safety.

This paper [which is a summary of a more detailed analysis contained elsewhere (*2*)] describes the characteristics of the 1991 and 1992 Honda Civics and demonstrates their equivalence in vehicle amenity. It presents the fuel economy technologies that Honda used to improve the efficiency of the Civic by more than 50 percent. It describes the methodology for estimating the cost of conserved energy (CCE) for these efficiency improvements and presents the results of our CCE calculations. The paper concludes by discussing the potential impact of gasoline taxes and "feebate" policies on both consumer and manufacturer behavior related to energy efficiency choices for these vehicles.

CHARACTERISTICS OF HONDA CIVICS

This section describes the level of vehicle amenity of the 1991 Civic DX and the 1992 Civic DX and VX. Koomey et al. (*2*) also describe a similar comparison between the 1991 Civic base-model hatchback and the 1992 Civic CX Hatchback. Examination of the specifications of these vehicles and actual test drives reveal that fuel economy gains were achieved with negligible impact on performance, driveability, and comfort. We can conclude from the results of this section that the cars deliver equivalent consumer utility.

General Description

The 1992 model year Honda Civics represent a "new generation" of Civics. Honda completely redesigned the engine, body style, suspension, aerodynamics, and other major features of this model but kept total interior space constant while improving performance. In addition, Honda added a new hatchback, the VX, to its Civic line. The VX is similar to the mid-cost Civic DX hatchback, except that the VX is optimized for fuel economy.

Table 1 presents specifications and features of the 1991 and 1992 Civic DX and VX hatchbacks (*3–6*; J. Leestma, personal communication). The major difference among the 1991 Civic DX, the 1992 DX, and the 1992 VX is the improved fuel economy of the 1992 vehicles. The 1992 DX is about 13 percent more fuel efficient than the 1991 model, whereas the 1992 VX has 56 percent higher efficiency (this estimate for the VX is for the "49-state" VX sold in all states but California).

The 1992 DX and VX are slightly larger than the 1991 DX, as shown by the interior and exterior dimensions given in Table 1. In addition, the 1992 models are equipped with a driver-side air bag, resulting in improved safety over the 1991 DX. The fuel tank of the VX is more than 7 L (1.9 gal), or 16 percent, smaller than those of the 1991 and 1992 DX. However, the improved fuel economy of the VX means that a VX owner would still have to refuel less often than an identical DX owner.

Performance

Other than fuel economy differences, operational and performance variations among the three cars are minimal. The 1992 VX and the 1991 DX are both rated at 92 horsepower. How-

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TABLE 1 Specifications/Features of Honda Civic Models

Specifications/Features	1991 DX	1992 DX	1992 VX
Fuel Economy			
Unadjusted liters per 100 km (city/hwy)	6.9/6.0 (34/39)	6.0/5.3 (39/44)	4.4/3.9 (53/61) (a)
Adjusted liters per 100 km (city/hwy)	7.6/6.7 (31/35)	6.7/5.9 (35/40)	4.9/4.3 (48/55) (a)
Adjusted liters per 100 km (composite)	7.2 (32.7)	6.3 (37.1)	4.6 (50.9)
Engine, Drive Train			
Horsepower (@ rpm)	92 @ 6000	102 @ 5900	92 @ 5500
Torque (Newton-meters @ rpm)	121 (89) @ 4500	133 (98) @ 5000	132 (97) @ 4500
Valve train	SOHC, 16-valve	SOHC, 16-valve	VTEC-E
Fuel induction (b)	DP Fuel Injection	MP Fuel Injection	MP Fuel Injection
Drive-train type	Front-wheel Drive	Front-wheel Drive	Front-wheel Drive
Transmission	5-Speed Manual	5-Speed Manual	5-Speed Manual
Final drive train ratio	3.89	4.06	3.25
Exterior Dimensions			
Wheelbase (cm)	250	257	257
Overall Length (cm)	399	407	407
Overall Width (cm)	168	170	170
Curb weight (kg)	979 (2158)	988 (2178)	950 (2094)
Coefficient of drag	0.33	0.32	0.31
Interior Dimensions			
Headroom front/rear (cm)	97.0/93.0	98.0/93.0	98.0/93.0
Legroom front/rear (cm)	98.0/93.0	108/77.5	108/77.5
Cargo volume (cu. m)	0.48	0.38	0.38
Passenger volume (cu. m)	2.1	2.2	2.2
Fuel capacity (l)	45.0 (11.9)	45.0 (11.9)	37.9 (10)
Power features			
Steering	no	no	no
Windows	no	no	no
Safety features			
Driver airbag	not available	standard	standard
Cost (1992 $)			
Invoice/dealer cost	8171 (c)	8663	9258
MSRP (b)	9563 (c)	10140	10840
Performance			
Seconds to go from 0 to 100 kph	NA	10.2	10.5

Source: Reference (2).

English units given in parentheses. Fuel economy: mi/gal; torque: ft-lbs; curb weight: lbs; fuel capacity: gal.

a. Fuel economy is for the 49-State version of the VX. The California version is less efficient.

b. DP = Dual-point; MP = Multi-point; MSRP = Manufacturer's suggested retail price.

c. 1991 costs adjusted to 1992 $ assuming 4% inflation.

ever, maximum horsepower is achieved at 5,500 rpm in the VX and at 6,000 rpm in the 1991 DX. Thus, the VX engine provides slightly more power at engine speeds up to 5,500 rpm, which is the range in which most drivers operate. The 1992 DX reaches a maximum horsepower of 102 at 5,900 rpm. However, in comparison with the VX, the horsepower difference is likely to go unnoticed unless one drives at engine speeds greater than 5,500 rpm (which few drivers ever do). The time required to go from 0 to 100 kph (62 mph) is also related to horsepower. There is little difference between the 1992 DX and the 1992 VX in this area: the 1992 DX takes 10.2 sec to reach 100 kph, whereas the 1992 VX takes 10.5 sec.

Another important indicator of vehicle performance is torque. High torque allows quicker acceleration at low engine rpm (e.g., when accelerating from a stoplight). The 1992 DX and the VX both provide slight torque improvements over the 1991 DX. The 1992 DX supplies 133 N-m (98 ft-lb) at 5,000 rpm, whereas the 1991 DX supplies 121 N-m (89 ft-lb) at 4,500 rpm. The VX is likely to have the best "pickup" at engine speeds comparable with those encountered in everyday driving, since it attains 132 N-m (97 ft-lb) of torque at only 4,500 rpm (J. Keebler, personal communication).

Driveability

The comparison of features and specifications has focused on the differences between the three vehicles on paper. However, before one can conclude that the Civic hatchbacks are identical in terms of the service they provide, one must also evaluate the cars on the road. A series of drivers who test-drove the VX found that, in general, it handled well and performance was impressive. Some drivers found that they had to adjust their driving styles to take advantage of the taller gearing of the VX (R. Maio, personal communication; K. Passino, personal communication). Taller gearing results in lower engine speeds than those typically experienced in a given gear. Some drivers also noted occasional engine "stumble," or hesitation, during quick acceleration in lean-burn operation (*7*). This hesitation occurs as the engine adjusts to a lower air/fuel ratio. All but one *Automotive News* reviewer believed that this effect would not adversely influence the average driver's perception of the vehicle's performance, and the reviewer who found the stumble unacceptable was a driver who preferred high-performance vehicles (J. Keebler, personal communication). For typical Civic drivers (who probably do not seek high power), we can conclude from these reviews that the performance and driveability of the VX are equivalent to those of the 1991 and 1992 DX.

Comfort and Amenities

Although the primary specifications and performance of the Civic models are essentially identical, minor differences exist in the cosmetic features of the DX and VX hatchbacks. These features and their estimated costs are described by Koomey et al. (*2*). The 1991 and 1992 DX models are both equipped with an adjustable steering column, rear cargo cover, rear windshield wiper, and bodyside molding, whereas the VX lacks these features but has a tachometer and lightweight alloy wheels. The cargo area cover adds utility to the DX models because it hides any cargo and makes it appear that the vehicle has a trunk. The lightweight alloy wheels on the VX are cosmetic in that they look "sportier," but they also affect fuel economy because of their lighter weight.

Safety

The safety of the 1992 Civic models was improved significantly by the addition of a driver's side air bag in both the DX and the VX. The 1991 DX does not have a driver's side air bag. The added safety provided by the air bag is reflected in reduced insurance premiums. For example, the United Services Automobile Association (USAA) Casualty Insurance Company reduces the premium for medical payments coverage (MPC) by 60 percent compared with the 1991 DX for owners of the 1992 DX or VX (V. Blackstone, personal communication). There is no difference in the premium for MPC for the 1992 DX and VX, which indicates that professional risk assessors of at least one major insurance company believe that the slight difference in weight of these two vehicles has a negligible effect on safety. Furthermore, because the VX is lighter than the DX, its use imposes less risk on other vehicles. There are currently no crash test data with which to further compare the safety of these vehicles.

Emissions

As described by Koomey et al. (*2*), CO and HC emissions from the 49-state version of the VX are comparable with those from the 1991 and 1992 DX. NO_x emissions are slightly higher in the 49-state VX than in the 1991 and 1992 DX models, and carbon dioxide emissions are lower in direct relation to the efficiency of the vehicles. All of these automobiles meet current emissions standards in the states in which they are sold.

FUEL ECONOMY TECHNOLOGIES

As discussed above, the 1992 VX provides a 56 percent improvement in efficiency over the 1991 DX. This is achieved by the use of technological improvements that increase the efficiency of converting fuel energy to usable work and reduce the amount of work required to move the vehicle.

The technological differences responsible for the improved fuel economy in the VX include

- VTEC-E engine with lean-burn,
- Changes in axle and gear ratios,
- Multipoint fuel injection,
- Decreased vehicle weight,
- Improved aerodynamic characteristics,
- Low rolling resistance tires,
- Reduced idle speed, and
- Shift indicator light.

Table 2 summarizes these technologies and presents estimated contributions to fuel efficiency and costs (in 1992 dollars) associated with each approach (*8–10*; T. Harrington, personal communication). More details on particular technologies are provided by Koomey et al. (*2*) and Bleviss (*11*).

The largest percentage improvements come from transmission/gearing and engine modifications. This fact is noteworthy because changing engine and transmission characteristics do not affect safety or vehicle size. Only weight reduction may have an effect on safety, depending on where the weight is removed. The weight changes in the VX are small (3 to 4 percent), so they are unlikely to significantly affect safety.

Capital Costs of Fuel Economy Improvements

The costs of the technologies listed previously are not readily available and vary widely depending on the source of the estimate. The process of estimating costs is further complicated by the fact that several of the technologies may overlap. For example, the variable valve feature of the VTEC-E engine permits the use of lean-burn technology and changes in drive ratio. Thus, an estimate of the cost of variable valve timing may also include the cost of lean-burn technology and drive ratio changes. Despite these complications, we provide estimated costs of fuel economy technologies in Table 2. The total estimated costs of these technologies range from $448 to $1,084.

Applicability of Civic VX Improvements to Other Vehicles

Not all technologies used to improve the efficiency of the Civic can currently be transferred to other new cars. We focus

TABLE 2 Technologies Used To Increase Efficiency in the 1992 VX

Technology	Efficiency Improvement (%) '91 DX to '92 VX	Cost (a) (1992 $/car)
Multi-point fuel injection	1.5	56-162
Low rolling resistance tires	1	21-22
VTEC-E engine		
variable valve timing	2.5	108 -164
lean burn	5 -10	150 - 500
reduced friction	1.5	35-65
roller cam followers	1	19-54
Weight reduction	2.5	37 - 78 (b)
Aerodynamic improvements	1.5	22 - 39 (c)
Gearing and drive ratio changes	21	N/A (d)
Reduced idle speed/rpm	3	N/A (d)
Shift indicator light	5	N/A (d)
Total	45.5 - 50.5 (e)	448 - 1084

Source: Reference (2).

a. All costs represent retail costs to the consumer. Most cost estimates adjusted from 1988 and 1990 $ based on 4.1% implicit price deflator for GNP for 1989 and assumed 4% annual deflator for 1990 to 1992.

b. Cost estimate from Greene and Duleep based on $0.50/lb reduced (1988$). Estimate from SRI based on 5% weight reduction.

c. Cost based on 10% aerodynamic improvement.

d. N/A = not available.

e. Totals based on simple addition do not add to 56% due to synergistic effects of fuel economy technologies (e.g., variable valve timing allows gearing changes and use of lean burn).

in particular on the applicability of the lean-burn engine. Details on how other efficiency options might apply to different portions of the U.S. automobile fleet are given by Ledbetter and Ross (*12*).

Keebler (*7*) reports that "heavy vehicles have poor driveability when calibrated with lean-burn fuel strategies," which implies that this strategy, as currently implemented, may not be directly transferable to the larger cars in the U.S. fleet. Because of increasingly strict NO_x emissions standards, lean-burn technology may not be viable in some vehicles until improved NO_x catalysts are developed. According to Sanger (*13*), Honda engineers believe it will be "several years . . . before they can transfer the technology to larger, less efficient engines." However, it has been reported that Honda plans to use lean-burn technology on its larger Accord model as early as the 1994 model year (*14*). Research on this issue is proceeding elsewhere as well. Recently, a company in Massachusetts announced the development of a new lean-burn engine that combines high efficiency and low NO_x emissions for an additional cost of $100 to $200 per car (*15*).

METHODOLOGY

The purpose of the calculations in the next two sections is to estimate the costs and benefits of improving the fuel economy of the 1991 Civic DX to the level of the 1992 Civic DX and VX models. Actual retail prices are used to estimate the cost of improving fuel economy, whereas projections of motor gasoline prices are used to estimate the levelized fuel price.

Definition of Cost-Effectiveness

By cost-effective, we mean that the costs of investing in automobile efficiency are lower than the costs avoided by this investment. The cost of an efficiency improvement is usually assessed by calculating the CCE. The costs avoided by the efficiency investment include the direct cost of the unused fuel and whatever social or external costs are associated with the consumption of gasoline that are not included in the gasoline price. Whenever the CCE is lower than the avoided direct costs plus external costs (in dollars per gallon), we can say that an efficiency investment is cost-effective.

Cost Perspective

We adopt the perspective of the buyer of a new car who will use the vehicle over its entire lifetime. This simplifying assumption is also roughly comparable with the societal perspective without externalities (assuming that the discount rate used reflects social and not individual preferences).

CCE

The CCE (in dollars per liter) is calculated using Equation 1:

$$\mathrm{CCE} = \frac{\text{capital cost (\$)} \times \dfrac{d}{[1 - (1 + d)^{-n}]}}{\text{annual energy savings (liters)}} \qquad (1)$$

where

d = discount rate,
n = lifetime of the automobile, and
$d/[1 - (1 + d)^{-n}]$ = the capital recovery factor.

The numerator in the right-hand side of Equation 1 is the annualized cost of the conservation or efficiency investment. Dividing annualized cost by annual energy savings yields the CCE, which is independent of, but can be compared with, the levelized price of fuel (in dollars per liter). More details on such calculations are given by Meier et al. (*16*) and Koomey et al. (*17*).

Consumer Choice Models

There is some controversy over the procedure that consumers actually use to choose the efficiency level of the automobiles they purchase. Greene (*18*), in a review of such decision algorithms, summarizes this controversy. The main issue of contention concerns the multifaceted nature of the purchase decision. Usually, the choice between vehicles is based on many decision criteria, most of which are unrelated to the efficiency of the vehicle. The use of a CCE model (or, equivalently, a life cycle cost model) to describe such choices is problematic in that it is a simple measure that does not address the complexity of the purchase decision.

Whereas this issue is important in assessing consumer choices over a broad range of vehicle types, it does not significantly affect our analysis. We have, to a first approximation, created a comparison between vehicles that have different fuel economy but are otherwise equivalent in terms of size, features, performance, and safety. For this reason, we believe that it is appropriate to discuss choices between these vehicles as if consumers were actually using a discount rate in a CCE calculation.

Discount Rate

The discount rate in our calculations is 7 percent real. This value roughly corresponds to the current cost of capital for consumers seeking an automobile loan (11 to 12 percent with inflation). We also perform a sensitivity analysis using real discount rates of 3, 10, and 30 percent. The results of the sensitivity analysis are described by Koomey et al. (2).

Miles Driven

We use an estimate of 16 400 km (10,200 mi) traveled per year for a typical U.S. automobile in 1988 [Davis and Morris (*19*)]. The source cited by Davis and Morris is the U.S. Department of Energy's Residential Transportation Energy Consumption Survey.

Rebound Effect

Greene (*20*) suggests, after reviewing the literature, that consumers will increase their vehicle miles traveled by 0.05 to 0.15 percent in response to a 1 percent decrease in the fuel cost per mile of their vehicles. We omit this factor in calculating the CCE, because if consumers use their vehicles more, the increased mobility must be worth more to them than the increased expenditure on gasoline. Therefore, our per unit cost-effectiveness calculation is unaffected by such rebound.

If one is interested in calculating total energy savings from a given policy affecting many such vehicles, this correction factor must be included. We do not make such a calculation here. In any case, the correction is a small one.

Vehicle Lifetime

We use an estimate of automobile lifetime of 13.3 years derived from a retirement curve for vehicles presented Davis and Morris (*19*). This curve applies to vehicles purchased between 1987 and 1989. We assume that the fuel economy improvement technologies used in the VX will not affect the vehicle lifetime.

Rated Fuel Economy

Fuel economy estimates based on the EPA test procedure have been found to diverge from actual performance. This divergence was significant enough to induce EPA to reduce the sticker fuel economy relative to the test procedure values to better account for real-world driving conditions. Beginning in 1985, EPA reduced the city fuel economy estimates from the test procedure by 10 percent and reduced the highway estimates by 22 percent to calculate the fuel economy rating on the sticker. This correction is important, because if actual miles per gallon (mpg) is lower than the rated mpg, using the rated mpg to calculate gasoline savings will underestimate those savings in absolute terms.

We use the city and highway fuel economy as listed on the EPA sticker for each car, which includes the preceding correction factors. We weight the city and highway fuel economy sticker values to estimate composite fuel economy for our cost-effectiveness calculations. This weighting assumes that 55 percent of driving is city driving and 45 percent is highway driving, as specified in Section 503 of the Energy Policy and Conservation Act passed in 1975.

Consistency of Comparison

All fuel prices and capital costs are in 1992 dollars. We use a real discount rate (without inflation) to levelize the prices and the same real discount rate to calculate the CCE. The comparison between the initial capital expense and the levelized fuel price is therefore consistent.

Fuel Prices

Average motor gasoline prices are taken from the *Annual Energy Outlook* (*21*) and are levelized using a 7 percent real discount rate [using the method of Kahn (*22*)]. According to the forecast, the retail price of motor gasoline will be $0.34/L

($1.27/gal) in 1992 and $0.43/L ($1.61/gal) in 2005 (in 1992 dollars, calculated assuming 4 percent inflation for 1990 to 1992). Levelized over this period (which corresponds to the lifetime of our Honda Civic purchased in 1992), the price of gasoline is $0.37/L ($1.40/gal).

This price includes roughly $0.07 to $0.08 per liter ($0.25 to $0.30 per gallon) of state and federal gasoline taxes, which are used primarily to fund highway construction and maintenance. Society does not avoid the construction and upkeep of roads if automobiles are more efficient, so a societal cost comparison should not include these costs in the avoided cost of fuel. This price also does not include the external costs associated with gasoline combustion, many of which are reduced by a more fuel-efficient car.

We show comparisons with the levelized fuel price with and without taxes. The case with taxes provides an understandable reference point and represents the situation in which avoidable external costs roughly equal the level of state and federal taxes. The case without taxes represents the situation in which external costs are assumed to be equal to zero.

Operation and Maintenance Costs

We assume that operation and maintenance (O&M) costs for the VX are unaffected by the technologies used to achieve improved fuel economy. Thus, we assume that lifetime O&M costs for the 1991 and 1992 DX models and for the 1992 VX are identical.

Invoice Cost Versus Manufacturer's Suggested Retail Price

Invoice cost is also known as dealer cost. It is the average price charged to the dealer by the automobile manufacturer. Manufacturer's suggested retail price (MSRP) is also known as sticker price and is supposed to represent the price of the car to the consumer. In this analysis, we rely on MSRP as an "official" price. The invoice costs are reported by Koomey et al. (*2*). The invoice cost and MSRP are taken from USAA (*5,6*) and documents from a local Honda dealer. The invoice cost and MSRP for the 1991 DX have been adjusted to 1992 dollars, assuming 4 percent inflation.

The MSRP is somewhat arbitrary. Good bargainers have been known to purchase automobiles at or below the invoice cost. Automobile manufacturers also give "volume incentives" to dealers that sell more than a target number of cars. Therefore, invoice cost and MSRP based on the sale of a single car may not actually reflect the true cost to the dealer.

Does Retail Price Reflect True Cost?

Automobile pricing is a complicated process, and the market price of a vehicle may have little to do with actual production costs. For example, antilock braking systems provided as an option on many cars are currently underpriced on the vehicle "sticker" to encourage the purchase of these safety-enhancing mechanisms (L. Rinek, personal communication). Some of the redesign costs for the new Civics are probably included in the MSRP, as are any savings from the redesign. Without detailed manufacturer data, we cannot determine the extent to which such cost changes are related to fuel economy improvements alone. We also cannot know whether Honda is taking a loss on the VX because it wants to gain experience with new technology in anticipation of growing demand for efficiency in a more environmentally conscious world.

We do not have access to Honda's cost data, and we cannot determine the manufacturer cost for improving the fuel economy in the Honda Civic hatchbacks. Nevertheless, we believe that the MSRP offers an approximate representation of the actual cost of improving automobile fuel economy in these vehicles.

Air Bags

The 1992 Civics both have airbags, whereas the 1991 DX does not. Except for a minor weight penalty, air bags are unrelated to fuel economy, and their cost should not be included in our assessment of the incremental cost associated with improving the efficiency of the 1991 DX. The MSRP cost of an air bag is $800 in a new Honda Civic and $1,200 to replace an air bag that has been "blown" in a collision (R. Maio, personal communication). We subtract $800 from the MSRP cost of the 1992 DX and VX to correct for this added cost.

Correction for Cosmetic Differences

The cargo cover is available as an option on the VX for $159. Costs for the other cosmetic differences can only be roughly estimated on the basis of estimates by the parts department of a local Honda dealer.

We add the average cost of hatch cover, body side molding, and rear wiper/washer to the cost of the VX (no correction is made for the cost of the adjustable steering column, since the costs of replacing the steering columns in the DX and the VX are the same). We add the midrange cost of the tachometer and half the cost of the alloy wheels to the price of the 1991 and 1992 DX. Only half the cost of the alloy wheels is added to the DX price because some fraction of their cost is attributable to their lower weight and the rest is attributable to their "sporty" appearance. We choose half arbitrarily, since we had no way to separate these two attributes of the wheels.

These cosmetic differences result in an additional MSRP cost of $365 on both DX models and $614 on the VX. By correcting for cosmetic differences and for the air bag, we have created a consistent comparison and can draw conclusions about the actual cost to improve the efficiency of the 1991 DX to the level of the 1992 VX. These corrections result in what we refer to as our "full correction" case, which represents our best estimate for the retail price of the fuel economy improvements in the VX compared with the DX.

Although these cost corrections make the comparison more consistent, they should be viewed as approximate for three reasons:

1. Actual costs for these options are speculative, since the features available on the VX are not available on the DX, and vice versa.

2. Actual production costs for standard features may be quite different from the costs for installing such features as options after the car is manufactured.
3. Separating the cost of the alloy wheels attributable to cosmetic differences from that attributable to fuel economy is problematic.

To account for the fact that some options are not available on specific models in the showroom, we also show a comparison between the 1992 DX and the 1992 VX that only corrects for the feature that is actually an option—the hatch cover. We refer to this case as the "as available" comparison.

Comparison of Estimated Technology Costs with Retail Cost Difference

When we compare the estimated costs of fuel economy technologies (Table 2) with the retail cost difference calculated after making the corrections described above, we see that the results are similar. The mean of the engineering cost estimates for the VX efficiency improvements (Table 2) is $766, whereas the cost difference between the 1991 DX and the 1992 VX in Table 3 (based on the "full correction" case) is $726. In view of the rather large range of error to be expected in such a comparison, we can conclude that the engineering costs and our retail cost calculation give roughly the same result, which gives us confidence that our calculations are of the correct approximate magnitude.

COST-EFFECTIVENESS OF FUEL ECONOMY TECHNOLOGIES

Cost of Improving 1991 DX Efficiency to 1992 DX and VX Levels

In this calculation, we estimate the cost of improving fuel economy of the 1991 Honda Civic DX to the levels of the 1992 Civic DX and VX. This information can be used to determine whether the fuel economy of a particular vehicle can be improved substantially at a cost less than the cost of fuel, while keeping vehicle amenity constant and without reducing safety.

Table 3 gives the results of this calculation. The MSRP cost of an air bag ($800) has been subtracted from the cost of the 1992 Civics, which makes the 13 percent efficiency improvement for the 1992 DX achievable at negative net cost. Engine torque also increased relative to the 1991 DX in this case. This result implies that Honda improved the fuel economy and power of this vehicle while reducing its initial cost.

After subtracting the cost of the air bag, the additional incremental cost for the VX over the 1991 DX is $477. The correction for cosmetic differences increases the incremental cost of moving from the 1991 DX to the 1992 VX by $249, giving a total incremental cost for the VX of $726. This $726 cost translates to a CCE of $0.20 per conserved liter ($0.77 per conserved gallon), which is about 45 percent less than the levelized price of gasoline with taxes and 30 percent less than the price without taxes. This CCE corresponds to a simple

TABLE 3 Cost of Conserved Gasoline for 1992 Honda Civic DX and VX Hatchbacks

				Changes in fuel economy, fuel use, and capital costs			
	91 DX	*92 DX*	*92 VX*	*Costs Fully Corrected 91DX to 92DX*	*Costs Fully Corrected 91DX to 92VX*	*Costs As Available 92DX to 92VX*	*Costs Fully Corrected 92DX to 92VX*
EPA fuel economy estimates							
Adjusted liters/100 km (city)	7.6 (31)	35	48	*13%*	*55%*	*37%*	*37%*
Adjusted liters/100 km (highway)	6.7 (35)	40	55	*14%*	*57%*	*38%*	*38%*
Adjusted liters/100 km (EPA composite)	7.2 (32.7)	37.1	50.9	*13%*	*56%*	*37%*	*37%*
Fuel used (liters/year)	1181	1041	757	-140	-424	-284	-284
MSRP cost (92 $)	9563	10140	10840	577	1277	700	700
MSRP cost adjusted for airbag+cosmetic diffs (92 $)	9928	9705	10654	-223	726	859	949
Annualized incremental MSRP cost ($/year)	1170	1144	1256	-26	86	101	112
CCE based on MSRP cost (92 $/liter)				< 0	0.20 (0.77)	0.36 (1.36)	0.40 (1.50)
Simple payback time-MSRP & gas price w/tax (yr)				< 0	4.6	8.2	9.0
Simple payback time-MSRP & gas price w/o tax (yr)				< 0	5.9	10.4	11.5
Other parameters							
Real discount rate	7%	Distance driven/year (km)				16415 (10200)	
Auto lifetime (years)	13.3						
Capital recovery factor	11.8%	MSRP cost of airbag (1992 $)				800	
City driving percentage	55%	Levelized cost of gasoline w/taxes (92$/liter)				0.37 (1.40)	
Highway driving percentage	45%	Levelized cost of gasoline w/o taxes (92$/liter)				0.29 (1.10)	

Source: Reference (2).
English units given in parentheses. Fuel economy: mi/gal; fuel used: gal; CCE: 92$/gal; distance driven: mi; cost of gasoline: 92$/gal.

payback time of about 4.6 years using MSRP and including taxes in the gasoline price and to 5.9 years when taxes are omitted.

Cost of the Consumer's Choice: 1992 DX Versus 1992 VX

We also investigate the actual efficiency choice available to consumers on the showroom floor (1992 DX versus 1992 VX). We show two cases: (*a*) the "as available" case, which corrects only for the cost of the hatch cover in the VX, and (*b*) the "full correction" case, which uses the cost estimates for all the cosmetic differences. Table 3 gives the results of this calculation, which indicates that the CCE relative to the 1992 DX (based on MSRP) is comparable with the levelized price of gasoline with taxes and roughly 25 to 30 percent higher than the levelized price of gasoline without taxes. This CCE corresponds to a simple payback time of 8 to 11 years depending on the treatment of taxes and cosmetic differences. These paybacks are long enough to make consumers think twice about spending the extra money for the VX.

Limitations of Cost-Effectiveness Calculations

These calculations were done without accounting for external societal costs. External costs include all costs to society that are not included in the market price of gasoline, such as increased health costs; costs arising from damage to agriculture; costs resulting from damage to physical structures due to air pollution from automobiles; increased national security costs from consumption of imported oil; and increased environmental damage from acid rain, carbon dioxide emissions, and other pollutants. In practice, exact numerical values for these externalities are difficult to calculate (*23*). Many authors have attempted to assess these costs in monetary terms, and in general they find that such costs are probably substantial (*24–29*). We do not estimate these costs here but simply note that accounting for them would improve the relative cost-effectiveness of efficiency improvements compared with the consumption of gasoline alone.

POLICY IMPLICATIONS

The range of issues surrounding policies designed to affect vehicle efficiency choices are too complex to describe in detail here and are described elsewhere (*30,31*). Our purpose in this section is to summarize the most important policy-related conclusions emerging from our work. These conclusions are described more fully by Koomey et al. (*2*).

Implications for Society

We have shown that improving the fuel economy of a particular vehicle (the 1991 Civic DX) was not only possible, it was cost-effective from society's perspective. The efficiency improvements in the 1992 Civic VX were achieved at a CCE that is about 45 percent less than the levelized cost of gasoline with taxes and 30 percent less than the levelized cost of gasoline without taxes (relative to the 1991 DX). This empirical evidence indicates that, at least for small cars similar to the Civic, improvements in fuel economy can be achieved at attractive costs.

Implications for Consumers

The 1992 Civic DX and VX deliver comparable performance, but the VX delivers higher fuel economy at a CCE that is comparable with the avoided cost of fuel. A consumer deciding between these two vehicles will have little, if any, direct economic incentive to choose the VX, although the United States as a whole might prefer the lower carbon dioxide emissions and reduced use of imported oil of the more efficient vehicle. According to estimates from Honda Corporation, about 5 percent of 1992 Civic sales were VXs (*32*).

Need for Public Policy

Because consumers have little economic incentive to purchase the more fuel-efficient vehicle, public policy is required to ensure that socially beneficial choices are made regarding fuel economy. Policies such as gas taxes and feebates (which impose fees on purchases of gas guzzlers while providing rebates for purchases of fuel-efficient vehicles) would make the VX more cost-effective relative to the DX for consumers. Thus, consumers would have incentive to act in a manner that benefits society.

CONCLUSIONS

Honda has demonstrated that modest efficiency improvements (13 percent) can be achieved at negative net cost in its 1992 Civics. Efficiency improvements of 56 percent can be achieved at a CCE that is 45 percent less than the cost of the saved gasoline with taxes and 30 percent less than the cost of the saved gasoline without taxes. Virtually all of the fuel efficiency improvements in the 1992 Civic VX were achieved using technologies that do not change safety or vehicle amenity. These results suggest that the difficulty and cost of improving fuel economy in new compact and subcompact automobiles may be less than has been suggested by U.S. automobile makers.

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Differences Between EPA-Test and In-Use Fuel Economy: Are the Correction Factors Correct?

MARIANNE MINTZ, ANANT D. VYAS, AND LESTER A. CONLEY

A vehicle's in-use or on-the-road fuel economy often differs substantially from the estimates developed by the U.S. Environmental Protection Agency (EPA) as part of its emissions certification program. As a result, the certification values are routinely adjusted by a set of correction factors so that the resulting estimates will better reflect in-use experience. Data from the Residential Transportation Energy Consumption Survey conducted by the Energy Information Administration of the U.S. Department of Energy were used to investigate how well the correction factors replicated the shortfall experience of all household vehicles on the road in 1985. Results indicate that the shortfall is larger than the EPA correction factors, and light trucks are experiencing significantly larger shortfalls than automobiles.

The 1970 amendments to the Clean Air Act established a Federal Test Procedure (FTP) to determine the exhaust hydrocarbon and carbon monoxide emissions of new light-duty vehicles over a prescribed driving cycle. The test procedure, both originally and as modified in 1975, is run on a chassis dynamometer and is based on a transient cycle representative of driving patterns in Los Angeles (the LA-4 cycle) in the early 1970s. Since 1973, fuel economy has also been calculated from the quantity and composition of the exhaust gas produced (*1*). Three fuel-economy ratings are derived from the FTP. Urban fuel economy is calculated from one portion of the FTP, highway fuel economy is calculated from another, and a composite fuel economy rating is computed as the harmonic mean (55 percent urban and 45 percent highway) of the two.

Since the late 1970s, the difference, or shortfall, between the EPA test and in-use fuel economy has been recognized by the motoring public and documented in various panel surveys (*2–4*). Whereas shortfalls varied by the year, make, and model of vehicle, it nevertheless became clear that a general pattern existed, and some type of adjustment was needed to maintain consumer confidence in the validity of the EPA estimates on new car labels and in the *Gas Mileage Guide*. Thus, in 1985, EPA officially acknowledged the shortfall and adopted a set of across-the-board correction factors based on earlier panel survey results for various model years and vehicle nameplates (*5*). These correction factors reduced urban fuel economy estimates by 10 percent, highway fuel economy estimates by 22 percent, and composite fuel economy estimates by 15 percent for all new vehicles. Since 1985, only the adjusted values have been reported in the *Gas Mileage Guide* published annually by EPA and the Department of Energy (DOE) (*1*).

The correction factors are intended to account for physical differences between real-world conditions and dynamometer tests like those performed by EPA. These differences include such random variables as driver behavior, maintenance practices, tire inflation, vehicle loads, weight distribution, type and condition of road surfaces, weather conditions, altitude, accessory loads, and variability within the test procedure itself. Weight distribution affects how well the rolling resistance of two tires on the dynamometer rolls can approximate that of four tires on the road. Generally speaking, these differences cannot be eliminated by revising the test procedure.

METHODOLOGY

Since the correction factors are based on surveys of in-use fuel economy conducted in the late 1970s and early 1980s, two questions arise:

1. Are shortfalls stable over time?
2. Do shortfalls vary for particular vehicles or groups of vehicles?

The answers to these questions have very different implications. If the random variables responsible for shortfalls are stable over time, we can continue to use the original correction factors to forecast fuel consumption. However, if underlying variables are changing in some systematic way, or if different vehicles are experiencing disproportionate shortfalls, development of vehicle- or size-specific factors may be advisable, along with periodic reexamination and revision of correction factors.

DATA

Two data sets were merged to investigate the above questions: the 1985 Residential Transportation Energy Consumption Survey (RTECS) and the Oak Ridge National Laboratory (ORNL) MPG and Market Shares data base (*6–9*). The 1985 RTECS is the most recent large-scale survey of in-use vehicle fuel economy. It contains fuel purchase diaries on 8,401 vehicles in 3,981 households and documents approximately 15,000

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fuel purchases during the survey year. Because of its size and representativeness, the file can be used to estimate travel, fuel consumption, and fuel economy for all household vehicles or particular subgroups of vehicles. Subgroups may be defined on the basis of population characteristics (e.g., residential location or income) or vehicle characteristics (e.g., nameplate, size class, model year, or import versus domestic origin).

ORNL's MPG and Market Shares data base is a PC file documenting new light-duty vehicle sales since model year 1976. Organized by nameplate and vehicle characteristics (e.g., curb weight, wheelbase, engine displacement, interior volume, engine/transmission type, EPA size class, and EPA-test fuel economy), it may be sales-weighted by various classifications. For this analysis, EPA size class and sales-weighted fuel economy values were retrieved from the MPG and Market Shares file for nameplates contained on the RTECS file. A merged file was then created consisting of the original RTECS household and vehicle data, along with the EPA size class and fuel economy codes obtained from the MPG and Market Shares data base.

Of the 8,401 vehicles in the RTECS data base, 6,028 (71.8 percent) are of model year (MY) 1976 or newer. Of these, 4,428 (73.5 percent) were matched to vehicle records in the ORNL MPG and Market Shares data base. Because of miscodes on the RTECS file, some matches were achieved by manually correcting obviously incorrect vehicle type codes (e.g., a 1979 Chevrolet Nova with a vehicle type code of motor home).

RESULTS

As shown in Figure 1, automobiles from the RTECS sample that were matched to MPG and Market Shares data had a fleet average EPA-test fuel economy of 24.9 mpg; light trucks had an EPA-test fuel economy of 20.8 mpg. By contrast, on-the-road experience (as measured by the RTECS fuel purchase diaries) was only 20.2 mpg for automobiles and 16.6 mpg for light trucks. The resulting gap or shortfall of 18.7 percent for automobiles and 20.1 percent for light trucks (shown in Figure 2) is significantly larger than EPA's 15 percent adjustment factor. Transport Canada has also obtained larger shortfalls. As shown in Figure 2, Transport Canada's estimates range from 9.3 to 22.5 percent for 1979–1986 MY automobiles (*10*).

Note that the last set of bars in Figure 1 is estimated by FHWA and applies to all vehicles (household and nonhousehold for all model years) that were in operation in 1985 (*11*). These values are approximately 10 percent lower than the RTECS on-road values for automobiles and 20 percent lower than the RTECs on-road values for trucks. Like RTECS, the FHWA values are computed from fuel sales and vehicle-miles traveled (VMT) and are therefore weighted by relative use. Unlike RTECS, however, FHWA's underlying fuel sales and VMT data include pre-1976 vehicles (which were not matched to the MPG and Market Shares file), commercial and government vehicles, small quantities of fuel used by other kinds of vehicles (e.g., lawn and garden equipment, pleasure boats, or other recreational vehicles), and heavier classes of light trucks (i.e., two-axle, four-tire trucks with gross weights above 10,000 lb).

Shortfall Variability over Time

Although more data are needed for definitive conclusions, shortfalls appear to be rising over time. The 18.7 percent shortfall (3.7 percentage points above the EPA estimate) obtained for automobiles is consistent with findings by Patterson and Westbrook, who project that the shortfall will rise to 29.7 percent by 2010 (*12*). The forces behind their projection—population and driving shifts, long-term trends in urban traffic congestion, and highway speeds—are clearly stronger today than in the late 1970s and early 1980s when the EPA adjustment factors were developed.

1. Population and driving shifts: In 1968, 52 percent of the VMT by automobiles occurred in urban areas (*11*). By 1991,

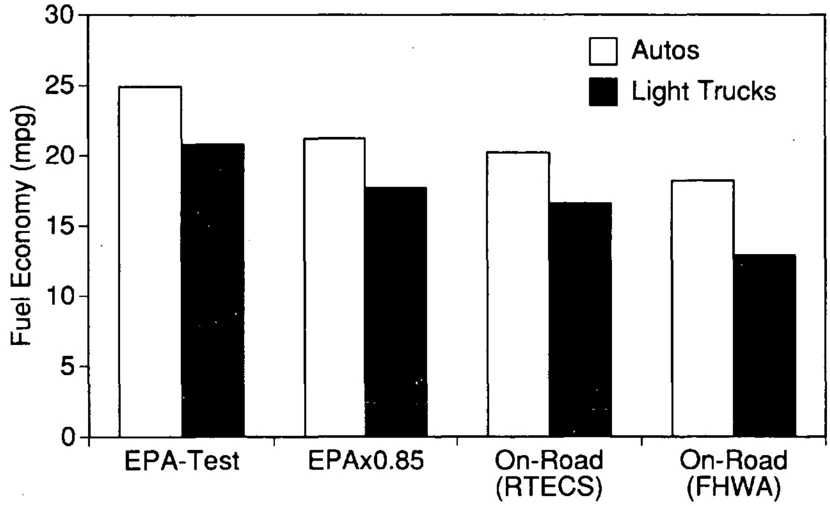

FIGURE 1 EPA-rated versus on-the-road fuel economy of automobiles and light trucks (1985 fleet average).

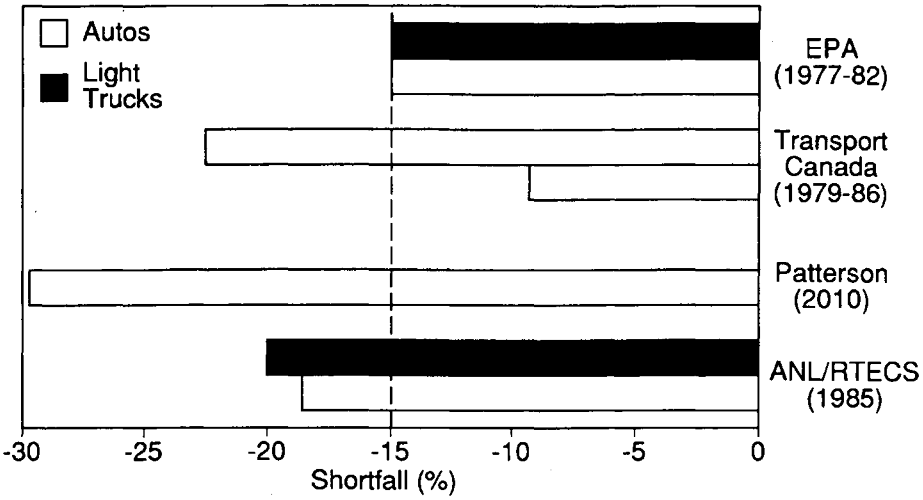

FIGURE 2 Estimates of fuel economy shortfall.

that figure had risen to 62.5 percent (*13*). As the U.S. Bureau of the Census classifies additional localities as "urbanized" or adds outlying areas to existing "urbanized areas," the share of urban vehicle-miles may be expected to grow still further. However, EPA makes no allowance for this continuing shift in the formula used to compute the composite fuel economy rating (which has assumed 55 percent urban and 45 percent rural driving since its inception). Patterson and Westbrook estimate a 0.2 percent increase in shortfall for every 1 percent increase in urban share (*12*). This alone could account for 1.6 of the 3.7 points of additional shortfall found in our analysis.

2. Traffic congestion: Roadway supply is measured in terms of lane miles, computed as road mileage times the number of traffic lanes. Traffic is measured in terms of vehicle miles, computed as the volume of traffic on a particular road segment times the length of that segment. Between 1975 and 1987, the supply of urban roadway rose 14.6 percent, while urban traffic rose 57.4 percent (*13*). As a result, the throughput, or traffic load, on urban roadways increased 38.9 percent (from 1.13×10^6 to 1.57×10^6 vehicle-miles/lane-mile). Whereas not all of this additional load produced congestion, it may be considered a reasonable upper bound. If all our observed shortfall were attributed to population shifts, congestion, and increased highway speeds (see below), the increase in urban congestion would account for 1.2 of the 3.7 points of additional shortfall.

3. Highway speeds: Between 1976 and 1991, the percentage of traffic exceeding 55 mph rose from 69 to 75.5 percent on rural Interstate highways and from 57 to 69.8 percent on urban Interstate highways (*11,13*). Most of these increases occurred in the higher speed range (i.e., vehicles traveling above 65 mph rose from 5 to 18 percent for urban Interstate traffic and from 10 to 20.9 percent for rural Interstate traffic). McGill has documented a 0.2 percentage point decline in fuel economy for every 1-mph increase in speed between 55 and 60 mph and a 0.35 to 0.4 percentage point decline in fuel economy for every 1-mph increase in speed between 60 and 66 mph (*14*). Patterson and Westbrook have estimated that increased highway speed accounts for 0.8 percentage points of additional shortfall (*12*).

Because the RTECS file is cross sectional, it can provide indications but no definitive proof of a rising trend in shortfalls. The file can be used to determine whether shortfalls are greater for vehicles that are driven fewer annual miles but not for vehicles with specific duty cycles. Presumably, low-utilization vehicles have a greater proportion of travel on short trips, without a fully warmed engine, or under congested conditions. All things being equal, either of these characteristics would tend to increase shortfalls. To test this hypothesis, the file was sorted into five mileage categories: under 5,000, 5,000 to 9,999, 10,000 to 14,999, 15,000 to 19,999, and 20,000 and over. Shortfalls were then computed and compared with the EPA correction factor. Differences between actual shortfalls and the EPA correction factor were insignificant for automobiles and light trucks driven 15,000 mi/year or more. For automobiles and light trucks driven fewer annual miles, the differences were highly significant (prob $|t| < 0.001$). Although it is indirect, the finding that shortfalls decline with increasing vehicle utilization provides further evidence that congestion and urban travel are behind much of the increasing trend in shortfalls.

Shortfall Variability Across Different Vehicles or Groups of Vehicles

Vehicle Type and Size

In the absence of major differences in materials composition or technology, fuel economy is inversely related to vehicle mass or size. In other words, for vehicles of comparable technology, the heavier the vehicle, the fewer miles it can travel on a gallon of fuel. For example, in Table 1 RTECS or on-road fuel economy drops from an average of 22.8 to 17.8 mpg and then to 15.2 mpg for small, mid-sized, and large automobiles, respectively.

The relationship between shortfall and vehicle size is less clear-cut. From an engineering perspective, one should expect little or no variation by vehicle type or size class. Our results confirm that shortfalls appear to be stable across size classes,

TABLE 1 EPA Test Versus On-the-Road Fuel Economy and Percentage Shortfall or Gap by Vehicle Type, Size Class, Model Year, and Origin

	Domestic Vehicles			Imported Vehicles			All Vehicles		
Vehicle Type, Size Class and Model Year (MY)[a]	RTECS (mpg)	EPA (mpg)	Gap (%)	RTECS (mpg)	EPA (mpg)	Gap (%)	RTECS (mpg)	EPA (mpg)	Gap (%)
Auto	18.6	23.2	-19.8[c]	26.1	30.9	-15.6	20.2	24.9	-18.7[c]
1983-1985 MY	21.2	26.6	-20.2	27.1	32.6	-17.1	22.7	28.1	-19.4[c]
1978-82 MY	18.3	22.8	-19.8	26.1	30.4	-14.1	20.1	24.5	-18.2[c]
Pre-1978 MY	14.6	18.0	-18.8	22.6	27.2	-17.1	15.7	19.3	-18.4[c]
Small	20.7	26.1	-20.9[c]	26.1	31.0	-15.6	22.8	28.0	-18.6[c]
1983-1985 MY	23.9	30.4	-21.4[c]	27.1	32.7	-17.1[c]	25.3	31.4	-19.5
1978-82 MY	20.9	26.4	-20.9[c]	26.1	30.4	-14.2	23.2	28.2	-17.6
Pre-1978 MY	15.7	19.5	-19.6[c]	22.6	27.3	-17.1	17.1	21.1	-19.0
Mid-Size	17.8	22.1	-19.5[c]	[b]	[b]	[b]	17.8	22.1	-19.5[c]
1983-1985 MY	20.2	24.9	-19.1[c]	[b]	[b]	[b]	20.1	24.9	-19.2
1978-82 MY	17.3	21.5	-19.8[c]	[b]	[b]	[b]	17.3	21.5	-19.6
Pre-1978 MY	13.2	16.4	-19.3[c]	[b]	[b]	[b]	13.3	16.4	-19.0
Large	15.2	18.3	-16.9	[b]	[b]	[b]	15.2	18.3	-16.9
1983-1985 MY	16.9	20.8	-18.8	[b]	[b]	[b]	16.8	20.7	-18.9
1978-82 MY	14.9	17.7	-15.6	[b]	[b]	[b]	14.9	17.7	-15.6
Pre-1978 MY	13.3	15.8	-15.9	[b]	[b]	[b]	13.5	16.0	-16.0
Lt. Truck & Van	15.9	19.8	-19.5[c]	20.2	26.1	-22.4[c]	16.6	20.8	-20.1[c]
1983-1985 MY	17.3	21.1	-18.1[c]	20.5	26.7	-23.0[c]	17.8	22.1	-19.2[c]
1978-82 MY	14.8	18.6	-20.3[c]	19.7	25.4	-22.5	15.6	19.7	-20.7[c]
Pre-1978 MY	13.3	17.5	-24.3	20.9	24.7	-15.5	13.9	18.1	-23.2[c]
Compact	19.7	25.1	-21.4[c]	19.8	26.1	-23.9[c]	19.7	25.4	-22.1
1983-1985 MY	19.4	24.7	-21.6[c]	20.0	26.8	-25.7[c]	19.5	25.2	-22.5
1978-82 MY	20.7	26.2	-20.9[c]	19.7	25.4	-22.5	20.3	25.9	-21.5
Pre-1978 MY	21.1	25.7	-18.0	20.6	25.8	-20.3	20.8	25.8	-19.3
Standard	13.7	16.6	-17.8[c]	21.3	26.1	-18.3	14.3	17.3	-17.9[c]
1983-1985 MY	14.8	16.8	-12.0	21.3	26.4	-19.2	15.9	18.4	-13.7
1978-82 MY	13.1	16.4	-19.9[c]	[b]	[b]	[b]	13.1	16.4	-19.9
Pre-1978 MY	12.8	17.1	-24.8[c]	[b]	[b]	[b]	13.2	17.3	-23.9

[a] Ages correspond to: 0 to 3 yrs, 4 to 8 yrs, and over 8 yrs.

[b] N < 10.

[c] Prob |t| <0.01.

but not across vehicle types. As was shown in Figure 2, a 20.1 percent shortfall was observed for light trucks and vans, compared with 18.7 percent for automobiles in the RTECS sample. The difference in shortfall between automobiles and trucks was statistically significant (prob $|t| < 0.0001$; $N = 3{,}770$ automobiles, 579 trucks). Furthermore, shortfalls for both automobiles and light trucks were significantly greater than the EPA adjustment factor. When desegregated by size class, shortfalls were also significant for all but large automobiles.

Large automobiles account for a decreasing share of light-duty vehicles and the fuel consumed by them. Thus, their relatively smaller shortfall may be another factor behind the trend toward increasing fleet-average shortfalls.

Vehicle Age

For the most part, automobile and truck shortfalls did not rise with increasing age. Standard (i.e., full-sized) trucks were a key exception (Table 1), rising from 13.7 percent for vehicles under 3 years old to 24.8 percent for vehicles more than 8 years old. This suggests that differences in duty cycle and maintenance practices may account for at least some of the additional shortfall. Quite likely, a greater proportion of older trucks are in off-road operation (e.g., on farms, at construction sites, or in mining) or improperly maintained, either of which could significantly degrade fuel economy. Since the average age of the vehicle fleet has been rising and trucks are accounting for an increasing share of light-duty vehicles, the factors responsible for the relatively greater shortfall of older trucks may become increasingly relevant to predicting trends in the shortfalls of all light-duty vehicles.

Note that variations in shortfall by vehicle age were not significant when vehicles were also categorized by annual mileage. This is to be expected, since mileage or vehicle utilization is highly correlated with age (Figure 3).

Vehicle Origin

Another factor affecting shortfalls was vehicle origin. Domestic automobiles had an average shortfall of 19.8 percent, whereas imported automobiles had an average shortfall of 15.6 percent. For light trucks, the reverse was true: domestic trucks had a 19.5 percent average shortfall, whereas imported trucks had a 22.4 percent average shortfall. For all but im-

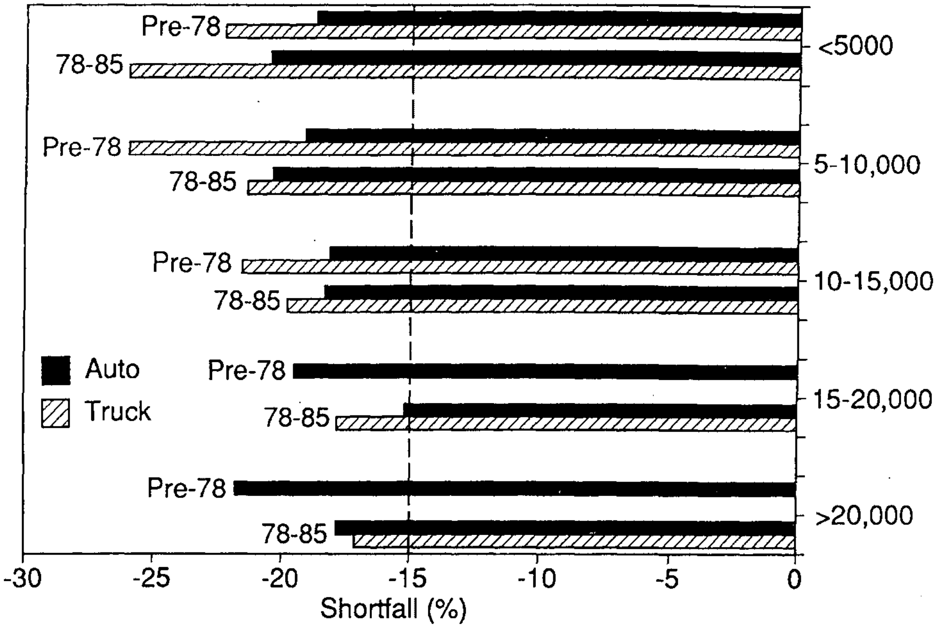

FIGURE 3 Fuel economy shortfall by vehicle type, vintage group, and annual mileage.

ported automobiles, shortfalls were statistically significant. For small domestic automobiles and standard trucks, shortfalls tended to decline with age. Imports exhibited no such pattern. Import shortfalls were also less likely to vary by annual mileage (Table 2).

Vehicle Nameplate

Results indicate that shortfalls exceed the EPA correction factor for all vehicle types, most sizes, both domestic and foreign makes, and for all except high levels of utilization. On an aggregate level, shortfalls are relatively stable. Are they equally stable on a desegregate level? To answer this question, the RTECS file was searched by nameplate. Sample size limitations precluded the investigation of model years within those nameplates (however, since all RTECS-matched vehicles were post-1976, the effect of model year should have been somewhat reduced). The largest discrete samples were obtained for Olds Cutlass ($N = 230$), Chevy Chevette ($N = 122$), Chevy Malibu ($N = 101$), and Buick Regal ($N = 96$). The resulting EPA-test, EPA-corrected (test × 0.85), and RTECS fuel economy values are shown in Figure 4. Again, shortfalls generally exceeded the EPA correction factor (Cutlass, prob $|t| < 0.0001$; Chevette, prob $|t| < 0.01$; Malibu, prob $|t| < 0.05$; Regal, prob $|t| < 0.1$).

IMPLICATIONS

In 1990, the total shortfall obtained from this analysis (i.e., 18.7 percent for automobiles and 20.1 percent for light trucks)

TABLE 2 EPA Test Versus On-the-Road Fuel Economy and Percentage Shortfall or Gap by Vehicle Origin and Annual Mileage

	Domestic Vehicles			Imported Vehicles			All Vehicles		
Size Class and Annual Mileage	RTECS (mpg)	EPA (mpg)	Gap (%)	RTECS (mpg)	EPA (mpg)	Gap (%)	RTECS (mpg)	EPA (mpg)	Gap (%)
Auto									
<5,000	18.1	23.2	-21.9[a]	24.9	30.2	-17.6	19.4	24.6	-20.9[a]
5,000-9,999	17.7	22.5	-21.2[a]	24.9	30.1	-17.2	19.2	24.0	-20.2[a]
10,000-14,999	18.7	23.3	-19.6[a]	26.1	31.0	-15.8	20.6	25.3	-18.5[a]
15,000-19,999	20.1	24.1	-16.6	28.8	32.4	-11.2	21.9	25.8	-15.2
20,000+	21.4	24.4	-12.5	29.4	33.1	-10.9	23.6	26.8	-12.0
Lt. Truck & Van									
<5,000	14.3	20.0	-28.7[a]	20.8	26.1	-20.3[a]	15.1	20.7	-27.4[a]
5,000-9,999	14.9	19.2	-22.4[a]	20.1	26.6	-24.6[a]	15.8	20.5	-22.9[a]
10,000-14,999	16.6	20.2	-18.1[a]	21.1	26.0	-19.1	17.4	21.3	-18.3[a]
15,000-19,999	17.7	20.4	-13.2	22.7	26.0	[b]	18.6	21.4	-13.1
20,000+	18.0	19.1	-5.8	15.1	25.0	[b]	17.6	19.8	-11.0

[a] Prob |t| <0.01.
[b] N < 10.

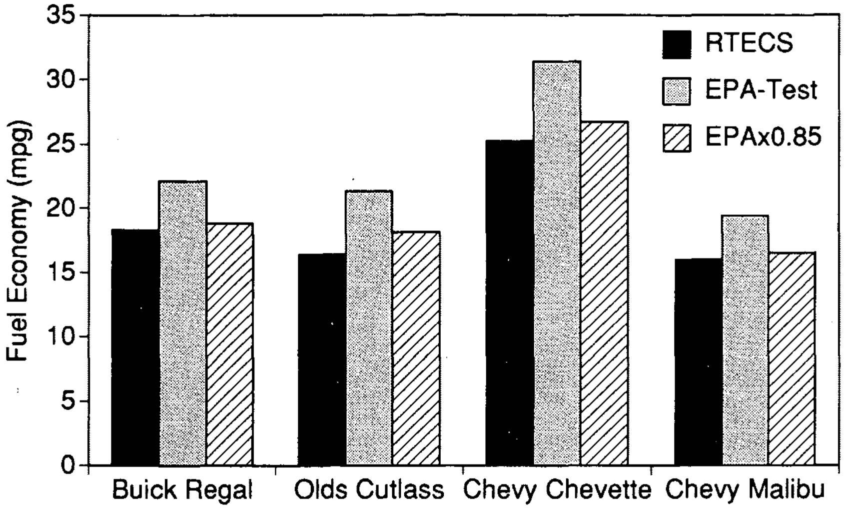

FIGURE 4 EPA-rated versus on-road fuel economy of four popular vehicle nameplates.

increased fuel consumption in the transportation sector by 2.3 quads, whereas that portion of the shortfall in excess of EPA's 15 percent estimate (i.e., 3.7 percent for automobiles and 5.1 percent for light trucks) increased consumption by 0.6 quads. Given the relationships discussed above, 55.5 percent of the current excess shortfall (0.3 quads) may be because of traffic congestion and speeding (either or both of which could be improved through more effective traffic control methods, transportation demand management strategies, congestion pricing, and speed enforcement programs). Even the remaining 44.5 percent of "excess" shortfall (0.3 quads) may be amenable to government intervention through improved control over land use, more effective transportation demand management (especially mode shift strategies), and more aggressive development policies (e.g., graduated taxes on new development to encourage densification and reduce urban sprawl). Because shortfalls are increasing over time, potential fuel savings could easily triple by 2010.

As discussed above, population and driving shifts, traffic congestion, and highway speeds are the primary factors behind increasing shortfalls. They are also key factors affecting vehicle emissions. Thus, it is quite likely that actual emission rates (as well as the degradation factors assumed in such models as MOBILE5) are larger than test values. The EPA is currently investigating this issue as part of its review of the FTP. Preliminary results from that effort indicate that the FTP simulates a more conservative cycle than is typical of most urban driving. In other words, vehicles in actual traffic tend to experience more extreme conditions (harder accelerations and decelerations and more time at idle and highway speed) than in the FTP, thereby increasing tail pipe emissions and fuel use (*15*).

CONCLUSIONS

This analysis compared EPA-test and on-the-road fuel economy for five vehicle-size classes for two types of vehicles and for four popular vehicle nameplates. Results indicate that (*a*) the shortfall or gap between the two measures of fuel economy is growing, (*b*) light trucks have a significantly larger shortfall than automobiles, (*c*) low-utilization vehicles experience much greater shortfalls than high-utilization vehicles, (*d*) domestic automobiles have a larger shortfall than imported automobiles, and (*e*) imported light trucks have a larger shortfall than domestic light trucks. For modeling and analytical purposes, EPA's 15 percent adjustment factor should be revised upward, and separate factors should be developed for automobiles and light trucks. For policy purposes, actions are less clear. However, programs to reduce shortfalls or to prevent their further growth present major conservation opportunities. Since the bulk of all shortfalls may be attributable to the driving cycle, the scope for reducing shortfalls may be limited to improving traffic flow, enforcing speed limits, increasing cold engine efficiency, and revising the FTP (see the preceding).

Beyond this, shortfalls provide a key policy perspective. At present levels, shortfalls effectively mask actual fuel use. This suggests that strategies like gas guzzler taxes are too coarse (as well as too temporally removed from fuel use) to provide the necessary incentive to conserve fuel. Since the true measure of fuel consumption is fuel purchased, these findings suggest that policies to reduce consumption are best levied at the pump.

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